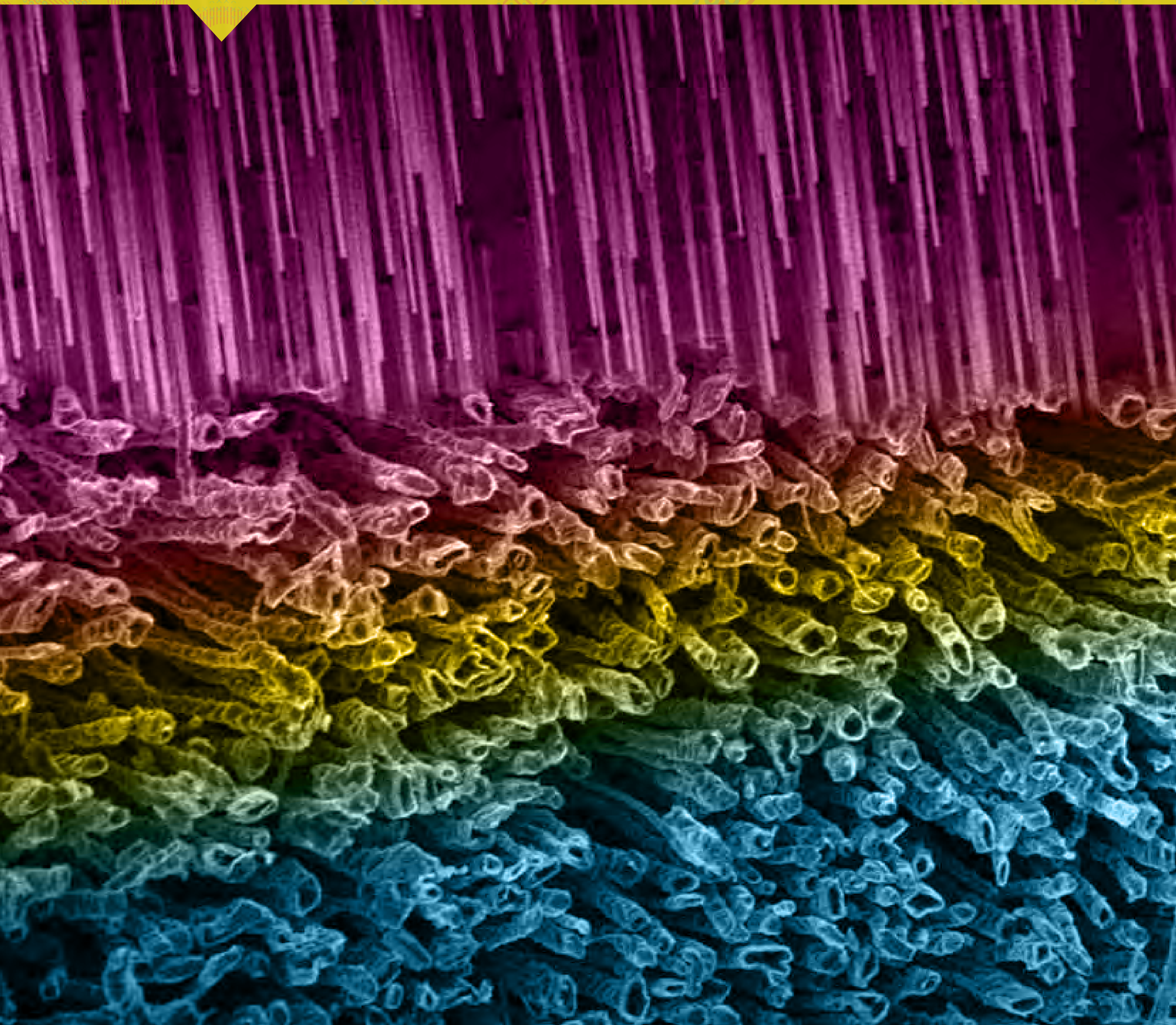
Australian Academy of Science

National Nanotechnology
RESEARCH STRATEGY



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Australian Academy of Science

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SECTION 1

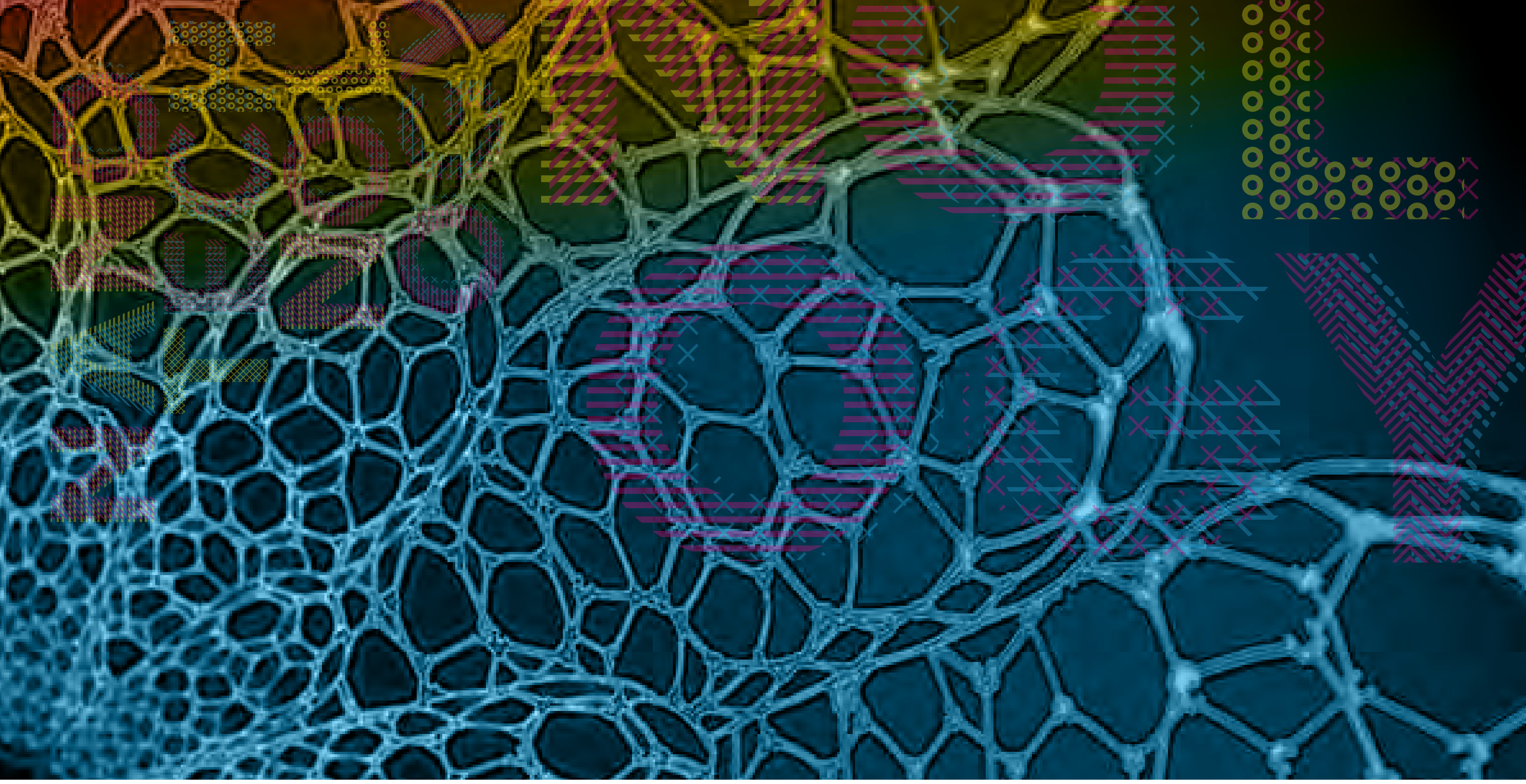
Foreword

Nanotechnology presents amazing opportunities for Australia.

When we consider materials at the nanoscale we can detect novel properties, and it is this novelty that makes nanotechnology research so exciting to researchers and is driving new technology and manufacturing opportunities in all areas of science. Researchers in disciplines as diverse as materials science, physics, chemistry, engineering and medical science are working on materials at the nanoscale, exploiting their novel properties. Nanotechnology research is enabling new technological developments that have the potential to improve our social and economic wellbeing. These range from applications in the clothing and cosmetics industry, to sporting equipment, optical and electronic devices, and public health.

As members of the Academy Council's Executive Committee, we thank the Academy Fellows and other experts who contributed to the preparation of this research strategy. This participation through discipline groups, attendance at workshops or through providing comments on the exposure draft has resulted in a comprehensive research strategy that will steer the direction of nanotechnology research in Australia.

In particular we acknowledge the considerable efforts of the Working Group members, Frank Caruso (Co-Chair), Lorenzo Faraone (Co-Chair), Susan Dodds, Andrew Dzurak, Joanne Etheridge, Julian Gale, Justin Gooding, Lloyd Hollenberg, Jim Williams and Liangchi Zhang. The Oversight Committee, consisting of Gordon Wallace and both of us, provided strategic guidance on the project and reviewed the document. We thank Gordon Wallace and all the experts involved



in developing this research strategy and we appreciate the feedback provided by the nanotechnology and broader community.

This research strategy outlines the most pressing strategic investments in people, in infrastructure, and in leadership that are needed to ensure that Australia remains at the forefront of nanotechnology research and benefits from nanotechnology-led solutions to some of the nation's most pressing challenges in areas such as health, security, environment, sustainable energy and water supplies.

Australia has the opportunity to develop new technologies – technologies that will be the new industries of tomorrow. We have a network of scientists undertaking cutting-edge nanotechnology research. Australia has developed outstanding infrastructure to support this research through a series of national investments. We now need to realise the full potential that our scientists and infrastructure have to offer and transform this research into the outcomes and products that have the capacity to improve the quality of life for all. This investment is essential if Australia is to reap the full dividend from its abundant natural resources.

Our special thanks are due to National Emerging Technologies Strategy, DIISRTE for supporting this project, and to Fiona Leves, Peter Thomas and the Science Policy section of the Academy for their efforts on research strategy development.

Professor Chennupati Jagadish FAA FTSE
Secretary (Physical Sciences)

Professor Andrew Holmes AM FAA FRS FTSE
Foreign Secretary

Introduction and vision

Nanotechnology is changing all our lives. It has made a range of new and enhanced consumer products possible such as stain-resistant clothes, clear sunscreens and cosmetics, ever-smaller and more-powerful smart phones and tablets with astounding functionality, and faster computers and communication systems. There are also new processing methods in agriculture and food treatment, stronger construction materials, higher performance sporting equipment, and novel sensors and nanomaterials that can monitor and improve environmental health. Revolutions in medicine such as slow-release pharmaceuticals and targeted drugs for fighting cancer also owe much to breakthroughs in the engineering of materials at the nanoscale. Indeed, nanotechnology has enriched the lives of all Australians over the past decade and this trend will continue to accelerate rapidly into the future.

Australia's nanotechnology research is at the forefront of many aspects of this broad discipline area, covering not only the fundamental end of the spectrum but also in selected strategic areas that underpin applications.[1] Research has already led to significant commercialisation in diverse areas of manufacturing, producing revolutionary new products based on Australian-developed nanotechnology, many of which are highlighted in this decadal plan. There is an exciting opportunity for Australia to build on this strong foundation of achievement by fully exploiting its leading nanotechnology research for the benefit of the nation, and with it, bringing about a nanotechnology-led economy.

Why is nanotechnology so revolutionary?

The reason lies at the heart of nanoscience—the science of the very small. Materials behave very differently at scales below about 100 nanometres, which equates to 200 times smaller than the width of a human hair. Desirable properties of nanomaterials can be exploited for exciting applications such as improved chemical reactivity, ability to absorb or reflect light, and differences in material strength, flexibility or response to rises in temperature or pressure. In addition, we can engineer or pattern materials at the nanoscale, such as in advanced silicon chips or nanosensors, to gain amazing enhancements in desired properties. Our ability over the past decade to observe, engineer, manipulate and exploit materials and manufacturing techniques at the nanoscale has led to the current nanotechnology revolution. This has been brought about through exceedingly multidisciplinary research—with physicists, chemists, materials scientists, engineers, mathematicians, biologists, medical scientists, environmental scientists, and even social scientists, economists and lawyers, coming together to fuel the advancement of nanotechnology research. A particular challenge for Australia is how to enhance support for and leverage off our nanotechnology research, not only for economic benefits, but also to embrace the opportunities that nanotechnology offers to address some of the nation's most pressing challenges in health, the ageing population, the environment, energy, water, the revitalisation of manufacturing industry, and national security.

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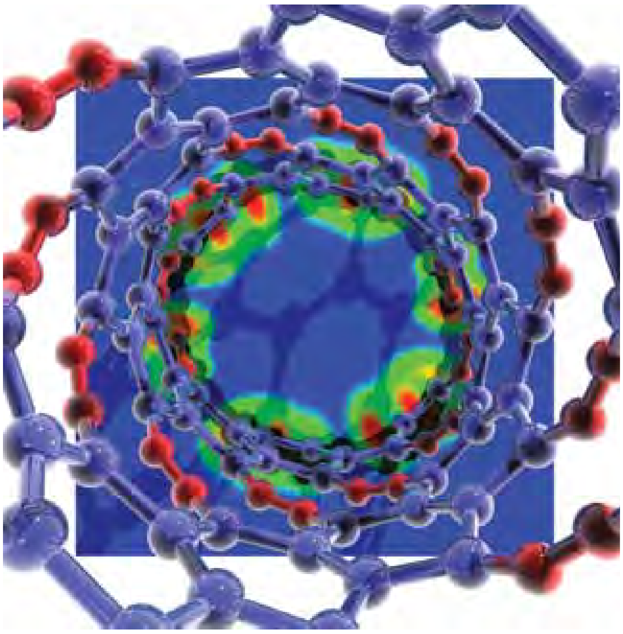
What is the nanotechnology vision?

The vision is for Australia to be a world leader in a nanotechnology-driven economy that draws on outstanding research and innovation in nanoscience and nanotechnology, and exploits this research for the nation's benefit. This involves a national approach that supports the entire spectrum of nanotechnology development, from fundamental research to developing the mechanisms needed to translate the technology to industry in an effective and timely manner. If this national strategy is put in place, there is potential for Australia to:

- capture more than its per capita share of the projected $3 trillion global revenue for nano-derived products by 2020[2]
- assist parts of the country's manufacturing industry to revolutionise their product portfolio[3]
- bring our research community and industries together with a primary focus: to commercially exploit novel nanotechnology research
- assist in bringing diverse discipline areas and different expertise together to help address the most pressing 'grand challenges' facing our nation.



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Australia's readiness for a nanotechnology-inspired economy

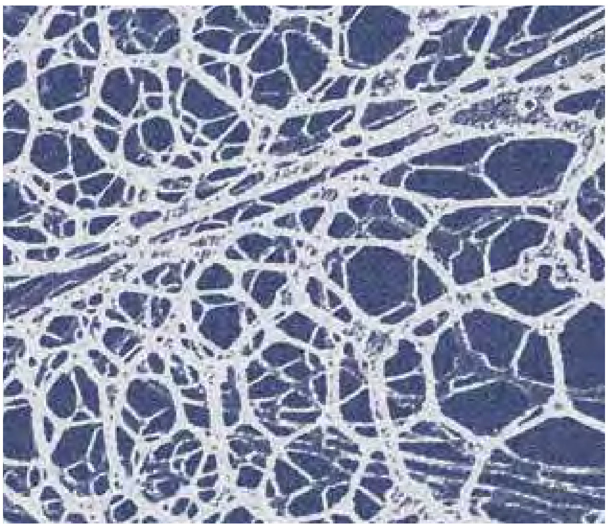
Australia needs to invest in nanotechnology to build an economy of the future. A recent assessment of the potential impact of nanotechnology on society by 2020[4] noted that 'the number of nanotechnology-enabled products and workers worldwide will double every 3 years, achieving a global $3 trillion market with 6 million (new) workers by 2020'. The strong implication is that economies and industries that fail to invest in nano-inspired technology will be left behind as new products with improved or entirely new functionality replace the old. To ensure that it reaps major economic benefit from the nano revolution, the United States has invested more than $12 billion since 2000 in nanotechnology research and development (R&D), second only to the space program in terms of civilian science and technology investment.[5] Furthermore, Japan, Korea, the European Union and its individual member economies, China, Taiwan, Russia, Brazil, India and several Middle Eastern countries have made similar investments as a proportion of GDP since 2000.[6] Based on this global investment, by March 2011 more than 1300 new nanotechnology-enabled products had been commercialised.[7] Therefore, among the key drivers for investment in nanotechnology is the pervasive economic impact.

Australia's current investment in nanotechnology

To date Australia has a track record of R&D investment in nanotechnology, being ranked eighth in the world in 2004, but we must continue to invest strategically if the benefits of nanotechnology are to impact on our economy.[8]

Measured in terms of publications and patents, which are something that can be readily quantified, Australia so far has been able to keep pace with the strong global increase in nanotechnology R&D, largely as a result of the early government investment in the field. However, with global publications and patents related to nanotechnology increasing at a rate of 20% a year over the past decade compared to far more modest growth in scientific output more generally, there is no scope for complacency. For example, China in particular has made nanotechnology a priority of its R&D investment.

As a result, a disproportionately high level of research in this field now originates from China compared to its overall scientific output, which is underpinning its rapid technological advance. This shift of emphasis towards nanotechnology is likely to be replicated by other developing countries experiencing rapid growth, making it even more challenging for Australia to remain competitive not only in R&D but, more importantly, in the uptake of nanotechnology by industry.



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Can Australia afford not to invest in the translation of its nanotechnology research to industry?

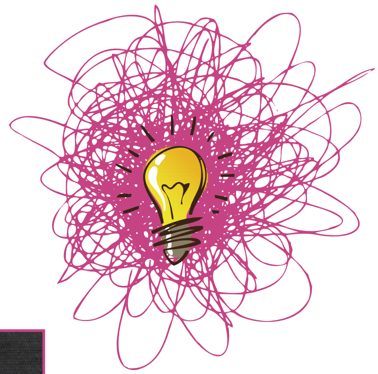
For many other technology-driven industries that have had a major impact on society, such as electronics, computing and communications, the technology and cost barriers to entry are high, and Australia is consequently a very small player. In contrast, the breadth of opportunity for commercialisation of nanotechnology-enabled products is enormous. There are relatively low financial and other barriers for existing and new companies (particularly small and medium enterprises (SMEs)) in Australia to work with and incorporate nanotechnology into products. Thus translation of nanotechnology research can form the basis for establishing many new SMEs as well as transforming existing industries through innovation. Australian success stories in commercialising nano-derived products can be an inspiration to other players and help develop a culture of entrepreneurship in the community.

Analysis suggests that Australia is well-placed to benefit from nanotechnology. A survey has found that 76% of the public are already aware of this field and 85% were 'excited or hopeful'[9], suggesting a higher level of community acceptance than in most developed countries.[10] Based on both Australia's early successes and the global trends in industry uptake of nanotechnology highlighted above, it is clear that nanotechnology can be an important economic driver for Australia. Not only will there be benefits to the economy, but nanotechnology research can be a vital contributor to solving the grand challenges Australia faces such as sustainable energy and clean water. Only through sustained investment and policy settings that promote commercialisation will we be in a position to exploit our present strong research base in nanotechnology and translate this into benefits for the nation.

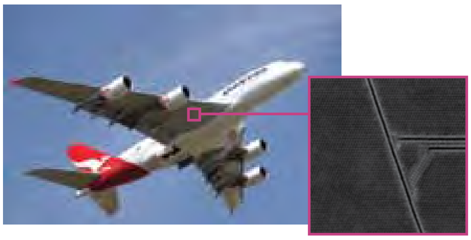
Nanotechnology: little solutions to big ideas that are reshaping our future

Australian Nanotechnology Network: helping to realise big ideas through connecting people (p. 16)

BIG IDEAS



Cutting edge facilities: providing the tools to make it happen (p. 45)



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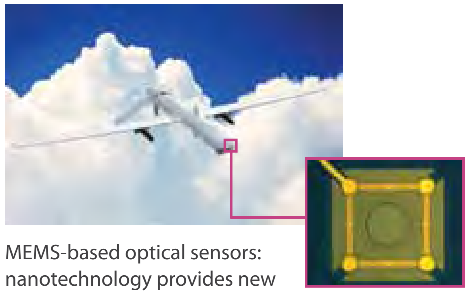

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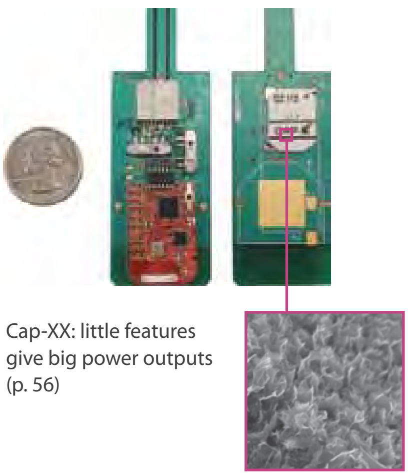
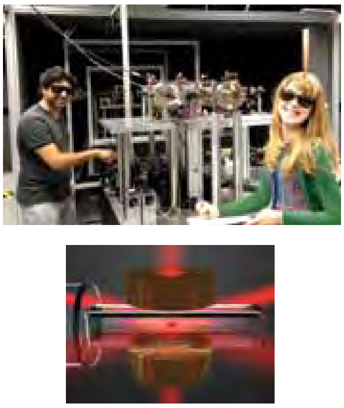
Printable solar cells: providing sustainable energy solutions just where we need them (p. 67)



Cap-XX: little features give big power outputs (p. 56)



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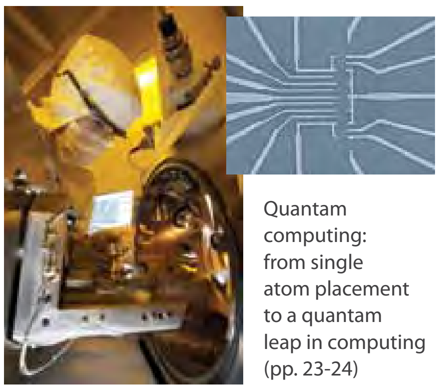

Quantum computing: from single atom placement to a quantam leap in computing (pp. 23-24)

(From top left, clockwise) Images courtesy of: Australian Nanotechnology Network (ANN); Australian Nuclear Science & Technology Organisation (ANSTO); istockphoto.com; University of Western Australia; S. Watkins, CSIRO; S. Watkins, CSIRO; Australian National Fabrication Facility (ANFF); D. Reilly, University of Sydney; N. Robins, Australian National University (ANU); N. Robins, ANU; CAP-XX (Australia) Pty Ltd; CAP-XX (Australia) Pty Ltd; ©Rolex Awards, Photographer – Julian Kingma; M. Kendall, University of Queensland; istockphoto.com; M. Weyland, Monash University.

Australian context: nanotechnology opportunities and impediments

For Australia, realising this vision of a nanotechnology-driven economy requires an understanding of the broad opportunities for exploitation and what the barriers to success are. Linking opportunities to the nation's grand challenges is one approach to providing benefit beyond the economic benefits of being a major player in commercialising a range of specific nano-inspired products. Some of the national grand challenges where nanotechnology can make a difference include improving community health, providing potable water and remediation of the environment, developing clean energy solutions, ensuring national security and revitalising the Australian manufacturing industry. All of these challenges can be innovatively addressed by applying nanotechnology in a multidisciplinary way with a sufficient critical mass of researchers to achieve solutions. Australian nanotechnology research is well-positioned to make an immediate impact in these areas of extreme importance to the country. What is now needed is national support, coordination and leadership of grand-challenge projects that build upon existing research strengths and develop the bridge with industry. This will ensure that the commercialisation pathways are in place to translate the technology into benefits for the nation. Particular opportunities are spelt out below.

Opportunities

Healthcare for an ageing population—Australian nanotechnology research provides many opportunities for existing and new enterprises to develop medical products for the rapidly increasing world market in this area. World-leading Australian research includes the monitoring of blood and cellular dysfunction using advanced sensors (p. 78), targeted drug-delivery using nanoparticles (pp. 79-80), nanoscale needleless vaccine delivery (see case study on p. 84) and revolutionary bionic eye technology (p. 58). Many of these developments already have commercial pathways.

Sustainable water—Provision of adequate, potable water for a growing population is a major issue for Australia. There are world-class Australian research efforts in various aspects of water purification involving nanotechnology. These include photocatalysts for the removal of organic contaminants; nanomembranes and nanoparticles to purify water (p. 47); and desalination and water splitting (p. 51). There are substantial opportunities for commercialisation with the market for nanotechnology in the global water industry predicted to rise from USD $1.6 billion in 2007 to $6.6 billion by 2015.[11] As a country with periods of great water stress and one of the largest fractions of water use for agriculture[12], Australia has particular opportunity to benefit in such areas.

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Sustainable agriculture and food security—Australian researchers are developing new nanotechnologies with important impacts, including the use of airborne infrared sensors for the precision-monitoring of crops to assess disease or growth conditions (case study on pp. 75-76) and the use of optical fibre sensors to monitor contamination in food and wine (p. 70)

Sustainable, clean energy—Nanotechnology research offers important products for low-carbon energy production, including nanostructured solar cells (p. 67), nanomaterial-based fuel cells (p. 51), and carbon capture and storage using nanomaterials (see CapXX case study) and nanoscale membranes (p. 56).

Security, defence and border protection—Researchers are developing novel applications, including the use of optical sensors and nanoelectromechanical systems to detect explosives and biological weapons (pp. 75-76), and nanoengineered infrared sensors that enable night vision and target recognition in hostile environments (p. 75). Commercial pathways will be needed to develop these areas further.

Application opportunities for nanotechnology

Grand challenge	Nanotechnology advancement and impact
Sustainable, clean energy	Higher efficiency solar cells Novel improved catalysts for clean coal Higher density energy storage devices Higher strength composites and fibres for energy efficiency New power devices for green energy and electric vehicles Solid state lighting
Advancing our manufacturing industry	New electronics and photonics for computing, communications, data storage, defence systems and displays Future quantum computing/communications devices and systems Advanced engineering manufacturing processes
Sustainable, clean water	Higher performance membranes for water filtration, purification and desalination Lower cost, higher performing sensors for water quality monitoring
Sustainable agriculture and food security	Higher performance sensors for food quality, safety and security Improved devices and systems for precision agriculture
Environment	Environmental sensors with improved sensitivity New and improved composite materials for reduced energy consumption and lower pollution emissions Novel membrane technologies for filtration and capture of pollutants Improved sensors and systems for environmental condition monitoring
Security/terrorism, defence and border protection	Higher performance sensors for security screening and border protection New composites and fibre materials for combat systems
Health/disease and ageing	Improved sensors for medical diagnostics and 'lab-on-a-chip' Highly specific targeted drug delivery systems New composite materials for protection in hazardous environments Advanced medical bionics: bionic ear and eye, and scaffolds for prosthetics

Table 1: Application opportunities for nanotechnology

Barriers to success

While Australian nanotechnology research is creating numerous opportunities for economic growth, its full potential can only be realised if steps are taken now to safeguard existing research capabilities, enhance training and interdisciplinary research, promote international and community engagement and ensure the effective translation of nanotechnology research to industry. Specific issues that need to be addressed to realise the full potential of nanotechnology research are briefly outlined below and the recommendations in the next section offer solutions that, if accepted, will smooth the path for realising our vision for nanotechnology.

Stability of investment in national nanotechnology research and research infrastructure—Nanotechnology research requires cutting-edge tools and highly experienced technical and research staff to be internationally competitive. Following significant investments over the past decade, Australia now has outstanding infrastructure and human capital that underpins a wide range of publicly funded and industrial nanotechnology research. We need to maintain and enhance this investment to ensure security over a decade to continue the R&D momentum, and to enable technology translation in part by providing industry access to these facilities.[13] (See footnote A)

Support for interdisciplinary research—The highly multidisciplinary nature of nanotechnology is a key driver for novel, highly innovative products. Existing sources of support in Australia can have difficulty dealing with research that crosses traditional discipline boundaries, so many opportunities can be missed.

Support for international engagement—The cutting-edge nature of nanotechnology often means that the highest-impact nanotechnology research requires collaboration with leading overseas research centres, research facilities and industries. There is currently only limited support for such international collaborations, and this is impeding progress.

Challenges for translation, including the growth of nanotechnology-driven SMEs—In the United States, where entrepreneurship is culturally entrenched, it is well understood by the business and investment community that the success rate for new technology-intensive start-ups is low. In Australia there remains a stigma of failure around unsuccessful start-ups, there is often not the necessary entrepreneurial skill sets and the risk-averse nature of Australian venture capital firms can all serve as deterrents to researchers and institutions to growing new businesses. There is also the uncertain landscape for R&D investment, which can deter high-risk investment in R&D by existing businesses. Over the past two decades there has been a variety of regimes in place, ranging from R&D tax concessions to the more recent R&D tax offset scheme.[14] Furthermore, while a number

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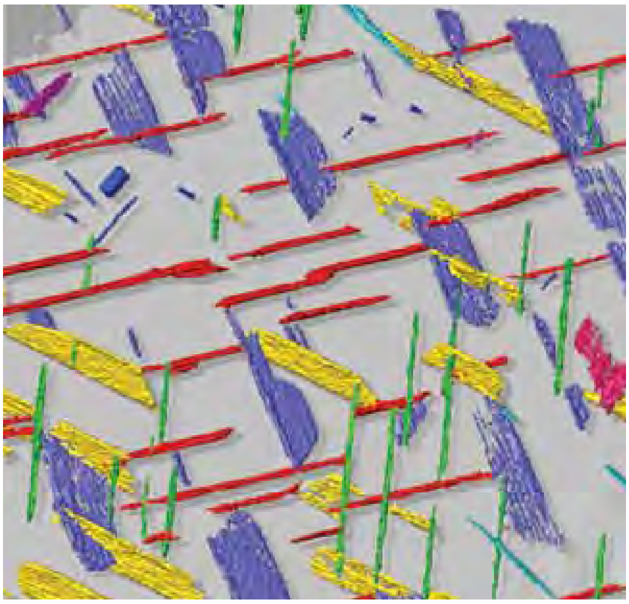
A A number of schemes provide limited funding for access (e.g. the NSW Government's TechVouchers program[16] and the Victorian Governments Technical Voucher Program) or free access (e.g. Flinders University NanoConnect[17] program) to publicly funded research institutions. Such schemes are particularly relevant to the translation of nanotechnology research and should be expanded.

of programs are in place to encourage researcher–industry linkage, coupled with industry investment, their scope and nature are insufficient to realise the full economic potential provided by Australian nanotechnology research.[15] (See footnote B)

Ensuring public health, safety and confidence—Like all new areas of science and technology, there are potential hazards and ethical issues surrounding nanotechnology that must be appropriately assessed and addressed at an early stage to ensure public health, safety and confidence.



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B There are also schemes that link publicly funded researchers with industry e.g. the ARC's Linkage Program[18] and provide seed funding to help establish or grow small businesses e.g. the Australian Government's Commercialisation Australia program[19]. While these schemes contribute to the growth of SMEs in the nanotechnology area, the requirement for matching funding from researchers or universities can often be an obstacle. The success of the United States in developing high-tech start-ups has been supported for many years via the Small Business Innovation Research (SBIR) and Small Business Technology Transfer programs.[20] The SBIR program was established to strengthen the role of small business in federally funded R&D and provides more than $20 billion annually to fund awards. The scheme requires all large federal agencies to allocate 2.5% of their R&D budget to SBIR programs. While the specifics of this scheme may not match Australian requirements, a similar scheme would provide a significant stimulus to Australian nanotechnology SMEs.

Recommendations

The following recommendations focus on what is needed to realise our vision for a nanotechnology-driven economy. It is essential that multidisciplinary research in nanoscience and nanotechnology is well supported through project funding, resourced networking and a national strategy for providing research infrastructure in terms of equipment, facilities and skilled technical staff. Training and education programs in nanotechnology will be required to service the research community and equip industry with a skilled workforce. Mechanisms need to be developed to bring researchers and industry together and to help translate research into new industries. Issues of regulation, occupational health and safety, and ethics, including public engagement, need to be integrated and addressed in a strategic and coordinated way to ensure the smooth commercialisation of nano-enabled products. Support for international engagement and collaboration is vital to provide the necessary links with global research and industry. Finally, the overall strategy needs national coordination by researchers to ensure that it remains on track and all the elements are in place to maximise success. These requirements are considered essential to realising a vision for nanotechnology that is focused on maximising the benefits for the nation.

Infrastructure

Recommendation 1: *Maintain and expand Australia's nanotechnology research infrastructure (human and capital) through the provision of stable, long-term financial support.*

World-class nanotechnology infrastructure is essential to ensure Australia's international competitiveness and increase the opportunity for commercialisation of our nanotechnology research. A critical component of this infrastructure is the human capital, comprising highly skilled research scientists and engineers who maintain, operate and develop the capability provided to researchers at our national facilities. National research infrastructure programs in computational science (e.g. the National Computational Infrastructure and others), nanofabrication (e.g. the Australian National Fabrication Facility (ANFF)), and nanocharacterisation (e.g. the Australian Microscopy & Microanalysis Research Facility (AMMRF) and the Australian Synchrotron) have been supported by the National Collaborative Research Infrastructure Strategy and the Australian Government's Super Science initiatives with more than $500 million investment over 2006–13. Both of these funding schemes are due to conclude with no identified replacement. A new funding mechanism of approximately $100 million per annum and which is stable for at least 10 years is pivotal to ensure that this infrastructure enables cutting-edge new research and is accessible for the next decade.

Interdisciplinary research

Recommendation 2: *Foster and support interdisciplinary research.*

Recognising that nanotechnology research draws heavily on the combined contributions of research at the interface of the physical, biological and engineering sciences, the Australian Research Council (ARC) and National Health and Medical Research Council (NHMRC) should allocate specific resources to support interdisciplinary research projects. Such measures could include the establishment of joint panels between the ARC and NHMRC and dedicated funding to interdisciplinary research.

Recommendation 3: *The ARC and NHMRC need to be provided with additional resources to facilitate their expanded role of supporting interdisciplinary research.*

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During the past decade, the ARC and NHMRC have had to administer an increasing number of grants and programs, with increasingly complex reporting and administration requirements. This has not been matched with increased resourcing of Australia's two major granting agencies to allow adequate support of interdisciplinary grants and centres.

International engagement

Recommendation 4: *Promote Australian nanotechnology on the international stage.*

Establish a dedicated fund of at least 0.2% of the overall science, research and innovation spend over the next 10 years to support the internationalisation of Australian research. For the nanoscience and nanotechnology communities, such programs will provide access to international facilities and connectivity, especially for early and mid-career researchers in establishing international partnerships that are universally recognised as enabling the best research exchange and dissemination. The future dividend on investment in promoting new Australian technologies abroad will provide the wealth creation that will power Australia into the Asian Century.

Industry and translation

Recommendation 5: *Establish an expert panel (comprising academia, industry and government) to develop a national framework for translating nanotechnology research.*

To maximise Australia's economic, social and environmental outcomes, it is critical that we translate the nanomaterials and nanodevices being developed in publicly funded research organisations into industries with nanotechnology-enabled products. The framework would encompass all aspects of the innovation pipeline: giving industry access to research facilities; upscaling nanomaterials production and integrating it into manufacturing; encouraging entrepreneurship; and integrating regulation, standards, ethics and safety into all stages of the pipeline. Providing stable, long-term investment programs and fostering a culture of entrepreneurship in Australia are seen as vital to encouraging the establishment and growth of technology-intensive SMEs.

Recommendation 6: *Expand training and reskilling programs to support and develop new nanotechnology-based industries in Australia.*

Australia has an opportunity to refocus its manufacturing sector on high value-added products based on nanomaterials and nanodevices. These new products and their coexisting industries will need a new, highly skilled workforce and reskilling of existing staff to make them nanotechnology ready. It is anticipated that much of the emerging (nano) manufacturing sector will involve SMEs. Training that fosters entrepreneurship and business skills among researchers and their institutions, and among undergraduate and graduate students, is necessary to fuel the innovation pipeline and, potentially, the establishment of new SMEs.

Community engagement

Recommendation 7: *In the interest of 'ethically responsible science' the nanotechnology research community should establish mechanisms to effectively engage with the public on the benefits and risks of nanotechnology, including social impact, regulation and ethical issues.*

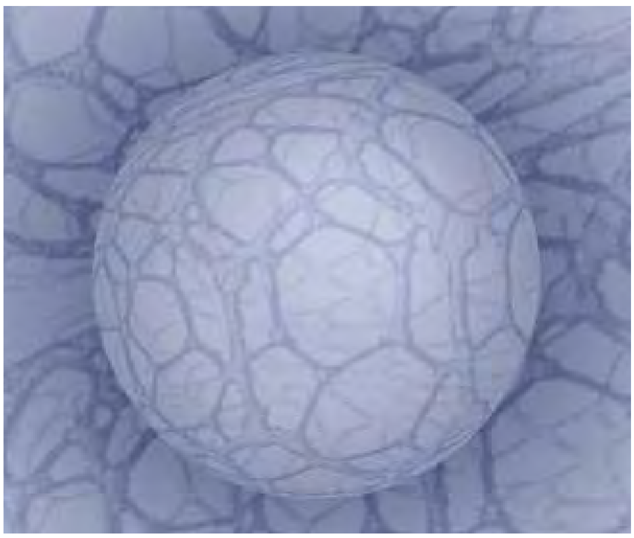
Nanotechnology scientists occupy a position of trust in the community, with a commensurate responsibility to effectively engage with the public. This could be achieved through public forums, by fostering community discussion and by providing opportunities for multistakeholder involvement facilitated by the ANN or the new coordinating body (see Recommendation 8). Effective translation of nanotechnology into new products and industries is increasingly reliant on the public's confidence in researchers and its awareness of the benefits and risks of the technology—as well as opportunities for its diverse members to have their concerns recognised and addressed. Rapid and effective translation of research requires concurrent treatment of regulatory, health and ethical issues: this in turn necessitates effective public engagement.

Overarching coordination

Recommendation 8: *Establish and fund a national nanotechnology coordinating body to provide leadership for the discipline at all scales and a mechanism for implementing the preceding recommendations.*

This one-stop shop would act as an agency for the nanotechnology community to facilitate and coordinate better access to knowledge; oversight the provision of appropriate infrastructure; engagement with industry; training and skills enhancement, including career development; and interdisciplinary interactions, international collaboration and public engagement. The new body could be built around the existing ANN, and be an advocate for Australian nanotechnology and an adviser to government, particularly on regulatory, safety and ethical issues in the public interest. The coordinating body would work with the national infrastructure platforms such as the ANFF, AMMRF, the national computation platforms, and industry groups such as the Australian Nanotechnology Alliance and the Australian Industry Group. Coordination of Australia's nanotechnology research effort would position us well to deploy these transformative and enabling nanotechnologies to address our and the world's grand challenges.

With a broader charter than the ANN, a new funding scale and model would need to be established. The authors of this report understand that, while an initial investment from government would be essential, long-term funding should not be the sole responsibility of government and leveraging contributions should be obtained from all research and industry stakeholders, with a pathway to sustainability built into the funding models.



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17. Roco MC, Mirkin CA, Hersam MC (eds) 2011, Op. Cit.
18. See: www.arc.gov.au/ncgp.
19. See: www.commercialisationaustralia.gov.au.
20. See: http://www.sbir.gov.

Australian Academy of Science

National Nanotechnology

RESEARCH STRATEGY

SECTION 2

Case study 1: Australian Nanotechnology Network

The Australian Nanotechnology Network (ANN) was initially established as part of the Australian Research Council's (ARC) research networks program. After completion of the original 5-year funding by the ARC in 2010, ANN received funding from the National Enabling Technologies Strategy of the Australian Department of Industry, Innovation, Science, Research and Tertiary Education as well as from the university sector and research institutions such as CSIRO the Australian Nuclear Science and Technology Organisation (ANSTO) and the Defence Science and Technology Organisation (DSTO).

ANN consists of approximately 1400 members and 250 research groups. Its aim is to bring together the research community to enable multidisciplinary and transdisciplinary research, collaborative linkages, skills development of early career researchers (ECRs) and PhD and Masters students, and public engagement activities, including public lectures, and school and industry visits. The network recently began working towards strengthening linkages between the university research sector and industry.

Figure 1: School visit in Queensland was part of the 2007 Young Nano Ambassador award, sponsored by the ANN. (Images courtesy of ANN)

The network also supports conferences, workshops, summer schools, short- and long-term collaborative visits, overseas travel fellowships, and Young Nano Ambassador Awards for students and ECRs. ANN publishes newsletters and outreach materials (e.g. NanoQ), which are distributed to schools, the public and policymakers.

ANN initiated the biennial International Conference on Nanoscience and Nanotechnology (ICONN) to bring together Australian and international researchers to exchange ideas, share knowledge and develop collaborative linkages. ICONN has been a highly successful forum, providing a great opportunity for students and ECRs to present work to the national and international community and to develop linkages. ANN provides free registration to all presenting Australian ECRs and PhD/Masters students. This acts as a strong incentive to young people to participate in conferences, develop skills and build linkages.

Overseas travel fellowship funding allows young researchers to gain skills and expertise in international laboratories and bring these skills back to Australia. The ANN's Distinguished Lecturer program provides opportunities for international researchers to visit key nanotechnology research centres in Australia, give seminars and public lectures, and share their knowledge with the Australian research community and public. ANN also provides facilities and databases of expertise that allow researchers to access the infrastructure and expertise available in Australia. The network acts as a resource for the Australian Government to reach out to the community for feedback on policy matters relating to emerging nanotechnology areas. ANN has organised bilateral workshops with the United States, the European Union, Japan, India, China and Singapore.

Membership is free and anyone is welcome to join. Further information about the network can be found at www.ausnano.net

Nanoscale theory and computation

Definition of discipline

Theory and computation may be broadly defined as the use of mathematical and numerical methods to study nanoscale structures and phenomena.

Often a theory is developed to articulate a particular problem or feature and to provide a means to interpret raw experimental measurement in terms of simpler underpinning phenomena. Typically, this leads to computer simulations that provide a more detailed understanding of a particular system or even a quantitative prediction in some cases. Computer simulation is akin to performing a *virtual experiment*, and like any other experiment, the true advantages of using theory and computation lie in their ability to provide complementary information that cannot be obtained in any other way. Computer simulation provides the unique abilities to make step-wise predictions with precision by rapidly screening massive numbers of possible scenarios and structures (in multiple dimensions) and visualising dynamical processes at subatomic levels. Theory and computation are cost effective, versatile and safe.

Australian strengths in nanoscale theory and computation

Summary of the key strengths in nanoscale theory and computation

1. **Advances in theory and computation for physics at the nanoscale.**
2. **Advancing quantum chemistry through new concepts and techniques, and their application to chemical systems.**
3. **Major advances in fundamental theories of chemical physics.**
4. **Simulation of materials and minerals at the nanoscale.**
5. **Taking new theories and ideas for efficient computation and translating them into software.**
6. **An emerging leader in computational science.**

Nanoscale theory and computation research is being undertaken in diverse areas, many of which are being driven by collaborations between experimental and theoretical groups (see Table 1). The research spans the spectrum, from fundamental understanding of nanoscale phenomena to the virtual design of improved materials for technological application.

Advances in theory and computation for physics at the nanoscale

Australia's long history of achievement in the fields of theory and computation continues to attract international recognition. Nanoscale science is underpinned by concepts from chemical physics, so while some contributions may not be overtly labelled as developments in the 'nano' field, they are nonetheless significant in this area. Some of these seemingly fundamental developments have led to technological revolutions. For instance, Australian advances in theory and computation for physics at the nanoscale contributed to the development of plasma displays and low-energy light bulbs, which have become household items.

Advancing quantum mechanics through new concepts and techniques, and their application to chemical systems

Australia has played a role in pioneering the development and application of *ab initio* quantum chemical methods through its involvement in early programs such as GAUSSIAN. This continues, with Australian researchers being in the forefront of new concepts to improve density functional theory—the most widespread computational technique used to probe the electronic properties of nanoscale objects.

While quantum chemistry initially focused on small molecular systems, advances in this domain, such as linear scaling of computational cost with system size, have allowed it to progress to the study of objects with dimensions in the nanometre range.

Major advances in fundamental theories of chemical physics

Beyond the numerical determination of the electronic behaviour of systems, there have also been contributions to the fundamental models. Electron transfer processes are critical to many applications of nanotechnology, not to mention biology. Here the contribution of Marcus-Hush theory was a major advance that has been recognised around the world.

Australia also continues to be at the forefront of statistical mechanics—the discipline that describes the thermodynamic and kinetic behaviour of all atomic systems. Understanding the fundamental relationships that determine the properties of matter is critical to processes such as self-assembly and confined fluids, which are pivotal to many nanoscale systems. The interpretation of the laws of thermodynamics in regard to entropy and the driving force for disorder has been transformed as a result of Australian research.

Simulation of materials and minerals at the nanoscale

Inorganic materials and minerals exhibit different behaviour at the nanoscale, as the thermodynamics of surfaces, and other defects, start to influence the stability of these materials. Australian researchers have made significant contributions towards predicting how the shape and underlying structure of nanoparticles can change with size, and how this can be manipulated through the incorporation of impurities at the surface.

Taking new theories and ideas for efficient computation and translating them into software

New theories and ideas on how to perform more-efficient computations have also been translated into software that has been distributed internationally. For example, Australian researchers have contributed to programs including QChem, GAUSSIAN, Tonto, SIESTA, GULP, Gromacs, CNDO/INDO and ADF. Many of these codes are extensively used around the world for nanoscale computation, and several have been made available to the community through the NanoHUB initiative funded in the United States as part of the global Network for Computational Nanotechnology.

An emerging leader in computational science

The Australian Government's recent Super Science initiative has seen Australia rise to ninth place in the ranking of the world's largest computers. This is expected to increase further when the Pawsey Centre in Western Australia is completed in 2014, and with the procurement of a petascale computer for the National Computational Infrastructure facility in Canberra. Both of these facilities are available for research into nanomaterials and are complemented by the Victorian Life Sciences Computation Initiative in computational life sciences for Victorian researchers. As a consequence of the major investments by both the Australian and state governments in radioastronomy, significant advances in computational capability, driven by the successful bid to host part of the Square Kilometre Array Square Kilometre Array radio telescope program, are likely in Australia for the foreseeable future,.

Selected areas of nanoscale research activity and computation in Australia	
Carbon nanomaterials	Nanophotonics and nanoplasmonics
Catalysis	Nanoporous materials for carbon capture and water treatment
Colloids and self-assembly	Nanostructured materials for clean energy (hydrogen storage, Li-batteries and fuel cells)
Condensed matter and surface science	Photovoltaics
Ion channel and biological modelling	Plasma nanofabrication
Mineral nanoparticles and environment	Quantum information technology
Molecular and nanoelectronics and magnetics	
Nanofluidics	
Nanomechanics	

Table 1: Selected areas of nanoscale research activity and computation in Australia.

Challenges and opportunities for nanoscale theory and computation

Summary of the key challenges for nanoscale theory and computation

1. **Advances in computing infrastructure will lead to challenges in how we manage increased energy consumption, data transfer, and fault tolerance.**
2. **New techniques for the analysis and visualisation of large volumes of data are required.**
3. **The results of fundamental research into nanoscale phenomena may well lead to changes in scientific thinking or create new paradigms for technology.**
4. **Experimental studies on complex nanosystems are becoming increasingly difficult to interpret and understand.**
5. **Knowledge from across different disciplines needs to be brought together for the next generation of scientific and technological advances.**

Combining nanoscale theory with high-performance supercomputers has led to an increased adoption of such techniques by the academic, government and industrial sectors. High-impact academic publications typically combine theory and computation with conventional experiments, and patent applications are frequently supported by simulations, particularly when forecasting of long-term stability is required.

Computational methods and resources are increasingly being used to tackle critical issues of national importance such as energy and water security, health and defence. We are now able to address important agricultural and environmental problems and use nanoscale theory and computation to reduce our impact on the environment. Both facets of this discipline are firmly established as important tools for exploration and understanding and, as we move into the generation of petascale computing, there is great potential for growth. However, the rapidly evolving nature of the discipline gives rise to both challenges and opportunities from a number of sources, as documented below.

Challenge: Advances in computing infrastructure will lead to challenges in how we exploit greater parallelism and new types of processors, while managing increased energy consumption, data transfer, and fault tolerance.

Opportunity: The availability of new architectures combined with the existing capacity to develop software gives Australia the opportunity to be at the forefront of research in this area.

Major changes in computing infrastructure are providing new possibilities for mathematical formalisms, algorithm design, and practical applications. These changes include the drive towards Exascale computing and the emergence of Cloud computing.

Already the creation of petascale supercomputers (machines that can perform 10^{15} floating point operations a second, or 'flops'), such as that being procured by the Pawsey Centre, has seen several major changes in the approach to advancing computer performance. Increasing the number of compute operations per second—possible through further miniaturisation of components—is no longer likely to be feasible as the critical dimensions approach the nanoscale. As a result, advancing high-performance computing is only possible by increasing the number of processors, thereby demanding far higher levels of parallelism than previously necessary. Typically, a petascale computer has in the order of 100 000 processors, leading to the anticipation that an exaflop (10^{18} flops) will require several million processors. At this size, it is likely that processor failure will be a routine occurrence, and so fault tolerance becomes a challenge. Furthermore, the energy consumption of both the computer and any cooling systems required has become a major limitation. To overcome this, each processing unit will become more complex through the emergence of hybrid technologies involving low power and reduced instruction set chips such as graphics processing units mixed with standard cores, leading to a heterogeneous system.

Cloud computing is an internationally available resource that, in principle, offers unprecedented power through remote distributed computers. Here the challenge lies in the need to transfer large volumes of data and to handle the slow communication between loosely coupled machines. Significantly, both petascale machines and Cloud computing demand very different software approaches than have been used historically. The current batch of commercial and scientific software available for simulation of nanoscale systems may soon become obsolete.

Australia has many research groups involved in software development for nanotechnology. These include programs that evaluate the electronic and nuclear structure of materials, surfaces, proteins and molecules, as well as programs that evaluate the effects of temperature and the dynamics of chemical processes, including catalysis. Availability of new architectures, combined with the capacity to develop the required software, gives Australia the opportunity to be at the forefront of research. This will allow better connection with experimentalists and improved time to market for technological products, and therefore a greater opportunity for Australia to directly exploit its intellectual property (IP).

Challenge: New techniques for the analysis and visualisation of large volumes of data are required.

Opportunity: Valuable scientific concepts can be discovered in the increasingly large volumes of data being produced by numerical simulations.

The rapid advance in the speed of numerical simulations results in the production of increasingly large volumes of data with diverse and rich content. While there are many opportunities to mine this vast quantity of data for valuable scientific results, the challenge is that we have already exceeded the point at which a human can comprehend the raw information, and so new techniques for analysis and visualisation are required. Sharing and curation of datasets are becoming an increasing requirement that demands new tools for collaboration. Through a number of federal initiatives, Australia is well-placed to take a leadership role in this aspect.

Challenge: The results of fundamental research into nanoscale phenomena may well lead to changes in scientific thinking or create new paradigms for technology .

Opportunity: Disruptive technologies create opportunities for research and commercial leadership.

Australian researchers are among the world leaders in the development of the basic mathematical formalisms for describing nanotechnology applications. This includes the fields of statistical mechanics, charge transport and quantum computing.

Statistical mechanics describes how collections of particles behave and was initially developed to explain the operation of steam and internal combustion engines. These equations require significant modification for use at the nanoscale, and the basic theory—expected to replace all undergraduate teaching in the area within 40 years—is being advanced rapidly by Australian researchers, who have made critical new breakthroughs in this centuries-old field.

Theoretical developments in the understanding of charge transport by Australian researchers are resulting in new developments in molecular electronics and photovoltaics. Significant advances have also led to many new algorithms being developed in Australia for quantum computing, a paradigm that could replace digital computing during the next 30 years. In these areas, theoretical advances keep leading to new critical experiments.

Challenge: Experimental studies on complex nanosystems are becoming increasingly difficult to interpret and understand.

Opportunity: Simulation, when combined with experiment, can provide insight at the atomic level and thereby drive future advances. This synergy between experimentalists and theorists is essential for fully exploiting developments in both arenas.

Many key experimental studies on nanosystems will in the future be supported by full atomistic simulations. This includes applications in many of the areas previously listed as active areas within Australia. Most computational nanotechnology groups in Australia are now closely connected to experimental projects, helping to design experiments and interpret results. Many more opportunities are being developed, and Australia is now well-poised to make significant scientific and technological advances.

Challenge: Knowledge from across different disciplines needs to be brought together for the next generation of scientific and technological advances.

Opportunity: In working to enhance collaboration opportunities and education across a broad range of theory and computation methods, Australia will maintain a leading position in nanoscale science and technology.

Australia has world-leading expertise in a wide range of nanoscale theoretical and computational methods. The next generation of scientific and technological advances will result from combining multidisciplinary knowledge and the different techniques used for modelling systems at a variety of scales. For example, biomimetic technologies, nanoscale therapeutics, materials design for clean energy applications, development of nanoporous membranes and fuel cells all involve multiscale, multidisciplinary expertise. Enabling opportunities to enhance collaboration and education in a broad range of theory and computational methods will help Australia maintain a leading position in nanoscale science and technology.

Summary of the key opportunities for nanoscale theory and computation

1. **The availability of new architectures, combined with the existing capacity to develop software, gives Australia the opportunity to be at the forefront of research in this area.**
2. **Valuable scientific concepts can be discovered in the increasingly large volumes of data being produced by numerical simulations.**
3. **Disruptive technologies create opportunities for research and commercial leadership.**
4. **Simulation when combined with experiment can provide insight at the atomic level and thereby drive future advances. This synergy between experimentalists and theorists is essential for fully exploiting developments in both arenas.**
5. **In working to enhance collaboration opportunities and education across a broad range of theory and computation methods, Australia will maintain a leading position in nanoscale science and technology.**

Developing the discipline

When considering the strengths and opportunities identified for Australian nanoscale theory and computation, several key themes emerge. These focus around the need for enhanced collaboration (between theorists and experimentalists and across disciplines) (Recommendation 8), ongoing support of infrastructure (Recommendation 1), harnessing knowledge (Recommendation 5) and, most strongly, the need for funding mechanisms that appropriately recognise the highly interdisciplinary nature of the discipline (Recommendation 2).

Case study 2: Quantum computers

The last decades of the 20th century saw a confluence of quantum and information sciences, which has produced remarkable ideas and concepts to compute using quantum bits (qubits)—physical bits of information that obey the complex laws of quantum mechanics. The vast information-processing potential of quantum systems has spurred an international race to build the first quantum computer.

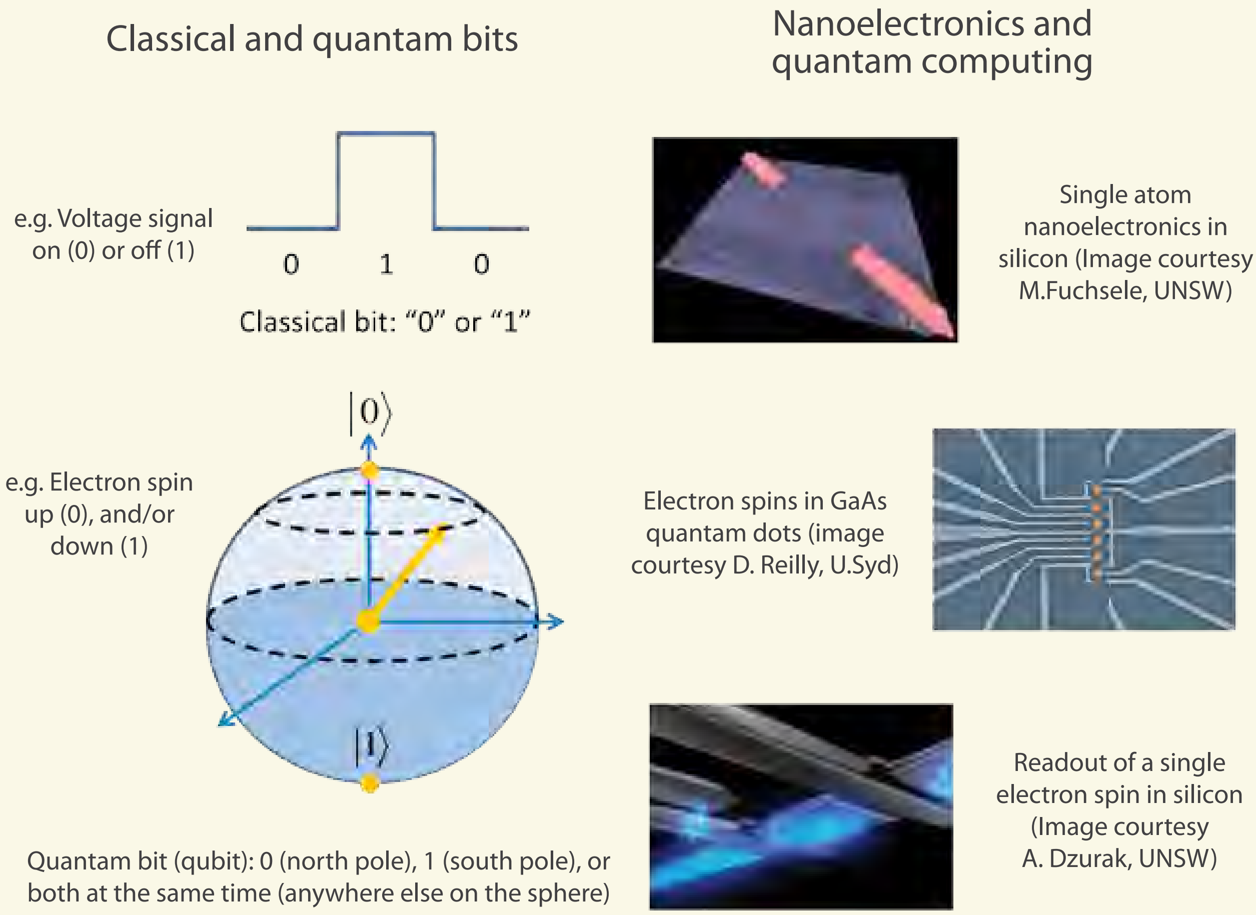


Figure 2: Left–The contrast between conventional (classical) information storage using bits and the quantum version—qubits, which allow the two possible bit states to exist at the same time and provide inherent parallelism in information processing. Right–Australian research in quantum computing related to nanoelectronics (see the case study on atomtronics describing approaches based on trapped atoms).

The fundamental parallelism of information processing using quantum mechanics is derived from the fact that quantum systems can exist in superpositions and entangled states—essentially multiple states at the same time. While a classical bit can only exist in the '0' or '1' state at any moment in time, a qubit can exist in both '0' and '1' states at the same time. Thus there is an inherent quantum parallelism where one can represent an exponentially increasing number of bit strings (numbers) with a linear number of qubits. A computation is carried out by creating special superposition states that are entangled, and interacting specific qubits as quantum logic gates according to a predefined algorithm. Although there are fast quantum algorithms for important problems such as data searching, linear equations and quantum chemistry, the most famous quantum algorithm is due to Peter Shor (1994), who showed that a quantum computer could find the prime factors of integers exponentially faster than any known classical algorithm. Given that this problem underpins internet data security, there is little wonder that quantum computing has attracted so much attention.

In Australia, several groups are working on qubits for quantum computing, with approaches that broadly split into photonic, atomic or electronic systems. In the Centre for Quantum Computation and Communication Technology, qubits comprising the spin of electrons confined to single phosphorus atoms in a silicon crystal are now fabricated and measured to high precision. In gallium arsenide, a qubit technology using electrons confined to electrostatically defined quantum wells (quantum dots) is being pursued by researchers at the University of New South Wales (UNSW) and the Centre for Engineered Quantum Systems. Another candidate system studied at the Centre for Quantum Atom Optics involves cold trapped atoms (see Atomtronics case study). As a result of this high level of support by the ARC, Australia is placed squarely at the forefront of this endeavour, with world-leading theoretical and experimental research in a range of qubit systems.

Nanocharacterisation

Definition of discipline

Nanocharacterisation measures the nanoscale structure or properties of matter.

Instrumentation and methods are developed to detect and quantify nanoscale phenomena. These methods are applied to probe and understand diverse materials, from human-made devices to biological structures and organisms.

Nanocharacterisation is essential to enable new discoveries in the nanosciences and their development into commercial nanotechnologies, and to provide the metrologies necessary to enable reliable and safe manufacturing. Nanocharacterisation underpins nanotechnology, allowing its benefits to society to be realised. It is a pervasive research capability enabling numerous areas of scientific endeavour.

Australian strengths in nanocharacterisation

Summary of the key strengths in nanocharacterisation

1. **The Australian Synchrotron (AS) has helped establish research strengths in X-ray-based techniques.**
2. **World-class neutron scattering facilities for nanocharacterisation are now available at the OPAL research reactor.**
3. **Australia has three major ion beam facilities that work closely together through the Australian Collaboration for Accelerator Science.**
4. **Australia has versatile and advanced capabilities in scanning electron microscopy, including in situ correlation of nanostructure with optical, spectroscopic and mechanical measurements.**
5. **Strengths in transmission electron microscopy are wide-ranging and include world-class capabilities in areas such as ultrahigh spatial resolution, theory and technique development and in situ measurements.**
6. **Any scanning probe microscopy experiment can be carried out in Australia, and there are leading specialised capabilities in lithography and the measurement of molecular interaction forces.**
7. **Australia has world-class atom probe instrumentation, including laser-assisted local electrode atom probes.**
8. **There are significant strengths in several super-resolution optical microscopies, including photoactivated localisation microscopy and stimulated emission depletion microscopy.**

Australia's strengths in nanocharacterisation are embodied in groups at large-scale research facilities such as the AS and the OPAL reactor at the Australian Nuclear Science and Technology Organisation (ANSTO); at a number of dedicated networks for nanocharacterisation such as the Australian Collaboration for Accelerator Science and the Australian Microscopy and Microanalysis Research Facility; at central facilities within universities and CSIRO; and within individual research groups. In many instances, these groups have strengths in the development of characterisation techniques through advances in instrumentation and/or interpretative theory, placing Australia at the forefront of capabilities in these areas. Techniques where Australia has notable strengths in nanocharacterisation research include: X-ray and neutron scattering analysis using tailored ion beams; scanning and transmission electron microscopy; scanning probe microscopy; atom probe microscopy; and advanced optical microscopies. These strengths have developed into cooperative and widely distributed networks of expertise in industry, government laboratories and universities. There are also important strengths across the country in a variety of relatively low-cost techniques located in individual research laboratories. Although this research plan cannot address each of these small-scale techniques explicitly, their importance should not be underestimated.

The Australian Synchrotron has helped establish research strengths in X-ray based techniques

Australia has many groups working at an international level in aspects of nanomaterial characterisation using X-rays as a probe, particularly since the opening of the AS in 2007. The key advantages of using synchrotron radiation for nanocharacterisation are highly collimated, high-brilliance X-ray beams with tunable energies that allow for studies of very small or in situ samples with excellent elemental discrimination. A significant amount of work is also done using laboratory-based sources around the country.

> Australian researchers are particularly strong in areas that have been offered for many years at overseas facilities through the Australian Synchrotron Research Program and are now available at the AS. These include X-ray powder diffraction (XRD), which is routinely used for nanomaterial structural characterisation; small angle X-ray scattering (SAXS), which is one of the key techniques for the study of bulk nanoscale systems on length scales ranging from one to several hundred nanometres; X-ray absorption spectroscopy (XAS), which has been available to Australian researchers at the Australian National Beamline Facility in Japan for almost 20 years and is also now at the XAS beamline at the AS; and X-ray microscopy and imaging via a world-leading X-ray fluorescence microprobe (XFM) beamline, which hosts many groups at the forefront of the use of this method. Finally, the soft X-ray beamline at the AS provides X-ray photoelectron spectroscopy and low-energy X-ray absorption for a strong community of materials scientists.

Internationally, there is strong growth in the implementation of X-ray techniques, particularly associated with synchrotron sources. Researchers in Australia are at the forefront of many of these, including the ability to perform measurements under extreme conditions, time-resolved measurements of rapid chemical and physical processes, imaging techniques, and investigation of hierarchical materials (having discrete structures on length scales from subnanometres to metres).

World-class neutron scattering facilities for nanocharacterisation are now available at the OPAL research reactor

Since 2008, Australia's 20 MW OPAL research reactor at ANSTO has provided state-of-the-art neutron scattering techniques for nanocharacterisation. Major advantages of using neutrons include the ability to penetrate a wide range of sample environments, the lack of beam damage to organic and biological samples and the ability to enhance scattering contrast for complex nanoscale systems by isotopic labelling of components with deuterium instead of hydrogen. Supporting this capability is the National Collaborative Research Infrastructure Strategy (NCRIS)-funded National Deuteration Facility, which provides deuteration of biological and chemical species for Australian researchers.

> Small-angle neutron scattering (SANS), performed using the QUOKKA spectrometer, is highly complementary to SAXS and allows for the characterisation of three-dimensional (3D) objects such as nanoparticles, vesicles, protein complexes, complex fluids, polymer nanocomposites and nanoscale magnetism. A second, complementary SANS instrument (BILBY) and an Ultra-SANS (KOOKABURRA) for studies of mesoscale structures are under construction. Neutron reflectometry (NR) is carried-out using the PLATYPUS neutron reflectometer, which allows for the study of nanoscale thin films, processes and structures produced on surfaces, including polymers, magnetic memory, solar cells, molecular sensors, organic optoelectronics and biomimetic cellular membranes (see Figure 3). Inelastic neutron scattering (INS) techniques at OPAL enable the study of motion, dynamics and the energetics of processes that occur on the nanoscale. The PELICAN cold neutron time-of-flight spectrometer is currently being commissioned, while the high-resolution EMU backscattering spectrometer (to be commissioned in 2013) will allow measurement of atomic and molecular motion on nanosecond timescales. ANSTO

also has high-resolution (ECHIDNA) and high-intensity (WOMBAT) powder diffractometers, which are particularly useful for studying materials which have light elements in the presence of heavy ones (Figure 4).

International neutron scattering facilities provide access for Australian researchers where local SANS and NR instruments are substantially oversubscribed, and additionally provide access to INS instruments that are currently under development.

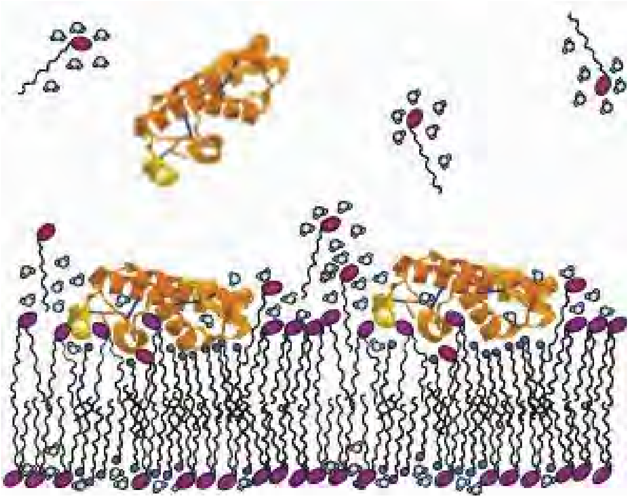


Figure 3: Phospholipase attack on supported biomimetic membrane by neutron reflectometry. (Reprinted from *Biochimica et biophysica acta,* Wacklin, H P *et al.* (2007) Distribution of reaction products in phospholipase A2hydrolysis, 1768: 1036–1049, with permission from Elsevier.)

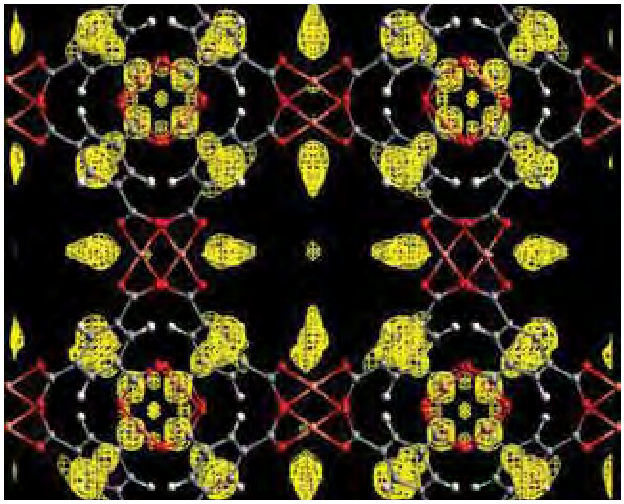


Figure 4: Nanoporous metal-organic framework containing molecular hydrogen (yellow) identified directly using neutron powder diffraction. (Image courtesy of V. K. Peterson)

Australia has three major ion beam facilities which work closely together through the Australian Collaboration for Accelerator Science

Tailored ion beams are sensitive, non-destructive probes for nanoscale systems due to their capacity to be generated from atoms ranging from H to U, and their ability to tune the ion beam energy from a few electron volts (eV) to hundreds of MeV. The structure and composition of materials can be examined as a function of depth down to a single monolayer of atoms on a surface. Techniques include Rutherford backscattering, elastic recoil detection analysis and nuclear reaction analysis, with major contributions in materials science, biology and environmental science.

There are three major ion beam facilities that work closely together through the Australian Collaboration for Accelerator Science. These are located at the Australian National University (ANU), at Melbourne University, and at ANSTO, which recently received $25 million in Commonwealth funding to develop the national Centre for Accelerator Science, doubling the number of accelerators on that site.

Secondary ion mass spectrometry (SIMS) is also well-represented within Australia, providing imaging mass spectrometry from a wide range of samples. Australia's capabilities include 'nanoSIM', which provides nanoscale maps of elemental and isotopic composition with subparts per million sensitivity, and time-of-flight SIMS, which can identify and map elemental and molecular ion species of solid surfaces.

Australia has versatile and advanced capabilities in scanning electron microscopy, including in situ correlation of nanostructure with optical, spectroscopic and mechanical measurements

Scanning electron microscopy (SEM) uses 'low'-energy (100eV to 30keV) electrons to provide nanoscale information about surface and subsurface morphology, crystallography, density-of-states (DOS), speciation, defect structure and composition that can be correlated with in situ measurements of optical activity, magnetic structure, and mechanical properties. Australia has versatile and advanced SEM capabilities, including high spatial and spectral resolutions and chemical sensitivity, multidimensional datasets and their advanced processing (e.g. spatial, temporal, thermal, optical and/or mechanical data), nanoscale maps with analytical spectra for each pixel, and real-time data acquisition for characterising nanoscale dynamical processes. Advanced SEM nanoanalyses are complemented in Australia by focused Ga^+ ion beam techniques as detailed in the Nanofabrication chapter.

Strengths in transmission electron microscopy are wide-ranging and include world-class capabilities in areas such as ultrahigh spatial resolution, theory and technique development and in situ measurements

Transmission electron microscopy (TEM) uses 'high' energy electrons (30keV to 1.5MeV) to measure and *correlate* the atomic structure, composition and electronic structure of nanomaterials through a variety of electron diffraction, imaging and spectroscopy techniques (see Figure 5).

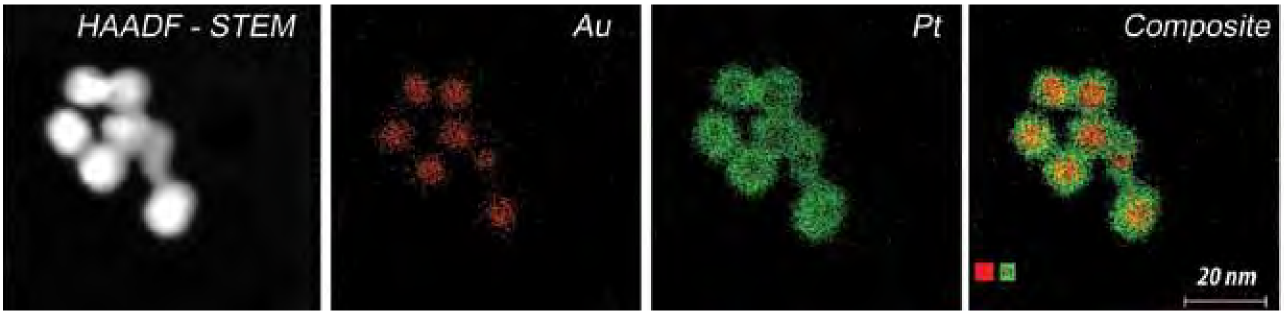


Figure 5: Electrocatalyst core/shell Au/FePt3 nanoparticles for use in membrane fuel cells. Maps of the chemical distribution in the nanoparticles using X-ray spectroscopy in a TEM: of Au (green), Pt (red) and their overlap. (Similar material published in *Nano Lett*. (2011) 11: 919-926; Image courtesy of Nestor J Zaulzec)

With the recent development of aberration-corrected electron optics, it has become possible to form electron probes much smaller than an atom, enabling structural and bonding information to be obtained from individual atomic columns probed selectively within a nanostructure. Australia established one of the world's first double aberration-corrected TEM capabilities and has particular strengths in the theory necessary for interpretation (see Figure 6).

In recent years, several other advanced TEM techniques have emerged in Australia, including electron tomography for the determination of 3D structure and morphology at subnanometre resolution (Figure 7), and in situ TEM, which allows the physical and mechanical properties of individual nanostructures (e.g. nanowires) to be examined under an external stimulus (forces, electrical voltages and currents).

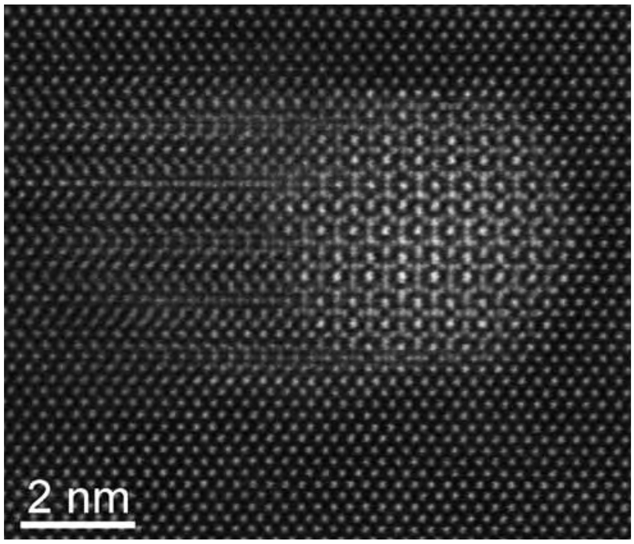
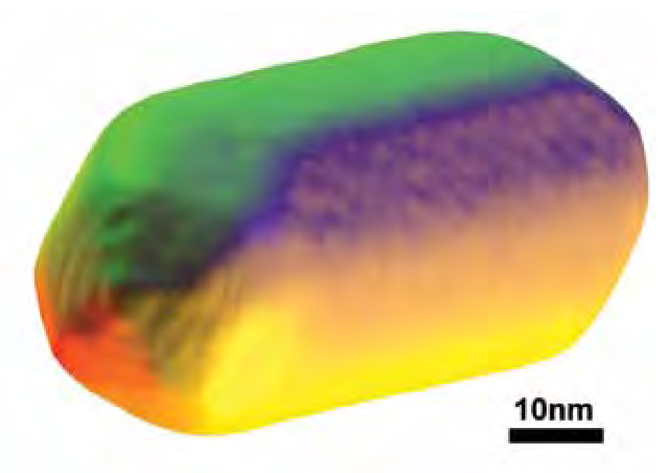


Figure 6: Image of the arrangement of atoms in a tin nano particle attached to an aluminium copper nano particle embedded in an aluminium alloy developed for high performance structural applications taken with a double-aberration-corrected TEM. (Reprinted from *Acta Materialia*, Bourgeois, L *et al.* (2012) The magic thicknesses of theta prim-prime precipitates in Sn-microalloyed Al-Cu, 60: 633–644 with permission from Elsevier; Image courtesy of Laure Bourgeois, Monash University)



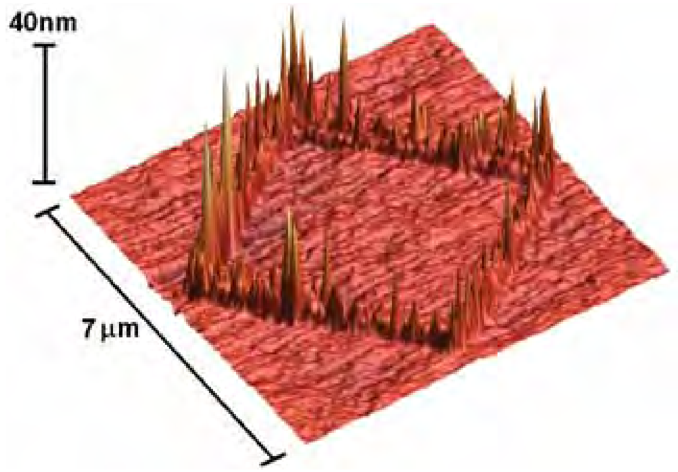


Figure 7: Gold nanorods for applications in biosensing. The shape was determined by aberration-corrected electron tomography. (Similar material published in *Nano Letts*, Katz-Boon, H *et al.* (2011) Three-dimensional morphology and crystallography of gold nanorods, 11: 273–278; Image courtesy of Hadas Katz-Boon, Monash University)

Figure 8: AFM Image of Patterned attachment of nanotubes to silicon created using AFM lithography. Reprinted from *Soft Matter,* Flavel B S *et al.* (2009) Patterned Polyaniline & Carbon Nanotube/Polyaniline Composites on Silicon, 5: 164 – 172; Image courtesy of Joe Shapter, Flinders University)

Any scanning probe microscopy experiment can be carried out in Australia, and there are leading specialised capabilities in lithography and the measurement of molecular interaction forces

Scanning probe microscopy (SPM) is a suite of techniques that have at their core the ability to move a very sharp probe to within nanometres of a surface and then control the position of that probe with the same level of accuracy. One of Australia's strengths in this area is its diversity, which means any SPM experiment can be done in Australia. There are some specialised capabilities in Australia that are world-leading, particularly in atomic scale lithography and the measurement of molecular interaction forces (see Figure 8). Australia also has world-leading capability in combining other techniques with SPM, allowing simultaneous measurement of properties such as surface topography, molecular composition through spectroscopy and material properties such as nanoscale hardness.

Australia has world-class atom probe instrumentation, including laser-assisted local electrode atom probes

Atom probe microscopes are capable of generating atomic resolution 3D compositional maps showing the type and position of atoms extracted from within a needle-shaped specimen with lateral resolution of ~0.4 nm and depth resolution of ~0.2 nm. By late 2012 Australia will have five atom probes located across three universities, including world-class, laser-assisted, local electrode atom probes capable of examining non-conducting specimens as well as conducting specimens. This will extend the range of applications to semiconductors, ceramics, thin films and biomaterials.

There are significant strengths in several super-resolution microscopies, including photoactivated localisation microscopy and stimulated emission depletion microscopy

Super-resolution light microscopy uses various techniques to extend the resolution of light microscopy beyond a limit imposed by the diffraction of light. These techniques are revolutionising the study of biological systems at the sub-100 nm scale. Many require 'fluorophores'—photoswitchable dyes and fluorescent proteins—which are strategically chosen to highlight the object under study. Australia has significant strengths in several super-resolution microscopies with resolution better than 100 nm, including photoactivated localisation microscopy (PALM) and stimulated emission depletion microscopy (STED). PALM can detect the localisation of single molecules in complex biological samples with a precision of 15–20 nm (Figure 9). This provides a unique capability for measuring protein distribution (as opposed to the underlying structure). It offers a high throughput and relatively inexpensive alternative to cryo-electron microscopy. STED uses two laser pulses to excite and de-excite fluorophores, offering the unique ability to image live cells with lateral resolutions of 30–100 nm.

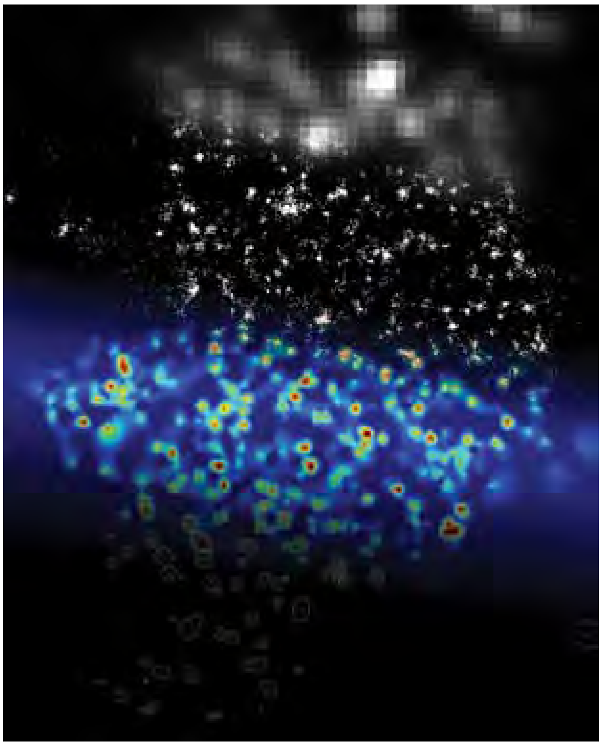


Figure 9: A montage of PALM images from a single, activated T cell. The top section shows how the cell appears on a conventional microscope. The section below that shows the super-resolution image (of the same cell). The next section shows a 'heat map' molecular clustering in the cell membrane derived from the PALM data and the final section uses the heat map to quantify the clusters of molecules. (Image courtesy of Katharina Gaus, UNSW)

Challenges and opportunities for nanocharacterisation

Summary of the key challenges for nanocharacterisation

1. **To maintain and advance capabilities in nanocharacterisation to address the major scientific challenges facing nanoscience and nanotechnology.**
2. **To build further beamlines at the Australian Synchrotron.**
3. **To take advantage of the OPAL neutron scattering facility once it has been upgraded.**
4. **To utilise the new and expanded ion beam analysis technologies at ANSTO.**
5. **To develop a high-resolution, low-damage capability in scanning electron microscopy.**
6. **To take advantage of emerging new technologies in transmission electron microscopy such as in advanced spectroscopy and in situ gas microscopy.**
7. **To develop scanning probe microscopy for real-time imaging of surfaces at the nanoscale.**
8. **To capitalise on Australia's capability in atom probe microscopy.**
9. **To take advantage of the rapid developments in super-resolution optical microscopies.**

Challenge: To maintain and advance capabilities in nanocharacterisation to address the major scientific challenges facing nanoscience and nanotechnology.

Opportunity: To develop next generation nanocharacterisation methods to discover and develop new nanotechnologies.

In the next decade, Australia must maintain and advance its capabilities in nanocharacterisation to provide the investigative tools necessary to address the major scientific challenges facing nanoscience and nanotechnology. In order to enable new discoveries and new technologies, next generation nanocharacterisation methods must be developed that can routinely and quantitatively:

- measure the position, type and bonding of individual atoms, such as dopants or vacancies, within the bulk (e.g. in quantum computing devices, quantum well nanostructures)
- measure the local properties of nanoscale structures with high spatial resolution (e.g. the electronic structure across an interface, the elastic constants in a nanoparticle, nanoscale forces in nanostructured systems and the electric field at a nanoparticle tip)
- characterise nanostructures in the environment in which they function (e.g. in solution or under extreme temperatures, pressures, magnetic fields etc.)
- characterise time-dependent processes from microseconds to femtoseconds with high spatial resolution
- measure the 3D arrangement and type of atoms in complex nanostructures (e.g. core-shell nanoparticles, semiconducting nanowires)
- measure the atomic structure of nanoscale structures embedded within macroscopic materials (e.g. nanoprecipitates in alloys, nanocomposite materials and interfaces).

Exciting new methodologies and instrumentation are emerging across each of these areas, which are outlined for each technique below. Australia is in an excellent position to address the challenges above by capitalising on its expertise and investments in nanocharacterisation, which include major investments in landmark facilities (AS, OPAL), the establishment of national characterisation facilities (NCRIS-funded Australian Microscopy and Microanalysis Research Facility (AMMRF) and the Australian Nanofabrication Facility (ANFF)) and a number of strategic capabilities purchased with funding from other sources, such as ARC Linkage Infrastructure, Equipment and Facilities grants. These various communities have demonstrated they can work together to manage and share advanced nanocharacterisation facilities and provide necessary support, training and specialist expertise. There is an exceptional opportunity to extend this success through ongoing support as well as new investments in nanocharacterisation infrastructure and expertise. In particular, it is critical that our real strength in these characterisation fields continues to derive not just from the investment in instrumentation, although this is crucial, but from the specialist expertise, knowledge and ability of researchers in nanocharacterisation. Continued investment in human capital is vital to Australia's strategy of leadership in nanocharacterisation, and hence nanotechnology.

Challenge: To build further beamlines at the Australian Synchrotron.

Opportunity: Further investment in the Australian Synchrotron would enable new techniques to be developed.

In the 4 years since the AS opened, there has been dramatic growth in the number, quality and outputs of groups involved in X-ray-based nanomaterials characterisation. This growth, and many new scientific opportunities, will continue if further investment is made in adequate operating funding, new beamlines and upgrades, as described in the Australian Synchrotron Development Plan. Only nine of a possible 38 beamlines have been built to date. The infrastructure at the AS is outstanding and the incremental cost of adding further beamlines is relatively modest. It is crucial that advantage is taken of this excellent opportunity to be at the forefront of characterisation using X-rays. Further investment in the AS would enable new techniques identified in the AS development plan in 2010, such as the ability to characterise material on far smaller length scales, to understand protein structure and interactions in solution and to study engineering materials with very high energy X-rays. Additionally, the International Synchrotron Access Program of the AS is a major resource that has made a significant contribution to our becoming world class in many of these areas, and it is essential to maintain such programs to continue our competitiveness in the international scene.

> Laboratory-based instruments are an important adjunct to major facilities as they allow researchers to perform preliminary measurements and gain expertise, which in turn leads to more effective usage of synchrotron sources. Recent developments in laboratory X-ray instrumentation offer great opportunities for capitalising on the developments described above if appropriate investment is made.

Challenge: To take advantage of the OPAL neutron scattering facility once it has been upgraded.

Opportunity: To expand the scientific capacity of the OPAL facility.

The OPAL neutron scattering facility, with seven operational spectrometers, is being upgraded, and six new instruments are under construction. These include a second SANS instrument and three inelastic neutron scattering instruments that will allow the study of molecular motions and dynamics on the nanoscale. There is an opportunity to further expand the scientific capacity of the OPAL facility by a further five to six instruments, with one of the next instruments planned being a neutron reflectometer designed specifically to study nanoscale thin-film magnetism. Planning has begun for a second neutron guide hall at OPAL with the capacity for a further 15 to 18 neutron scattering instruments. New capabilities should include protein and membrane diffraction using neutrons, and bridging structures obtained by synchrotron-based protein diffraction and small-angle scattering. The development of the second neutron guide hall will require strong commitment for capital and operational funding, but is essential if Australia is to grow its profile in nanoscale and nanomaterials characterisation.

Challenge: To utilise the new and expanded ion beam analysis technologies at ANTSO.

Opportunity: To tailor ion beam energies and types to characterise a broad range of materials using specific elements and isotopes.

The Centre for Accelerator Science at ANSTO will provide novel and expanded ion beam analysis (IBA) technologies for Australian researchers. Four new IBA beamlines will be constructed on a 6 MV tandem accelerator, including a heavy ion confocal X-ray microprobe and a high-resolution nuclear reaction analysis beamline. These new facilities can be used to study radiation damage to materials, to characterise thin films, to develop multilayered structures and coatings with increased sensitivities, and to obtain better depth resolutions down to atomic scales and the ability to distinguish most elements in the periodic table, including key elements like hydrogen.

Developments in SIMS are heading towards brighter ion sources that will increase the sensitivity and resolution. Other developments include cryo-methodologies that will allow the in situ analysis of organic material without chemical fixation.

Challenge: To develop a high-resolution, low-damage capability in scanning electron microscopy .

Opportunity: New technologies are emerging, such as scanning helium ion microscopy, with improved high-resolution imaging and nanoanalysis capabilities.

The interaction of focused low-energy electron beams with samples provides nanoscale information about the morphology and properties of a sample. However, resolution is limited by the electron sample interaction volume. In addition, the electron beam may damage or modify the sample during analysis. There is therefore an unmet need in Australia for a scanning nanocharacterisation technique with more-efficient signal generation, non-destructive low-power operation and improved high-resolution imaging and nanoanalysis capabilities. The recently developed scanning helium ion microscope can meet these needs, but is not available in Australia. Given Australia's recognised world-class expertise in scanning electron and ion beam methods, the potential benefits associated with this nanocharacterisation technique provide superlative opportunities for high impact, fundamental and applied nanotechnology research.

Challenge: To take advantage of emerging new technologies in TEM such as in advanced spectroscopy and in situ gas microscopy.

Opportunity: To deliver new capabilities in TEM such as bonding measurements and plasmonic maps at ultimate resolution and in situ studies of crystal growth.

Emerging new technologies such as improved monochromators, electron sources and detectors promise revolutionary improvements in the spatial (<0.06 nm) and energy (<0.1eV) resolution of TEM. These are already enabling fundamentally new measurements and discoveries in the nanosciences, including the mapping of surface plasmon excitations at the near infrared with nanometer spatial resolution (Figure 10 and Figure 11) and atomic resolution chemical mapping (Figure 12) with near-atomic resolution electronic structure mapping and single-dopant atom sensitivity. Australia has the world-class expertise to capitalise on such new technologies, both in ultrahigh spatial resolution TEM (developed around one of the world's first double aberration-corrected TEMs) (Figure 5 and Figure 6) and in ultrahigh energy resolution TEM (developed around world-class theory groups and

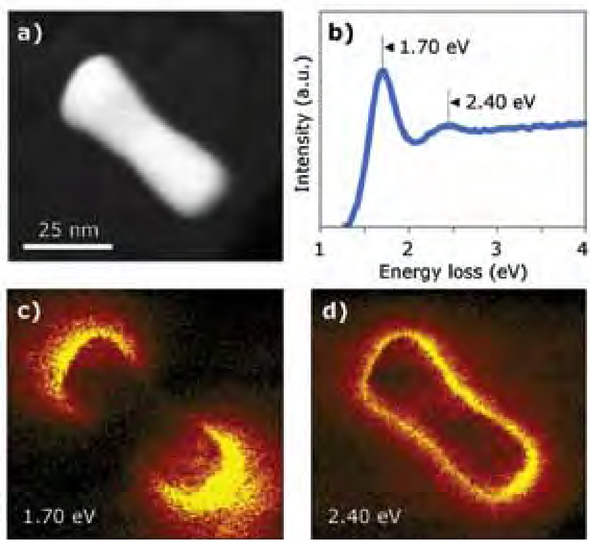


Figure 10: Australian researchers were the first to publish maps of surface plasmon excitations in a nanoparticle, in this case, a gold nanorod. (Reprinted from *Nanotechnology* 18 165505 (2007) with the permission of IOP Publishing ; Image courtesy of Vicki Keast, University of Newcastle)

applied on overseas instruments) (Figure 11).

Environmental TEM is another important advance relevant to Australia's needs. Small amounts of gases (and in special cases, liquids) can be injected into the TEM specimen area, so that chemical reactions, such as catalysis, can be imaged in situ down to the atomic level. For example, environmental TEM is enabling the study of the nucleation and growth of nanostructures such as 'nanowires'. In other TEM developments, next generation electron holography methods are enabling nanometre resolution maps of magnetic field distributions (see Figure 13) and dopant-potential profiles within nanostructures.

Challenge: To develop scanning probe microscopy for real-time imaging of surfaces at the nanoscale.

Opportunity: High-speed scanning probe microscopy of dynamic biological and materials processes.

Scanning probe microscopy is a laboratory-based technique that is rapidly moving from a method that provides exceptionally high-resolution 3D quantitative images of the surface topography of samples to one that uses the ability to probe a sample on the nanoscale to interrogate the specimen with other probes (e.g. photons) and forces (e.g. magnetic, Coulombic). This is opening the door to providing unprecedented resolution of properties such as chemical composition or changes in material properties. Additionally, time-resolved multidimensional analysis on the nanoscale is now a matter of priority. Rapid-scan systems are becoming available and it is only a matter of time before true video-rate data capture is feasible on a wide range of samples in a wide range of environments. The ability to scan at video rates will provide the opportunity to 'watch' important fundamental processes on the nanoscale in areas as diverse as biology and mineral processing. This will enhance our understanding of processes critical in fields ranging from healthcare to manufacturing. There is an opportunity to build on the existing national capability to be at the forefront of developments in high-speed imaging of many important systems ranging from crystal growth, which is fundamental in materials development, to enzyme action, which is key in biological processes. For example, researchers could 'watch' in real time the interactions of proteins with lipid membranes and how drugs or disease affect this interaction.

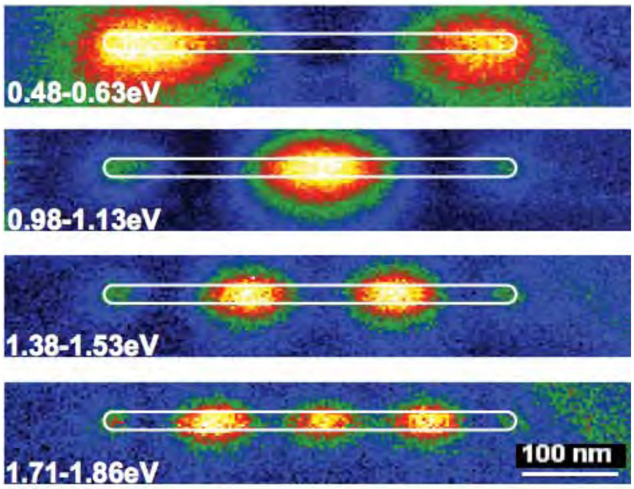


Figure 11: Silver nanoantennas. Using latest advances in TEM, surface plasmon-polariton resonances can be detected at nanometre resolution in individual antennas. (Reprinted from *Nano Letts* (2011) 11:1499–1504 with permission from ACS Publications; Image courtesy of the Canadian Centre for Electron Microscopy, McMaster University).

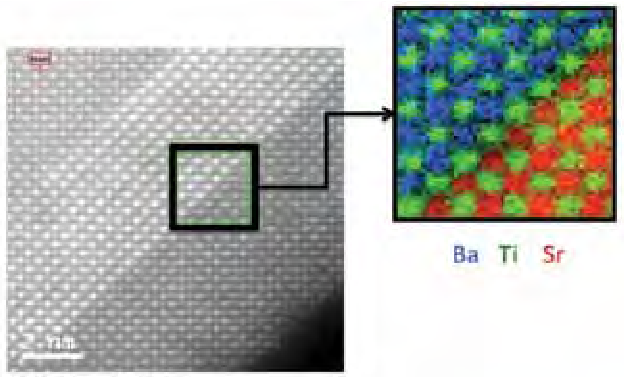


Figure 12: Atomic resolution chemical maps of a BaTiO3/SrTiO3 interface for functional electronics using the electron energy-loss signal from a next-generation aberration-corrected, monochromated TEM. Australian researchers contributed to the theoretical interpretation. (Reprinted from *Ultramicroscopy* 110, 926 (2010) with permission from Elsevier; Image courtesy of the Canadian Centre for Electron Microscopy, McMaster University).

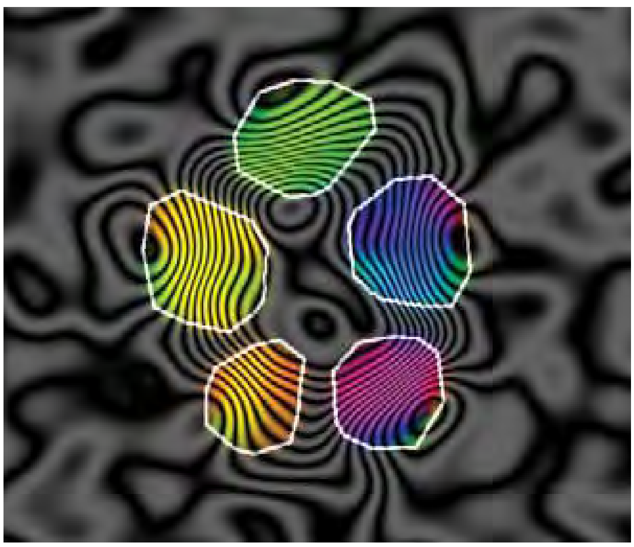


Figure 13: Magnetic field distribution in magnetic nanoparticle arrays measured using electron holography. The scale bar is 20nm. (Reprinted from *Nature Materials* (2009) 8: 271-280; Image courtesy Rafal E. Dunin-Borkowski)

Challenge: To capitalise on Australia's capability in atom probe microscopy.

Opportunity: Emerging atom probe technologies will increase the efficiency with which atoms are detected and distinguish different charge states.

Emerging opportunities in atom probe microscopy include ultraviolet (UV) lasers that can include new detectors to increase the efficiency with which atoms are detected (currently ~60%), improve mass resolution and distinguish different charge states. This will greatly improve compositional estimates. In addition, efforts are underway internationally to fund the development of a local electrode atom probe combined with a scanning transmission electron microscope to deliver the benefits of both techniques within one instrument.

Challenge: To take advantage of the rapid developments in super-resolution optical microscopies.

Opportunity: New super-resolution optical microscopies promise to revolutionise the in situ investigation of live biological systems.

Rapid developments in this suite of techniques are expected to lead to further improvements in resolution and targeting. Coupled with their ability to study live systems in situ, they are expected to revolutionise the study of biological systems and drive major developments in nanobiotechnology and nanomedicine.

Summary of the key opportunities for nanocharacterisation

1. **To develop next generation nanocharacterisation methods to discover and develop new nanotechnologies.**
2. **Further investment in the Australian Synchrotron would enable new techniques to be developed.**
3. **To expand the scientific capacity of the OPAL facility.**
4. **To tailor ion beam energies and types to characterise a broad range of materials using specific elements and isotopes.**
5. **New technologies are emerging, such as scanning helium ion microscopy, with improved high-resolution imaging and nanoanalysis capabilities.**
6. **To deliver new capabilities in transmission electron microscopy, such as bonding measurements and plasmonic maps at ultimate resolution, and in situ studies of crystal growth.**
7. **High-speed scanning probe microscopy of dynamic biological and materials processes.**
8. **Emerging atom probe technologies will increase the efficiency with which atoms are detected and distinguish different charge states.**
9. **New super-resolution optical microscopies promise to revolutionise the in situ investigation of live biological systems.**

Developing the discipline

Nanocharacterisation is underpinned by cutting-edge instruments and methods, and the specialist research of scientists and engineers who invent, develop and apply them. It is therefore imperative that there are stable, long-term funding mechanisms to sustain and advance Australia's nanocharacterisation capability, both in terms of instrumentation and expertise (Recommendation 1). Mechanisms that optimise interdisciplinary research (Recommendation 2) and international engagement are also important (Recommendation 4) for this discipline.

Case study 3: Nanostructured light metals for energy-efficient transport

Nanostructured metal alloys are pivotal to the design of the latest generation of energy-efficient aircraft and motor vehicles. They are engineered to minimise weight in order to minimise fuel usage, while increasing strength to increase capacity—ultimately reducing both operating costs and carbon emissions.

Intrinsic to the design of these 'light metals' are nanoparticles. Pure metals, such as aluminium, are light but too weak and pliable for use in an aircraft wing, for example. By adding a tiny percentage of different types of atoms, such as tin or copper, a network of nanoparticles can be grown within the metal to form a nanoscale scaffold, which can increase strength dramatically without any significant increase in weight. This is a classic example of nanoscale phenomena driving the macroscopic performance of materials, in this case, high-performance materials for structural engineering.

The development of next generation commercial light metals requires a fundamental understanding of the nanoparticle scaffolds (such as atomic structure and growth kinetics) in order to optimise their performance. Australia has world-class research activities in the design of light metals, such as those under the umbrella of the ARC Centre of Excellence for Design in Light Metals. With major industry support, Australian researchers are involved in the development of the latest commercial light alloys such as the types used in the Airbus A380.

Australia's ability to execute these programs requires high-level expertise in many of the disciplines described in this report, such as nanoscale modelling, nanocharacterisation, nanomaterials, nanofabrication and translational nano research.

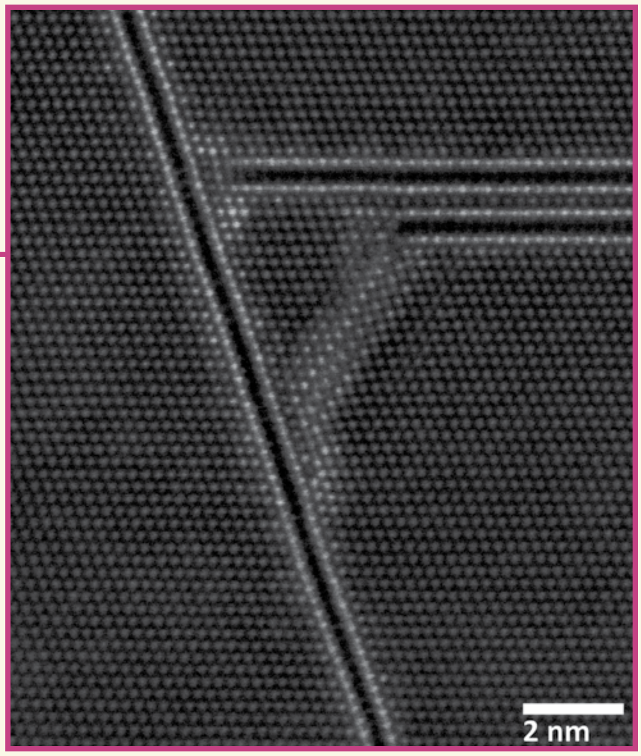


Figure 14: An image (right) of the arrangement of atoms (white 'dots') in a high-performance, lightweight aluminium alloy used in the Airbus A380 aircraft (left), showing the nanoparticle scaffold which gives it its strength. The atomic structure of these nanoparticles was determined in Australia. (Image (right) courtesy of Matthew Weyland, Monash Unviersity)

Nanofabrication technologies

Definition of discipline

Nanofabrication technologies involve advanced physical and chemical techniques and tools that enable production of nanostructured materials, devices and prototypes needed for nanotechnology research and development.

Nanofabrication is a key enabling technology that provides the essential structures and devices needed for subsequent research in areas including nanomaterials, nanoelectronics, nanophotonics and nanobiotechnology/nanomedicine. It can be categorised into:

i) **Synthesis and structuring**—including bottom-up, self-assembly of nanoparticles and nanoscale-layered structures, together with structuring techniques for polymers or glasses, including nanoembossing and extrusion.

ii) **Growth and deposition**—including epitaxial crystal growth with atomic-layer precision and the deposition of metals, inorganic layers and organic materials, including carbon nanotubes.

iii) **Lithography and etching**—involving top-down nanopatterning techniques such as optical and electron beam lithography, ink jet printing of organic materials and top-down etching of structures using chemicals or plasmas.

iv) **Integration and packaging**—of electronic, optical and medical devices.

Nanofabrication capabilities are vital to increasing the innovation dividend from Australian nanotechnology research strengths by progressing research outcomes to market through engagement between industry and the research community. The integration of cross-disciplinary nanofabrication solutions is central to this. For example, the interaction between biology and soft matter with traditional inorganic hard matter device technologies underpins new applications in bionics, sensors, plastic electronics and drug delivery. The fabrication of quantum/nanoscale photonic, electronic and electromechanical structures, and nanoparticulates, will have a major impact on all areas of information and communication technology (ICT) and sustainable energy technologies as well as mining, defence and security systems.

Australian strengths in nanofabrication technologies

Summary of the key strengths in nanofabrication

1. **Major investments in capital and human infrastructure for nanofabrication, including the Australian National Fabrication Facility (ANFF).**
2. **Leading expertise in organic conductor and solar cell fabrication.**
3. **World leadership in microstructured polymer and specialty glass optical fibres.**
4. **Leadership in the growth of nanowires based on III-V compounds.**
5. **Leadership in molecular beam epitaxy and HgCdTe-layered structures.**
6. **World-leading expertise and capability in electron beam lithography.**
7. **High-impact research in nanomachining and nano microelectromechanical sytems (NEMS)/ microelectromechanical sytems (MEMS) devices.**
8. **World leadership in silicon nanofabrication and single-atom device fabrication.**
9. **Leading expertise and facilities in laser direct-write patterning.**
10. **World-leading reputation in bionics.**

Compared to other nations, Australian research in nanofabrication technologies has a higher proportion of research related to applications in nanomedicine and nanomaterials, which is a consequence of Australian high-tech manufacturing being dominated by medical devices, pharmaceuticals and materials processing (e.g. for mining). However, Australian researchers also undertake high-impact work in nanoelectronics in emerging areas such as nanowire fabrication, metamaterials and single-atom electronics/spintronics, facilitated by strong international collaborations and partnerships with overseas companies and funding agencies.

Figure 15: ANFF clean facility. (Image courtesy of ANFF, NSW)

Australia has made major investments in capital and human infrastructure, including the ANFF.

Australia's strength in nanofabrication has been underpinned over the past decade by major investments in capital and human infrastructure, totalling more than $A150 million over 2006–2013, from the Australian and state governments through NCRIS and the Education Investment Fund. These investments were used to establish ANFF, a national, networked facility incorporating 19 institutions providing state-of-the-art micro- and nanofabrication facilities to researchers from universities, publicly funded organisations (e.g. ANSTO, CSIRO, DSTO) and industry. The national investment has allowed large-scale, clean-room laboratories to be established in most states, each with a broad range of nanofabrication tooling and with each node providing capabilities matched to local research strengths. In addition to ANFF, smaller nanofabrication capabilities (individual tools or groups of tools) are maintained in many universities, CSIRO and in industry, usually dedicated to specific projects or project areas.

ANFF in Australia is commensurate in per capita terms with its international equivalents such as the US National Nanotechnology Infrastructure Network. ANFF is recognised as having a high level of collaboration between nodes at different universities, with many research projects supported by a combination of nodes.

Synthesis and structuring

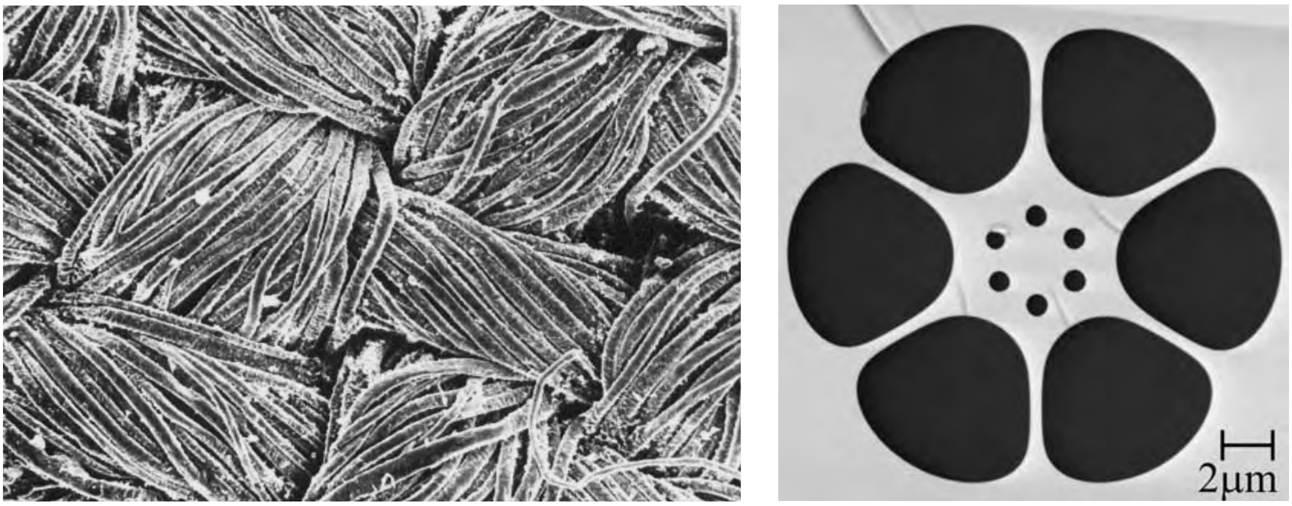


Figure 16: Examples of synthesis and structuring techniques. (Left) Spun and weaved polymer fibres. (Image courtesy ANFF, University of Wollongong). (Right) Nanostructured optical fibre. (Image courtesy of ANFF, University of Adelaide)

Leading expertise in organic conductor fabrication

Organic conductors are custom-designed materials based on new advances in functional organic chemistry, with applications in artificial muscles, photovoltaics, batteries and biomedical devices. Following organic synthesis in solution, nano- and microstructures are formed using processes such as ink jet printing and dip pen nanolithography to create 2D and 3D structures. Australia has leading expertise in organic conductor fabrication at the ARC Centre of Excellence for Electromaterials Science (ACES) at Wollongong University, Queensland University and Newcastle University, and at CSIRO.

Leading groups working in nanofibre spinning and weaving

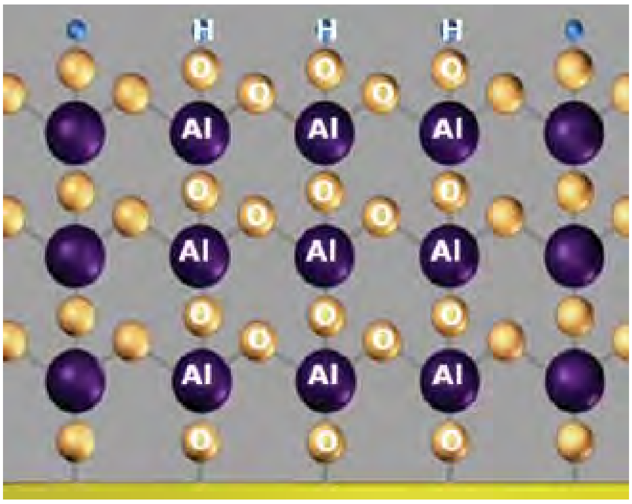
Woven (e.g. knitted) and non-woven fibres, based on nanomaterials, such as carbon nanotubes, represent an exciting new class of structures with applications in a variety of areas, including nanomedicine. Structures include surface-activated fibre scaffolds for tissue engineering, nanocomposites and electroactive material fibres, fabricated using electrospinning and gel-spinning approaches. Leading groups exist at the Centre for Material and Fibre Innovation at Deakin University, and at ACES at Wollongong University.

Organic solar cells offer the prospect of low-cost, large-area solar energy conversion. These include thin-film heterojunction devices that utilise photoactive layers of nanostructured organic materials (small molecules, polymers or dendrimers) and dye-sensitised or photoelectrochemical solar cells. The component materials and interfaces involve nanoscale synthesis. Leading expertise exists at ACES at Queensland University, Melbourne University and Newcastle University, and at CSIRO.

World leadership in microstructured polymer and specialty glass optical fibres

Australia has world-leading expertise in microstructured polymer optical fibres at ANFF and the Institute of Photonics and Optical Science, University of Sydney. It also has expertise in multimode high-bandwidth and hollow-core fibres, with significant leadership in the area of low-loss, single-mode fibres. Australia also has leadership in the fabrication of nanostructured hard (e.g. silica) glass and soft (e.g. ZBLAN) glass specialty fibres (e.g. Institute for Photonics and Advanced Sensing, University of Adelaide). Complex submicron structures are produced following drawing of fibres from structured preforms—see Figure 16. Applications include chemical sensors for industry and biological sensors for medical diagnostics; for example fibres coated with metal and antibodies that can trap and measure the presence of flu virus particles using surface plasmon resonance.

Growth and deposition



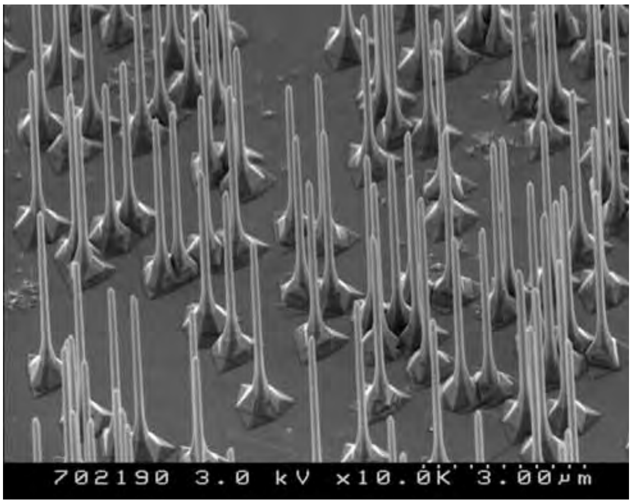


Figure 17: Examples of growth and deposition techniques. (Left) Growth of thin film using atomic layer deposition, (Image courtesy of Cambridge nanotech). (Right) III-V compound semiconductor nanowire growth. (Image courtesy of ANFF, ANU)

A leader in the growth of nanowires based on III-V compounds

Australia is a leader in the growth of nanowires based on III-V compounds, such as gallium arsenide, that use metal-organic chemical vapour deposition (see Figure 17 (above)). Nanowires are possible building blocks for next-generation electronics and photonics. Extensive facilities have been established at the ANU, which is also a hub for research in this area, along with collaborators at UNSW, Queensland University, the University of Western Australia (UWA) and Sydney University.

High-impact work into nanocarbon, carbon nanotubes (CNTs) and graphene

Nanocarbon (e.g. C_{60}), together with its 1D form (CNTs) and 2D form (graphene), are recognised worldwide as important nanomaterials of the present and future, with applications in new structural materials, medical devices and electronics. Fabrication of nanocarbon and nanotubes is achieved using gas plasma deposition or growth, with overseas vendors now supplying commercial quantities of these materials. Australian research groups undertake high-impact research in the synthesis and characterisation of these materials, including at the ACES, the Centre of Excellence for Functional Nanomaterials, Queensland University, Newcastle University, UNSW and CSIRO.

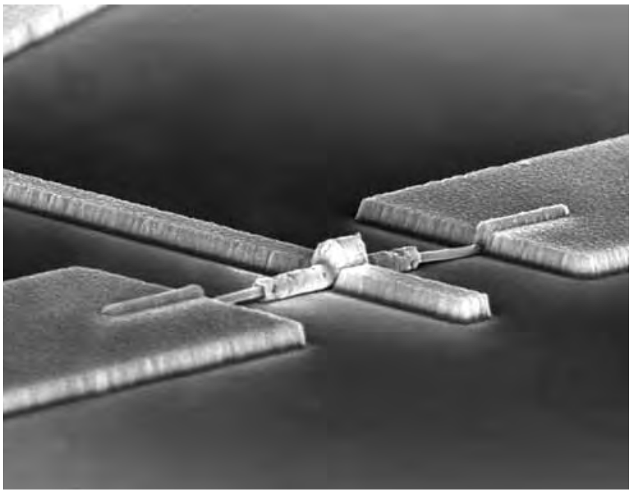
Leadership in molecular beam epitaxy and HgCdTe layered structures.

Australia has leadership in molecular beam epitaxy of HgCdTe-layered structures at the UWA, with key applications in infrared sensor technology. The combination of epitaxial crystal growth with micromachining techniques at ANFF has enabled the development of integrated tunable infrared spectrometers, with applications in night vision systems for defence, together with airborne-imaging systems for agriculture and environmental monitoring.

Developed ultrahigh precision multilayer mirrors and etalons for astronomy

Australian researchers (e.g. CSIRO Precision Optics) have developed ultrahigh precision, multilayer mirrors and etalons for astronomy (e.g. Laser Interferometer Gravitational-wave Observatory, LIGO), aerospace, energy and defence applications.

Lithography and etching



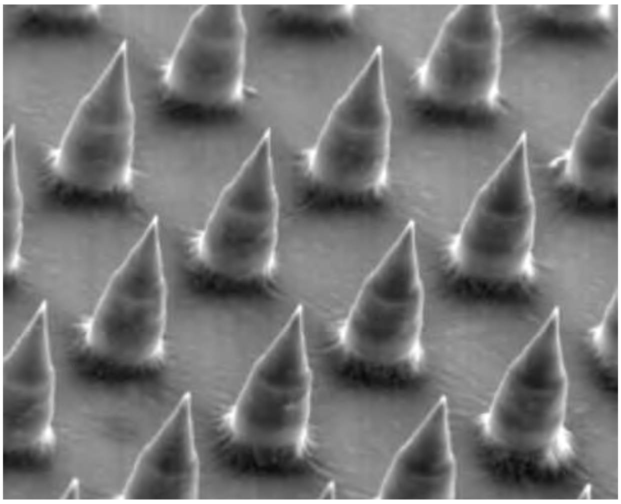


Figure 18: Examples of lithography and etching techniques. (Left) Semiconductor nanowire with electrodes patterned by electron-beam lithography. (Image courtesy of Adam Micolich, UNSW and Kristian Storm, Lund). (Right) Silicon microneedles fabricated using reactive ion etching. (Image courtesy of ANFF, University of Queensland)

World-leading expertise and capability in electron beam lithography

High-resolution electron beam lithography (EBL) is a key enabling nanofabrication technology for the patterning of arbitrarily designed structures at dimensions down to 10 nm. Because it is a serial (or direct-write) patterning process it is not suitable for large-volume manufacture, but plays a critical role for high value-added components and in the research and development (R&D) stage of new frontier technologies, in particular nanoelectronics (e.g. quantum dots and nanowire transistors—see Figure 18 (above)), nanophotonics (e.g. plasmonics, photonic crystals, waveguide couplers) and quantum engineered devices (e.g. superconducting quantum interference devices (SQUIDs). Australia has world-leading expertise and capability in EBL, primarily through ANFF facilities at UNSW, ANU and the Melbourne Centre for Nanofabrication.

High-impact research in nanomachining and NEMS/MEMS devices

Nanoscale machining technologies, including plasma and chemical etching or focused ion beam (FIB) milling of semiconductors and metals, represent another key enabler for constructing a wide range of nanoscale devices. High-impact Australian research areas underpinned by these technologies include NEMS/MEMS, including HgCdTe/Si electrically tunable infrared sensor arrays; nanomachined optical waveguides and photonic crystals for telecommunications; and microneedle arrays for the 'nanopatch' needleless vaccine delivery system—see case study 9.

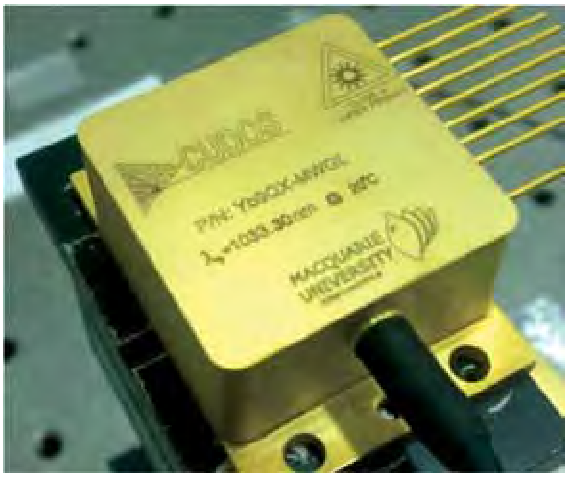
World leadership in silicon nanofabrication and single atom device fabrication

Silicon is the dominant material in the trillion-dollar global electronics industry, in particular for computer processor and memory integrated circuits. Australia has leading expertise in the development of next generation silicon nanoscale devices, including silicon-based qubits for quantum computers. Australia has recognised leadership in novel and ultrasmall Si MOSFET fabrication, single atom doping using single ion implantation, and scanned probe (STM) lithography of atomic precision nanoelectronic devices, including single atom transistors. Key expertise and facilities are located at the Centre of Excellence for Quantum Computation and Communication Technology at UNSW and the University of Melbourne.

Leading expertise and facilities in laser direct-write patterning

Laser patterning is a flexible technology capable of fabricating microcomponents in a wide range of materials (e.g. metals, polymers, glasses, crystals) with applications in all branches of nanotechnology. Australia has leadership in two-photon polymerisation methodologies to fabricate 3D nanostructured waveguides in polymer substrates with applications in biosensing, metamaterials, astrophotonics and telecommunications. Key centres of expertise are at ANFF, Macquarie University and Swinburne University.

Integration and packaging



World-leading reputation in bionics

Australia has a world-leading reputation in bionics (e.g. Cochlear Pty Ltd) for which the issue of hermetic sealing of electrical components is critical. Australian groups have developed significant expertise in new materials for encapsulation for biocompatible device components, including parylene and diamond. Centres of expertise include ANFF Melbourne Centre for Nanofabrication, the University of Melbourne, and CSIRO.

Figure 19: An example of packaging; optical device packaging. (Image courtesy of ANFF, Macquarie University)

Challenges and opportunities for nanofabrication technologies

Summary of the key challenges for nanofabrication

1. **Moore's Law scaling must come to an end within the next two decades.**
2. **The skills base in optical device design and CMOS-compatible optical materials processing needs to be strengthened nationally.**
3. **Australia has few facilities for wafer-scale optical lithography.**
4. **Low-cost, large-scale nanopatterning, such as nanoimprint lithography, requires development to make nanotechnology products more commercially attractive.**
5. **A greater diversity of functional (doped) diamond films and nanoparticles is needed to enhance the capabilities of diamond-based nanostructures.**
6. **Nanotechnology research demands an increased focus on integrated, cross-disciplinary research.**
7. **Industrial nanotechnology applications require multidisciplinary expertise in nanomaterials synthesis, biocompatible materials, top-down lithography, device design and simulation.**
8. **Access is required to highly advanced and capital-intensive nanofabrication infrastructure that is well-resourced and maintained by skilled staff.**

Challenge: Moore's Law scaling must come to an end within the next two decades.

Opportunity: Australia has world-leading concentrations of expertise in quantum nanostructures and new materials and devices that could take the place of Si-CMOS.

While silicon (and other semiconductors) nanoelectronic devices will continue to dominate consumer electronics and ICT for at least the next decade, it is well-understood that conventional Moore's Law scaling must come to an end sometime in the next two decades, due to a combination of on-chip power (heat) dissipation and speed limitations. It is therefore inevitable that new materials and devices will take the place of Si-CMOS and related devices, which have dominated the market for the past 40 years. The major part of international nanofabrication research is therefore directed to identify and develop new devices, systems and materials for the future.

As a result, international research in nanofabrication technologies has a significant focus on the processing of new nanomaterials with improved electrical and optical properties (e.g. graphene, carbon nanotubes, semiconductor nanowires), together with ultrahigh resolution nanopatterning for mass production (e.g. advanced resist technologies for deep UV lithography, block copolymers, extreme UV lithography, nanoimprint lithography). Australia already has active research efforts in most of the above areas and is well-placed to take a leading role in each of these major international research challenges.

Australia also has a world-leading concentration of expertise in quantum devices, nanostructures and photonics, with four ARC centres of excellence (quantum atom optics, quantum computation and communication, engineered quantum systems, and ultrahigh bandwidth devices) in this area. Quantum electronic, spintronic and photonic devices all require high-resolution patterning techniques such as electron beam lithography and related device nanofabrication processes (e.g. etching, metal deposition, epitaxial growth). This area will likely grow even more in Australia and will be underpinned by further advances in nanofabrication technologies.

Challenge: The skills base in optical device design and CMOS-compatible optical materials processing needs to be strengthened nationally.

Opportunity: Australia has excellent capabilities in nanomachining technologies.

Australia has leadership in many types of optical devices and excellent capabilities and expertise in the nanomachining technologies (e.g. using EBL, reactive ion etching, FIB) necessary to construct integrated photonics. However, the skills base in optical device design and CMOS-compatible optical materials processing needs to be strengthened nationally to fully exploit the opportunity here.

Challenge: Australia has few facilities for wafer-scale optical lithography.

Opportunity: A new 150 mm wafer stepper for UV lithography has recently been installed through the ANFF network, opening the pathway for expanded research.

Because of limited local semiconductor manufacturing, Australia has had few facilities for wafer-scale UV lithography, with the only submicron UV scanner (130 nm features; 200 mm wafer size) privately maintained by Silanna Pty Ltd (Sydney). A 150 mm wafer stepper for UV lithography to ~100nm resolution has recently been installed through the ANFF network, opening the pathway for expanded research in integrated photonics, optoelectronic devices and custom-designed on-chip electronics for hybrid devices.

Challenge: Low-cost, large-scale nanopatterning, such as nanoimprint lithography, requires further development to make nanotechnology products more commercially attractive.

Opportunity: Australia has an embryonic capability in nanoimprint lithography that could be developed as a convenient production method for researchers and industry alike

Nanoimprint lithography is a high-throughput nanofabrication process in which a master die patterned with nanoscale features is used to replicate the pattern many times by embossing a polymer resist over scales of many centimetres. Australia now has a small number of these facilities available through ANFF, but further research is needed to make this a robust and convenient production method for researchers and industry alike.

Challenge: A greater diversity of functional (doped) diamond films and nanoparticles is needed to enhance the capabilities of diamond-based nanostructures.

Opportunity: Integrating diamond nanostructures with silicon-integrated circuits has potential for electronic and photonic devices.

Diamond-based applications are expanding rapidly worldwide and Australia is at the forefront. Applications include bioimaging and biomedical devices (e.g. retinal electrodes for the bionic eye) and quantum photonic structures for quantum computing and secure quantum communications (based on nitrogen vacancy defect centres in diamond). To exploit Australia's strength in this area will require development of a greater diversity of functional (doped) diamond films and nanoparticles. Integration of diamond nanostructures with silicon (e.g. CMOS)-integrated circuits requiring localised nanodiamond growth or positioning also has great potential for electronic and photonic devices.

Challenge: Nanotechnology research demands an increased focus on integrated, cross-disciplinary research.

Opportunity: The co-location of key nanofabrication/characterisation facilities provide opportunities to enhance cross-disciplinary collaboration.

While each of the above examples focuses on specific nanofabrication technologies or application areas, it is widely accepted that nanotechnology research demands an increased focus on integrated, cross-disciplinary research. Consideration therefore needs to be given to the benefits and opportunities that may arise through co-location of certain fabrication facilities with characterisation, health discovery and translation, sustainable energy, and defence and security facilities. This will enhance cross-disciplinary collaboration, reveal new areas for investigation and encourage the development of industrial applications.

Challenge: Industrially relevant nanotechnology applications require multidisciplinary expertise in nanomaterials synthesis, biocompatible materials, top-down lithography , device design and simulation.

Opportunity: Australia's collaborative approach to research infrastructure provides a natural environment for multidisciplinary research to solve industry problems.

Many Australian high-technology companies are small-to-medium enterprises (SMEs) with a focus on speciality high value-added products. Their nanofabrication requirements are often highly multidisciplinary, requiring a combination of expertise in nanomaterials synthesis, biocompatible materials and more conventional top-down nanolithography. Advanced simulation tools are also essential to enable the design of new nanoscale materials and structures, together with complex electronic and optical devices and circuits. Applied nanofabrication research supporting the nanotechnology industry in Australia therefore tends to focus on the novel combination of existing platform nanofabrication techniques to create new process flows and production methodologies. An example of this is the development of diamond electrode arrays as a retinal stimulator for the bionic eye project (Bionic Vision Australia, Melbourne University and ANFF Melbourne Centre for Nanofabrication), which combines new biocompatible materials growth with top-down nanolithography and systems integration. This type of multidisciplinary approach is very common in nanotechnology R&D worldwide, since most international nanotechnology research is being driven and inspired by start-up companies rather than large, established multinationals. Australia's collaborative approach to research infrastructure provides a natural environment for multidisciplinary research to solve industry problems.

Challenge: Access is required to highly advanced and capital-intensive nanofabrication infrastructure that is well-resourced and maintained by skilled staff.

Opportunity: Australia has established cutting-edge national nanofabrication infrastructure with great potential to provide a stable and ongoing research environment.

Underpinning all of the above opportunities is the need for access to highly advanced and capital-intensive nanofabrication infrastructure such as that provided by the Australian National Fabrication Facility (ANFF). The annual staffing and operational costs of such national facilities are considerable (of the order of $10–$20 million) and will require ongoing support from all levels of government, together with host institutions. Most importantly, the cohort of expert technical and engineering staff who maintain the knowledge base underpinning these facilities must be secured, nurtured (with career progression), and preferably expanded.

Figure 20: Research training and human capital. (Image courtesy of ANFF, NSW)

Summary of the key opportunities for nanofabrication

1. **Australia has world-leading concentrations of expertise in quantum nanostructures and in new materials and devices that could take the place of Si-CMOS.**
2. **Australia has excellent capabilities and expertise in nanomachining technologies.**
3. **A new 150 mm wafer stepper for UV lithography has recently been installed through the ANFF network, opening the pathway for expanded research.**
4. **Australia has an embryonic capability in nanoimprint lithography that could be developed as a production method for researchers and industry alike.**
5. **Integrating diamond nanostructures with silicon integrated circuits has potential for electronic and photonic devices.**
6. **The co-location of key nanofabrication/characterisation facilities provide opportunities to enhance cross-disciplinary collaboration.**
7. **Australia's collaborative approach to research infrastructure provides a natural environment for multidisciplinary research to solve industry problems.**
8. **Australia has established cutting-edge national nanofabrication infrastructure with great potential to provide a stable and ongoing research environment.**

Developing the discipline

Australia's existing nanofabrication strengths have emerged in part because of a successful system of collaboration. This ability to maintain and expand this networked set of fabrication facilities (Recommendations 1 and 2) and to effectively train technical staff (Recommendation 4) will be essential if the identified opportunities for nanomaterial and nanodevice translation are to be realised (Recommendation 3).

Case study 4: Australia's cutting-edge facilities for nanofabrication and nanocharacterisation

Australia is well-positioned to make and measure the materials and devices needed for nanotechnology research, with new cutting-edge facilities established over the last decade.

Figure 21: ANFF Fabrication facilities. (Image courtesy of ANFF, NSW)

Figure 22: Scanning electron micrograph of carbon microcoils. The coiled fibres range from 250nm–900nm wide. (Image courtesy of AMMRF, University of Sydney)

The Australian and state governments have invested more than $500 million over the past decade to establish new capabilities through the NCRIS and the Landmark Facilities program. These facilities provide support to all Australian researchers, including universities, industry and publicly funded organisations.

A key aspect has been the creation of a national cohort of highly skilled scientists and engineers who operate and maintain these facilities and also serve the vital role of training the next generation of nanotechnology researchers and innovators to drive forward Australian industry. This investment in human capital is recognised as equally important to that in physical infrastructure.

The Australian National Fabrication Facility (ANFF) is a networked facility encompassing 19 institutions in most states, providing state-of-the-art micro- and nanofabrication capabilities that are used to make new materials, devices and systems for research and industry. Each node provides capabilities matched to local research strengths and many incorporate large-scale, clean-room laboratories with a broad range of nanofabrication tooling. ANFF supports over 1500 researchers nationally and is commensurate in per capita terms with international nanofabrication infrastructure networks in the United States and Europe.

The Australian Microscopy and Microanalysis Research Facility supports more than 3000 researchers nationally via six major nodes and six linked laboratories around Australia. It specialises in instrumentation, methodologies and applications of materials characterisation using ion and electron beams, scanned probes, X-rays, and light and laser optics. Over 250 individual instruments, run by expert staff, support more than 60 different techniques that provide finely tailored experimental approaches to diverse nanotechnology research questions.

The Australian Synchrotron is one of fewer than 40 similar facilities around the world and is the largest stand-alone piece of scientific infrastructure in the Southern Hemisphere. It is a source of powerful X-rays and infrared radiation, millions of times brighter than those produced by conventional X-ray machines in laboratories and hospitals. The facility provides an impressive array of non-destructive, high-resolution, rapid real-time imaging and analysis techniques. These generate elemental, structural and chemical information from diverse sample types ranging from living cells to advanced materials, industrial components and mineral processes.

Figure 23: Australian Synchrotron (Image courtesy of the Australian Synchrotron)

Nanomaterials

Definition of discipline

Nanomaterials research involves the nanoscale design and production of natural, synthetic, functional and structural materials.

The building blocks of these materials, whether they be metallic, ceramic, semiconductor, polymeric, or hybrid, are nanometer-size atomic or molecular units in the 1–100 nm size range. The focus of nanomaterials research is in preparing, characterising, understanding and utilising them, especially in the exploitation of their novel properties for a wide range of technological applications.

Benefits to society mainly derive from their novel properties, which differ from those of bulk materials and allow nanomaterials to address many of the technological and societal challenges facing humankind. For example:

- Nanomaterials are contributing to improved health through highly specific diagnosis and targeted drug delivery and treatment methods.
- Environmental problems are ripe for nanomaterials implementation in areas such as zero emissions processing, nanoparticle sensors for detecting toxic wastes, nanoporous membranes for water purification, and nanoparticle catalysts for converting harmful emissions to benign by-products.

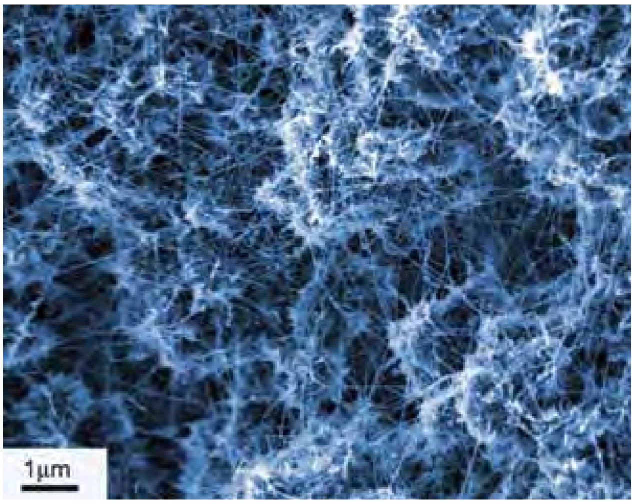


Figure 24: Boron nitride nanotubes. (Image courtesy of ANU)

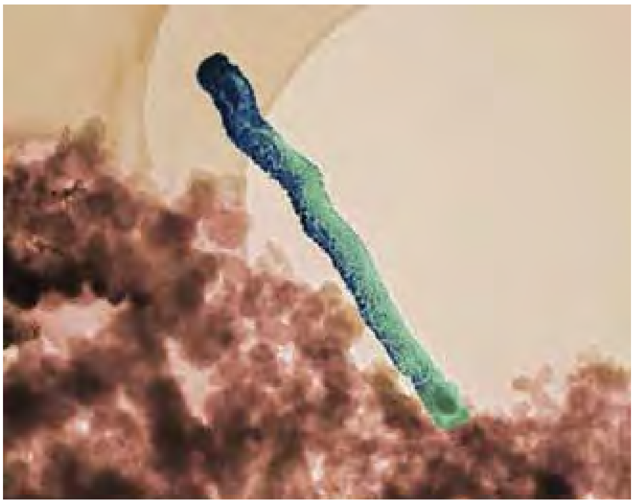


Figure 25: Platinum-coated carbon nanotube for fuel cells (Image courtesy of ANU)

- Nanomaterial-based portable biosensors can detect emerging infectious diseases.
- Nanomaterial capacitors, batteries, and fuel cells are enabling high-energy density storage devices, and nanoparticle solar cells have higher efficiency.
- Semiconductor nanostructures are driving current rapid advances in ICT as well as enabling the development of innovative sensors.

By gaining a greater understanding and mastery of atomic, ionic and molecular structures and processes at the nanoscale, we can produce a steady stream of commercially valuable and socially useful nanomaterials technologies.

Australian strengths in nanomaterials

Summary of the key strengths in nanomaterials

1. **A world leader in the design and production of novel, high-performance nanomaterials for energy applications.**
2. **A high concentration of effort in the development of nanomaterials for addressing environmental concerns.**
3. **World-class design and production of microporous and mesoporous materials.**
4. **A significant body of outstanding research in the development of nanomaterials with health applications.**
5. **Internationally regarded strengths in nanomaterials in ICT and sensor applications.**
6. **Significant research and development activity in the 'industrial scale' production of nanomaterials.**

Nanomaterials research in Australia is focused on issues of national and international significance, namely the continued and sustainable supply of energy, food and water, improved human and environmental health, and improved consumer products, and is a major driver for advances in ICT, novel sensors and areas of advanced manufacturing. A number of world-class research groups and centres that develop or utilise nanomaterials have been established to achieve these goals. A summary of these can be found below.

World-class groups and centres focused on nanomaterials research

- ARC Centre of Excellence for Functional Nanomaterials (hosted by UNSW).
- Centre for Strategic Nano-Fabrication (UWA).
- ARC Centre of Excellence for Electromaterials (hosted at University of Wollongong).
- ARC Centre of Excellence for Quantum Computer and Communications Technologies (hosted at UNSW).
- Photovoltaic ARC Centre of Excellence (UNSW).
- Cooperative Research Centre (CRC) for Polymers.
- Research School of Physics and Engineering (at ANU).
- Melbourne Materials Institute (at University of Melbourne).
- Centre for Advanced Materials Technology (at University of Sydney).
- Institute for Superconducting and Electronic Materials (at University of Wollongong).
- CO_2 CRC
- Ian Wark Research Institute and Mawson Institute (at University of South Australia).
- ARC Centre of Excellence for Design in Light Metals (hosted by Monash University)
- Australian Institute for Bioengineering and Nanotechnology (at University of Queensland).
- Flinders Centre for NanoScale Science and Technology (Flinders University).

A world leader in the design and production of novel, high-performance nanomaterials in energy applications

Australia is a world leader in nanomaterials R&D for energy applications involving solar and other renewable energy solutions. Some particular energy-related strengths involving nanomaterials include, in the area of solar, their use for producing novel semiconductor-based photovoltaic (PV) cells with improved performance that involves selective light absorption through quantum dot structures and nanowires, or for utilising plasmonic and metamaterials in novel architectures. Organic PV and smart polymer applications are a further focus at several universities. Solar coatings is also an active area of R&D in several Australian research laboratories as well as in industry, and involves the use of nanoparticles for selective absorption and reflection of light. In other renewable energy applications by a number of research laboratories, nanomaterials-based catalysts are used for water splitting (hydrogen production), whereas carbon nanomaterials, nanowires and nanomaterials are used for energy storage and fuel-cell applications. The company CAP-XX manufactures energy storage devices based on nanomaterials (see case study).

A high concentration of effort in the development of nanomaterials for addressing environmental concerns

In addressing environmental concerns that are specific to its needs, Australia has a particular focus on nanomaterials. These include waste, environmental remediation and recycling, and water and air purification. In the waste area, research is focused on zero emission products, nutrient and precious metal recovery, elimination of toxic waste from the environment, and developing novel sensing technology to monitor contamination. There is also specific research into 'waste to energy' and 'waste to product' technologies. These include:

- conversion of waste to nanocomposites
- zero emission design for the pulp and paper industry
- bioremediation to generate value-added by-products
- (nano)membranes for environmental remediation
- new green processes for bioderived or re-usable polymers.

In addition, there are significant programs in absorbent nanomaterials for carbon capture and separation technology as well as membrane systems for selectivity of CO_2 sequestration. In the water and air purification area, significant nanomaterials research involves gold photocatalysts to eliminate organic contaminants and other airborne pollutants, development of novel nanomaterials and membranes to purify water, and the use of photocatalysts for both water and air purification.

World-class design and production of microporous and mesoporous materials for applications in resource development and improving food products

In resource extraction and minerals processing, Australia is particularly active in areas involving microporous and mesoporous materials research to sequester radioactive elements and recover precious metals, and 3D imaging and analysis of mineral cores on the subicron scale, which has applications in oil and gas recovery. In agriculture and food, nanoingredients are being used to create more appealing food products with longer shelf life or containing nutrients that are normally difficult to incorporate. Animal vaccines and environmentally friendly pesticides are also being produced using advanced nanomaterials.

A significant body of outstanding research in the development of nanomaterials with health applications

Since many biological processes occur at the nanoscale, a major impact area of nanomaterials research in Australia has been in health and medicine, with applications in advanced drug delivery systems, new therapies, and in vivo imaging. Perhaps the largest activity is in design and production of nanoparticles to deliver active compounds such as drugs and imaging agents, with the objective to maximise bioavailability of the active compound at specific places in the body and over specific times. The focus of the research is on the development of nanoparticles that can avoid the body's defence mechanisms but deliver the payload to the target tissues where the active compound can be released in a controlled manner. Australia's internationally recognised research in this area includes that into biocompatible nanopolymeric materials and nanomaterials for targeted delivery and controlled release of chemotherapeutic drugs and therapeutic reagents—for example, to cancer cells, tumours, the pancreas and the brain—and into developing methods to fabricate radioactive nanoparticles for biomedical applications such as deep vein thrombosis diagnosis (imaging) and liver cancer treatment. Several Australian start-up companies, including BioParticle Technologies, CeramiSphere, pSivida, and Micronisers, are also active in this space.

In the area of scaffolds, implants and tissue engineering, nanomaterials are used to fabricate biocompatible scaffolds and implants that, for example, promote growth of new tissue. Examples include:

- novel methods to manufacture and surface engineer polymeric scaffolds for both drug delivery and tissue engineering
- nanobased biomimetic polymer scaffolds to generate bone, cartilage and soft tissues, and to aid the functional interface of a bionic eye
- new composite hydrogels with improved cell and tissue responsiveness
- fabrication and surface modification of nanoporous titanium alloy scaffolds and composite materials from pearl nacre to engineer bone tissue
- severe plastic deformation to produce nanostructured materials with superior mechanical properties for use in surgical implants
- nanostructured titanium alloys for stent applications.

Internationally regarded strengths in nanomaterials in ICT and sensors

Although further details of these areas are treated more fully in the disciplines of nanophotonics and nanoelectronics, there are specific underlying nanomaterials strengths in Australia that are of high international standing. These include:

- fabrication of nanomaterial structures on silicon for nanoelectronics and quantum computing applications
- fabrication of III-V quantum dots, nanowires, metamaterials, plasmonic structures and photonic crystals for applications in electronics and photonics, including novel sensors
- fabrication of a range of nanostructured glasses for novel optical fibres used for sensors and ICT applications
- fabrication of novel MEMS and nanostructures in II-VI semiconductors and germanium for applications in sensors, nanophotonics and nanoelectronics.

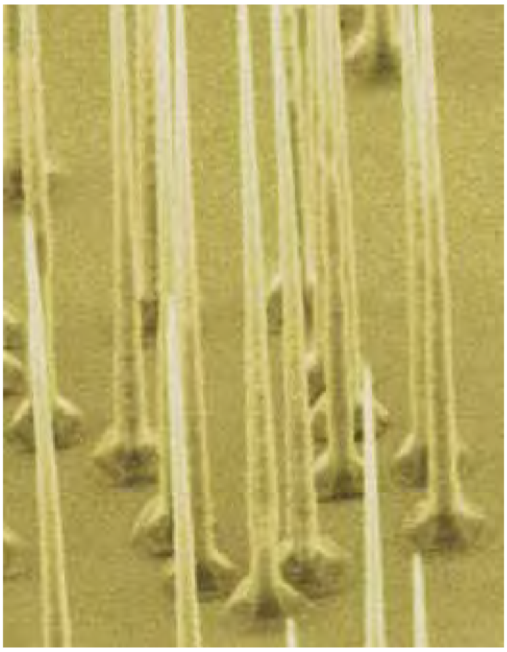


Figure 26: Semiconductor nanowires for optoelectronics. (Image courtesy of ANU)

Figure 27: Ellipsoidal silica-coated magnetite for enhanced ultrasound imaging. (Image courtesy Rose Amal, UNSW)

Significant research and development activity in the 'industrial scale' production of nanomaterials

Economic, sustainable, scalable and environmentally friendly manufacturing processes are prerequisites for widespread applications of nanomaterials that underpin many of the technologies discussed in this report. There is significant Australian research and development activity in the 'industrial scale' production of nanomaterials. Examples include:

- the scale-up of continuous-flow processing technologies to deliver specific nanoparticles with minimal impact on the environment
- demonstration of a cost-effective technique to bulk produce nanomaterials for catalytic applications, including recycling
- industrial-scale growth of compound semiconductor quantum dot and nanowire structures, which are the basis for sensor and optoelectronic device fabrication
- development of processes for large-scale synthesis of carbon and other nanotubes
- development of living free-radical polymerisation to create nanopolymers with predetermined average molecular size and narrow molecular size distributions
- nanocomposite development for reinforced automobile components and for building construction materials.

Australian companies—some listed previously—have developed and commercialised nanomaterials. The Very Small Particle Company, for example, produces nanoscale complex metal oxides for battery applications, and Hydrexia produces cast magnesium alloys with novel nanostructure for hydrogen storage.

Challenges and opportunities for nanomaterials

Summary of the key challenges for nanomaterials

1. **Addressing the goal of a sustainable energy future through renewable energy.**
2. **Protecting the environment and improving water quality and usage.**
3. **Ensuring that Australia maintains its world-leading position in harnessing and exploiting our natural resources.**
4. **Producing nanomaterials by processes that are manufacturable and scalable.**
5. **Developing a nationally coordinated nanoscience and nanotechnology entity to stimulate and focus nanomaterials research into commercial areas.**
6. **Engaging industry to fully exploit existing research strengths and emerging opportunities from nanomaterials.**
7. **Translating green chemistry approaches involving nanotechnology to industry.**

There are significant challenges, existing strengths and R&D opportunities for nanomaterials in a number of broad areas. These include energy, environment and water, mineral resources and products, agriculture and food, health, smart sensors, advanced ICT, and national security. These vitally important and challenging areas for Australia involve developing renewable energy and a more sustainable use of resources while protecting the environment and food security, and being proactive in improving health and health care for an ageing population. They also involve the development of purpose-specific sensors to monitor the environmental and explore far-reaching applications in ICT, including national security systems. Nanomaterials have the potential to fuel advancement in all of these areas.

Our investment through national competitive grants has positioned us to be a world leader in many of these areas through the application of nanoscience and nanotechnology. Opportunities for nanomaterials research that build on our strengths and contribute to the above areas include:

- exploiting novel properties of metamaterials and plasmonics and designing nanocomposites, nanofibres, nanocrystalline metals, energy generation and storage materials
- developing thermoelectric materials
- integrating inorganic and organic materials
- scaling up materials production
- developing and exploiting smart nanomaterials.

This chapter has more of a focus on energy, the environment and water, resources and agriculture, and materials production. Other applications areas that build on nanomaterials are covered in more detail elsewhere in this report.

Challenge: Addressing the goal of a sustainable energy future through renewable energy.

Opportunity: Contributing towards renewable energy research that will have a major international impact with potential to generate commercial returns.

Renewable energy is one of the major contemporary challenges, and nanomaterials can make unique contributions to improving existing technologies and uncovering new and more efficient energy supply and energy-saving methods. Considerable excellent research is already happening in these areas. However, real opportunities to make a major international impact and foster commercial returns will require further national focus and coordination. Opportunities, and their corresponding challenges, include:

- developing nanomaterials for energy storage in batteries and supercapacitors, where a nationally coordinated effort is essential—as is the continuity of funding to provide a bridge between the more fundamental studies and industry exploitation
- developing nanomaterials (including plasmonics and metamaterials) for efficient energy generation; for example in fuel cells and PV devices. There is good funding from the Australian Solar Institute for developments closer to the commercial end, but this thrust needs to be supported by funding and national coordination at the fundamental end so as to build and capitalise on excellent nanomaterials research in areas of organic PV, thin-film cells, advanced Si PV, and quantum dot and nanowire approaches to high-efficiency compound semiconductor cells
- developing nanocatalysts to convert biomass into liquid fuels. This is an area of active but embryonic research in Australia and needs to be ramped up to realise maximum benefits to the nation.

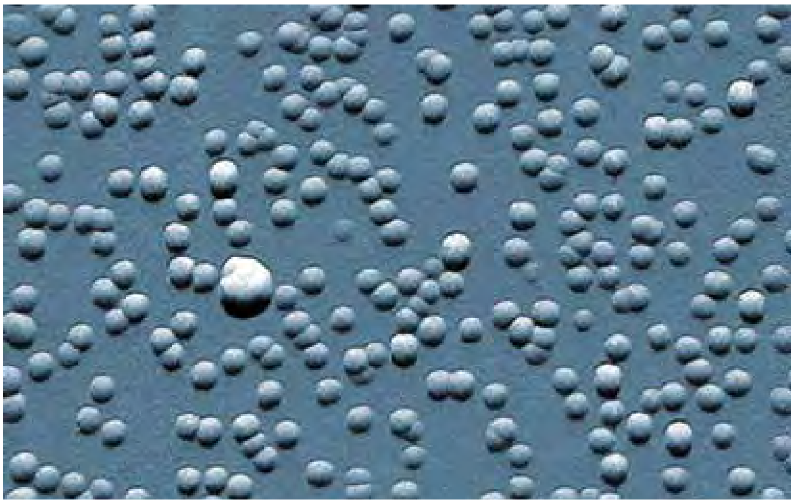


Figure 28: Quantum dots used for high efficiency semiconductor solar cells. (Image courtesy of ANU)

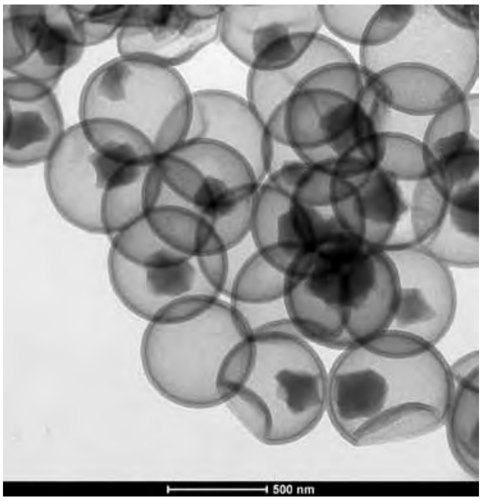


Figure 29: Silica hollow sphere for O_2 delivery to cell. (Image courtesy of Rose Amal, UNSW)

Challenge: Protecting the environment and improving water quality and usage.

Opportunity: Developing innovative uses for nanomaterials in environmental remediation.

Protecting the environment and improving water quality and usage are major challenges for a relatively arid continent of fluctuating climate extremes. Nanomaterials with unique properties can play a pivotal role, as already demonstrated in a number of existing research activities across the country. However, further effort is warranted in the light of the considerable challenges facing us.

There is a real need is for industry to come on board in several of the areas to exploit the commercial opportunities. However, appropriate government incentives may be needed to support industry in this important but commercially difficult field of environmental remediation. Opportunities for increased research effort and for new research include:

- remediation of contaminated waters—considerable research is already occurring in this area, but further effort is needed to solve the myriad of existing pollutant problems. Scale-up of successful laboratory demonstrations is essential
- desalination—with opportunities in photolytic splitting of water followed, for example, by burning the hydrogen for energy and clean water and postdaylight photovoltaic generation of energy. This is an area that can build on some excellent research but, like other areas, needs focus and coordination if Australia is to fully exploit innovative research and technology
- specific development of membranes, catalysts and absorbent material for purification, metal recovery and nutrient removal from water, air and soils—a more coordinated program of research as well as technology transfer to industry are essential in this area
- sensor development and real-time monitoring—using the potential of nanotechnology is an important need in the environmental area and there is an opportunity here for smart nanomaterials that can change their properties in an easily detectable way, optically or electrically, when in contact with specific pollutants.

Challenge: Ensuring that Australia maintains its world-leading position in harnessing and exploiting our natural resources.

Opportunity: Exploiting nanomaterials and nanostructures and methods to detect them in minerals exploration and agriculture.

In the resources area, the characterisation and 3D imaging of material (mineral) nanostructures has become extremely important for mineral (as well as oil and gas) exploration and recovery, particularly when coupled with digital analysis. Although not a specific area of nanomaterials research, the related challenges that arise for recovery and carbon sequestration lend themselves to a deep understanding of nanomaterials and their interactions with gases and fluids. This is an area of research that should be strongly supported, as it will benefit Australia's mining and petrochemical sectors.

There is good existing research in the use of nanomaterials in agriculture, as indicated previously. This effort should be continued at a faster pace to exploit new opportunities. The research topics of nanofibres (for novel fabrics), food packaging, nutrient enrichment of food, controlled release (packaging, fertiliser) and zero waste food are all areas where nanomaterials research could have a huge impact. Currently, there is limited research and expertise in these areas in Australia. However, it is an area of such importance that a focused effort should be encouraged and funded at an appropriate level to maximise research and ultimately deliver commercial returns.

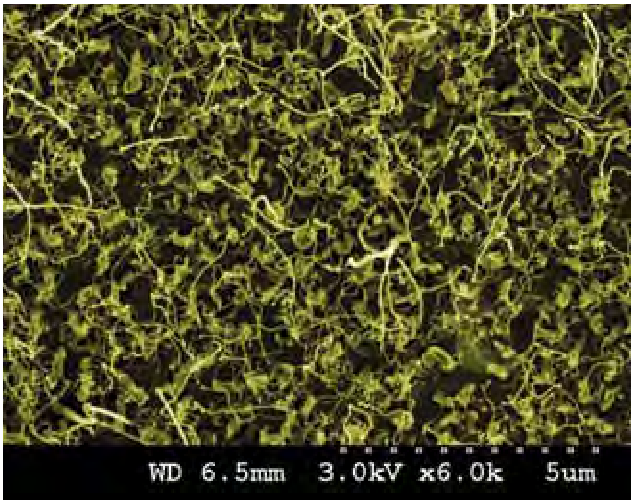


Figure 30: Glass 'nanowool' made by ion implantation. (Image courtesy of ANU)

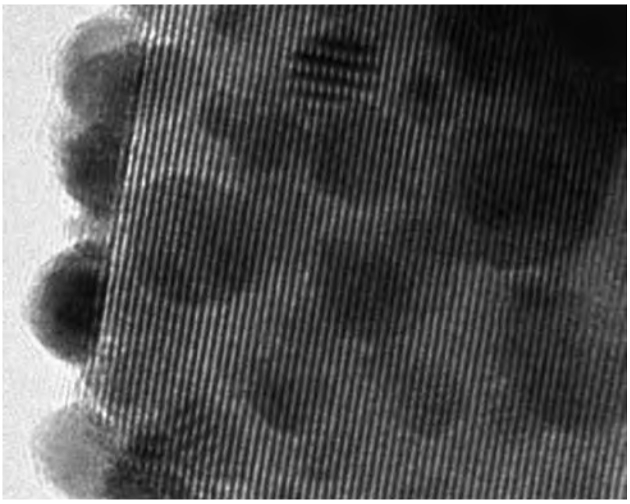


Figure 31: Gold seeded magnetite for highly sensitive environmental sensing. (Image courtesy of Rose Amal, UNSW)

Challenge: Producing nanomaterials by processes that are manufacturable and scalable.

Opportunity: Developing nanomaterials production and scale-up processes for manufacturability as a separate research effort.

The array of processes for nanomaterials production is vast since the nature of nanomaterials is extremely broad. It ranges from isolated nanoparticles, nanotubes, nanofibres, nanoinclusions and nanostructure in bulk materials, nanocomposites, self-assembly of structured templates, membranes, high surface area nanocatalysts and ordered arrays of quantum dots and nanowires. The range of research strengths in materials production to build on includes process intensification—for example in microfluidics, electrospinning and flame spray pyrolysis—and chemical, mechanical and self-assembly processes, including metal organic chemical vapour deposition and vacuum deposition to produce novel (epitaxial) crystalline nanomaterials. As the key starting point for most nanotechnology solutions in industry, these technologies are at the heart of many of the above challenges. Nanomaterials production and processing methods therefore should be supported as a separate research effort together with the scale-up issues that are essential to commercial exploitation.

Challenge: Developing a nationally coordinated nanoscience and nanotechnology entity to stimulate and focus nanomaterials research into commercial areas.

Opportunity: Establishing a national nanotechnology umbrella body to speak for and coordinate research.

The success of nationally coordinated nanoscience and nanotechnology centres overseas in stimulating and focusing nanotechnology research into commercial areas highlights the importance for Australia of developing an effective way to coordinate nanotechnology research thrusts nationally to maximise the returns to the nation. One way is to establish a national umbrella body to speak for and coordinate research and resources (people and facilities) that support nanotechnology and its future development. This body could also provide a focus for networking, industry links, and regulatory issues. Because nanomaterials cover the entire nanospace, the nanomaterials discipline sees this coordination is as vital.

Challenge: Engaging industry to fully exploit existing research strengths and emerging opportunities from nanomaterials.

Opportunity: Developing strong links between the nanomaterials research community and industry to help stimulate research into applications that have commercial value and enable industry-relevant education programs to be established.

Fully exploiting existing research strengths and emerging opportunities from nanomaterials means bridging the gap between research and commercial exploitation by industry. Whereas the ANN has provided the basis for bringing researchers together to address major research challenges, an effort is needed to bring research and industry together to focus on realising commercial opportunity. The Australian Nanotechnology Alliance, centred in Brisbane, has partly taken on this role, but it needs to be ramped up on a national scale. Being able to take the research findings to the market place by engaging with industry through a single body is attractive. Strong links between the nanomaterials research community and industry would also stimulate important research at the applications/precommercial end of the spectrum so that, if supported by funding, these links would further foster commercialisation.

Education and training are vital for building nanotechnology industries in Australia for a number of reasons, including provision of a trained workforce for industry. Generic skills covering business, commercialisation and patent law are important to ensure that the training at the PhD and ECR stages facilitates the forging of links with industry and also fosters a spirit of establishing spin-out companies. Overall benefits of education and research training in nanotechnology are:

- training of highly qualified personnel (both research and skilled technicians) who will be in demand from academia, industry and government laboratories, and who can make educated decisions on future industrial needs
- development of the expertise pool and IP for new nanotechnologies
- advanced (short) courses to keep industry abreast of developments in nanotechnology and allied fields, and to assist with effective networking nationally and internationally
- a professional education program, from undergraduate through to technician, Masters and PhD, to industry-update courses, to help place Australia at the forefront of nanoscience and nanotechnology.

Challenge: Translating green chemistry approaches involving nanotechnology to industry.

Opportunity: Incorporating green chemistry metrics at the inception of research.

Incorporating green chemistry metrics at the inception of the research represents a major opportunity in developing nanotechnology for a sustainable future, and in tracking towards a zero waste society. Australia is a recognised leader in green chemistry in general, and translating this approach to nanotechnology is a significant opportunity to engage industry in strategic fundamental research through to taking products to the market place. Key issues include minimising the generation of waste, using renewable materials, addressing scalability at the early stages of research and designing products that have minimal impact on the environment.

Summary of the key opportunities for nanomaterials

1. **Contributing towards renewable energy research that will have a major international impact with potential to generate commercial returns.**
2. **Developing innovative uses for nanomaterials in environmental remediation.**
3. **Exploiting nanomaterials and nanostructures and methods to detect them in minerals exploration and agriculture.**
4. **Developing nanomaterials production and scale-up processes for manufacturability as a separate research effort.**
5. **Establishing a national umbrella body to speak for and coordinate nanotechnology research.**
6. **Developing strong links between the nanomaterials research community and industry to help stimulate research into applications that have commercial value and enable industry-relevant education programs to be established.**
7. **Incorporating green chemistry metrics at the inception of research.**

Developing the discipline

Maintaining Australia's strength in nanomaterials research will require continued and improved support by funding agencies for what are frequently highly interdisciplinary funding applications (Recommendation 2). It will also require better coordination of research effort and support of local and international linkage mechanisms to ensure Australian research remains at the cutting edge (Recommendations 4 and 8). To realise the commercial opportunities provided by Australia's nanomaterials research capacity, we need better mechanisms to support the translation of research into industry (Recommendation 5), more workforce training (Recommendation 6), and to effectively communicate the benefits of nanomaterials research (Recommendation 7).

Case study 5: CAP-XX–an innovative Australian company using nanomaterials to produce novel energy storage and delivery systems

CAP-XX products are the result of pioneering supercapacitor research, materials expertise and superior production technologies. Over nearly 15 years, CAP-XX has developed its technology in association with local and foreign research organisations, universities and companies to produce unique products and processes to give the world's highest power supercapacitors.

CAP-XX has been recognised for its breakthrough nanotechnology process for producing high capacitance (1 farad or more), low equivalent series resistance (< 100 milliohms) supercapacitors that deliver the highest energy and power densities in a thin, flat, prismatic package suitable for portable electronics devices, which meet the pulse-power requirements of portable electronic devices.

The company's supercapacitor technology uses carbon electrodes on aluminium foil, with a porous separator between the two electrodes arranged in multiple flat layers connected in parallel. The aluminium foil moves the charge current into and out of the carbon where the actual charge is stored in the supercapacitor. CAP-XX has used nanotechnology to optimise the capacitance per unit volume of carbon by increasing the surface area, and to lower the resistance of the interfaces within the device.

These optimisations, along with the unique structure and fabrication processes using multiple flat layers, have resulted in industry-leading energy density and the world's highest specific power, exceeding 200 kW/L.

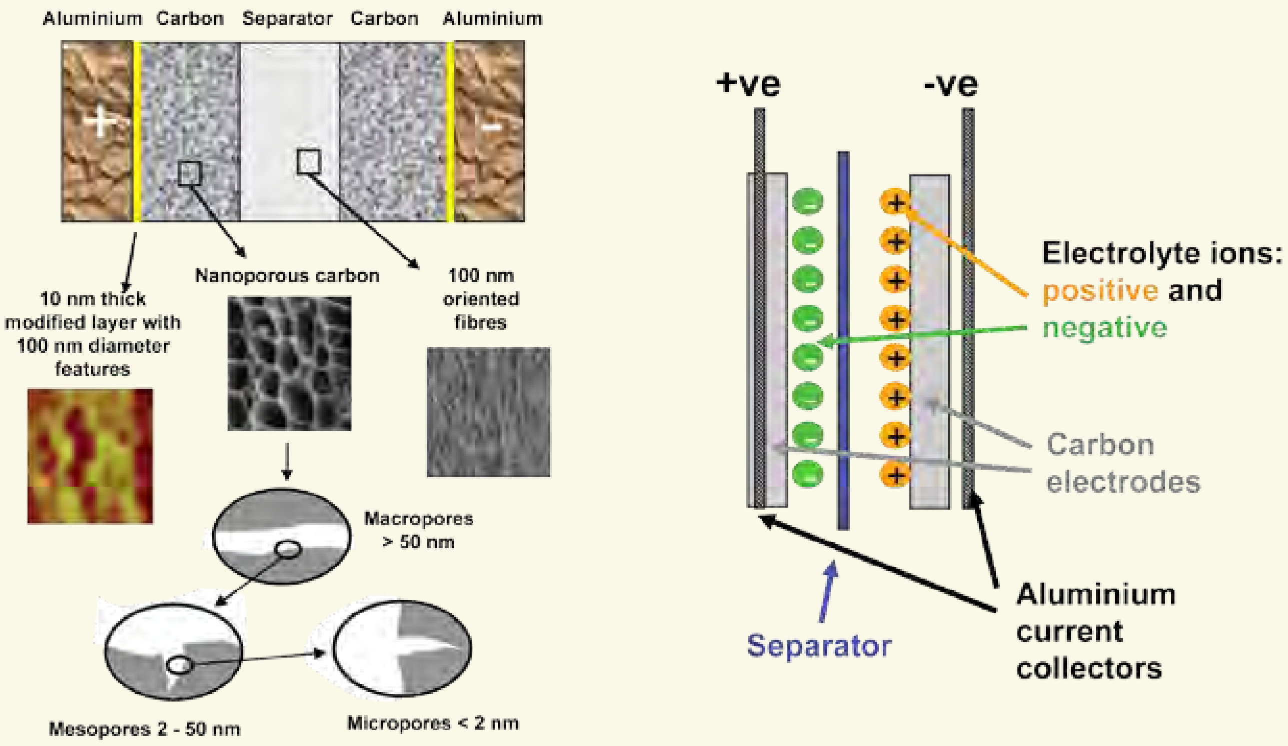


Figure 32: Illustration of CAP-XX supercapacitors illustrating the nano-structured materials and interfaces, and a schematic of a CAP-XX EDLC. (Image courtesy of CAP-XX (Australia) Pty Ltd)

The above electron microscope photographs of the CAP-XX carbon electrodes show the supercapacitors' nanostructure and construction which optimises the capacitance and lowers the series resistance. Prismatic supercapacitors allow designers to produce thinner, longer-running products such as cell phones, PDAs, medical devices, AMRs, and notebooks.

Nanoelectronics and nanomagnetics

Definition of discipline

Nanoelectronics and nanomagnetics involve the study of phenomena or functional properties that depend on electron charge and/or spin constrained to the nanoscale.

This field contains elements of nanoscale semiconductors, spintronics, nanomagnetics, superconductors, atomic and molecular electronics, optoelectronics and plasmonics, nanophotonics, nanophononics, and nanomechanics. There is a strong overlap between these fields and the other discipline categories, as this nanotechnology area intersects many traditional fields such as physics, chemistry, material science, and engineering.

Beyond the benefits of conducting world-leading fundamental research, there are many important applications that flow from nanoelectronic and nanomagnetic device development. These impact areas, such as new technology for ICT applications, beyond current limits of conventional transistor miniaturisation, sustainable energy production and storage, and new sensors in the life sciences. According to a 2009 report by Global Industry Analysts, the global nanoelectronics market is expected to reach over $400 billion by 2015 (www.strategyr.com). Expansion of the existing high-tech industry seeds in Australia based on nanotechnology, including nanoelectronics and nanomagnetics, will therefore provide opportunities for Australia's long-term prosperity.

Australian strengths in nanoelectronics and nanomagnetics

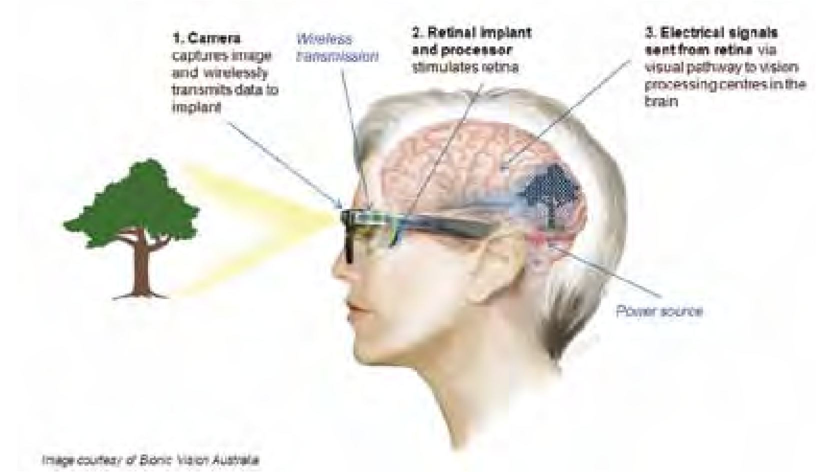
Summary of the key strengths in nanoelectronics and nanomagnetics

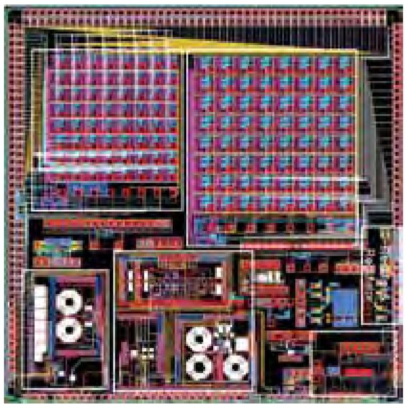
1. **Major research activities are underway into future mobile and wireless technology, bionic implants, and nanostructured materials for energy applications.**
2. **Australia has world-leading groups in beyond Moore's Law technologies covering the whole spectrum, from fundamental physics and theory to fabrication and measurement of devices.**
3. **Many research groups are highly active in the areas of spin-based electronics, multiferroics and ferroelectrics, developing new materials and theories for applications for information control and storage at the nanoscale.**
4. **Superconductivity is a strong area of applied research within Australia with the development of high-current capacity wires, and devices for nanoscale magnetometry and mineral exploration.**
5. **Australia has large collaborative efforts in quantum science and quantum technology based on individual molecular, atomic and electron systems.**
6. **Many research groups are working in the fast-growing area of plasmonics and the interaction of light with nanoelectronic systems.**

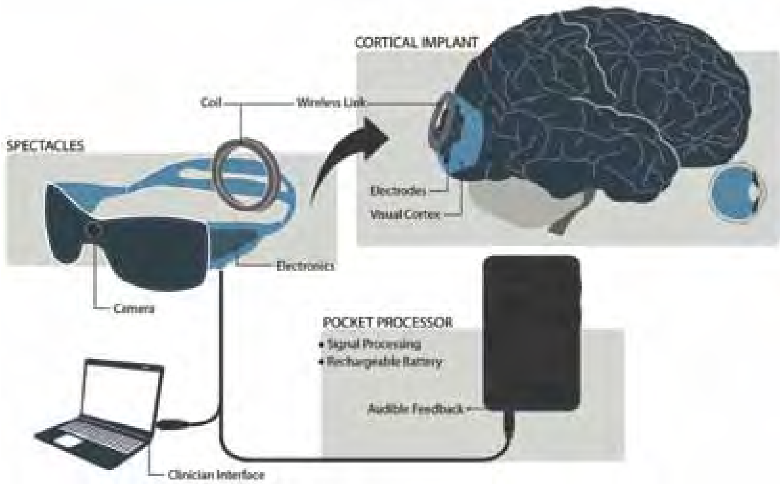
The scope of activities in nanoelectronics and nanomagnetics is multifaceted, from fundamental research into the properties of materials at the nanoscale to the use of these systems in cutting-edge device applications. Basic underpinning research encompasses electronic behaviour in solid state, atomic and molecular, and photonic/plasmonic systems. As such, research into nanoelectronics and nanomagnetics intersects with virtually all areas of nanoscience and technology—materials fabrication, characterisation/imaging, photonics and theory—and beyond into other areas of engineering and biology as new applications arise and these fields converge. Internationally, there is a significant emphasis on the importance of nanoelectronics and its role in the innovation cycle. In particular, governments and their associated research funding agencies highlight and prioritise the potential opportunities offered by nanoelectronics for the development of new technology and ensuing new industry. Australian researchers are well-represented across a broad range of activities, and indeed lead the world in many areas.

Major research activities are underway into future mobile and wireless technology, bionic implants, and nanostructured materials for energy applications.

At the border between micro- and nanoscales there is considerable activity in designing and improving electronic devices for communication, computing, sensing and energy applications. Major activities at CSIRO, the Centre of Excellence for Electromaterials Science, National ICT Australia (NICTA), the Institute for Superconducting and Electronic Materials, and at several universities, involve the development of devices that may provide future mobile and wireless technology, nanostructured materials for energy storage, efficient THz emitters, and thermionics. Research into nanomechanical devices, and feedback control, is of great interest for atomic force microscopy and scanning tunnelling microscopy applications, where nanoscopic (or better) precision is required. The fabrication of conducting micro/nanowires in various materials is of immediate practical use, as in new sensors in biology, such as the bionic eye application, which has two large-scale programs—Bionic Vision Australia and the Monash Vision Group—funded under the ARC Research in Bionic Vision Science and Technology Initiative.







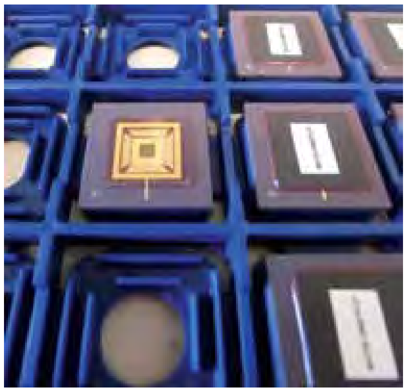


Figure 33: Complementary approaches in the Australian bionic eye program. Top–overview diagram of the Bionic Vision Australia technology using retinal implants and the layout of the first generation `high-acuity' bionic eye electronics incorporating transceiver, power harvesting and high-density stimulation array prototypes. (Images courtesy of Bionic Vision Australia). Bottom–overview of the Monash Vision Group technology combining state-of-the-art digital and biomedical technology to produce a direct-to-brain bionic eye. The device directly stimulates the visual cortex of the brain with electrical signals, which the brain will learn to interpret as sight. (Images courtesy of Monash Vision Group)

Australia has world-leading groups in beyond Moore's Law technologies covering the whole spectrum, from fundamental physics and theory to fabrication and measurement of devices.

As the fundamental switching elements of computer chip technology approach the limits of miniaturisation dictated by Moore's Law, the physics of confined electrons (and/or holes) in nanoscale structures begin to dominate and in some cases disrupt device functionality. There is now enormous interest in alternative technologies for creating nanoscale switching elements that may transcend the limits of CMOS technology. This is the regime of quantum electronics, where electron behaviour and transport through highly confined structures, such as quantum dots and nanowires, are governed by quantum effects. In Australia, this area of research is particularly active with a number of world-leading groups, university initiatives and centres of excellence. Research covers the whole spectrum from fundamental physics and theory to fabrication and measurement of a range of quantum devices. Localisation of electrons is achieved through various means such as atomic confinement, electrostatic formation of two-dimensional electron and hole gases, or by nanoscale materials engineering.

Many research groups are highly active in the areas of spin-based electronics, multiferroics and ferroelectrics, developing new materials and theories for applications for information control and storage at the nanoscale.

Spintronics is an important new direction for electronics involving the control and manipulation of the spin degree of freedom of electrons, and may lead to faster and lower power-switching elements. Already spintronics plays a role in memory and sensing devices through magnetoresistance effects. In Australia, many groups are working on various aspects of spintronics, including materials and memory devices, experimental and theoretical studies of magnetic excitations in magnetic materials, spin transport in hole-based devices, molecular magnets, spin transport and spin polarisation-based devices, and manipulation of spins and domains at the nanoscale. Multiferroics is a new, emerging area at the intersection of spintronics and electronics based on interactions between magnetic and electrical dipoles. Researchers at several universities and centres have been active in research on novel multiferroic materials, the study of manual control of magnetic and electric dipoles/domains by electric or magnetic field, and domain dynamics at the nanoscale.

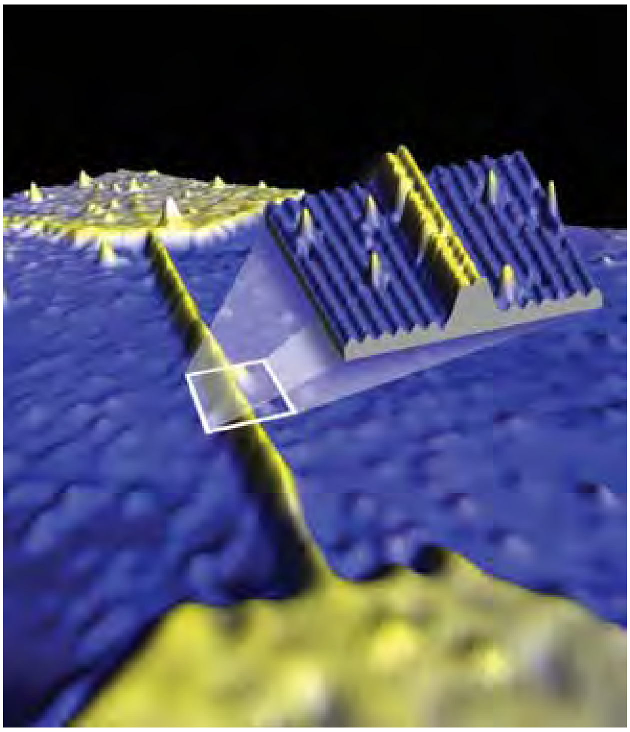


Figure 34: Researchers at UNSW have created the world's thinnest nanowire in silicon, just a few phosphorus atoms wide, and demonstrated that it still has a high conductivity. (Image courtesy of Bent Weber, UNSW)

Superconductivity is a strong area of applied research within Australia with the development of high-current capacity wires and devices for nanoscale magnetometry and mineral exploration

In Australia a number of groups are working on applied aspects of superconductivity, including improvement of device performance via nanoscale engineering, SQUIDs for sensing and medical imaging applications, and the physics of high-temperature superconductivity. As a demonstration of the use of nanoscale superconductor technology for sensing applications, CSIRO researchers have developed SQUID magnetometers for mineral exploration, underwater detection of unexploded ordinates, and nanoscale sensing. High-temperature superconductor Josephson junctions are also used in THz detection and microwave oscillators and mixers. At the Institute for Superconducting and Electronic Materials, researchers have developed the technology of high-current capacity magnesium diboride superconductor wires.

Australia has large collaborative efforts in quantum science and quantum technology based on individual molecular, atomic and electron systems.

Research in nanoelectronics and nanomagnetics has steadily progressed in scale, from the control of electron spin and charge degree of freedom in nanoscale bulk matter, down through the regime of quantum dots and nanowires to individual molecules and atoms. In the intermediate regime, several groups are investigating, both experimentally and theoretically, the unique electronic properties of carbon nanotubes and atomically thin crystals such as grapheme. At the atomic and molecular level, research in the fundamental properties of single molecules and trapped atoms lays the foundations for control of these individual units and timescales down to the attosecond regime. Using techniques such as laser cooling and trapping, atoms can be confined at extremely cold temperatures, where quantum mechanics dominates and the atoms behave more like waves than particles. Such technology is being pursued in the Centre for Quantum-Atom Optics. At ultracold temperatures, the atomic de Broglie waves of adjacent atoms can be made to overlap, creating the matter-wave analogy of the laser, and can be applied to measurement with exquisite precision, with applications such as quantum computing/ emulation, atomic clocks for time standards, and interferometers for measuring gravity gradients in geoexploration.

The nanoelectronic control of individual electron spins as building blocks for quantum computer technology in a sense represents the ultimate limit and convergence of nanoelectronics and nanomagnetics, and is being actively pursued by the Centre for Quantum Computation and Communication Technology and the Centre for Engineered Quantum Systems, using single donor atoms in silicon and confined quantum dots in gallium arsenide respectively. The quantum-optical properties of electronic and spin states of atomic defects in diamond and silicon, pioneered at ANU, form the basis of new quantum technologies, including nanoscale magnetometry, single photon sources, and quantum memories currently under development by several groups.

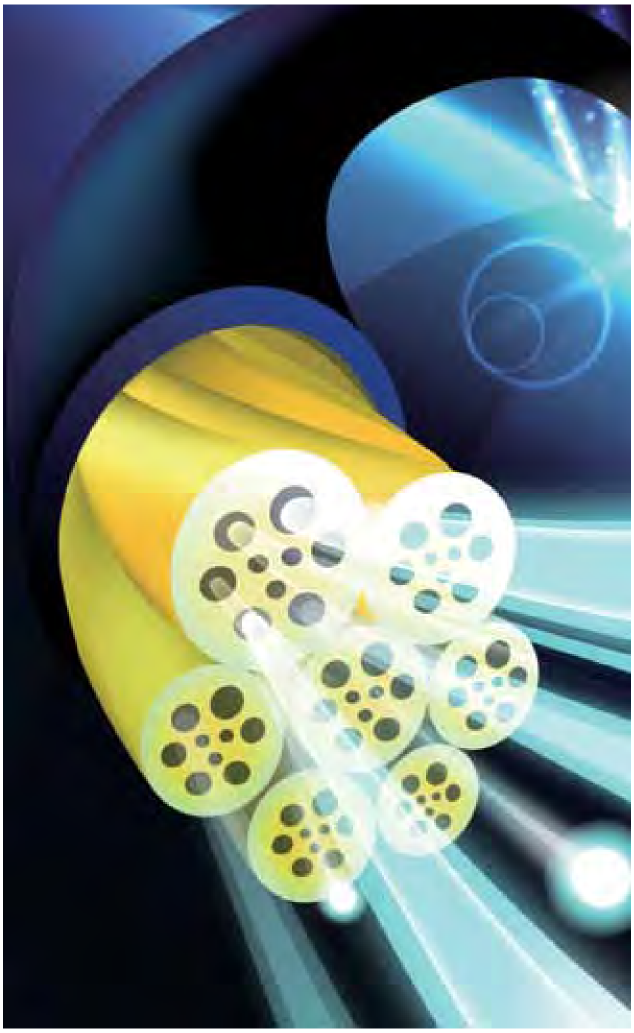


Figure 35: Schematic of nanoscale carbon doped magnesium diboride superconducting multifilament wires, which currently hold the world record in critical current carrying capacity, fabricated at the Institute for Superconducting and Electronic Materials. (Image courtesy of S. X. Dou, University of Wollongong)

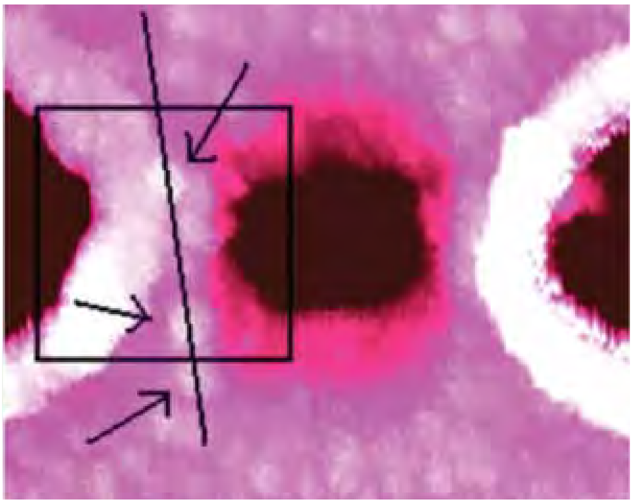


Figure 36: Researchers at CSIRO have used a Nb nano-SQUID pictured here (the central nanoSQUID hole is about 150 nm across) to detect the magnetism of single nanoparticles of native horse-spleen ferritin (location indicated by the arrows). (Image courtesy of Simon Lam, CSIRO)

Many research groups are working in the fast-growing area of the interaction of light with nanoelectronic systems and plasmonics.

The interaction of light with nanoelectronic systems opens many new areas of fundamental research, and device functionality and application opportunities. In solar cell technology, nanostructure properties can improve the conversion of photon energy to charge motion. In Australia, many groups work in this space. The Centre of Excellence for Advanced Silicon Photovoltaics and Photonics has for a number of years led the world in basic research and device development, setting a world record for solar cell efficiency in 2008. Major efforts in solar cell research related to nanoelectronics now include the Australian Solar Institute as well as large-scale initiatives at the CSIRO Solar Energy Centre in Newcastle.

At the fundamental end of the research spectrum into solar cells, a number of groups are working on new materials and devices such as organics, nanowires and quantum dots, including at the Victorian Organic Solar Cell Consortium, the CRC for Polymers, the Centre of Excellence for Electromaterials Science at Wollongong, the Australian Synchrotron, the Centre for Organic Electronics at Newcastle, and the Centre for Organic Photonics and Electronics in Queensland. Plasmonics involves the collective excitations of electrons to confined nanostructures and couples the regimes of nanoelectronics and photonics, including research into metamaterials and the generalisation of light-guiding media. The potential to develop the next generation of high-speed switching, energy production and communication devices has spurred a lot of activity in this area. In Australia, research in this direction is very strong in several universities and in the Centre of Excellence for Ultra-high Bandwidth Devices for Optical Systems. The current world record for thin film nanoplasmonic solar cell efficiency is now held by the technology developed by the Victoria-Suntech Advanced Solar Facility at Swinburne.

While it is difficult to capture all research groups and directions in such a diverse field as nanoelectronics and nanomagnetics, it is clear that, overall, Australia has a large effort including not just major groupings and initiatives, but also individual groups at the university level conducting spectacular world-class research in all aspects, from fundamental research to applications development.

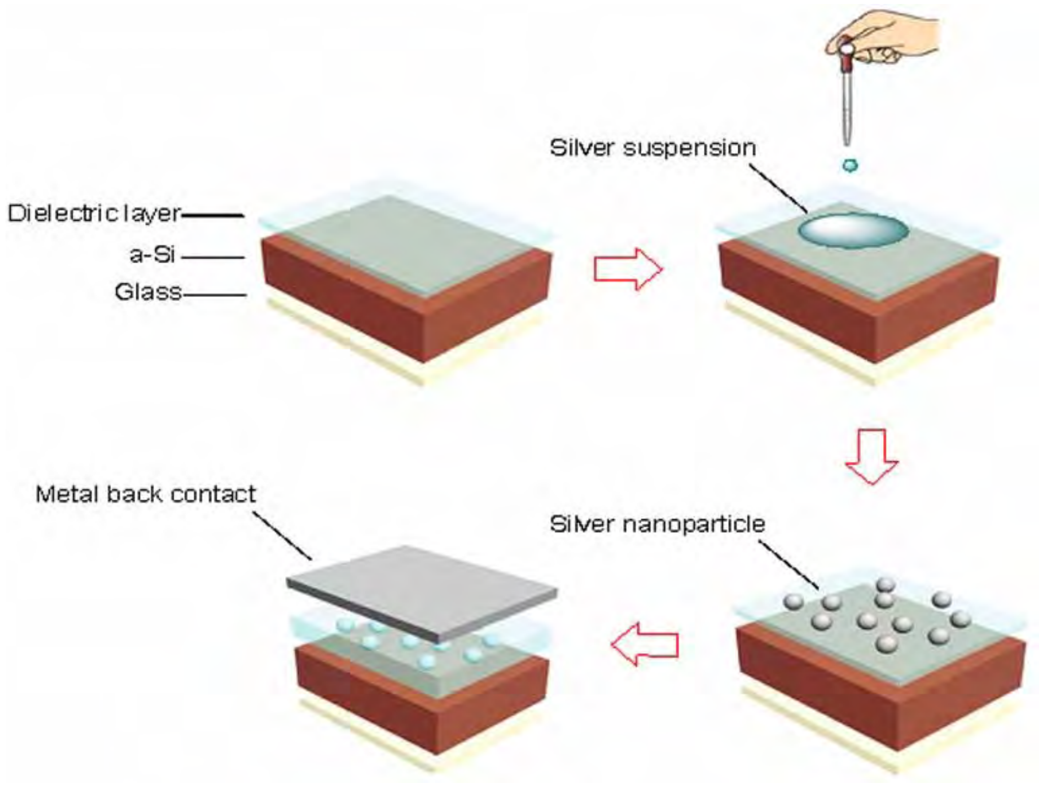


Figure 37: Increasing the efficiency of thin-film nanoplasmonic solar cells to a new world record by integration of silver nanoparticles into amorphous silicon solar cells. (Reprinted from *Nano Letts* (2012) 12: 2187-2192; Image courtesy of M. Gu, Swinburne University of Technology)

Challenges and opportunities for nanoelectronics and nanomagnetics

Summary of the key challenges for nanoelectronics and nanomagnetics

1. **Moving beyond conventional computer chip miniaturisation scaling.**
2. **The development of quantum information technology.**
3. **Developing new concepts and materials for nanoelectronics and nanomagnetics.**
4. **Taking advantage of new ways to manipulate light and spin and integrating them into nanoelectronic devices and sensors.**
5. **The convergence and application of nanoelectronics and nanomagnetics to life sciences and other disciplines.**
6. **Making best use of existing international partnerships and developing new linkages.**
7. **Taking full advantage of the major investments that have been made in advanced new nanofabrication facilities.**
8. **To continue development of education and training in nanoelectronics and nanomagnetics.**
9. **Creating strong links between academia and industry and the commercialisation of current nanoelectronics and nanomagnetics research.**

Given that various estimates of the nanoelectronics-based global market approach the trillion-dollar level, there are significant opportunities for Australian researchers participating in this subdiscipline.

Challenge: Moving beyond conventional computer chip miniaturisation scaling.

Opportunity: The strong research base into a broad range of nanoelectronics and nanomagnetics means that researchers will make significant contributions to development of More-than-Moore technologies

In the International Technology Roadmap for Semiconductors (www.itrs.net) it is well recognised that to continue the scaling of CMOS technology in the medium term (i.e. beyond 2018) the development of new materials is required to replace conventional transistor structures. Beyond this, as the miniaturisation of CMOS technology approaches the fundamental scaling limits of the extreme nano and atomistic regimes, there is an imperative to research new devices for information processing and memory storage. The possibilities are vast and it is impossible at this stage to pick winners. With a strong base of research into a broad range of nanoelectronics, nanomagnetics, and optoelectronics, Australian researchers are ready to make significant contributions to More-than-Moore technology development.

Challenge: The development of quantum information technology.

Opportunity: There are new and significant opportunities for device functionality predicated by the fundamental rules of quantum mechanics.

The ability to fabricate, control and measure individual electronic and magnetic degrees of freedom down to the single electron level is opening up new opportunities for device functionality predicated by the fundamental rules of quantum mechanics. A popular vision is that a quantum computer based on processing information encoded on qubits may be the ultimate More-than-Moore technology. Internationally, research into quantum computer technology is a significant and still growing driving force producing new interactions between fundamental physics, engineering, and computer science. Candidate technologies relevant to this subdiscipline include superconductors, diamond defects, atomtronic systems, quantum dots and donors in silicon. These are already actively pursued by Australian researchers. While most workers in the field would view quantum computing as a relatively long-term prospect, emergent quantum technology, such as quantum key distribution, is already at the commercial phase. The development of long-range quantum communication technology is a key problem requiring quantum repeaters that are based on small-scale quantum computer hardware, and hence ensure a cross-fertilisation of these fields. Quantum technology based on cold atomic gases or single atom systems are providing new opportunities for a range of applications, including quantum computing, atomic clocks and ultrasensitive electrometry and magnetometry, and nanoscale magnetic resonance detection in biology.

Challenge: Developing new concepts and materials for nanoelectronics and nanomagnetics.

Opportunity: Many nanoelectronic materials advances at a basic research stage show great potential for future device technologies.

While many of the nanoelectronic advances in the past decade have already had an impact on mainstream electronics, advances with new materials show great promise for the coming decade. Examples include carbon-based electronics (including graphene); self-assembled nanowires and nanotubes; the development of multiferroic materials; dilute magnetic semiconductors; materials based on layered oxides; and materials with topologically protected quantum states. New approaches to electronic and magnetic devices that store and process information and manipulate magnetic and ferroelectric domains at the nanoscale can be envisaged. Although many of these are still at the basic research stage, they have great potential for a range of future device technologies.

Challenge: Taking advantage of new ways to manipulate light and spin and integrating them into nanoelectronic devices and sensors.

Opportunity: Metamaterials have potential applications ranging from advanced biosensors and chemical sensors through to communications, high-efficiency solar cells, and hybrid optoelectronic devices.

The engineering of materials at the nanoscale not only provides new electronic and magnetic functionalities, it also allows new ways of manipulating light and integrating light-sensing into devices and sensors. These 'metamaterials' can be engineered to have optical properties with no counterparts in nature and have potential applications ranging from advanced biosensors and chemical sensors through to communications, high-efficiency solar cells, and hybrid optoelectronic devices. Similarly, the ability to transfer optical information to and from the spin states of electrons will have applications ranging from high-speed communications through to quantum computation.

Challenge: The convergence and application of nanoelectronics and nanomagnetics with life sciences and other disciplines.

Opportunity: Convergence with biology will lead to the development of new sensing, imaging and bionic technologies for the life sciences.

Convergence of physical sciences, engineering and life sciences has been identified as one of the key emerging areas of the 21st century. Nanoelectronics/nanomagnetics and related emerging technologies will have significant impact in areas unrelated to information technology. An important example of this is the development of micro/nanoelectronics for bionic systems beyond the bionic eye projects. New nanoscale sensors will be far smaller and more sensitive than existing technologies, with applications ranging from detecting massive gravitational waves through to magnetic resonance imaging at the nanoscale, particularly in biology. Breakthrough applications in life sciences are already starting to emerge, with research into hyperpolarised nanoparticles for high-contrast and site-specific MRI imaging, and nanowire/nanoelectronic sensors for in situ detection of neuron signals.

Challenge: Making best use of existing international partnerships and developing new linkages.

Opportunity: Through the use of dedicated funding, an exchange of staff and research students between institutions, and grants, could allow researchers access to leading international laboratories.

Nanoelectronics and nanomagnetics are a major international endeavour, exemplified by, but not confined to, the International Technology Roadmap for Semiconductors. Australian researchers have established extensive international collaborations and linkages with leading international laboratories and universities, with most nanoelectronics research in Australia involving international partnerships. There are significant opportunities to further exploit these partnerships and build new linkages. This requires funding sources primarily to support the exchange of staff and research students between institutions, and research linkage grants. This relatively small level of dedicated funding provides excellent value for money, giving access to facilities and expertise unavailable in Australia as well as invaluable experience for ECRs, and access to leading international laboratories.

In the United States, many large initiatives around nanotechnology are already in place. The peak organisation is the National Nanotechnology Initiative, which, in the 2013 budget, will be funded at around $USD1.8 billion (www.nano.gov). This covers all of nanotechnology; however, many initiatives cross over to the nanoelectronics regime. The National Science Foundation funds a number of nanoscience centres and university networks and, with the Semiconductor Research Corporation's Nano-electronics Research Initiative (NRI), is supporting research (and education) specifically on the topic of 'Nanoelectronics for 2020 and Beyond' and the Electronics, Photonics, and Magnetic Devices program. The projects funded by NRI explore a range of innovative approaches relevant to More-than-Moore technology, as per NRI's mission of 'looking for the next switch to propel technology beyond its current limits'.

In Europe, the UK Engineering and Physical Sciences Research Council has a number of priority areas within the broad area of ICT related to nanoelectronics and nanomagnetism. These include photonics for future systems, non-CMOS device technology, optoelectronic devices and circuits, and graphene and carbon nanotechnology. Other major activities across European member states include EU Framework Programs and the ENIAC Joint Undertaking (JU)—a public–private partnership focusing on R&D in nanoelectronics—and the Association for European NanoElectronics Activities. The ENIAC-JU grants for 2011 totalled €175 million (www.eniac.eu).

In our region, Asia has for many years been focused on becoming a leader in nanotechnology research and development. For example, Japan was the first to create a national nanotechnology research program, with the Ministry for Technology and Industry committing $200 million to nanotechnology research in 1991. By 2005, funding in Japan for nanotechnology research had reached $950 million with a major focus on nanoelectronic devices and structures (Roco MC, *J. Nanoparticle Research* 2005). In addition, research into incorporation into devices of functionalities that do not necessarily scale according to Moore's law is addressed through a program on 3D integration named the 'dream chip'. An example of major centres in Japan is the Nanoelectronics Collaborative Research Centre, which was established at the University of Tokyo with the goal of developing core technologies for information devices and a focus on becoming an international centre of excellence in advanced nanophotonics and electronics.

A key challenge for Australian nanoelectronics and nanomagnetics research in general is to gain access to, and participation in, these international initiatives beyond the current levels.

Challenge: Taking full advantage of the major investments that have been made in advanced new nanofabrication facilities.

Opportunity: Providing dedicated funding and specialised technical staff will allow researchers to exploit the full potential of the new nanofabrication facilities.

Australia has recently made a major investment in advanced nanofabrication facilities through the NCRIS funding scheme. This provides state-of-the-art tools for fabricating advanced nanoelectronic devices, with major nanofabrication facilities located throughout Australia. To ensure that the full potential of these facilities is exploited, it is essential that researchers have dedicated funding to access them and that ongoing financial support is provided to the facilities themselves to support the specialised technical staff required to keep the equipment operating.

Challenge: To further develop education and training in nanoelectronics and nanomagnetics.

Opportunity: Providing training for local and international undergraduate and postgraduate students for the electronics industry.

Education is already Australia's third largest export industry and there is an ongoing opportunity to provide the training for local and international undergraduate and postgraduate students for the large electronics industry located in the Asia-Pacific region. The training of highly skilled scientists and engineers also benefits Australian SMEs: companies such as Silanna are already recruiting students from Australian nanoelectronics research groups. While Australia has some university-level courses in nanotechnology, internationally there is considerable emphasis on education and training, with many universities overseas offering education programs in nanoelectronics and related areas. The nanoHub initiative in the United States is an excellent example of an online resource for nanoelectronics spanning education and research-level usage.

Challenge: Creating strong links between academia and industry and the commercialisation of current nanoelectronics and nanomagnetics research.

Opportunity: Creating new spin-off technologies and spin-out companies will provide new employment and economic opportunities.

Basic nanoelectronics and nanomagnetics research has reached a level of development that allows knowledge to be translated by industry into products. Many of the concepts and materials being developed differ from existing technologies, so there will be strong demand for linkage between academia and industry to bring these new technologies to fruition. As well as translating university research into the existing industrial base, there is enormous opportunity to develop new industry through the rapid development and commercialisation of current nanoelectronics and nanomagnetics research. The creation of new spin-off technologies and spin-out companies will transform the SME landscape in Australia and provide new employment and wealth creation opportunities in the future.

Summary of the key opportunities for nanoelectronics and nanomagnetics

1. **The strong research base into a broad range of nanoelectronics and nanomagnetics means that researchers will make significant contributions to development of More-than- Moore technologies.**
2. **There are new and significant opportunities for device functionality predicated by the fundamental rules of quantum mechanics.**
3. **Many nanoelectronic materials advances at a basic research stage show great potential for future device technologies.**
4. **Metamaterials have potential applications ranging from advanced biosensors and chemical sensors through to communications, high-efficiency solar cells, and hybrid optoelectronic devices.**
5. **Convergence with biology will lead to the development of new sensing, imaging and bionic technologies for the life sciences.**
6. **Through the use of dedicated funding, an exchange of staff and research students between institutions, and grants, could allow researchers access to leading international laboratories.**

7. **Providing dedicated funding and specialised technical staff will allow researchers to exploit the full potential of the new nanofabrication facilities.**
8. **Providing training for local and international undergraduate and postgraduate students for the electronics industry.**
9. **Creating new spin-off technologies and spin-out companies will provide new employment and wealth creation opportunities.**

Developing the discipline

Continuation of nanoelectronics and nanomagnetics as an Australian research strength is reliant on coordinating and improving collaboration opportunities at both the national and international level (Recommendations 4 and 8) and sustaining infrastructure support (Recommendation 1). It is critical to ensure there are funding mechanisms that appropriately support interdisciplinary basic research (Recommendations 2 and 3) and other mechanisms that help education and training opportunities (Recommendation 6), and that enable the translation of research into successful commercial outcomes (Recommendation 5).

Case study 6: Printable solar cells

Organic photovoltaics (OPV) have recently emerged as a revolutionary new technology that promises a low-cost route to high-volume solar cell manufacture by virtue of its inherently low materials and manufacturing costs. At the heart of these solar cells are materials designed and structured on the nanometre scale.

This nanotechnology is enabling an entirely new approach to solar cell design and applications. The key difference between OPV technologies and conventional silicon-based solar cells is that OPVs use very small amounts of relatively cheap materials in very thin films. This means that flexible devices, such as solar cells printed on plastic, can be fabricated, Furthermore, this can be undertaken with manufacturing equipment already in place in industries using printing and coating processes.

This technology is being developed in Australia by the Victorian Organic Solar Cell Consortium (VICOSC), which brings together researchers from the University of Melbourne, CSIRO and Monash University as well as industry partners BlueScope Steel, Securency, Innovia Films Ltd and Robert Bosch South East Asia, with funding from the Victorian Government and the Australian Solar Institute.

The optimisation of OPVs is targeted at improving the cost, efficiency, lifetime and aesthetics of solar cells. This requires expertise in several nanotechnology areas, including nanocharacterisation, nanofabrication, nanomaterials and additive nanomanufacturing. Within the next few years, it is anticipated that short-term applications in packaging and advertising will be followed by the use of OPVs in portable electronic devices, followed by architectural applications such as windows and, eventually, in large-scale commercial deployments. An example of a short-term application is a combination of a flexible solar cell with a low-cost, flexible light that could be used in remote or developing parts of the world to replace kerosene lamps. In the longer term, solar cells integrated directly into steel roofing is a key goal of VICOSC. Globally, it is estimated that the market for OPVs will be $17 billion p.a. by 2020 (IDTechEx, 2011).

Figure 38: A roll of printed solar cells. (Image courtesy of Scott Watkins, CSIRO)

Figure 39: Fully printed solar cells. (Image courtesy of the Victorian Organic Solar Cell Consortium)

Case study 7: Technology from atomtronics

Atomtronics is an underpinning technology that uses lasers and quantum mechanics to control individual atoms. This exquisite control delivers the power to create devices that can make highly sensitive measurements. Australia not only has great expertise in this technology, but also in the fundamental theories and innovative computational tools vital in developing techniques to manipulate and control atomic systems to perform tasks at the frontiers of science. Particular examples include the most precise measurement devices known to science, such as atomic clocks and atom interferometry.

Atomic clocks

Throughout history clocks have been the most sensitive measurement tools available to mankind. Clock performance has improved by over a million times in the past 60 years, principally due to the exploitation of the properties of isolated and controlled atoms and ions. Clocks and oscillators are crucial for the highest-precision scientific and industrial measurements and the foundation of modern communications technology. The current world time standard exploits the microwave hyperfine splitting in ^{133}Cs to a precision exceeding 4 parts in 10^{-14} in one second. Recent developments in laser-cooled clocks at optical frequencies promise a hundredfold improvement, and subsequently revolutionary changes to global navigation, timekeeping and precision measurement. Over the past 10 years the best clocks have been used to search for temporal changes in the values of the fundamental constants as well as to precisely test Einstein's Theory of General Relativity. Australia has built time standards based on ytterbium ions (at the National Measurement Institute in Sydney) and on neutral calcium atoms (at the University of Western Australia). Future developments in optical lattice clocks (pictured below) will push the precision of time measurement to the 10^{-18} level.

Atom interferometry

Atom interferometry using ultracold atoms at temperatures just above absolute zero is the technology of choice for precision measurement of the curvature of space–time and local gravity. Such devices can be used for mineral exploration, oil and gas-well monitoring, watertable monitoring, and inertial navigation. Atom interferometry is also an important scientific tool allowing tests of Lorentz invariance, the universality of free fall, the universality of clock rates and measurements of fundamental constants such as the gravitational constant G. Australia is well-placed to advance this field substantially in the coming years. Through its work in quantum squeezing and correlations, quantum noise limited measurement and cold atom technology, Australia has considerable expertise in the fundamental physics of atom interferometry and is also the home to one of a few laboratories in the world capable of precision inertial measurements using cold atoms. The current focus is on the measurement of gravity and gravity gradients.

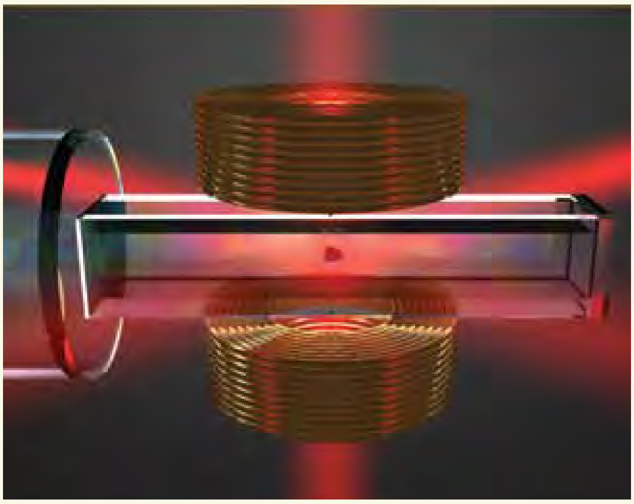


Figure 40: Schematic of a magneto-optical trap. Circularly polarised laser beams are shown in red, and a quadrupole magnetic field is produced by two solenoids. Atoms are trapped inside an ultrahigh vacuum system in the centre of the apparatus (Image courtesy of Nick Robins, ANU)

Nanophotonics

Definition of discipline

Nanophotonics is the science and technology of light and its interaction with matter at the nanoscale.

Nanophotonics encompasses optics and optoelectronics as well as nanostructured plasmonics and metamaterials. It also implicitly encompasses less-exotic photonic components such as optical cavities, sources, detectors and light transmission/manipulation based on nanostructured materials, Bragg mirrors and thin-film elements that incorporate nanoscale structures.

The outcomes of this research have a direct impact on many technologies and applications, including quantum computing/information technology, photovoltaics, integrated photonics, sensing (particularly biological and chemical), optical fibre-based technologies and 'lab on a chip' applications.

These technologies are already deployed, or being deployed, in a broad range of applications. The impact of nanophotonics on these technologies will have consequences ranging from incremental improvements through to dramatic paradigm shifts in their application, to strategic and important national interests spanning mining and oil and gas, food and agriculture, national defence and security, environmental monitoring, health and biomedical applications, ICT and education.

Australian strengths in nanophotonics

Australia's research strengths in nanophotonics cover the spectrum from fundamental science, such as light-material interaction, to direct applications, such as devices used for sensing and medical purposes. Six broad subdisciplines of nanophotonics have been identified.

Summary of the key strengths in nanophotonics

1. **Nanoscale quantum optics.**
2. **Photonic chips.**
3. **Active and tunable metamaterials.**
5. **Optical sensors and nanoelectromechanical systems for biological/chemical detection at the molecular light at the nanoscale.**
6. **Manipulation of light at the nanoscale.**
7. **New fabrication technologies.**

Nanoscale quantum optics

Quantum optics involves quantum mechanical phenomena arising from the interaction of light with matter. The resulting photons can be exploited for applications in quantum information processing and communications analogous to the classical counterparts using electrons. Although most research to date involves the use of large optical tables with bulk optics, macroscopic lasers and free-space light beams, the miniaturisation of these components down to the nanoscale has tremendous potential, such as for on-chip implementation. Work is being undertaken at the ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC2T) and at the ARC Centre for Excellence for Engineered Quantum Systems.

CQC2T leads the world in small-scale quantum logic circuits and will push towards developing unique architectures for scale-up implementation. Australia possesses world-leading theoretical, experimental and commercial expertise in quantum key distribution. In close partnership with QuintessenceLabs and LockHeed Martin, the centre works with government agencies to provide the highest level of intragovernmental information security.

Photonic chips

Arguably, the major limitation in current optical data/telecommunication systems is the inherent interface between fast optical and slow electronics components, which severely restricts the speed at which data could be processed or transmitted. To overcome this bottleneck problem and fully exploit the large bandwidth available with optical communications, it would be ideal if all signal processing could be done in the optical domain. Research in this field is primarily conducted at the Centre for Ultrahigh Bandwidth Devices for Optical Systems (CUDOS), which is a consortium among seven universities.

CUDOS is developing groundbreaking integrated photonic signal processors by using nonlinear optical signal processing in photonic chips, which is now opening up new areas of opportunity for energy-efficient optical signal processing and quantum processors that can massively increase data processing and information capacity of the internet.

Active and tunable metamaterials

Plasmonic nanostructures provide enhanced light–matter interactions (for highly sensitive sensors, energy harvesting, enhanced light-collection efficiency, enhanced optical fields for data storage), and allow nonlinear processes to be greatly enhanced due to the achievable electric field enhancements (for controlling light in plasmonic waveguides and plasmonic crystals).

Metamaterials are artificially engineered composites that exhibit properties unknown in nature. These include bending light in the opposite direction, hyperlensing, invisibility cloaking, and ultrasensitivity to a change in the light intensity, with novel applications in defence, imaging, sensing, photonics, and even solar cell technologies. The strong photonics and compound semiconductor expertise in Australia has seen exciting research effort at a number of institutions in active (with gain) and tunable metamaterials.

Optical sensors and nanoelectromechanical systems for biological/chemical detection at the molecular level

Next generation optical sensors would have to be able to detect chemicals and biomolecules down to the molecular scale. They would also be able to detect extremely low concentration (picomoles) and volume (picolitres) levels. For example, by using micro/nanostructured optical fibres, biomolecule sensors capable of measuring small sample volumes and/or low concentrations have been developed. On the other hand, by using optical nanoelectromechanical systems, highly sensitive chemical and biological sensors can also be fabricated. This new generation of optical sensors has many practical applications in corrosion sensing, in vitro precision monitoring of complex liquid processes—for example, wine fermentation, embryo monitoring and soil and water quality monitoring. Indeed, several Australian institutions are jointly developing these technologies with pharmaceutical companies, government agencies (such as defence, agriculture peak bodies) and food and wine companies.

Manipulation of light at the nanoscale

At the nanoscale level, light emission, propagation and absorption are strongly modified. To achieve large-scale integration in optical devices for the next generation photonic integrated circuits and a whole myriad of sensing applications, light needs to be generated, detected, confined and manipulated in very small spaces.

Australia has a strong and very visible profile in the synthesis of nanoscale materials, in particular quantum dots and nanowires. Nanowire research is a fast-emerging field and this exciting material is expected to revolutionise our technological world in the way new devices and components are made from new concepts. These nanowires become an important candidate as the nanobuilding blocks for a new generation of optoelectronic devices such as light emitting diodes (LED), lasers, single-photon sources, photoconductive sensors, photodetectors, photovoltaic devices and optical interconnects.

In the area of sources, work is now being carried out on generating lasing action from these nanowires and on how plasmonic effects can be used to modify the emission kinetics. Organic LEDs based on small molecules and flexible substrates are also being developed for a myriad of emerging applications in displays and lighting.

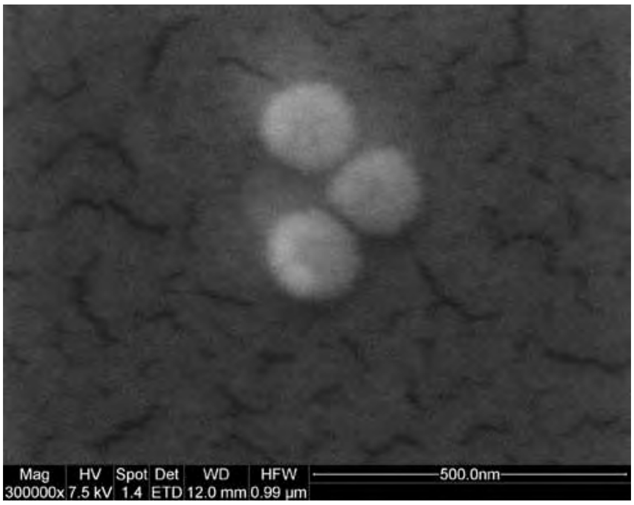
One of the biggest uses of nanophotonics in enhancing the detection of light is in the area of photovoltaics and artificial photosynthesis. Due to the relatively poor absorption of light in most PV materials, novel light-trapping schemes using plasmonics, surface nanostructuring, quantum dots, and nanowires, are being investigated to enhance light absorption in solar cells. There is also significant research effort in photodetector applications using optical cavities, nanowires, quantum wells/dots and photonic crystal effect.

A key component in optical systems is waveguide. The research focus in this field is in silicon and chalcogenide-based materials. Both of these waveguides can lead to high optical nonlinearity effect, which in turn result in a host of interesting optical phenomena that can be exploited for many applications.

In addition to sources, detectors and waveguides, there is emerging expertise in super-resolution techniques to circumvent the diffraction limit for visible light and allow resolution of objects at the nanoscale. Other areas of research activity include near-field optics, optical 3D nanoscopy, and optical trapping/manipulation of nanoobjects.

New fabrication technologies

Nanoscale structures and devices require new fabrication techniques and self-assembly to be developed and these new technologies need to be more readily available to researchers. Under NCRIS, ANFF was established in 2007 to provide researchers and industry with unique and unparalleled access to state-of-the-art fabrication facilities. It is an eight-node, university-based facility, with nodes distributed throughout Australia, built upon existing infrastructure and expertise. The capability provided by ANFF enables users to process hard materials (metals, semiconductors, composites and ceramics) and soft materials (polymers and polymer–biological moieties) and transform these into structures that have application in sensors, medical devices, nanophotonics and nanoelectronics. ANFF's commitment to provide a world-class user facility is underpinned by the sharing of best practice in service provision across the nodes. More importantly, dedicated expert staff who are experienced in meeting user requirements and maintaining leading-edge instrumentation need to be available at each node to assist researchers.



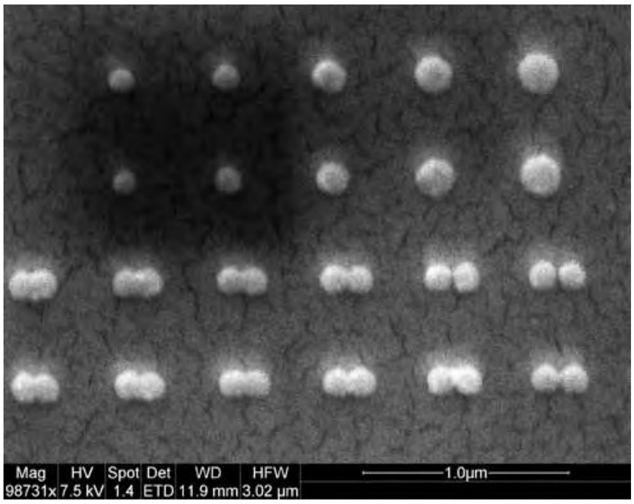


Figure 41: The new Melbourne Centre for Nanofabrication, funded by NCRIS, can produce nanophotonic structures by electron beam lithography with spaces down to 5 nm. Here small gold discs exhibit tunable electronic and optical features such as Fano resonances, controlled by the particle size, shape and interparticle spacing. (Image courtesy of Xingzhan Wei, University of Melbourne)

Challenges and opportunities for nanophotonics

Summary of the key challenges for nanophotonics

1. **Understanding how light interacts with nanoscale structures and the new physics.**
2. **Taking advantage of nancoscale-structured hybrid materials.**
3. **Taking advantage of photonic platforms that have been developed for other purposes.**
4. **Incorporating nanoparticles in the matrix in a precise, controllable and reproducible manner.**
5. **Extending the reach of photonic platforms via surface functionality.**
6. **Fabricating nanoscale devices with an unprecedented degree of control.**

The field of nanophotonics is rapidly developing, driven by the advent of new fabrication technologies and the increasing recognition that the capacity to control light using nanoscale structures opens up new ways of probing matter and controlling electromagnetic fields in unprecedented ways. In a field that is progressing so rapidly, there are some key challenges, which have been outlined above. Nanophotonics is particularly enriched by strong synergies with other fields and nourished by a plethora of applications ranging from advanced solar cell technologies to medical diagnostics and health care. Nanophotonics is also a clear area of emerging strength within Australia, building on our historical capabilities and expertise in photonics.

The purpose of this section is not to dwell on the challenges, but to articulate Australia's emerging strengths within the field of nanophotonics and highlight how each of these key challenges can be viewed as emerging research areas, providing us with opportunities for achieving powerful future scientific and economic outcomes. This document has been structured to highlight research opportunities rather than in terms of the anticipated industry they will benefit since many of these fields have the potential to produce technologies that will cut across a number of industry sectors.

Challenge: Understanding how light interacts with nanoscale structures and the new physics.

Opportunity: The fabrication of nanostructures on a large scale.

It is now possible to fabricate structures in optical materials at subwavelength dimensions in many ways using a broad range of techniques, from electron beam lithography through to self-assembly. Australia's approach to investing in nationally accessible nanofabrication research infrastructure via NCRIS and the Education Investment Fund programs has enabled Australia to identify gaps and emerging nanofabrication techniques and build a strong national community of interlinked researchers and highly skilled technical staff.

Challenge: Taking advantage of nanoscale-structured hybrid materials.

Opportunity: Using subwavelength structures to create artificial materials that can be tailored to offer a richer range of optical characteristics.

Existing strengths include the capacity to define subwavelength features in materials, including semiconductors, glasses, polymers and metals, with a clear trend towards the nanoscale to enable access to new optical regimes. Sustained research on nanophotonics is driven by diverse structures of particular interest, including nanowires, metamaterials, photonic crystals and hybrid materials that combine materials of more than one type with nanoscale structural features. The capacity of nanowires to capture light is driving their development into solar cells with improved efficiency as well as their use as a platform for interacting light with liquids and gases to create new measurement and sensing tools. Australia has recognised strengths in photonic crystals and is developing strengths in metamaterials—nanoscale-structured hybrid materials that can offer tantalising and radically new properties such as negative refractive index, leading to discoveries such as approaches to spatial and temporal cloaking. These materials offer these new opportunities by using subwavelength structures to create artificial materials that can be tailored to offer a richer range of optical characteristics than is available using naturally occurring or bulk media. These novel characteristics include the capacity to act as new sources, detectors and tools for metrology.

Challenge: Taking advantage of photonic platforms that have been developed for other purposes.

Opportunity: Exploiting the plasmonic resonance effects of photonic platforms.

Optical cavities, photonic crystals and metamaterials create powerful photonic effects by exploiting surface resonances. Indeed, surface resonances (excitonic, phononic, magneto-optical, plasmonic etc.) in general are a clear emerging area of interest in the field of nanophotonics since they enable subtle effects to be magnified and measurements of interest to be isolated. Of particular note is the field of plasmonics, where there are emerging opportunities as a result of the capacity to interrogate resonances within nanostructured metals using light. Many of the photonic platforms developed initially for other purposes, such as optical fibres and photonic crystals, are experiencing a renaissance in activity as the introduction of nanoscale features and metals is enabling the exploitation of plasmonic resonance effects.

Challenge: Incorporating nanoparticles in the matrix in a precise, controllable and reproducible manner.

Opportunity: Tailoring and enhancing the characteristics of nanoparticles through the use of nanophotonic structures.

Nanoparticles can be made from a wide variety of material systems and are well-established as a versatile route towards new light sources and as tools for probing nanoscale systems, particularly in biology and medicine where, for example, they have numerous applications in targeted drug delivery. A clear emerging focus is the use of nanophotonic approaches in conjunction with nanoparticles, and a few distinct examples are given below. An emerging strength is the introduction of nanoparticles to bulk materials to enable the novel properties of nanoparticles to be harnessed without the requirement for nanopositioning. This can be done via incorporating nanoparticles into a broad range of photonic materials, devices and platforms. Recent examples include nanoparticle-coated devices for enhanced Raman effects, glasses and optical fibres enriched with diamond nanoparticles that can emit single photons, and sensor architectures that exploit nanoparticles as a means of communicating between the sensing platform and the species to be detected. Opportunities exist to tailor and enhance the characteristics of nanoparticles via the use of nanophotonic structures as well as to use nanophotonic architectures as a practical means to exploit the useful properties of nanoparticles, in essence providing access to a continuous chain of effects from the nanoscale to the macroscale. Important areas include the incorporation of quantum dots in optical cavities for tunable vertical cavity-emitting lasers, and LEDs.

Challenge: Extending the reach of photonic platforms via surface functionality.

Opportunity: Adapting the techniques developed over the past few decades in the biotechnology industry to photonic device platforms.

Nanophotonic materials and devices enable the control of photons on the nanoscale, and this becomes particularly powerful as a means of interrogating and interfacing with nanoscale systems. One particularly powerful way of doing this is by imbuing photonic devices (whether they be nanowires, photonic crystals, optical fibres etc.) with novel surface functionality to interface with photonic effects with areas of interest in chemistry, biology, medicine, the environment and national security.

One clear emerging opportunity lies in the adaptation of the techniques developed over the past few decades in the biotechnology industry (for example antibody assays) to photonic device platforms. This has enabled the sensitivity enhancements resulting from the nanoscale control of light to be combined with the biological recognition elements that only biology can offer. Similar examples exist in chemistry; for example the use of novel chemical recognition systems (one example of which is an ion cage) in conjunction with photoswitches, enabling the use of light to control the nanoscale interactions of molecules with the photonic device. This foreshadows the development of new tools for measurement as well as practical sensing devices that can be reset using light.

Challenge: Fabricating nanoscale devices with an unprecedented degree of control.

Opportunity: Harnessing advances and emerging strengths in nanophotonics to drive down the scale and cost of nanoscale devices.

While Australia has recognised strengths in source, detector and waveguide technologies, most systems and devices, both in research laboratories and practical applications, rely on the use of relatively large-scale technologies. As new applications demand more functionalities and less power consumption, the dimensions of these devices need to be reduced, and very often down to the nanoscale. As their dimensions are now of the order of the wavelength of light, small imperfections during the fabrication process will severely degrade their performance. The challenge pushing the limit of current tools is to fabricate these nanoscale devices with an unprecedented degree of control.

There are clear opportunities to harness advances and emerging strengths in nanophotonics to drive down the scale and cost of these devices. This will allow the development of new industries and tools for monitoring and decision-making. Ultimately, devices that host on-chip lasers, nanophotonic sensing or optical data processing and detectors will be able to find applications ranging from new consumer devices to the management of pandemics, to national security threats and the management of environmental resources.

Opportunities for growing strengths in Australia include engagement in nano- and microscale laser and detector research in materials, including silicon, glass and semiconductors as well as hybrid material systems.

It is now possible to control pulses of light on the scale of a single optical cycle and create pulses on the scale of an attosecond. Ultrafast science is a powerful means of probing and controlling fast processes, and Australia has significant opportunities to develop critical mass and new technologies in this field.

Summary of key opportunities for nanophotonics

1. **The fabrication of nanostructures on a large scale.**
2. **Using subwavelength structures to create artificial materials that can be tailored to offer a richer range of optical characteristics.**
3. **Exploiting the plasmonic resonance effects of photonic platforms.**
4. **Tailoring and enhancing the characteristics of nanoparticles through the use of nanophotonic structures.**
5. **Adapting the techniques developed over the past few decades in the biotechnology industry to photonic device platforms.**
6. **Harnessing advances and emerging strengths in nanophotonics to drive down the scale and cost of nanoscale devices.**

Developing the discipline

There are many opportunities for nanophotonics research to be translated into real-world applications. However, this will require continued support by research-funding agencies at the interface between the physical and biological sciences (Recommendation 6) and through more broad support of translational research itself (Recommendation 3). Continued support of critical fabrication facilities will remain important if translation is to be undertaken in Australia (Recommendation 2).

Case study 8: Nanostructured Bragg mirrors for optical nanoelectromechanical systems-based infrared sensors and imaging systems

The strategic need: Current state-of-the-art infrared sensors and imaging systems are primarily based on integrated intensity signals over a broad range of wavelengths, effectively providing black-and-white intensity-only images with a significant amount of 'colour' information being lost by integrating the signal over a wide spectral band.

Critically, the added dimension made available by acquiring spectral information can be used in defence and security applications to identify targets and threats using fewer pixels than image recognition techniques. Furthermore, high-resolution spectral sensors can also provide information on the chemical and biological species present, which has numerous and broad applications in food and agriculture, biomedical diagnostics, remote sensing, forensics, environmental monitoring, resources exploration etc.

The major drawbacks of current hyperspectral infrared imaging systems are their large bulk, the high costs and the huge amount of data that needs to be processed. There is limited application of such technologies to high-cost systems that can be housed on large platforms, with data processing undertaken offline after acquisition. The primary need addressed by the technology developed at the University of Western Australia (UWA) has been the realisation of the key component of a lightweight, low-cost, high-speed, high-performance hyperspectral imaging system that is robust and able to offer the acquisition flexibility needed to overcome the signal processing load currently preventing the use of hyperspectral infrared imaging in real-time applications

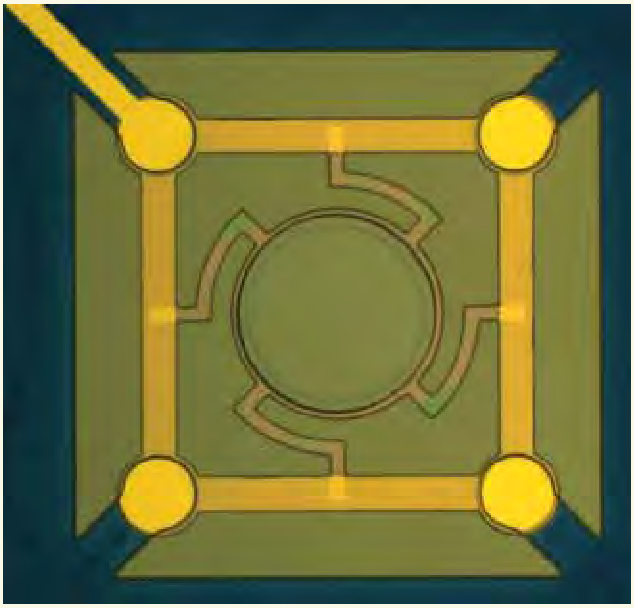


Figure 42: Microspectrometer chip for next-generation, wavelength-tuneable infrared imaging sensors. (Image courtesy of MRG UWA)

Innovation: UWA has been developing a range of MEMS-based tunable Fabry-Perot infrared optical filters for applications in real-time adaptive multispectral sensing and imaging. Such filters have been based on multilayer, thin-film Bragg mirrors and incorporated into a range of surface micromachined MEMS structures, primarily for applications in agriculture and food, and in defence and security. For applications requiring high spectral resolution, such as in chem-bio sensing, the technology has been limited by the difficulty of fabricating high-finesse cavities, which requires very high reflectivity Bragg mirrors. Recently, UWA has developed novel Bragg mirror designs based on nanostructured optical thin films. These that have the potential to make possible high-resolution spectral sensors and imaging systems and can provide the unique capability of real-time chem-bio sensing at the pixel level in a relatively low-cost module.

Figure 43: Unmanned Aerial Vehicle (UAV) equipped with infrared imaging sensors for intelligence, surveillance and reconnaissance in defence and security applications. (Image: istockphoto.com)

Potential for revolutionary sensors: The range of MEMS-based, multispectral sensing and imaging technologies developed at UWA has already had a major national and international impact, as evidenced by the award of the 2008 Eureka Prize for Outstanding Science in Support of Defence or National Security and the strong funding support from end-users and industry such as the US Defense Advanced Research Projects Agency, the Grains Research and Development Corporation and, more recently, Goodrich ISR. The new capabilities that will be made available with the advent of high-performance nanostructured Bragg mirrors will enable the development of a range of disruptive platform nanotechnologies with the potential to make a major international impact across a broad spectrum of industry sectors

Nanobiotechnology and nanomedicine

Definition of discipline

Nanobiotechnology is the convergence between nanotechnology and biotechnology; nanomedicine is the translation of nanobiotechnology for medical applications.

Nanobiotechnology includes all methods and techniques at the nanoscale that can serve to control and characterise biological systems and molecules, including using nanotools to understand biological processes at the subcellular level and develop new materials using biological molecules. Nanobiotechnology presents major opportunities to develop improved and more cost-effective healthcare. Improvements to healthcare will come from earlier and more accurate personalised diagnosis (in vitro and in vivo) and better-targeted therapies through developments in diagnostics, pharmaceutical delivery and regenerative medicine.

Australian strengths in nanobiotechnology and nanomedicine

Summary of the key strengths in nanobiotechnology and nanomedicine

1. **Australia has major, globally recognised biomedical and biotechnology institutions augmenting nanobiotechnology expertise and providing problem- focused nanobiotechnology that addresses major challenges.**
2. **Research strengths in understanding the bio–nano interface.**
3. **Particular strengths in diagnostics and imaging, with programs focused on the early detection of disease.**
4. **Strengths in nanomaterials, including cell therapies, tissue engineering and smart implants.**
5. **Widespread activity in developing drug delivery platforms.**

Australia has major, globally recognised biomedical and biotechnology institutions augmenting nanobiotechnology expertise and providing problem-focused nanobiotechnology that addresses major challenges

By its very nature, nanobiotechnology is a highly multidisciplinary field. The current research emphasis in Australia is predominantly on the fundamental science of nanobiotechnology or translating this science for medical applications (nanomedicine). Nanobiotechnology research is conducted across individual research groups across Australia, with few large interdisciplinary collectives of researchers working collaboratively on major challenges in the field. The few larger entities include the Australian Institute for Bioengineering and Nanotechnology in Queensland, the Australian Regenerative Medicine Institute in Victoria, the Australian Centre for NanoMedicine in New South Wales, and the ARC Centre of Excellence in Electromaterials across New South Wales and Victoria. There is also a corpus of major, globally recognised biomedical and biotechnology institutions augmenting the existing nanobiotechnology expertise and providing problem-focused bionanotechnology that addresses major challenges of global significance. Furthermore, it is apparent that, with a strong agricultural and environmental culture within Australia, activity in the development of bionanotechnology for agriculture, veterinary, food and the environment is beginning to emerge.

Internationally, there is a major drive towards large interdisciplinary institutes, with major funding initiatives for such institutes in the United States, Europe, Japan, China, and even Africa. Such institutes are targeted towards both fundamental science with applied implications and towards institutes targeting specific diseases. An example of the former relates to understanding how cells operate at the nanoscale so that new therapies and technologies can be developed. Both Europe and the United States have nanomedicine roadmaps to try to obviate a laissez faire approach to nanomedicine that will be inefficient in generating clinical and commercial outcomes. Commercial outcomes, however, have already been shown to be significant: nanotechnology pharmaceuticals and healthcare products have been estimated to be worth $3.2 trillion in 2012, and 50 cancer-targeting drugs based on nanotechnology were in clinical trials in the United States alone in 2010.

Research strengths in understanding the bio–nano interface

An overriding aim of most nanobiotechnology, and of all application areas, is to gain a greater understanding of interactions between biological components and human-made materials. Australia has considerable research strength in understanding the bio–nano interface, which is imperative for nanobiotechnology and nanomedicine to mature into a higher throughput, more predictable science. From an application perspective, the major activities within the more medically related nanobiotechnology can be subdivided into the broad areas of diagnostics and imaging, regenerative medicine and cell therapies (including smart biomaterials, implants and biomimetics), and drug delivery. These subdivisions and Australia's strengths will be discussed in turn.

Particular strengths in diagnostics and imaging, with programs focused on the early detection of disease

Diagnostics and imaging can be subdivided into in vitro and in vivo technologies—areas of particular strength in Australia. In vitro diagnostics are mostly directed towards portable point-of-care (POC) devices and high-throughput screening technologies. Almost all programs focus on early detection of disease, although several of the technologies being explored could also be applied to food and environmental detection. The POC research is spread across many Australian institutions. Most of these research groups are concentrating on electrochemical and optical biosensing-type devices, although there is expanding interest in developing bioassays and using cells within diagnostic devices for medical use. These academic activities are complemented by CSIRO and other commercial entities within these areas. High-throughput screening technologies are less spread across the country, but there are some strong programs in universities and medical research institutes.

In vivo diagnostics and imaging technologies generally target the detection of dysfunctional events or therapeutic activities and collectively cover a wide spectrum of nanotechnologies, including quantum dot development as sensors and imaging contrast agents; gadolinium polymers for magnetic resonance imaging contrast agents; sensors for protease detection; and cubosomes in imaging. There is considerable activity in these activities in a number of universities and at CSIRO.

Underpinning this research into diagnostic devices are biomarker discovery and research into understanding the bio–nano interface. There are research programs in biomarker discovery in university nanobiotechnology research groups, but most of the research is conducted within medical institutes and biomedical university departments.

Strengths in nanomaterials, including cell therapies, tissue engineering and smart implants

Regenerative medicine (including cell therapies, tissue engineering and smart implants) includes applying cutting-edge strategies to therapies that can be greatly enhanced by developments in nanobiotechnology, but where direction from clinicians is an imperative. Regenerative medicine seeks to repair, replace or regenerate diseased or damaged tissues using a variety of approaches. In the Australian context, a number of groups are working across this domain, with particular strengths in the development of nanomaterials, cell therapies (including stem cell), tissue engineering, and in the understanding of cell and tissue-materials interactions. Across Australia, activity comes from within universities, medical research institutes, ANSTO, CSIRO and some commercial organisations. Australian commercial organisations include Invetech, a world leader in automation for cellular therapies, and Mesoblast, the world's largest stem cell company (both based in Melbourne). Research activities are focused on determining cell and tissue behaviour in response to materials and agents within the nanoscale for targeting nerve (spinal cord, central nervous system and peripheral nerve), muscle (skeletal and cardiac), diabetes, bone regeneration, the control of cancer induction, and development of materials for cell production and delivery. Activities also encompass determination of nanoscale physicochemistry (structural) and molecular constitutional effects on molecular biological pathways in stem and precursor cells (neural, muscle, adipose, endothelial and iPSC) to the effects of nanoscale agents on regenerative or transformed tissue/cell response.

As tissue engineering can be regarded as a subset of cell therapy, several institutions are also engaged in using or otherwise developing nanotechnology for tissue engineering. Other activities in relation to regenerative medicine include the engineering of functional adipose, cardiac and pancreatic tissue. Tissue engineering emanating from stem cell applications, including materials development for stem cell production, sees major activities through universities, medical research institutes and CSIRO.

Bionics relates to materials that integrate electrical components with cells and tissue systems to provide artificial organ functions (e.g. muscle). Bionic devices are being developed at several universities and other organisations. In particular, bionics activities related to development of the bionic eye and existing Cochlear implant technologies are being pursued. These activities involve multicentre collaborations with hospital centres, universities and commercial partners.

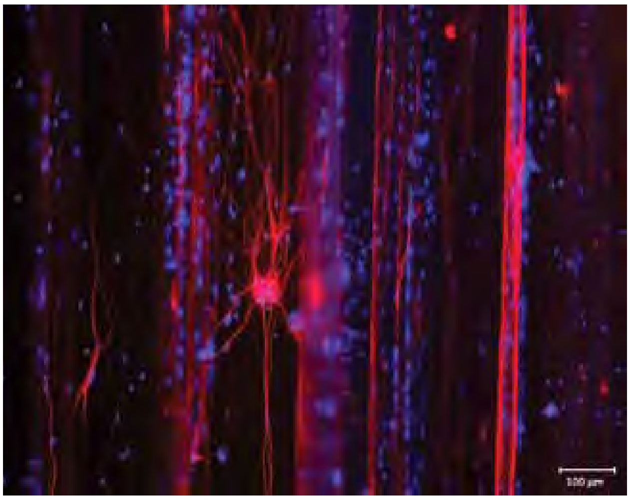


Figure 44: A hybrid polypyrrole/biodegradable polymer fibre platform to promote rapid directional nerve cell growth as a neuroregenerative scaffold and to electronically connect to a medical bionic device. (Image courtesy of University of Wollongong)

Internationally, there is a focus on the integration of academic, commercial and clinical activities, with an emphasis on the major diseases afflicting society. For example, the British Government recently announced a £50 million investment in a Technology and Innovation Centre in Cell Therapy, which will include industry, academia and government and seek to share in a cell therapy industry expected to be worth £3 billion by 2014. The centre, based in London, will capitalise on the United Kingdom's 'leading position in the science of stem cells and regenerative medicine, its supportive regulatory environment, the NHS as a potential lead market, access to mature capital markets and established pharmaceutical, biotechnology, medical device and blood transfusion industry sectors'.

Widespread activity in developing drug delivery platforms

Drug delivery is seen as a cornerstone of nanobiotechnology, and nanomedicine as a means to more effectively deliver both small-molecule and biological therapeutics. Current treatments for various diseases (e.g. cancer) are limited by the harmful side effects of chemotherapy drugs before they reach the site of action. Developments in vaccine and gene therapy are also challenging, due to degradation of sensitive cargo such as DNA, RNA or peptides. Recent trends focus on the use of carrier systems to improve drug delivery, as they have the potential to improve treatment options by protecting the cargo from degradation in vivo, thus limiting any potential harmful side effects and targeting the therapeutic directly to the site of action. Significant efforts are also being focused on examining the benefits of active targeting (e.g. antibody-mediated uptake) vs. passive targeting of carriers.

Australia has successes in this area with the cervical cancer vaccine (Gardisil), and with recent development by pSivida (sustained drug delivery systems for ophthalmology, oncology and cardiology) and Starpharma (dendrimer-based systems). There is widespread activity in Australia in developing drug delivery platforms using a diverse range of approaches. Major endeavours for drug delivery using nanotechnologies are underway at centres across the country. A wide variety of activities are being conducted in this area. They include particles, which involve drug/polymer complexes, cubosomes, polymers and dendrimers, self-assembling polymers/systems, virosomes and porous silicon materials; nanotherapeutic materials that are being developed and include peptide or nucleic acid-polymer conjugates and glycopeptide drug conjugates; and macroscopic devices that utilise nanotechnologies to better package or deliver drugs. Collectively, these technologies focus on delivery of therapeutic nucleic acids (siRNA, antisense), peptides and other small-molecule drugs to target cancers and functional tissue disorders.

Internationally, drug delivery platforms are a subject of intense activity, partly because of the slowing in approvals of new therapeutics and partly because of the new classes of therapeutics that could be delivered. The 2009 expert report of the joint European Commission/Nanomedicine European Technology Platform, *Roadmaps in nanomedicine towards 2020*, predicts the global market for nanopharmaceuticals will be of the order of €20 billion by 2020, with a large proportion of this market being due to the delivery of protein and DNA-based nanomedicines. The optimism regarding nanopharmaeuticals is related partly to the large number of nanomedicine drug delivery strategies being trialled (more than 50 products) and partly to the range of innovative nanoscale drug delivery systems being developed. Internationally, the key to translating new technologies is regarded as organising coordinated research programs where the ability of new technologies to be translated is considered very early in the research development.

Challenges and opportunities for nanobiotechnology and nanomedicine

Summary of the key challenges for nanobiotechnology and nanomedicine

1. **There is not a concentration of nanobiotechnology researchers in some areas of key importance to Australia.**
2. **There is a need to gain a greater understanding of the synthetic material/biological interface, nanoparticle life cycle/fate, and to understand the correlation between properties/behaviours observed in vitro with those observed in vivo.**
3. **Many diseases require early detection and targeted treatments.**
4. **Exploiting advanced nanotechnologies to make major contributions to drug delivery.**
5. **Using regenerative medicine to improve healthcare through the application of cell (stem) therapies, tissue engineering and smart materials.**
6. **Taking advantage of the broad skills base that is required, and exists, in Australia, to make major advances in nanobiotechnology.**

Challenge: There is not a concentration of nanobiotechnology researchers in some areas of key importance to Australia.

Opportunity: There are significant opportunities for nanobiotechnology to have major effects in the fields of agriculture, veterinary, food and the environment, given increased human capital.

The research strengths outlined point clearly towards a focus in the Australian nanobiotechnology community on fundamental nanobiotechnology, with an emphasis on nanomedicine. Translating these skills and technologies towards medical and commercial outcomes represents big scientific opportunities for Australia. Again, there are clearly enormous opportunities in fields such as agriculture, veterinary, food and the environment, all of which are of major importance to Australia. At present, however, there does not seem to be the concentration of nanobiotechnology researchers in these fields to create a major impact. This highlights a clear need to further increase our human capital in nanobiotechnology, especially by providing well-defined career pathways for emerging researchers and opportunities for international exchange.

Challenge: There is a need to gain a greater understanding of the synthetic material/biological interface, nanoparticle life cycle/fate, and to understand the correlation between properties/behaviours observed in vitro with those observed in vivo.

Opportunity: Fundamental research into the entire life cycle of nanodevices will facilitate safer and more efficient translation of nanobiotechnologies.

There are still a number of fundamental nanobiotechnology challenges and opportunities in translating nanobiotechnology to real-world clinical applications. We need to attain a far greater understanding of the synthetic material/biological interface that is so pivotal to much of nanobiotechnology. In a similar vein, understanding nanoparticle life cycle/fate both in vivo and ex vivo is highly important but not well understood. The need to understand the fate of nanoparticles also highlights another important opportunity, which is to improve our understanding of the correlation between properties/behaviours observed in vitro with those observed in vivo. Further, opportunities exist in the development of molecular/nanoassembly technologies for 3D materials and surfaces that may or may not comprise biological molecules. A critical but poorly investigated opportunity at present is the scaling-up of nanomaterials and bionanomaterials for successful nanodevices to be translated to commercialisation.

Challenge: Many diseases require early detection and targeted treatments.

Opportunity: Nanoscience is poised to make major contributions to diagnostic technologies that can provide not only early detection of disease but also information on the efficacy of treatment.

Within the field of diagnostics and imaging devices there are major opportunities that align with existing and emerging strengths within the Australian research community. The opportunities exist for diagnostic devices and imaging technologies in the areas of early disease diagnosis, the determination of the efficacy of treatment strategies and the personalisation of treatment strategies. Particularly important targets for diagnostic devices are the early diagnosis of diseases—for example many cancers—and the detection of degenerative diseases such as Alzheimer's disease, ageing macular degeneration and Parkinson's disease. Many such diagnostic technologies will operate in vivo, hence improved and targeted imaging agents that combine biological recognition with the imaging agent to concentrate the imaging agent at the site of a pathology are being developed. Smart nanosensors that can be interrogated remotely, whether in the body or by a home-based diagnostic device sending information to the doctor's surgery, will become increasingly important. Theranostic devices that detect and treat a condition by combining a diagnostic device with a means to deliver the appropriate level of a therapeutic will be developed. In vitro sensors/bioassays for personalised medicine, whether cell-based or genetic, will become prevalent. Many of these same sensing devices also present significant opportunities to assist in biological discovery and research, such as biomarker identification, or to monitor the fate of biomolecular markers in vivo. All these advances in diagnostics, facilitated by nanobiotechnology, will result in major savings in terms of the financial and social cost of diseases.

Challenge: Exploiting advanced nanotechnologies to make major contributions to drug delivery.

Opportunity: There are opportunities for targeted drug delivery, slow release of therapeutics and drug delivery triggered by a particular stimuli.

The area of advanced nanotechnologies for drug delivery is one in which Australia, with its number of active programs, is poised to make major contributions. Nanoscale vehicles for drug delivery represent a major opportunity. As the rate of discovery of new therapeutics declines, the emphasis is shifting to better and more-efficient approaches to deliver drugs. Opportunities exist in areas as diverse as targeted drug delivery, slow release of therapeutics, and drug delivery that is triggered by particular stimuli, such as a disease. There are further opportunities in drug delivery vehicles that provide additional diagnostic information through imaging agents or sensing devices. The field of nanopharmaceuticals also provides opportunities to deliver macromolecules or molecules that are not currently 'druggable'. A related opportunity is in macroscope devices with nanoscale architecture to deliver therapeutics such as vaccines. Here, too, Australia is poised to make major contributions.

Challenge: Using regenerative medicine to improve healthcare through the application of cell (stem) therapies, tissue engineering and smart materials.

Opportunity: The skills and capabilities in regenerative medicine already exist in Australia. The opportunity is to integrate nanotechnologists with clinicians and biologists in application-focused, interdisciplinary research collectives.

Regenerative medicine has the potential to have a revolutionary impact on health care through the application of cell (stem) therapies, tissue engineering and smart materials. Nanotechnology can play a role in several aspects of these developments and Australia has the skills and capabilities to contribute. However, to be successful, a truly integrated, multidisciplinary approach is required, with a focus on translation to meet market needs (unmet clinical need driven by clinicians and company-driven commercial opportunities). In particular, nanobiotechnology can contribute novel nanomaterials (injectable, self-assembling, biomimetic and switchable). These materials can be designed with appropriate physical and mechanical properties that mimic tissue biology, by incorporating nanotopography and bioactive agents that are displayed in the necessary spatial context and released in a way that directs biological response. Methods of fabrication for such materials are required that are reproducible, scalable and manufacturable. Successful application of these materials will require detailed understanding of biological and biochemical responses to them. In this context, opportunities exist to develop high-throughput methodologies for in vitro testing of cellular and biochemical responses to nano-enabled materials targeted at specific disease states. In relation to cellular therapies, there are opportunities for nanotechnology in the transplantation of both stem cells (in collaboration with the ARC Stem Cell Initiative) and differentiated cells, and tissue-engineered constructs. Despite the growth in understanding of stem cell biology, deeper understanding is required, as are methods to ensure appropriate regulatory regimes (safety and quality) and minimise production costs through automation and integration of enabling technologies. Nanotechnology can provide smart, functionalised materials for cell production in bioreactors, delivery and encapsulation, and non-invasive methods to monitor implanted cells, among others.

Challenge: Taking advantage of the broad skills base that is required, and exists, in Australia to make major advances in nanobiotechnology.

Opportunity: Combining the broad nanobiotechnology skills base into large interdisciplinary centres/ collectives with biologically driven and industrially relevant projects to help tackle grand challenges such as targeting specific cancers, Alzheimer's disease, arthritis and osteoporosis.

Australia has broadbased skills in fundamental aspects of nanobiotechnology such as surface modification, biomolecular assembly and nanomaterial synthesis. It also has an outstanding track record in biomedical science and the translation of biomedical science to the clinic. These skills, and a very collaborative research community, make Australia an ideal country for interdisciplinary nanobiotechnology research. The opportunities in nanobiotechnology in Australia therefore relate to combining these skills so that nanobiotechnology focuses on biologically driven, industrially relevant research that addresses major health and medical challenges. Achieving this requires the assembly of large interdisciplinary teams to work in a coordinated fashion on particular grand challenges. There are some moves towards assembling such teams by individual universities (the Australian Institute for Bioengineering and Nanotechnology, at the University of Queensland, the Australian Centre for NanoMedicine, at UNSW etc.), but little activity so far in forming large, interinstitution collectives that can interface with the strong medical institutes culture of Australian biomedical science to tackle major problems of Australian and global need. Such centres would require major funding through organisations such as the ARC, the National Medical and Health Research Council (NHMRC), the CSIRO Flagship Program, and CRCs. The opportunity for such centres of excellence lies in tackling a grand challenge of nanobiotechnology. Such grand challenges could include targeting a specific cancer, Alzheimer's, arthritis or osteoporosis. Australia has strong medical research capabilities in all of these areas, but by choosing a major, cross-disciplinary challenge that included nanodiagnostics, nanoassembly technologies and nanodrug delivery, we could make an impact with nanomedicine. A cooperative research program with strong leadership from universities, CSIRO, medical research institutes and hospitals should accelerate the use of nanotechnology imaging diagnosis, drug delivery and therapeutic monitoring for Alzheimer's disease within the decade. This type of program could be competitive and jointly arranged by the ARC, NHMRC, CSIRO and a significant not-for-profit organisation.

Summary of the key opportunities for nanobiotechnology and nanomedicine

1. **There are significant opportunities in the fields of agriculture, veterinary, food and the environment where, with increased human capital, nanobiotechnology can have major impact.**
2. **Research systems have the capabilities to trial and progress new technologies to progress research in this area.**
3. **Nanoscience is poised to make major contributions to diagnostic technologies that can provide not only early detection of disease but also information on the efficacy of treatment.**
4. **There are opportunities for targeted drug delivery, slow release of therapeutics and drug delivery triggered by a particular stimulus.**
5. **The skills and capabilities in regenerative medicine already exist in Australia. The opportunity is to integrate nanotechnologists with clinicians and biologists in application-focused, interdisciplinary research collectives.**
6. **Combining the broad nanobiotechnology skills base into large interdisciplinary centres/ collectives with biologically driven and industrially relevant projects to help tackle grand challenges such as targeting specific cancers, Alzheimer's disease, arthritis and osteoporosis.**

Developing the discipline

Australia's long history of excellence in biomedical research has ensured that our nanobiotechnology and nanomedicine are cutting edge. Our strengths in this field mean there are substantial opportunities to translate basic research into medical devices and diagnostics. For Australia to reap this benefit, there is a need for well-funded infrastructure (Recommendation 1), well-resourced support of large research teams and collaboration at both the national and international levels (Recommendations 2, 4 and 8). In addition, effective schemes to develop the translation of research, and workforce skills, will be essential (Recommendation 5 and 6).

Case study 9: The nanopatch for vaccine delivery

Imagine a technology that gives more effective vaccination with 1/100th the dose of vaccine, does not require refrigeration during storage, is safer for medical practitioners to administer, and is needle-free for wider adoption. Such attributes may sound too good to be true, but they are all features of an Australian nanobiotechnology solution to vaccine delivery.

The invention, by Professor Mark Kendall and his team at the Australian Institute of Bioengineering and Nanotechnology at the University of Queensland, is called the nanopatch. It is smaller than a postage stamp but has 20 000 projections per square centimetre, which are coated with the vaccine. Where the patch is applied to the skin, the projections painlessly penetrate and deliver the vaccine to just where it is needed—in the layer of immune cells just below the skin that are responsible for the body building up its natural defences against the disease the vaccine is designed to protect you from. What this means is needle-free vaccination. Needle-delivered vaccines are the cause of phobia and needle-stick injuries—a cause of an estimated 30% of unsafe vaccinations in Africa due to cross-contamination.

The nanopatches are made using nanofabrication techniques, which are available through the Australian Government-funded Australian National Fabrication Facility. The technology combines plasma-assisted etching of silicon needles at the nanoscale, with nanoscale modification of the silicon surface to allow effective biointerfacing with the patient. As nanopatches are fabricated from silicon wafers, their production can be massively parallel, and hence compatible with commercial micro/nano-fabrication processes. With all these features it is no surprise that nanopatches form the foundation of a new vaccine delivery company, Vaxxus Pty Ltd, which has recently been supported with $15 million investment from venture capital groups.

Figure 45: Nanopatch (Image courtesy of Mark Kendall, University of Queensland)

The nanopatch is just one example of how the interdisciplinary field of nanotechnology can revolutionise our lives for the better, in this case with a novel, low-cost health care solution that could be on the market within 5 years.

Translational nano research

Definition of discipline

Translational nano research (TNR) is research into the issues arising from the translation of nanoscience and nanotechnologies from the laboratory to industrial-scale manufacture, particularly throughout the life cycle of commercial production, use, disposal and recycling or degradation.

TNR is necessarily cross-disciplinary. It encompasses research in:

- **manufacturing**
- **materials science and engineering**
- **physics**
- **commerce**
- **toxicology**
- **metrology**
- **characterisation**
- **environmental science**
- **law and regulation**
- **ethics and social science research on risk**
- **social impact and public attitudes as applied to products involving nanomaterials, nanodevices or nanoprocesses.**

TNR involves identifying how different nanoengineered product types (e.g. those involving nanoparticles as compared to stable nanofilms, or those used in nanomedicine as compared with those used in building materials) raise different kinds of challenges to existing industrial, regulatory, safety, legal, ethical or social processes. Key concerns of TNR include human and environmental health and life cycle safety; the challenges of scaling of production for industrial manufacture; and the social, ethical and legal impacts of the wider adoption of nanotechnologies.

The benefits of TNR include its ability to underpin a knowledge-based economy in the transition of Australia's manufacturing industry to higher-value products and SMART design. TNR is centrally involved in the integration of safety, measurement, regulatory and social-ethical concerns in manufacturing and commercial development of nanotechnologies. It also underpins the capacity to deliver the promised outputs and benefits of other areas of nanotechnology research, by identifying, preventing or mitigating risks and challenges associated with the large-scale adoption of these technologies. Its financial impact needs to be understood as a function of the importance for timely translation of nanotechnologies into industrial or commercial applications and products.

The research supporting the translation of nanotechnologies into industrial or commercial applications and products includes the areas of manufacturing, environment, health and safety, regulation and the ethical and social impacts of nanotechnologies. Each of these contributes to the realisation of the potential for nanotechnologies to develop to the industrial scale. In the area of manufacture, TNR research includes addressing the challenges of scaling up production and ensuring the stable supply chains required for industrial-scale manufacture of high-value goods. These products could focus specifically on Australian challenges (e.g. water, energy, depletion of natural resources) and, more broadly, nanotechnology could uniquely contribute to a suite of tools to address major health and environment challenges. TNR research into metrology, toxicology, and work and environmental health and safety will prove to be essential for the development of nanotechnologies as important economic drivers. Manufacturers need materials and processes or engineered nanoproducts that can be produced to a consistent standard and quality, and are safe (to humans and the environment) throughout their lifespan. TNR research in metrology and health and safety also links to that concerning national and international policies and regulatory approaches to nanomaterials and engineered nanoproducts (including workplace and consumer protection), and to legal liability concerning materials, processes and products (including therapeutic goods involving nanomaterials). Finally, the potential social and ethical impacts of nanotechnologies form a fourth aspect of TNR research, which again links consumer, social, environmental and industrial interests.

Australian strengths in translational nano research

Summary of strengths in translational nano research

1. **International acknowledgement of Australia for our role in the development of comprehensive technical infrastructure and technologies.**
2. **The Australian Consortium's contribution to the OECD Working Party on Manufactured Nanomaterials (WPMN) nanosafety testing program is currently seen by the international scientific community as being highly integrated and effective in providing timely results.**
3. **Researchers are active in shaping the international debate around regulation, risk, identity, democratic engagement and human enhancement.**

There has been a strong focus internationally on the potential applications of nanotechnology as part of a suite of tools to develop solutions to a wide range of problems. There is also a general trend towards linking national challenges and priorities, with the focus of nanotechnology research and manufacturing being undertaken in each country. This is based on a general belief that nanotechnology allows the potential to address major issues in a way that will use fewer chemicals and materials and less energy, and will provide better outcomes. However, competing with this is the general uncertainty around the risks and potential side effects. This has prompted the formation of a number of national and international groups to deal with these concerns.

Internationally acknowledged for its role in the development of comprehensive technical infrastructure and technologies

Australia is acknowledged internationally as having developed comprehensive technical infrastructure (equipment and systems) for testing, metrology, nano manufacturing/fabrication, toxicology and safety. It is also recognised that Australia's manufacturing industry needs to transition to higher-value products to remain competitive in a global market. Australia has long led international efforts in multidisciplinary research in the social studies of science and the ethics of emerging technologies. Australian research on regulation and legal implications of nanotechnology provided early, comprehensive advice to government on the possibility that some nano applications may fail to trigger regulatory oversight in the existing regulatory framework, and therefore fail to contribute to international efforts to develop effective regulatory measures.

In the nanomanufacturing sector, several countries in Asia are continuing their strong development of nanotechnology capabilities despite the global financial crisis. For example, investments are being made in nanomedicine and nanobiotechnology in India, in nanoelectronics in Japan, Taiwan and Korea, and in hardware development in China and Japan. Although some European countries have seen steep declines because of the global financial crisis, countries like Germany and France have remained strongly involved in nanomanufacturing, as this is also related to country-specific government policies.

Overall, Australian nanomanufacturing research has been highly recognised in this international context and continues to attract high levels of funding internationally, with much of the research being driven by multinational companies and industrial consortia. The primary strengths are in the following areas:

- advancing nanomanufacturing processes for surface engineering, including optics, new coatings and functional surfaces, with damage-free, 'self-repairing' manufacturing of surfaces
- developing new methods for characterisation of materials, devices and structures at the nanoscale, including the assessment of the electrical, optical and mechanical properties of nanomaterials such as nanowires, nanotubes, and graphene
- developing integrated circuits of enhanced performance by scaling of dimensions deeper into the nano domain, introducing new materials and new material systems (e.g. graphene) and inventing new process technologies
- creating integrated devices to incorporate diverse functionalities by combining electronic functions with optics, microfluidics and mechanical structures, enabling the creation of new sensors and actuators, biochips and other novel devices
- developing new materials and manufacturing processes for new applications, including:
    - biosensors, biomaterials, engineered tissues and prostheses such as cochlear implants, bionic eyes, and biocompatible orthopaedic implants
    - microlenses and microlens arrays with complex, submicron features
    - biomedical devices for medical imaging, therapeutics, vaccination, and point-of-care diagnostics (e.g. 'doctor on a chip' technology)
    - nanofibres and nanocomposites.
- developing and applying nanotechnology to agriculture and food production, improving agricultural food-growing practices, food processing and food packaging.

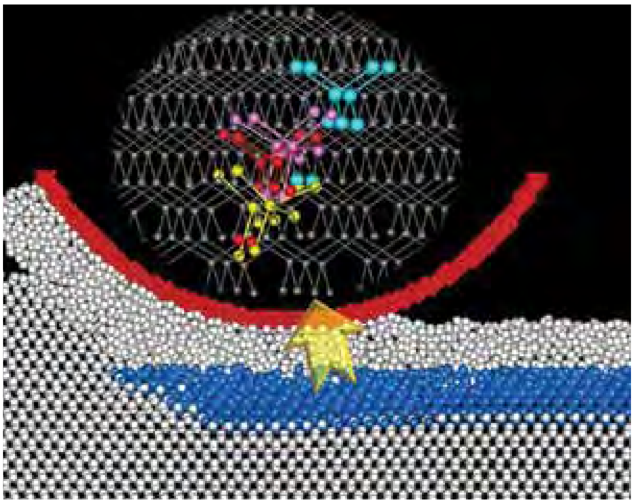


Figure 46: A nanomanufacturing process to create functional, layered microstructures of distinguished electronic properties in silicon. The layers showing from top to bottom are amorphous silicon, bct-5 silicon (in blue) and diamond silicon, respectively. (Image courtesy of Liangchi Zhang, UNSW)

Figure 47: The ultraprecision machining centre installed at UNSW is capable of manufacturing large surfaces of up to 0.35 m in diameter but with functional features of submicron accuracy. The insert demonstrates a series of manufactured aspherical lens arrays. (Image courtesy of Liangchi Zhang, UNSW)

A number of areas of these Australian research strengths in manufacturing are ready to be leveraged to develop a high-value local manufacturing industry. The Australian research in photoelectronics will enable scaled productions of internationally leading devices such as high-performance sensors, actuators, photoelectronic-materials, and functionally gradient materials. The Australian advances in the nanomanufacture of integrated devices will be able to create many new techniques for making devices of high-performance integrated circuits and solar cells, advanced medical devices (e.g. biomedical prostheses and implants) and integrated optical, electronic and mechanical functionalities (e.g. MEMS and NEMS).

Australia's strength in the development and characterisation of functional surface nanomanufacturing technologies will provide many opportunities to shape and form industry sectors for the characterisation of nanoscale surface morphology, manufacture for renewable energy devices, regeneration/growth of tissues and bones, and miniaturised functional surfaces. Australia's leading reasearch in micro/nanosurfacing will further enhance the development of nanocoating technologies and nanosurfacing for semiconductors and high-performance optical communication devices and elements (e.g. optical fibres and microlenses).

The Australian Consortium's contribution to the OECD WPMN nanosafety testing program is currently seen by the international scientific community as being highly integrated and effective in providing timely results

Within Australia, and more generally on the international stage, growing concerns about the potential health and environmental effects of some current nanotechnology applications (e.g. overuse of the biocide nanosilver, reducing its medical usefulness and affecting agriculture) has seen a steady and consistent approach towards the development of more-tailored and some nano-specific regulatory and labelling processes. As there is an existing major effort to establish an effective global harmonisation scheme for chemical and substance regulations, the general approach has been to see how to integrate nanomaterials and engineered nano products into these evolving regulations and processes. Consequently, governments and international bodies continue to work on the development of infrastructure and governance structures with respect to work and environmental health and safety, toxicological assessment, international measurement systems and documentary standards in which Australian researchers have also participated (e.g. through the International Standards Organisation Technical Committee (TC229) on Nanotechnology, and the OECD WPMN, through the nanosafety testing program). The Australian Consortium's contribution to the OECD WPMN nanosafety testing program is currently seen by the international scientific community as being highly integrated and effective in providing timely results in 2011–12 for Phase 1 of this program, now uploaded into the NANOhub database (see OECD highlight in Executive Summary).

Australian research that has directly contributed to the international effort in developing specific nanosafety resources has also been established to aid in toxicology assessment and the safe development, manufacture and use of nanomaterials. A strength of the Australian research is its direct links with this international effort and its collaborations; for example with the European Strategy for Nanosafety (EU Nanosafe2 and NANOhub), the UK Health and Safety Executive and Safety of Nanomaterials Interdisciplinary Research Centre, the German Federal Institute for Occupational Safety and Health and BASF AG and, in the United States, the National Institute of Occupational Safety and Health, the Environmental Protection Agency, the Department of Energy Nanoscale Science Research Centers, the International Council on Nanotechnology, and the Environmental Defence–DuPont Nano Partnership.

Australian researchers are active in shaping the debate around regulation, risk, identity, democratic engagement and human enhancement

Australian research capacity in law and ethics in nanotechnology and biotechnology is currently ahead of efforts to enhance social acceptance and uptake of these potentially disruptive emerging technologies. Australian legal researchers have led debate about weaknesses or 'regulatory gaps' for addressing nanomaterials, processes and products within existing regulatory structures. Australia has begun to identify governance and regulatory regimes to fill those gaps and has explored potential for regulatory harmonisation (discussed above). Australia is recognised as a world leader in bioethics relating to emerging technologies. Australian researchers have demonstrated strength in research on deliberative approaches for engaging the public in understanding the impact of nanotechnology and research on the social and ethical implications of human enhancement.

Multidisciplinary efforts are beginning to address this broad range of issues, as well as others such as technology assessment; equity and responsibility; legal aspects of nanotechnology (e.g. at the US-based Consortium for Nanotechnology in Society); privacy and anonymity (e.g. Delft University of Technology and University of Ottawa); nano risk, regulation and governance (e.g. The Netherlands NanoNextNL consortium, University of Michigan's Risk Science Centre; University of Trømso, Denmark); and the ethical and political aspects of nanomedicine (e.g. UNESCO and the European Commission's European Group on Ethics in Science and New Technologies). Australian researchers collaborate with researchers at each of the international centres and have been particularly active in shaping debate around regulation, risk, identity, democratic engagement and human enhancement.

Challenges and opportunities for translational nano research

Challenge: Maintaining the technical infrastructure required for testing, metrology, nanomanufacturing/fabrication, toxicology and safety to help the realisation of translational opportunities.

Opportunity: There is an opportunity to build a permanent critical mass of nanosafety research capacity to support Australia's nanomanufacturing sector.

Australian TNR research contributes significantly to developments in the field internationally. Australia has had a public research funding system that encourages targeted research collaboration based on skills and merits. When aligned with the perceived direction of global development for the next decade, the existing strengths of nanomanufacturing in Australia will bring about emerging technologies and significant opportunities for the Australian research and production sector. This will enable the Australian industry and researchers to play a more important role in the international nanomanufacturing community, particularly in instances where we are already leading such as research, development and production in the areas of nanomanufacturing for renewable energy, biomedicine and biomedical engineering, multiscale manufacturing and characterisation, precision agriculture, and water treatment. Maintenance of Australia's technical infrastructure for testing, metrology, nanomanufacturing/fabrication, toxicology and safety is vital for these opportunities to be realised. The current international recognition of the Australian Consortium's contribution to the OECD WPMN nanosafety testing program has created the opportunity to build a permanent critical mass of nanosafety research capacity to support Australia's nanomanufacturing sector. Maintenance of this capacity through ensuring a critical mass of nanosafety research resources is vital for Australia's continued contribution to this international research effort.

Challenge: Developing a high-value manufacturing industry in photoelectronics, integrated electromaterial devices and functional surface nanomanufacturing processes.

Opportunity: Growing the next generation of safe and reliable high-value nanomanufacturing will require a comprehensive consideration of commercialisation opportunities and the translation of IP into economically viable companies.

With its recognised research strength, Australia is poised to develop a high-value manufacturing industry in photoelectronics, integrated electromaterial devices and functional surface nanomanufacturing processes. To grow Australia's next generation of high-value nanomanufacturing will require a comprehensive consideration of the approaches to commercialisation (develop SMEs or encourage the investment of international companies in Australia). It is critical for both these approaches that IP rights (primarily patents) are protected appropriately and that the manufacturing infrastructure is developed sufficiently to prevent the manufacturing and IP being readily taken overseas. Further, there is need to develop skilled senior management to facilitate the translation of IP into economically viable companies.

Challenge: Making use of the existing strong capabilities, knowledge and skills within Australia to develop new e-platforms.

Opportunity: Developing new techniques and reference materials to enhance Australia's characterisation capacity.

There is potential to develop new techniques and reference materials to enhance Australia's characterisation capacity, including modelling and metrology. This could take the form of new platforms through eMeasurement, eDatabase establishment and eManufacturing, by making use of the globally notable convergences of knowledge and skills within Australia—for example, Australia's strong capabilities in health, ICT, chemistry, materials, precision and nanosurface manufacturing, advanced mechanical manufacturing, safety and metrology.

Challenge: Building on existing strengths in the social sciences, ethics and regulation.

Opportunity: Providing a multidisciplinary education that draws together the knowledge of the science and social sciences, ethics and regulation to enable students to participate in global nanotechnology debates.

Australia also has the ability to build on its existing strengths within the social sciences, ethics and regulation. Social science scholars and the non-government community have already contributed to national, transnational and international debates on nanotechnologies, and there is a continuing and increasing opportunity for such stakeholders to provide an important external perspective to ethical and regulatory debates on nanoscience and nanotechnology in society.

For such Australian stakeholders to strengthen their role in these global debates, it will be important for those within the university sector to work together to build human and intellectual capacity within the undergraduate and graduate student body. Provision of a multidisciplinary education that draws together the knowledge of the science and the social sciences will provide such students with the skills to participate in the global debates.

Challenge: Participating with international bodies to have an impact on important societal issues.

Opportunity: Influencing the international nanotechnology agenda.

There are a number of international organisations and bodies where Australia can participate in driving forward key questions about stakeholder engagement, regulatory dimensions relating to nanomaterials, ethical and bioethical issues pertaining to the technology and IP regimes. These include, but are not limited to:

- the OECD's two nanotechnology-focused working groups
- the United Nations Educational, Scientific and Cultural Organization
- the World Commission on the Ethics of Scientific Knowledge and Technology
- the World Economic Forum's Global Agenda Council on Emerging Technologies
- the Food and Agriculture Organization, in partnership with the Codex Alimentarius Commission.

Ethical, legal and social concerns relating to nanotechnologies raised by the Australian community will be mirrored around the world. For Australia to have the greatest impact on addressing these societal issues, its research community must continue to strengthen its level of engagement and collaboration with multidisciplinary research centres addressing these concerns around the world. Research in these areas will help ensure that the translation of Australian developments in nanotechnology is informed by a clear understanding of the regulatory, social and ethical context and the possible impacts of the scaling up of the technology. Multidisciplinary research collaborations with centres around the world will assist Australia in thinking about these issues from varying perspectives, will enable new techniques for evaluation of impacts to be tested by leading researchers, and will improve the capacity of policymakers and members of the broader community to anticipate and respond to developing nanotechnologies.

Developing the discipline

Australia has a demonstrated ability to provide high-level input into leading nanomanufacturing technologies, international safety, regulation and ethics debates, and to effectively leverage these contributions to gain access to overseas research. To effectively translate research, and to develop new Australian industries, we need to support and sustain our technical infrastructure (Recommendation 1), support translational opportunities created by the sustained development of leading technologies (Recommendations 2, 5 and 6), and continue to effectively engage on safety, regulation and ethics (Recommendation 7) at a local (Recommendation 8) and international level (Recommendation 4).

Case study 10: National cooperation among researchers, government and industry can really work!

In 2007, the OECD called on the international scientific community to help produce urgently needed safety data for manufactured nanomaterials. The OECD Working Party on Manufactured Nanomaterials (WPMN) asked countries at short notice to volunteer to determine the physical and chemical properties and material characterisation of 13 representative manufactured nanomaterials and to investigate their potential human and environmental health impacts. National research consortia were formed across the globe. The Australian Office of Nanotechnology funded a workshop at CSIRO in October 2008, which led to the formation of a consortium of researchers, allowing Australia to participate in the OECD program as a co-sponsor for testing locally important nanomaterials—that is, zinc oxide, silver, and cerium dioxide nanoparticles.

Australian Consortium members include researchers from universities and government departments, and stakeholders from regulatory agencies and industry. CSIRO's Nanosafety Theme and the National Measurement Institute's Nanometrology Section jointly coordinate the consortium. Formal communication to the OECD WPMN is via Australia's chemical regulator, the National Industrial Chemicals Notification and Assessment Scheme. Two Australian companies, Micronisers Pty Ltd and Antaria Ltd, are important consortium members, and have also supplied test materials to the whole OECD program. Consortium workshops and international linkages, supported by the Australian Department of Innovation, Industry, Science and Research (now the Department of Innovation, Industry, Science, Research and Tertiary Education) were crucial for the program's success.

Phase 1 of the OECD program ended in June 2012. Researchers have uploaded their initial findings, having in many cases developed new methods to prepare and test nanoparticle samples to investigate their physical and chemical properties, their fate and transport in the environment, and their toxicities in mammalian and ecological systems. The Australian Consortium rose successfully to the OECD program's challenge. Its efforts have been applauded by the international scientific community, and some of its methodologies have been adopted internationally.

The consortium demonstrates that national collaboration among Australian researchers, government, and industry to address a major challenge can achieve results at the highest levels and provide critical support for the development of nanotechnology.

Figure 48: Characterising OECD test nanomaterials at the NMI. Left: measuring the aggregation of OECD test nanomaterials using a disc centrifuge in NMI's Nanometrology Section. Right: researchers characterising the physical chemical properties of OECD test nanomaterials using equipment in the NMI's Nanometrology Section. (Images courtesy of NMI)

Appendix A

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NANO TECH NOLOGY

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