



ANFF

Australian National Fabrication Facility

A Platform for Innovation

CASEBOOK 2014



ANFF – A platform for innovation



Rosie Hicks
Chief Executive Officer
Australian National Fabrication Facility

Innovation – the creation of new products and services – holds the key to a bright future for a healthy, prosperous Australia.

We face global challenges including, energy, healthy ageing and security, but these are also global opportunities. Solutions to many of these challenges lie at the nanoscale. We are seeing a convergence of disciplines. As physics, chemistry, biology, and engineering come together new possibilities are opening up enabling the development of new technologies, such as micro factories for the rapid development of high-value bio chemicals, and the production-scale fabrication of advanced materials such as graphene.

Indeed, nanomanufacturing has been described as a mega trend, with the potential impact to exceed that of the digital economy.

Australia is poised to take a significant part of the global nanotechnology market due to its research leadership in photovoltaics, quantum computing, infrared sensing, silicon-carbide memories, high-bandwidth photonics, and electro-active polymers.

For Australia to secure access to this market, it must undertake cutting-edge R&D and be able to translate the work into prototypes that form the basis

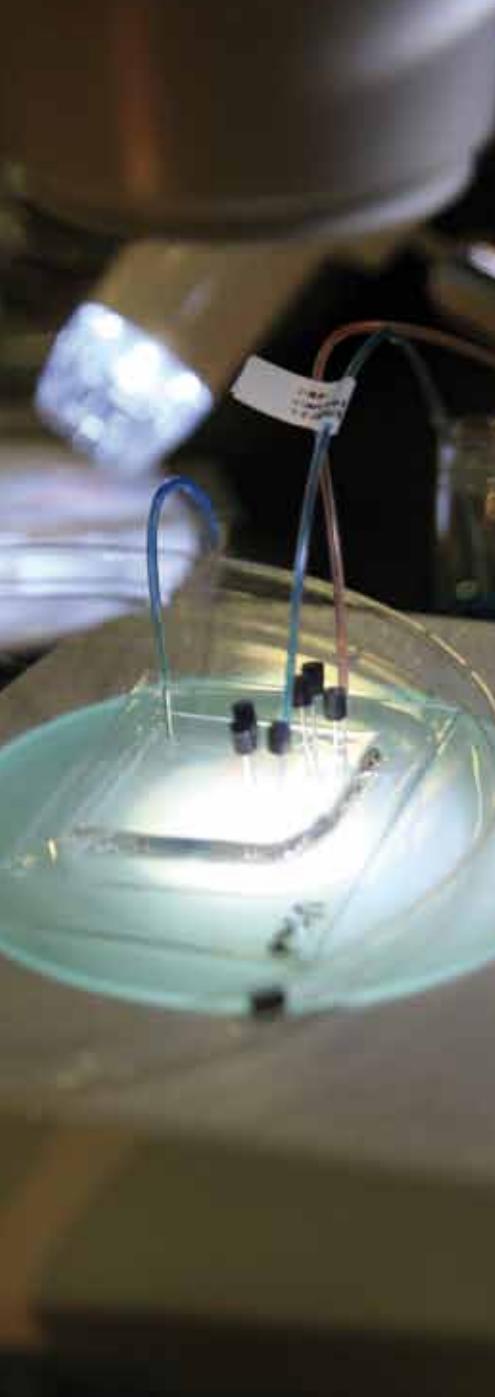
of new industries. We must build an innovation pipeline.

The Australian National Fabrication Facility, with its focus on the fabrication of new materials and devices, underpins the innovation pipeline. In 2013/14 nearly 2600 researchers from academia and industry undertook projects using ANFF facilities. Usage grew to 128,642 hours and 23% of these were for projects with industry partners.

Five of the Australian Research Council's Centres of Excellence are supported by access to ANFF capabilities.

National research infrastructure facilities provide rapid access to state-of-the-art capabilities. For early-career researchers this removes the need to establish a laboratory before generating high-impact research outcomes. For start-ups and established companies it provides a way to build and test new innovative designs before committing to a production line. For all researchers, ANFF provides a hub for collaboration. ANFF is a platform for innovation.

For now, please enjoy the latest case studies from ANFF – *A Platform for Innovation*.



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ANFF

Australian National Fabrication Facility Ltd

151 Wellington Road
Clayton VIC 3168

T: +61 3 9902 9619

E: info@anff.org.au

www.anff.org.au

Credits

Editor

Gareth Moorhead

Design

Peta Blackwell



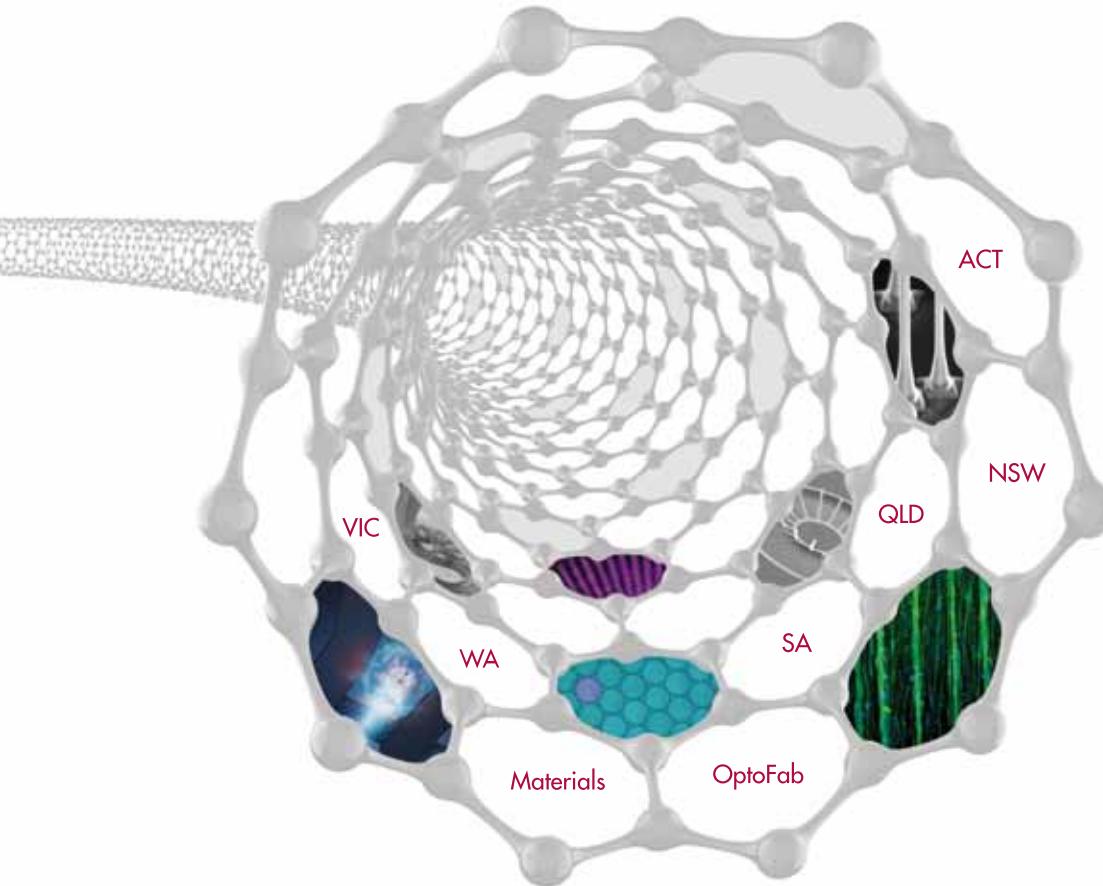
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Snapshot of ANFF

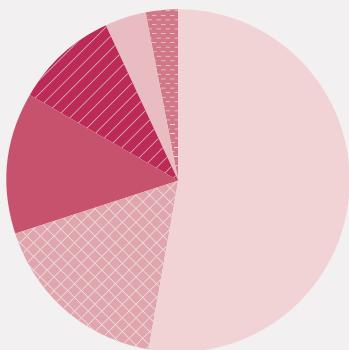
ANFF was established under the Australian Government's National Collaborative Research Infrastructure Strategy (NCRIS).

ANFF's mission is to provide micro and nano fabrication facilities for Australia's researchers.

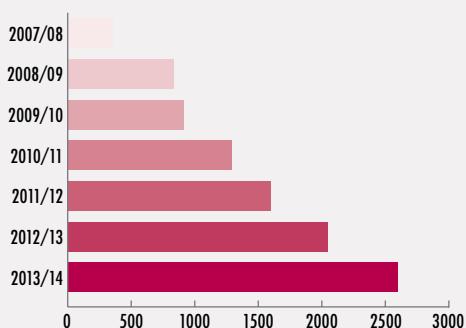
Over 500 facilities are located across 21 institutions around Australia in a national network of 8 nodes. Each node offers facilities and a critical mass of knowledge in their specialist fields.



User distribution



Number of Users



Supporting Australian researchers

The number of researchers accessing ANFF continues to grow, reaching over 2,500 users in 2013/14. The number of hours grew by 26% to 128,600 hours

Access to ANFF supports Australian industry. Industry projects, including collaborative ARC Linkage grants, accounted for 23% of the usage, which is up from 18% last year. The 2014 casebook includes examples from sectors as diverse as agriculture, construction and advanced manufacturing.

Access to ANFF supports research excellence. 542 journal papers were published in 2013. We report on projects from five ARC Centres of Excellence and international collaborations including testing of devices under microgravity with NASA.

The 2014 casebook truly demonstrates that ANFF is *a platform for innovation*.

▼ Demonstration of optical fibre-based sensors at ANFF booth, ICONN 2014



MAXIMISING

food security and agricultural productivity

Australian grain remains one of our most important exports. Not only does it constitute 24% of all Australian agricultural exports <http://www.grdc.com.au/About-Us/Our-Grains-Industry>, it materially contributes to food security around the world. But in a world of increasingly variable climate and severe stress on water supplies, maintaining and increasing productivity is a huge challenge. It is a challenge being met increasingly with science and technology – by doing things smarter, using fewer resources to achieve greater outcomes.

One way that science is contributing is through infra-red spectroscopy, a new tool in the farmer's kit that can:

- measure soil moisture and nutrients;
- measure grain protein content, so that premiums can be maximised; and
- identify stress in irrigated crops to maximise the productivity of water used.

Until now, IR spectroscopy has been mainly a research tool, too expensive, too fragile, too complex, too cumbersome, for practical use in day to day farming operations. But the Grain Research and Development

Corporation, partnering with the University of Western Australia, is changing all that. The vision of this partnership is for highly portable, rugged, low cost, hand-held devices that will give broad-acre farming new perspectives and new “eyes” with which to see critical features in the crops and landscapes not previously visible. When combining such an instrument with experience and with intelligent software farmers will be able to:

- control watering so that wastage is greatly reduced and crop growth optimised;
- apply fertiliser optimally, reducing costs and environmental impacts such as algal blooms in waterways; and
- maximise the value through better managing yield and quality.

Microelectromechanical Systems (MEMS) are micro-scale machines that produce micro-scale motion in response to an electrical signal. MEMS sensors are becoming increasingly popular. Common MEMS devices include acceleration and pressure sensors in mobile phones, giving the phone a sense of direction and location.



So what has nanofabrication got to do with grain farming and export profits? The novel spectrometer technology is built using nanofabrication, the same processes and technologies as computer chip manufacture. Starting with a silicon wafer, the device structures are patterned on to the surface using photolithography. The structural and optical layers are created using plasma enhanced chemical vapour deposition (PECVD) techniques as well as electron-beam deposition. The final result is a small chip, a few millimetres square, in a package with an optical window to admit light, including infra-red light.

The critical technology that is making this exciting new idea possible is a micro-scale spectrometer based



“This technology has potential to be used through the entire agriculture value chain.”

John Thorne, commercialisation consultant to the Grains Research and Development Corporation

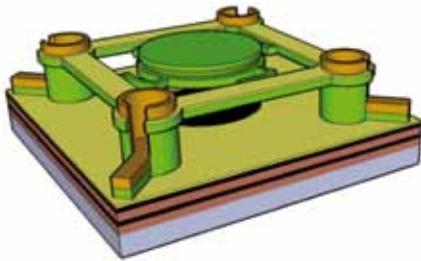
on microelectromechanical systems (MEMS) technologies. The MEMS spectrometer was developed by the Microelectronics Research Group of The University of Western Australia, using the facilities of ANFF-WA. Originally motivated by the needs in defence for better target identification, the technology was awarded in the 2008 inaugural DSTO Eureka Prize for Outstanding Science in support of Defence or National Security. Although still an important application, the promise of helping Australia and the world improve agricultural productivity, food security and climate adaptation has inspired the GRDC to invest \$2M into this work so far.

Winthrop Professors Lorenzo Faraone and John Dell initiated this key research area over 15 years ago. For the last 5 years, the partnership has been continuing under the leadership of Professor Dilusha Silva.

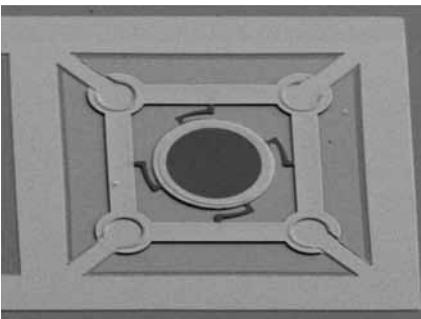
The technology is presently in the early stages of commercialisation,



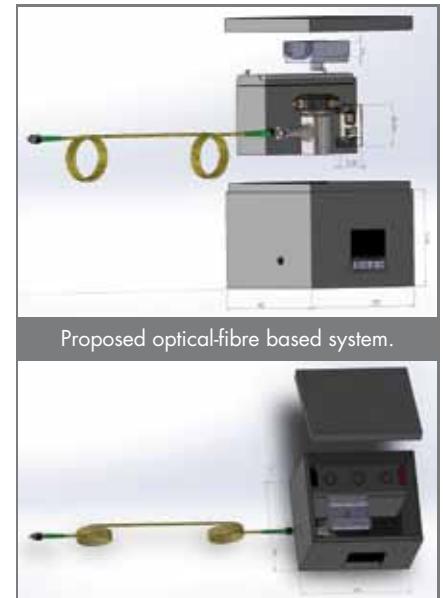
▲ Device in a package with window.



▲ MEMS spectrometer 3D view (vertical scale heavily expanded).



▲ MEMS spectrometer micrograph.



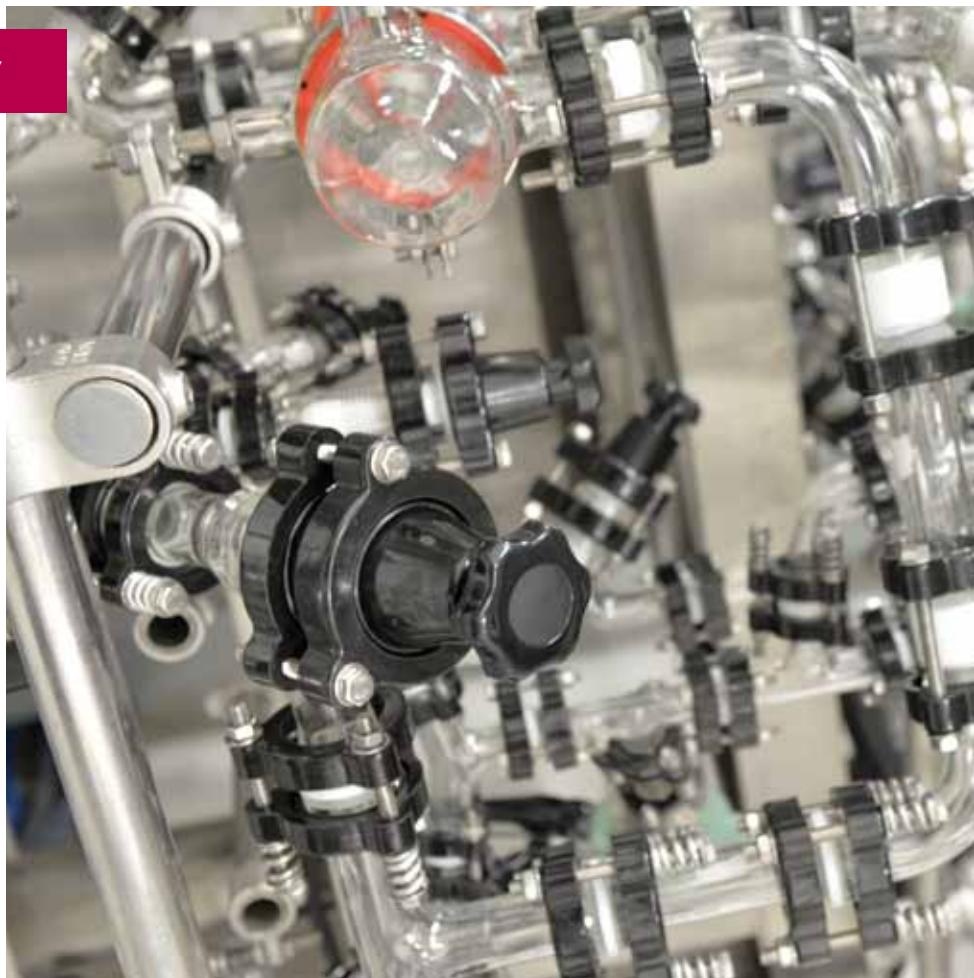
Proposed optical-fibre based system.

and commercialisation options and partnerships are being actively explored. A number of sensor systems for farm applications are being developed at the University of South Australia using this MEMS spectrometer as the core measurement engine.

Graphene for industry

ANFF is delivering on a key NCRIS principle of maximising contributions of Australian R&D to national economic development through providing world-class infrastructure and expertise with low access barriers to new technology start-ups.

NanoCarbon Pty Ltd, a new NSW based start-up company, is a great example. NanoCarbon has recently announced that it has licensed a novel process for the manufacture of graphene from the University of Wollongong which, will provide graphene of sufficient quality in the quantities required to support industrial application. The patented process for the production of graphene was based upon a 2008 paper in the journal *Nature Nanotechnology* that has been cited more than 3,000 times. The new process enables the production of industrial quantities of surfactant-free graphene dispersions. Graphene consists of thin sheets of carbon that are extracted from raw graphite. It has extraordinary mechanical and electrical properties; being stronger than diamond, more



▲ The new 30 l pilot-scale plant for graphene platelet synthesis at ANFF Materials, located on the University of Wollongong's Innovation Campus.

conductive than copper and more flexible than rubber and has the potential to provide improved mechanical, electrical, thermal, energy and barrier properties to a number of existing engineered composite

materials used in advanced manufacturing. By supporting world-class research from the ARC Centre of Excellence for Electromaterials Science (ACES) with the commercialisation expertise afforded by NanoCarbon,



the ANFF Materials Node will assist in the translation of research from the bench to the factory. Key ANFF investments in a pilot-scale plant for the scalable production of graphene in liquid solutions will lead to innovative applications for graphene that can

be ink-jet printed, spray coated, processed in roll-to-roll coating systems, blended into composites, and even 3D printed.

NanoCarbon CEO Chris Gilbey said: *"We believe that the time is fast approaching when graphene will be integrated into numerous manufacturing processes. We have great respect for the quality of the people and the relevance of the research undertaken by ACES and ANFF and anticipate working very closely with the team over the foreseeable future to achieve great commercial outcomes."*

The UOW IP license to NanoCarbon will enable ongoing work with ACES and the ANFF Materials Node to explore new opportunities for application of graphene and, importantly, opportunities for incorporating graphene in existing manufacturing lines and processes. This development exemplifies a successful collaborative effort between the university researchers, the ANFF critical mass investment in pilot-scale equipment and the industrial engagement that has created a core competency in graphene materials and methods particularly relevant to real-world manufacturing.

Nature Nanotechnology 3, 101-105 (2008); doi:10.1038/nnano.2007.451]

NanoCarbon

ARC Centre of Excellence for
**Electromaterials
Science**





Global Innovation Award

for Graphene-on-Silicon Carbide MEMS technology

Dr Francesca Iacopi and her team from Griffith University's Queensland Micro- and Nanotechnology Centre (QMNC) have joined stellar company in Washington DC as 2014 winners of a TechConnect World Global Innovation Award for their discovery of new processes and material systems supporting the

practical fabrication of graphene microstructures on silicon carbide (SiC). These global awards are presented to the top technologies ranked for the likely positive impact on their industry sectors, and are designed to assist in accelerating international exposure to potential commercialisation partners.

Graphene has extraordinary material properties for electronic and electro-mechanical micro-devices; however, most graphene synthesis methods are not compatible with the manufacture of complex devices. The new process developed by the Griffith team, which synthesises graphene from SiC on Si wafers, is an exciting breakthrough

◀ Griffith University researchers working on the next generation of graphene silicon wafers. From left to right: Mohsin Ahmed, Neeraj Mishra and Ben Cunning.

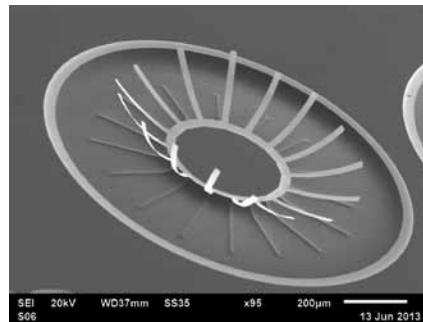
because it provides opportunities for realistic mass production.

At high temperatures we know that Si atoms can be evaporated from the top surface of crystalline SiC wafers, leaving behind carbon in a graphitic form through a process called sublimation. Dr Iacopi's team has instead used a lower temperature, catalytic approach to obtain graphene from epitaxial SiC films on Si wafers, thus enabling a substantially cheaper way to obtain high-quality patterned graphene at the wafer-level. Industry standard Si wafers are used in the place of extremely expensive SiC wafers. Furthermore, the SiC on Si can easily be machined through conventional micromachining processes.

ANFF-Queensland commissioned an Australian-first SiC epitaxial reactor. The MkII, a custom-designed and built system was jointly developed with global volume semiconductor industry equipment manufacturer SPTS Technologies (www.spts.com). This new system can handle industrial scale 300 mm wafers in batch quantities to potentially deliver self-aligned high quality graphene, in a transfer-free, low-temperature process,

directly onto complex patterns of SiC over large areas.

The combination of a crystalline SiC core with a surface graphene coating is ideal for sensing devices. The already exceptional mechanical properties of SiC (which is the second hardest material after diamond) can be further enhanced by graphene,



▲ Graphene structure on a SiC on Si wafer produced by the innovative process developed at Griffith University using the ANFF-Q SiC epitaxial reactor. This structure is an example of patterns that are useful in sensor and electronic design.

resulting in extraordinary fracture strength. The applications for this breakthrough are numerous and already the team have produced SiC micro-resonators by replacing the traditional metal layers with a molecule-thick, transparent, highly conductive graphene layer. The graphene, less than a nanometre thick, is as conductive as gold. Additionally, graphene offers a wealth

of surface chemistry approaches for targeting specific ions and molecules. The research targets devices such as extraordinarily sensitive and versatile chemical micro-sensors that have applications ranging from health to environmental monitoring.

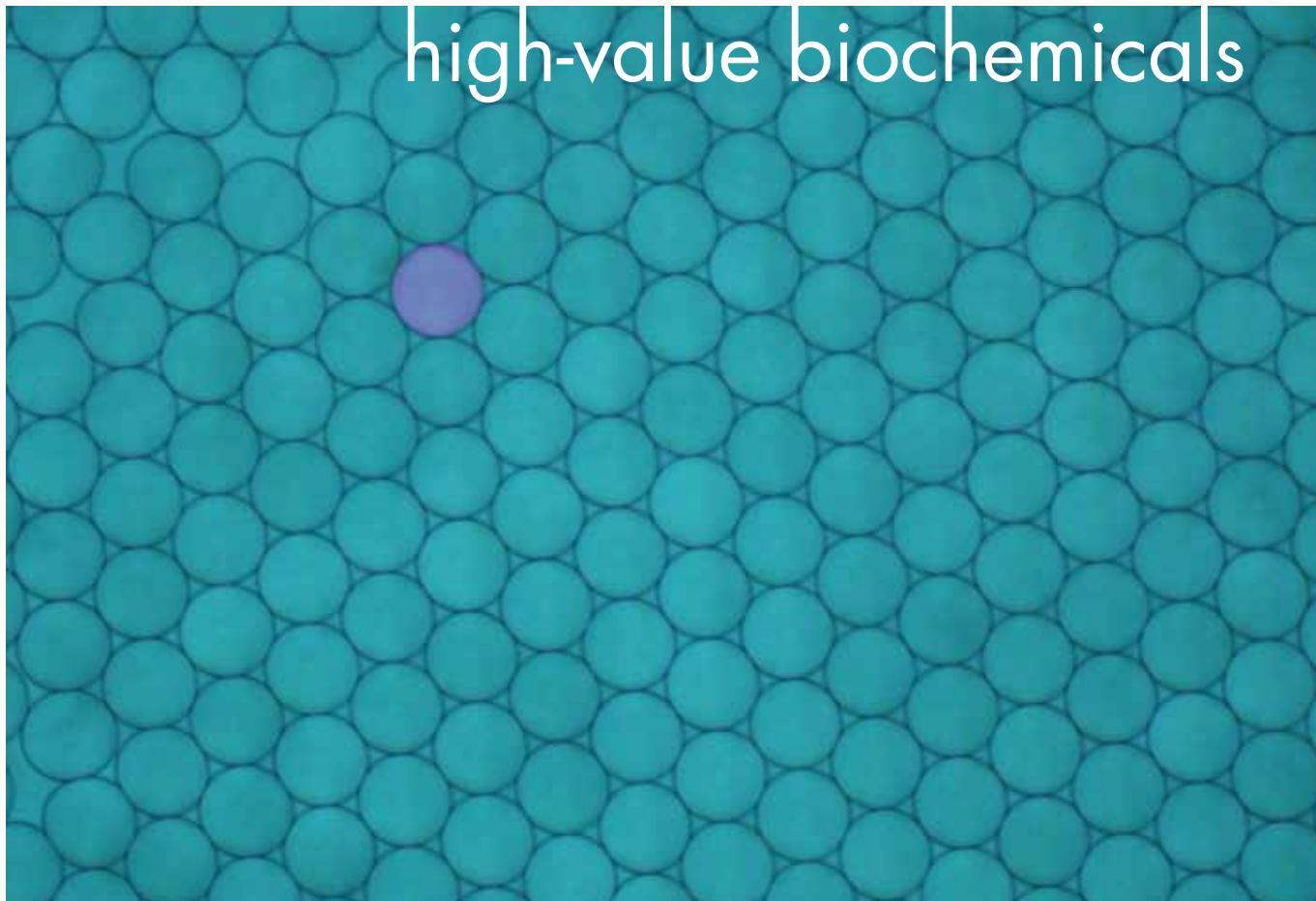
Dr Iacopi, an ARC Future Fellow, believes that:

"In the next decade silicon carbide, and other wide band gap materials, will unlock technology behind a vast range of energy-efficient smart devices. These devices will increase the efficiency of photovoltaic panels, hybrid/electric cars, high-power industrial drives, motor drives, smart grids and power utilities, improving energy efficiency and lessening our carbon footprint. There's also potential for accelerometers and gyroscopes for aerospace and automotive applications, as well as in the harsh environments of mining and deep sea exploration."

Reference: <http://www.techconnectworld.com/>



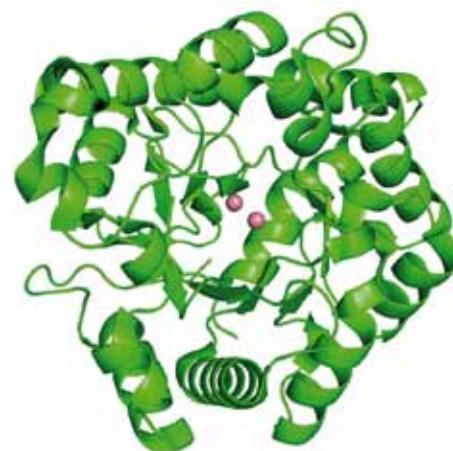
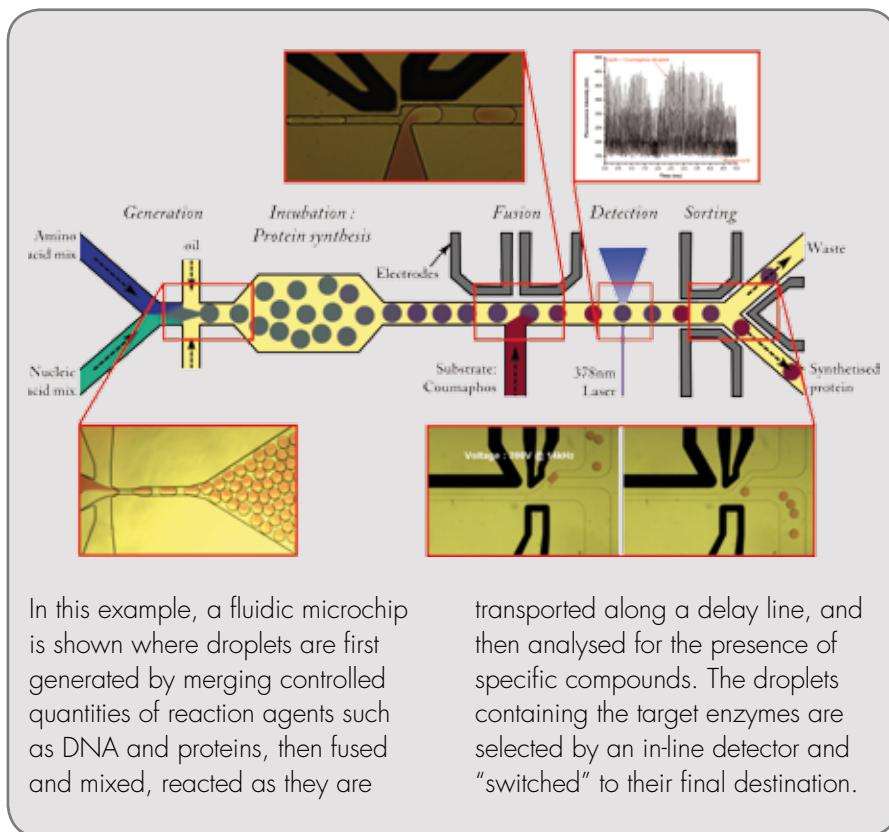
“Micro-factories” for rapid development of high-value biochemicals



Internationally the race is on to discover new enzymes and other biomolecules with valuable properties such as pharmaceuticals.

Vast libraries of candidate genes and enzyme variant combinations need to be produced, screened and selected against many different potential targets. Discovery might require millions, or even billions, of reaction combinations to make a valuable strike.

CSIRO is working at the Melbourne Centre for Nanofabrication, ANFF's headquarters and flagship facility in the manufacturing heartland of Victoria, to create a new microchip technology to give Australian industry tools for success in this race.



▲ OpdA – an enzyme produced using the CSIRO microchip technology

OpdA is an enzyme that degrades organophosphates, with applications such as the bioremediation of pesticides in the environment.

droplets, inserting exactly measured tiny amounts of the specific chemical and biological reagents, mixing and incubating with real-time control of reaction times and conditions, performing in-situ analysis using a variety of micro-fabricated optical and electronic assays, and transporting selected droplets at high speed to final destinations based on the real-time analysis results. All within a plastic microchip a few centimeters long that can be mass produced in the ANFF MCN laboratories.

Just as electronic microchips revolutionised our economy, fluidic microchips are set to transform a whole range of industries, from "tricorders" that put a pathology laboratory in a doctor's hand, to micro-factories to produce the next generation of pharmaceuticals or industrial catalysts.

Led by Dr Yonggang Zhu, a Senior Technology Fellow at MCN, the CSIRO team is building fluidic

microchips that create "micro-reactors" out of tiny droplets of reaction components surrounded by oils that contain and transport these chemical and biological processes.

These tiny droplets are a few microns across, containing only picolitres of fluid that can mimic the physical and chemical conditions inside natural biological cells for controlled reactions. They are created by sequentially merging water in oil



Source: NASA

ANFF IN SPACE

Or so far, at least, in microgravity

The space industry is growing rapidly in Australia as we seek to transition our economy towards new high-value manufacturing. Central to success in this area are products and technologies able to perform in the space environment of zero gravity.

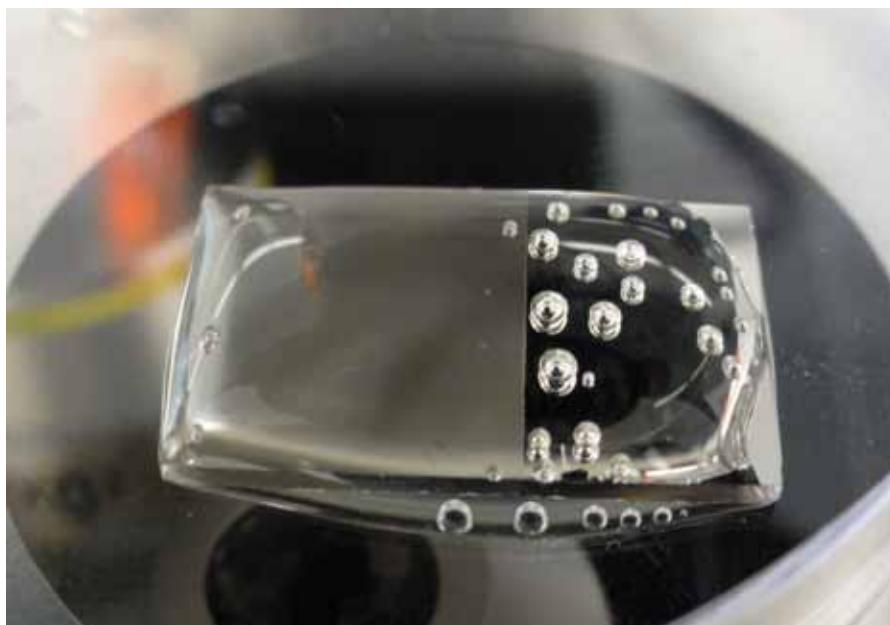
The University of South Australia, the University of Puerto Rico and NASA are studying new fuel cell designs for zero gravity. Their goal is to develop a new fuel cell that can perform the dual roles of generating electricity

and decomposing or recycling waste products. Ammonia fuel cells offer the chance to recover energy from human waste, but their performance can significantly decrease in space where the reduced gravity affects removal of the gaseous product, nitrogen, from the electrodes.

- ▶ Dr Craig Priest, Senior Research Fellow at the University of South Australia in micro-gravity in NASA's "Weightless Wonder" research aircraft. Dr Priest was on board to test new Australian-developed microstructured electrodes for use in fuel-cell technologies.



Professor Carlos Cabrera has studied ammonia oxidation in microgravity (near zero G) and reported a 65% lower current density compared with experiments conducted under normal conditions (1 G). Now, Professor Cabrera and Dr Priest are working to overcome these limitations for applications in orbit and on earth. Microstructured electrodes, fabricated at the laboratories of ANFF-SA, are designed to prevent electrode fouling by gas bubbles. These structures employ capillarity, rather than buoyancy, to release bubbles from the electrode surface. The rapid and spontaneous removal of bubbles should refresh the electrode surface for the electrochemistry of the fuel cell to continue unhindered. Structured electrodes were tested in reduced gravity for the first time in July 2014 onboard NASA's "Weightless Wonder" – a C-9 aircraft based out of NASA's Ellington Airport facility, Houston, and capable of cycling from 1.8 G to microgravity using parabolic flight trajectories. Each parabola gives the research team approximately 20 s of microgravity to conduct an experiment, which is repeated many times in a single flight. The experiments ran smoothly and are expected to provide new insight into the role and significance of buoyancy in the operation of electrochemical cells.

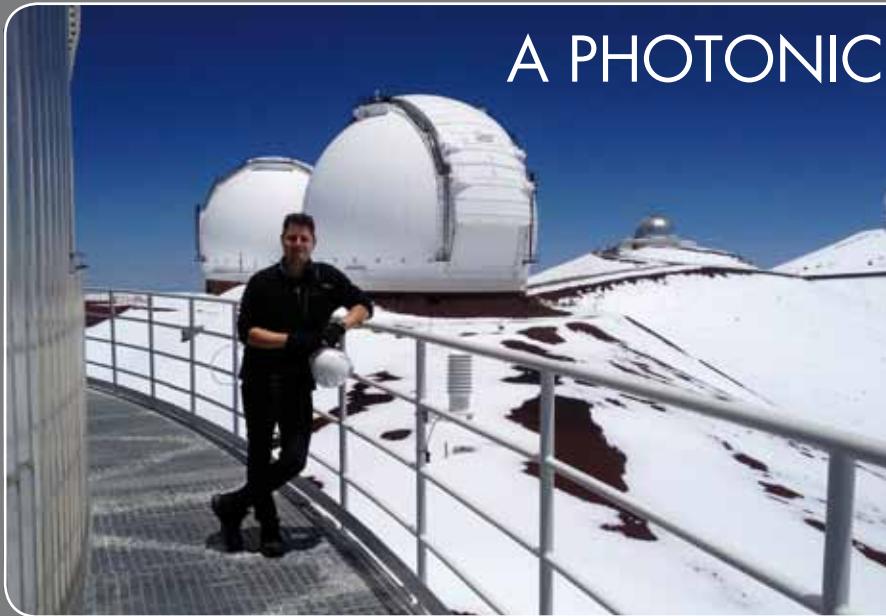


▲ Platinum electrode with structured (left) and flat (right) regions.

▼ Participants in the NASA Reduced Gravity Flight Program (Source: NASA).



A PHOTONIC PLATFORM for next



▲ Dr Cvetojevic at the Subaru Telescope, Mauna Kea Hawaii.

Innovations in terrestrial optical astronomy continue to push the boundaries of instrument complexity, sensitivity and scale.

As ground-based optical telescopes grow into the realm of grand engineering challenges (such as the effective 22 metre diameter collecting mirrors of the Giant Magellan Telescope, scheduled for completion in 2020 in Chile) the miniaturisation of the downstream optics, such as spectrographs and cameras, is mandatory to maximise their potential.

This is because surveys conducted with the next generation of telescopes will be able to collect data from thousands of celestial objects simultaneously. To squeeze into the limited space, integrated photonic technologies that scale down the detection hardware and even improve its resolution must be used.

Australia has long been a leader in photonic technologies. Now, using the capabilities of the ANFF, Australian astronomers are able to design, fabricate and test similar technologies for the next generation of astronomical instruments. Especially important for the

development of all these instruments is the production of precision laser-cut aperture masks and optical assembly and packaging facilities by the OptoFab Node of ANFF. OptoFab is also well placed to act as the foundry for future photonic chips that transfer from R&D and go into manufacture for large scale instruments.

Professor Peter Tuthill leads a team of Australia's best and brightest that includes astronomers from the Sydney Institute of Astronomy and photonics scientists from the ARC Centre of Excellence for Ultrahigh bandwidth Devices for Optical Systems (CUDOS), and the Australian Astronomical Observatory (AAO). The team is engaged in design, fabrication and performing "on-sky" demonstrations of creatively named instruments such as VAMPIRES and Dragonfly. Hybrid integration of existing and frontier optoelectronic technologies is also being used to help miniaturise the often bulky and unwieldy optical trains of conventional telescope facilities.

The VAMPIRES instrument (Visible Aperture-Masking Polarimetric Interferometer for Resolving Exoplanetary Signatures) is an exciting new tool being developed and demonstrated by a team from

generation optical astronomy

the University of Sydney. It's the core research project of PhD student Barnaby Norris. VAMPIRES has recently been demonstrated "on-sky" at the 8.2 metre Subaru Telescope (National Astronomical Observatory of Japan) on Mauna Kea, Hawaii,

with excellent results that

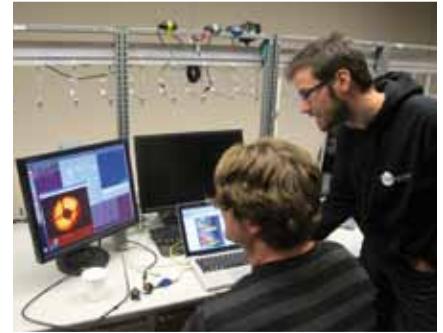
will contribute to our understanding of the formation of stars and their planetary families.

VAMPIRES is an aperture

masking-interferometer: it fragments the pupil plane of the telescope and interferes the segments, revealing the signatures of circumstellar gas and dust responsible for forming new solar systems, which would otherwise be invisible to conventional imaging.

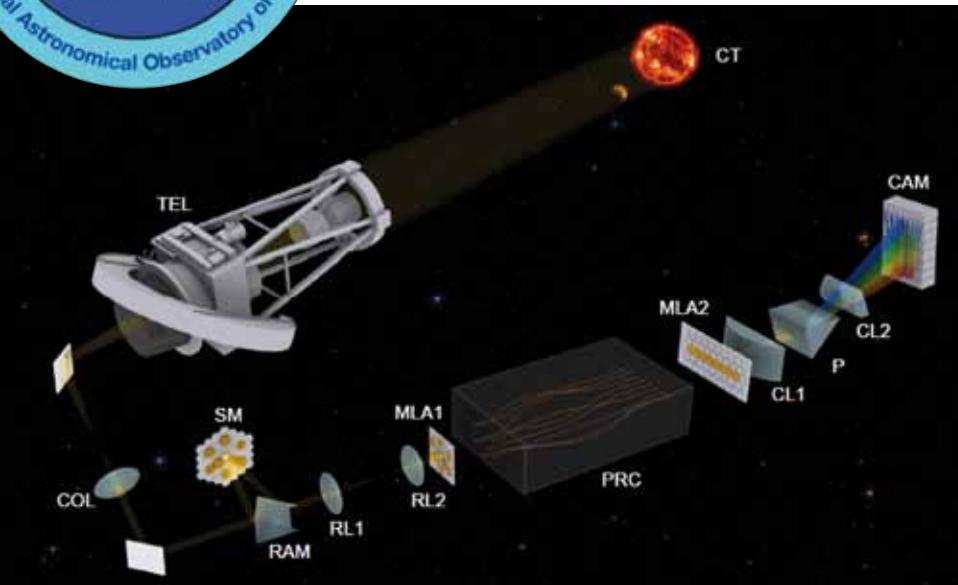
The Dragonfly instrument is also an interferometric instrument, but at its core lies a 3D photonic chip. Dragonfly has been demonstrated "on-sky" at the Anglo Australian Telescope at Siding Spring NSW.

▼ Schematic of the Dragonfly instrument, which features a 3D photonic chip.



▲ Barnaby Norris in the Subaru telescope control room.

Plans to deploy it are in an advanced stage. Researchers have brought together many photonic technologies, from femtosecond direct-write waveguides to microlens arrays and adaptive optics to make the Dragonfly instrument a reality. Dragonfly will revolutionise our capabilities in detecting extra-solar planets and binary star systems that cannot be resolved by conventional telescope technologies.



SUSTAINABLE BUILDING MATERIALS FOR A GLOBAL MARKET



▲ Rifle Range Footbridge at Bargara, Bundaberg, Queensland, built with new pultrusions incorporating resins.

ANFF-Q enables Queensland SME to create new sustainable building materials for a world market by providing easy access to world-class R&D infrastructure

Science is risky: maintaining a critical mass of internationally competitive scientific equipment requires major

capital investment. And without highly specialised staff to run the facility, the potential is never unlocked. Such

investment is the province of large universities, research agencies and multi-national companies.

ANFF addresses this challenge by bringing the research equipment, and more importantly, the skilled scientific and technical staff to operate it with

excellence – out from the ivory towers and into the real world of small and medium Australian companies. By leveraging this sizable pool of infrastructure and expertise, we can open new avenues of development to Australian industry.

At Wagners Composite Fibre Technologies, a Queensland company with a global footprint, the in-house R&D staff have been able to access the fantastic resources of ANFF-Queensland, effectively leveraging their own expertise and direct market knowledge by adding the capabilities of a world-class research laboratory, allowing them to embark on an ambitious new product development strategy to address major emerging global markets for sustainable building materials.

Traditionally the production of composite fibre technologies has been done from the wealth of empirical knowledge that dates back many decades. Wagners CFT is internationally recognised as a leader in the production and application of composite fibre technology. In 2011, it was recognised by the Queensland Premier's ClimateSmart Sustainability Award for the development of 'Earth Friendly Cement', a new geo-polymer based low-emissions alternative to Portland cement that also re-uses industrial wastes such as blast furnace slag and fly-ash.

“The wide range of equipment and expertise at ANFF has enabled us to really understand the fundamental chemistry and morphology of our products.”

Deborah S Ward, CFT Materials and Polymer Technologist, Wagners CFT

Composite fibre technology involves a fibre or woven material being impregnated with a polymer resin to produce, after curing, a reinforced polymeric material with substantial advantages over traditional materials.

Primarily used for bridges, boardwalks and electrical cross arms, Wagners CFT products are a fraction of the

weight of traditional building materials and extremely durable – up to six times stronger than steel or concrete.

Wagners is now looking towards the production of the next generation of materials. It's using the facilities available at ANFF-Q to inform the development pathway. By studying the resin mixes that are currently used and how they are affected by different parameters, a realistic landscape of the properties can be generated. With this valuable knowledge, especially at the microscale, Wagners will further enhance its current products and maintain or extend their competitiveness internationally for high-tech green building products.

www.wagnerscft.com.au.



▲ Differential scanning calorimeter at ANFF-Q.

Tiny lasers lighten up future electronics

Researchers at the Australian National University recently caused great excitement by the publication of the first room-temperature GaAs nanowire lasers, with an article and interview in the prestigious journal *Nature Photonics*.

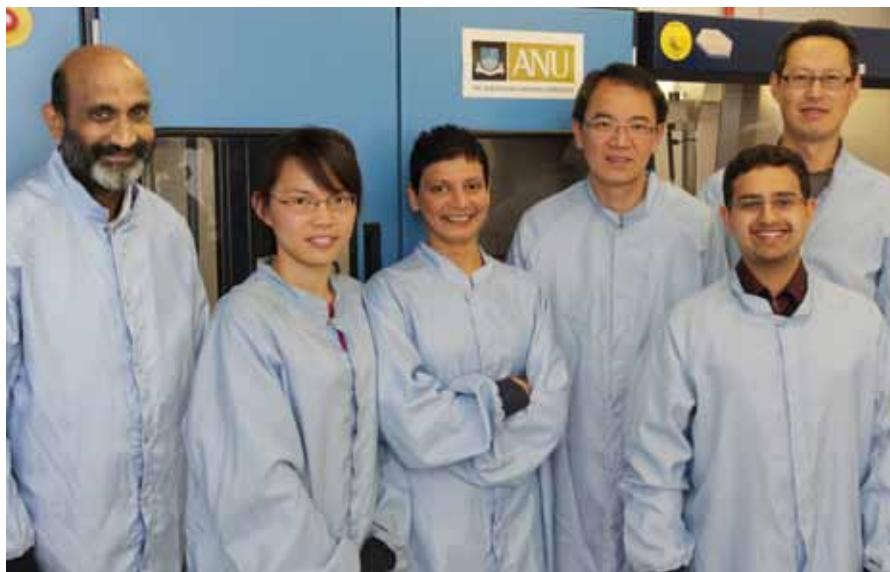
The significance of this groundbreaking work lies in the achievement of a practical, manufacturable technology for nano-scale devices operating in the near infra-red. Gallium arsenide (GaAs) is already a technologically important material, widely used for near infra-red opto-electronic devices. However, nanoscale GaAs structures are not suitable for optoelectronic devices because of large surface area-to-volume ratio, which deteriorates their optical/electronic characteristics. The group, led by ARC Laureate Fellow Professor Chennupati Jagadish, has demonstrated an approach that makes GaAs nanostructures suitable for optoelectronic applications, leading to the fabrication of GaAs nanowire lasers.

Working at the ACT node of the ANFF, the group has achieved the world first GaAs nanowire laser

operating at room temperature by designing and fabricating GaAs nanowires with very high material quality. The nanowires are 'grown' using Metal Organic Chemical Vapour Deposition. This is the technique preferred by the semiconductor industry due to its scalability. Billions of nanowires are grown in one step. The group used gold nanoparticles as catalysts to grow GaAs as nanowires. The group has perfected the art of growing uniform, high quality

nanowires. The surface effects are mitigated by in-situ growth of a co-axial AlGaAs passivation layer around the GaAs nanowire. The uniformity and surface passivation are absolutely critical for device applications.

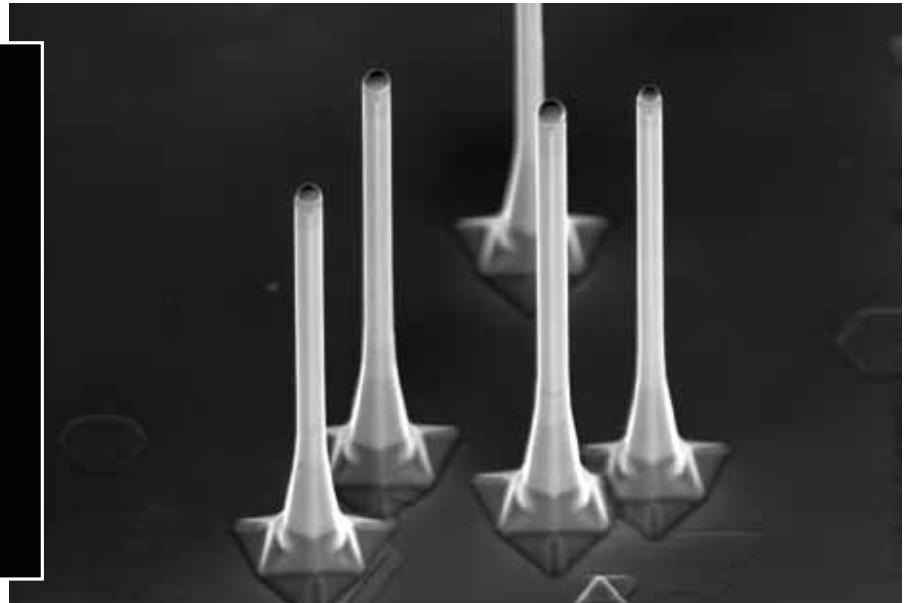
Nanowires act as excellent optical waveguides and confine light along their axis. The ends of the nanowire act as tiny mirrors and form a cavity, eliminating the need for specialised processing steps to form a cavity or coupling to an external cavity. This reduces the footprint of the devices allowing for high density device integration. The group carefully controlled the shape of the nanowire cavity to maximise the



▲ From left to right, Prof. Chennupati Jagadish, Ms Nian Jiang, Dr. Sudha Mokkalapati, Prof. Hark Hoe Tan, Mr. Dhruv Saxena and Dr. Qiang Gao in front of the MOCVD reactor.



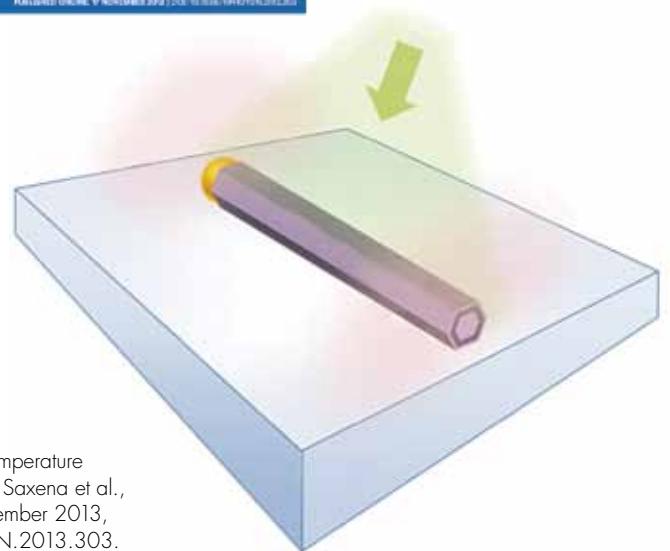
▲ GaAs nanowire laser



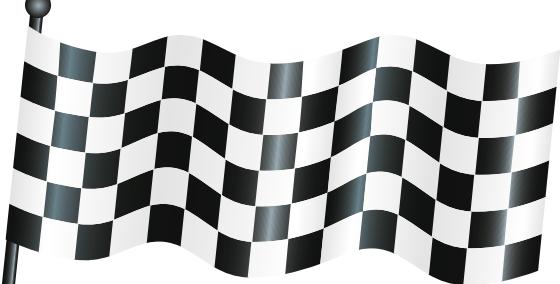
▲ State-of-the art GaAs nanowires grown using MOCVD

optical confinement that led to lasers operating at low powers. The shape of the nanowires also allows for easy coupling of laser light into optical fibres. This opens up opportunities to build smaller lasers and other light emitters that can be integrated into micro-chips and micro-systems.

Now that room temperature operation of nanoscale GaAs devices has been demonstrated, the group hopes that miniaturisation of GaAs-based near infra-red optoelectronic devices will be fast tracked. This is a significant milestone that may lead to faster and more energy efficient data communication systems in the near future.



Optically pumped room-temperature GaAs nanowire lasers, D. Saxena et al., Nature Photonics 17 November 2013, DOI: 10.1038/NPHOTON.2013.303.



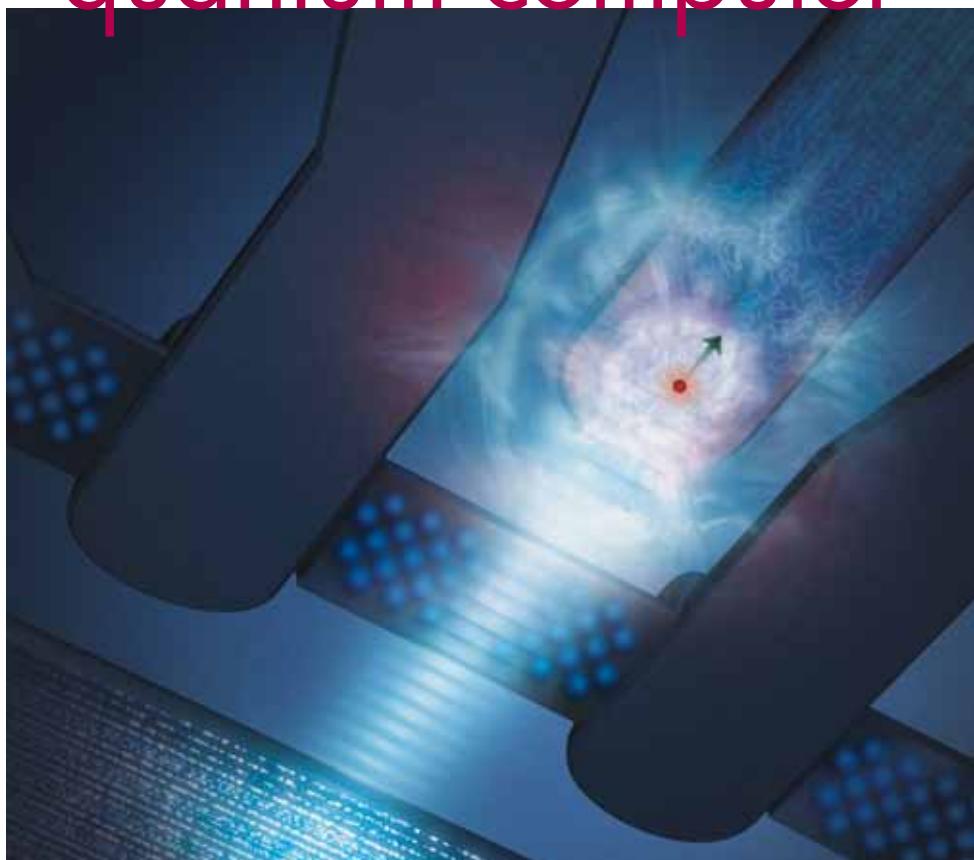
The race to build a quantum computer

Since its inception in 2006, ANFF has been instrumental in creating the research environment that has led to Australia's leadership in the global race to develop quantum computers that are capable of solving problems beyond even the most powerful supercomputers available today.

The power of modern computers has increased exponentially in the last half century. In spite of this, there are still important computational challenges that remain intractable. For example, complex bio-molecular processes implicated in major diseases, or potential new manufacturing processes cannot yet be tackled computationally.

The solution to this problem is widely believed to be the *quantum computer* – a computer intrinsically built upon the laws quantum mechanics. Such a quantum computer would revolutionise medicine and drug design by allowing detailed simulations of important complex biochemical processes and the targeted design or discovery of new molecules to manipulate those processes.

These important applications have made quantum information research a priority for countries such as the USA,



▲ Artist's impression of a single atom quantum bit device, containing a single phosphorus atom (red sphere surrounded by electron cloud, with arrow showing the spin direction) coupled to a silicon single-electron transistor. A burst of microwaves (blue) is used to 'write' information on the electron spin.

UK, Singapore and the European Union. In 2000, the Australian government and the Australian Research Council (ARC) recognised

the great potential of this research, and now two ARC Centres of Excellence compete in this race: the Centre for Engineered Quantum Systems

(EQuS) and the Centre for Quantum Computation and Communication Technologies (CQC2T). In order to be competitive in such a hot international race, world-class tools are essential – tools made available in the cleanrooms of the ANFF.

EQuS is a multi-institutional collaboration working to study and exploit some of the strangest features of quantum physics. At the University of Sydney, Professor David Reilly and his group in collaboration with Harvard, the Neils Bohr Institute in Copenhagen, TU Delft and the University of Tokyo have been creating *quantum bits* (“qubits”) in *gallium arsenide*, a semiconductor material, at the ANFF-NSW facility. Recently Professor Reilly has demonstrated a new way to read the state of a qubit that may prove technologically possible to scale up to realise a large-scale quantum computer. This ground-breaking work was published in *Physical Review Letters* in 2013.

CQC2T takes an alternative approach, focusing on another semiconductor: *silicon-based quantum computing*. In the four years since launching, CQC2T has achieved a number of breakthroughs that have gained international attention and led to numerous awards and recognition. In 2010, teams lead by Professor Andrew Dzurak and Associate



▲ Andrew Morello with Prime Minister Tony Abbott after receiving the Malcolm McIntosh Prize for Physical Scientist of the Year in 2013.

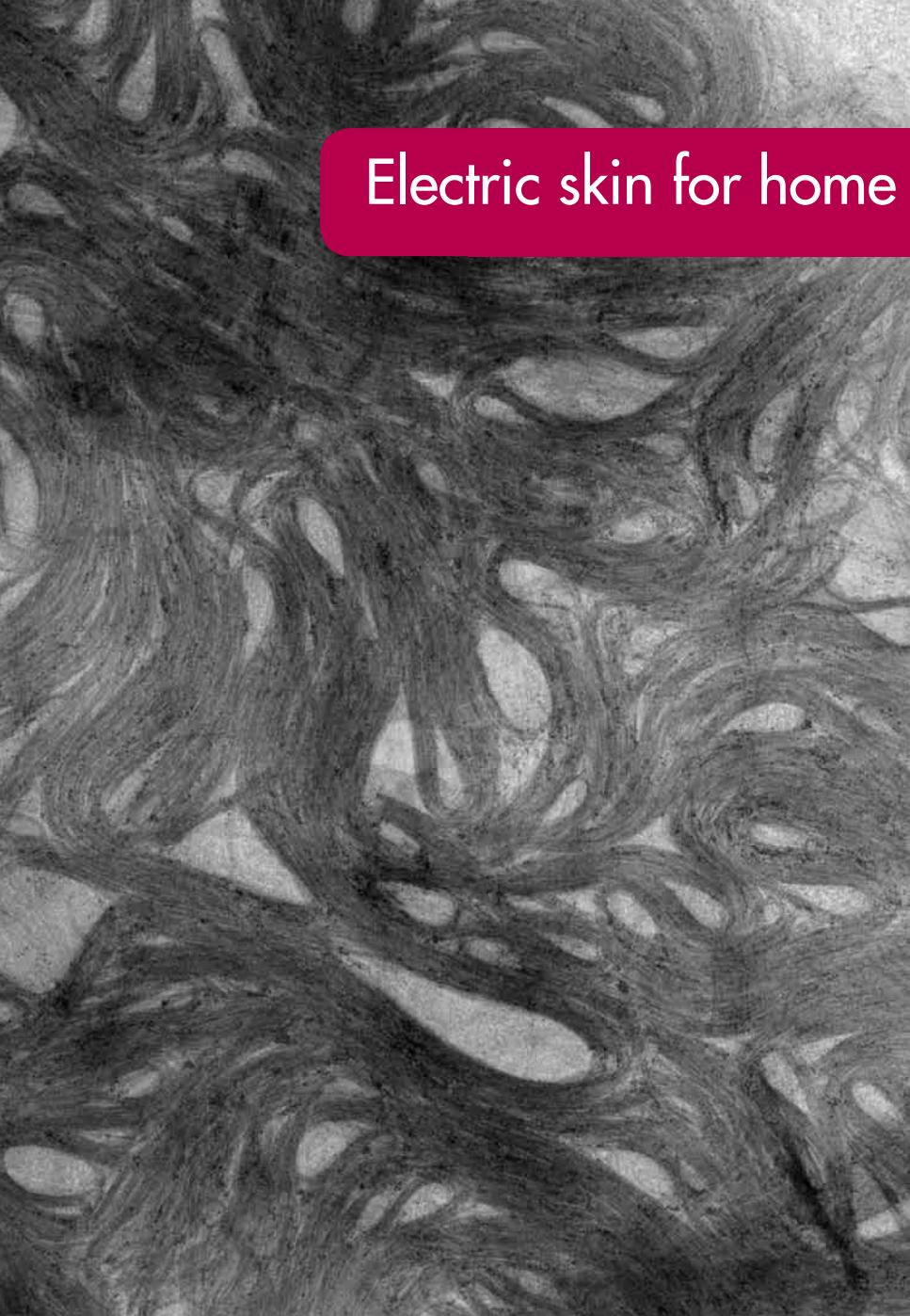
Professor Andrea Morello at UNSW combined to demonstrate a “single electron reader”, a device that has the astounding ability to read the spin, or magnetic orientation, of a single electron in silicon. This result was published in the journal *Nature* in 2010 and led to the award of the 2011 UNSW Eureka Prize for Scientific Research to Dzurak and Morello. The same researchers went one step further in 2012 and demonstrated the world’s first single atom quantum bit (or *qubit*) – the fundamental component of a future silicon quantum computer. A year later they used the spin of a phosphorus atom nucleus to encode a nuclear spin qubit, using similar technologies. The electron qubit and the nuclear qubit

results were each published in *Nature* in 2012 and 2013, respectively, and for this work Andrew Dzurak received the NSW Science and Engineering Prize in 2012, while Andrea Morello received the Malcolm McIntosh for Physical Scientist of the Year in 2013.

In the race to find new technologies it’s important to pursue many possible routes to success. Also at CQC2T, Professor Michelle Simmons leads a team that is able to place individual atoms using scanning probes to create a remarkable range of nano-electronic devices including a single atom transistor. This single atom transistor caught international attention in 2012 when it was published in *Nature Nanotechnology*. In the same year the group constructed the world’s narrowest conducting wire in silicon – with a width of only two phosphorus atoms – as reported in the journal *Science*. For these and other achievements Simmons was awarded the 2012 NSW Scientist of the Year and in 2014 became an elected Fellow of the American Academy of Arts and Science.



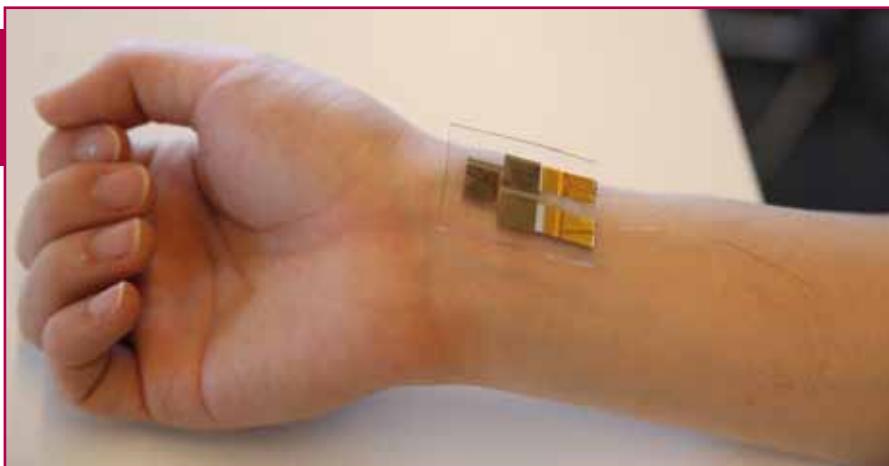
ARC CENTRE OF EXCELLENCE FOR
ENGINEERED QUANTUM SYSTEMS



Electric skin for home health monitoring

The connection between electronics and the physical world is becoming increasingly ubiquitous, creating whole new classes of products and new expectations of what electronics can do for us beyond simply moving data. An accelerometer measuring the direction of gravity tells our smartphone when to rotate its screen, and a solid state magnetic compass tells it which way is North. These are the nanotechnologies that make modern electronics so much more than just a telephone or just a computer. Very cheaply mass produced devices create new functionality through their ability to interface between the virtual and the real. One class of such devices that promises to become important in the near future is “electric skin”, thin, tough, flexible material that conforms to the body, providing feedback for robotics, control of prosthetics or medical monitoring.

Associate Professor Wenlong Cheng and his team at Monash University have recently published a new technology in *Nature Communications* that promises to address a number of challenges that are faced by currently available technology. The breakthrough



is the combination of ultra-thin gold nanowires only about two nanometers thick but ten thousand times as long, into a thin mesh layered between sheets of the inert, non-toxic silicon based organic polymer PDMS. This material can be patterned with electrode arrays to form thin, flexible pressure sensors that can resolve complex forces such as pressure, bending, twisting and acoustic vibration. In an electric skin

application, for example, it is both sensitive and fast enough to resolve and monitor radial artery blood pulses in real time. The fabrication process has dual advantages of very low cost chemical processing combined with lithographic patterning. This makes available a wide range of specific engineering designs for precise control of functionality, a highly desirable combination of low cost manufacturability and technological

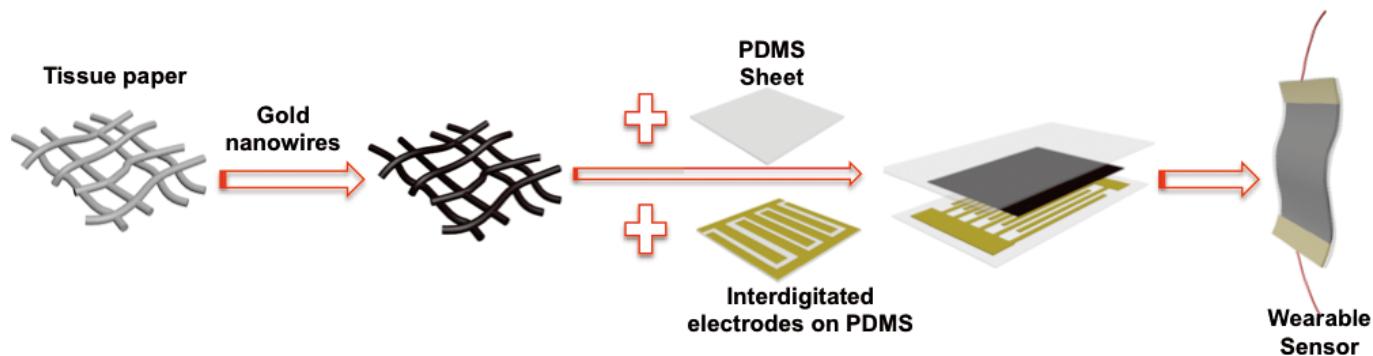
sophistication that promises wide application.

This unique combination of attributes is inspiring new product development. The next step will be developing flexible near-field readout circuits for communicating wirelessly, for example relaying health information to a smartphone or home Wi Fi that allows the elderly or disabled to live safely in the community.

This work was carried out at the Victorian Node of ANFF, at the Melbourne Centre for Nanofabrication.

Nature Comm., 5:3132, DOI: 10.1038/ncomms4132

▼ Schematic of fabrication process for gold nanowire-based pressure sensor. A tissue paper is first immersed into an inking solution of ultrathin gold nanowires, turning the paper into a conductive mat. Then the conductive tissue paper is sandwiched between a blank PDMS sheet and an interdigitated electrode array on PDMS. After external wiring, a wearable nanowire-based pressure sensor is obtained.





PRINTING CERAMICS

Cutting edge capability for research and industry

New 3D printing of a broader range of materials, including ceramics and metals, creates important new opportunities for research and industry to reduce the proof-of-concept and prototyping development cycles. However, such systems are expensive and require skilled technologists to operate at an advanced research level. ANFF is addressing this opportunity by creating a new facility in Adelaide that will enable both the research community and industry to solve manufacturing problems and innovate with Australia's first open-access ceramic printer – a Phenix Systems PXM selective laser melting metal and ceramic 3D printer for medium-scale production.

This new capability is hosted at the ANFF OptoFab facility at the University of Adelaide's Institute for Photonics and Advanced Sensing (IPAS) where it is available for general access by research and industry from across Australia. By partnering with the additive manufacturing expertise of the ANFF Materials node, ANFF now provides the Australian R&D community

with an even more comprehensive and accessible capability for prototyping and small production runs of complex, computer-designed shapes in many different materials. The Phenix PXM 3D printer can be used for a wide variety of metal and ceramic powders for the production of parts directly from Computer Aided Design (CAD) drawings. The printer can manufacture large build volumes up to 140 mm length x 140 mm width x 100 mm height.

In one application, IPAS is using 3D printing for manufacturing extrusion dies that produce the intricate patterns for the production of specialised optical fibres. These dies can sometimes only be made in multiple pieces through traditional subtractive manufacturing, and some potentially useful die structures are just too difficult if not impossible to manufacture using standard methods. 3D printing allows many die designs to be made in one piece, and from exotic materials, such as ceramics. Ceramic dies are much stronger and more robust at the higher temperatures that are needed to extrude materials such as silica glass.



▲ 3D printed part.

The opportunity of using 3D printed dies offers unprecedented flexibility in the design for unlimited tailoring of fluid flow within the die, paving the way towards extruded items of arbitrary shape. The latest ground-breaking demonstration of this has been recently published by Associate Professor Heike Ebendorff-Heidepriem and team [Optical Materials Express, 1 August 2014, Vol. 4, No.8, DOI: 10.1364/OME.4.001494]

3D printing offers a great opportunity for local manufacturers and industry



▲ South Australian Minister for Manufacturing and Innovation, Susan Close with Professor Tanya Monro in May 2014.

to gain a competitive edge in the development of new products or to make improvements in existing parts or existing products, – 3D printing allows rapid prototyping direct from new designs – producing the new part in hours rather days or weeks, ready for quick feedback and refining of designs. It can also be used to improve parts – making them lighter or stronger or from innovative materials including ceramics. This offers great benefits to both industry and researchers.

The first company to use the ANFF ceramic printer is global mining technology company Maptek, which has its headquarters in Adelaide. This project has been supported by the Manufacturing Works Photonics Catalyst Program – a joint SA Department of State Development and University of Adelaide initiative. Maptek is investigating the potential of 3D printing to manufacture the optical chassis for the I-Site laser scanner – one of their key mine survey products.

But it is not only industry benefiting from the availability of 3D printing. The recently announced ARC Centre of Excellence for Nanoscale BioPhotonics, which is focusing on the nanoscale control of light-matter interactions for understanding chemical, biological and physical processes within complex and dynamic nano-environments in living

organisms, will also benefit from specialised optical fibres being developed. This science will underpin a new generation of devices capable of probing the response of cells within individuals to environmental conditions or treatment, creating innovative and powerful new sensing platforms.

ANFF OptoFab's glass and fibre manufacturing capability, now bolstered by the addition of a 3D printer, its suite of surface functionalisation and chemical synthesis equipment, much of which was also made available through ANFF funding, has significantly contributed to, and will continue to underpin much of the research of not only the Centre, but also other research and development in a diverse range of fields and endeavours.



