FLEET

ARC CENTRE OF EXCELLENCE IN FUTURE LOW-ENERGY ELECTRONICS TECHNOLOGIES

IMPACT REPORT

2017 2018 2019 2020 2021 2022 2023 2024

FLEET has laid the foundation for a long lasting legacy...

FLEET: the Australian Research Council Centre of Excellence in Future Low-Energy Electronics Technologies received funding from 2017-2024.

FLEET's central mission was to enable a sustainable future for computing, by developing a new generation of electronics that operate at significantly less energy, utilising novel materials in which electricity can flow with minimal resistance and dissipation of heat, and devices in which that dissipationless electric current can be switched on and off at will.

A SNAPSHOT OF FLEET OUTCOMES

2017–2024

FLEET's bold research mission envisioned extending the information technology revolution sustainably into the future through a new, more energy-efficient electronic technology – developed in Australia.

To achieve its mission, FLEET utilised new, atomically-thin, electronic materials and new topological physics that allow transmittal and switching of electrical currents with minimal energy dissipation.

Since its commencement in June 2017, the Centre made remarkable progress, placing Australia at the forefront of international electronics technology research through the development of scientific foundations and backing intellectual property for future low-energy electronic systems.

228
early-career researchers trained

83
new collaborating organisations

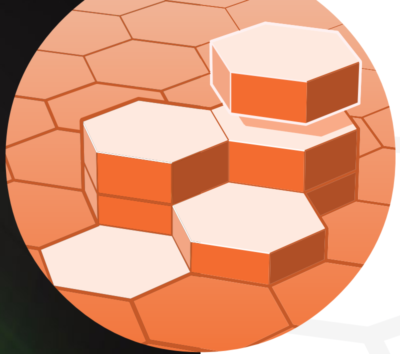
>679
publications

10
patents lodged

2
spin-offs

76,328
members of public reached in outreach events

FLEET.org.au



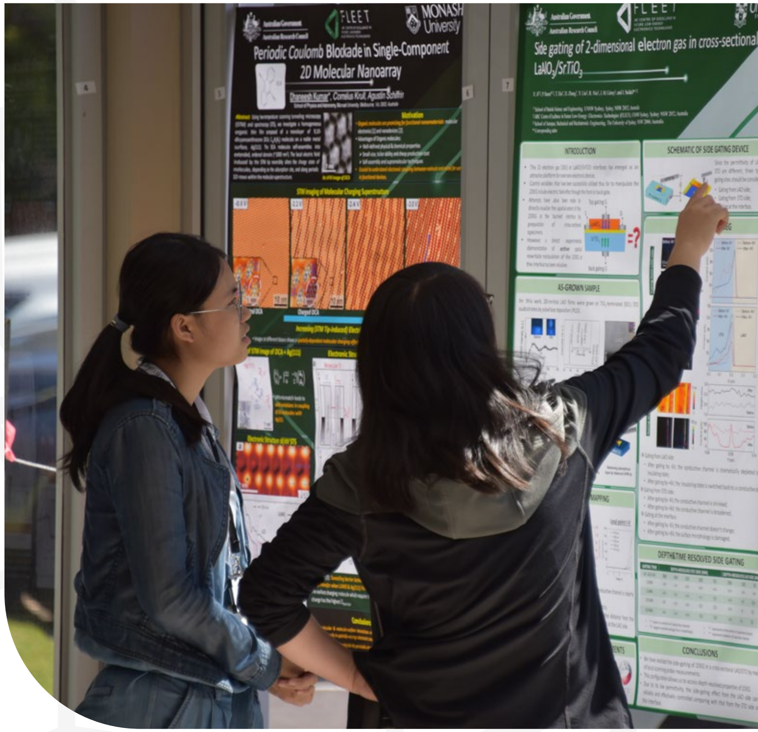
117
higher-degree research students trained

111
postdoctoral researchers trained

70
skill development workshops held

IMPACT

Building **CAPACITY**



FLEET trained a significant workforce for the electronics, semiconductor materials and quantum industries of the future, building a capacity in Australia for advanced electronics research.

FLEET has placed Australia at the forefront of the international electronics industry through the development of innovative electronics technologies and networks.

FLEET's capacity building has galvanised the Australian research community to take the lead in quantum materials and electronic materials research more broadly.

The ongoing workshops on Future Electronic Materials Research in Australia (FEMRA), initiated by FLEET, will maintain links forged within domestic and international expertise to address 'grand challenges' in this field.

Ultimately it will be FLEET alums as much as research outputs that define the success of the Centre.

In seven years FLEET trained over 230 new researchers to become future science leaders by providing world-class training and mentoring programs, translation opportunities, and training toward becoming independent science communicators (see case study on page 15).

FLEET brought Australian strength in microfabrication and nanofabrication together with world-leading expertise in novel and atomically-thin materials, alongside fundamental quantum theorists and experimental quantum materials experts.

$1.6M
in equity initiatives invested

7
Women and Diversity in FLEET fellowships

52
equity scholarships offered

IMPACT

INNOVATION beyond the lab

Fostering creativity and exploring new ideas, encouraging different ways of doing things to create change.

FLEET applied a philosophy from the outset that it was not ‘sufficient’ to merely excel in *science*. The Centre’s leadership team wanted to ensure that innovation was also applied other areas of governance: for example equity, training, translation and communication.

FLEET’s pioneering approach to recruitment helped increase the number of women at research fellow level, and was subsequently expanded to include wider definitions of diversity (see the case study on page 14).

Seeing a unique opportunity to change the culture in which research is done, the Centre set out to create a more diverse and inclusive working environment in STEM.

FLEET pioneered family-friendly workshops, which was a bold experiment at the start but was a resounding success, providing an exemplary model for research institutions worldwide.

With many FLEET members bringing their families to workshops, a more welcoming and inclusive environment was created for everyone. International visitors to FLEET’s workshops frequently commented on their surprise that this was possible, and their admiration for the resulting environment.

>679

research papers published at June 2024

68

h-index at June 2024

3

ARC Linkage and 2 industry-funded projects established

IMPACT

Creation of **KNOWLEDGE**

Shaping the scientific community and industry through ground-breaking innovations, technologies and discoveries.

FLEET's mission was to advance science towards reducing the energy used in electronics and computation so as to create a sustainable future for computing. This was accomplished by enabling discoveries at the scientific frontier.

FLEET has developed scientific foundations and intellectual property for fundamentally new electronics technologies to supersede silicon.

The Centre has achieved a key goal that was outlined at the start: realising topologically-protected, dissipationless transport of electrical current at room temperature, and developing the intellectual property to build novel devices based on the ability to switch on and off this dissipationless current. (See the case study on page 10.)

In addition, FLEET demonstrated excitonic dissipationless transport at elevated temperatures, driving systems out of equilibrium to explore new paradigms in electronics (see the case study on page 12).

17

carers' grants offered

54

children attended FLEET workshops

136

members benefited from FLEET equity-support initiatives

IMPACT

LEADERSHIP

Pioneering a transformative workplace culture marked by inclusivity, family-friendly policies, a strong sense of community, transparency and collaboration.

From the outset FLEET sought to establish a collaborative culture that would encourage partnerships between members who were geographically scattered, and among diverse scientific fields and personnel that make up the Centre.

The Centre fostered inclusiveness, diversity and transparency via Women in FLEET and Diversity in FLEET fellowships and scholarships (see page 14), and by ensuring that early-career researchers participated in all Centre governing committees.

FLEET cultivated a supportive environment with family-friendly events that supported work-life balance, including policies and funding to accommodate caregiving responsibilities.

Partnerships were encouraged between geographically dispersed personnel through collaborated project designs, including collaborations across disciplines and career stages.

Centre alums were kept connected via communications and events, building an ongoing sense of community.

A non-hierarchical culture was encouraged via outreach and presentations, with all members, from Director to students, contributing 20 hours of outreach annually, and with students and researchers presenting at workshops while senior investigators presented posters.

FLEET shared outreach and diversity best practices and initiatives with other ARC Centres of Excellence and made formal submissions to government policy on equity in STEM, critical technologies and quantum strategy, playing a part in establishing lasting, big-picture changes in Australian science policy and practise.

By implementing these initiatives, FLEET created a workplace culture fostering innovation, inclusiveness and collaboration, while developing future scientific leaders and influencing national policies.

7747
hours invested in outreach activities

89
home science activities demonstrated

29,785
teachers and students reached via outreach

IMPACT

STEM-EDUCATION

Making quantum and science accessible to schools, and fostering community through scientific outreach.

At the outset FLEET set itself ambitious goals around outreach, laying out a requirement that each member, from Director to PhD student, would do 20 hours of outreach each year.

By putting in over 7700 hours of outreach-focused work at over 800 outreach events, members reached a staggering 76,000 students, teachers and members of the public in face-to-face events. In the process, FLEET:

- Improved public awareness of FLEET research areas
- Made quantum science more accessible
- Raised awareness of FLEET's key challenge: the unsustainable energy consumption of electronics.

FLEET was able to improve scientific literacy and understanding of FLEET science amongst primary and secondary students, and improve the capability of teachers to teach FLEET-relevant physics (see the case study on page 13).

Putting forward a diverse and personal face to science for students encouraged students to consider participation in science and physics in senior high school and through to university, in particular for students from marginalised groups in STEM.

In the process, Centre members developed their own communication and engagement skills, and learned the impact of their research outside academia.

FLEET developed methods to evaluate the impact of outreach activities and shared these with other Centres.

$99.6M
of additional research funding secured

10
patents lodged

2
spin-offs and 1 technology licensed

IMPACT

SUSTAINABILITY

Fostering a sustainable future for computing through energy-efficient technologies.

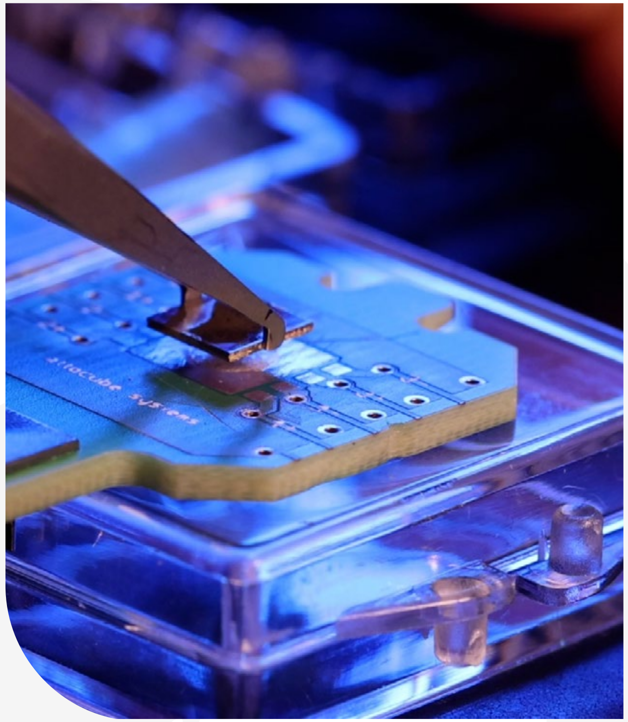
Computing provides overwhelming benefits to the community and economy. FLEET's mission has been to enable the continuing growth of computing, without that growth being 'throttled' by the availability and costs of energy.

The challenge is to reduce the energy used in information and communication technology, which accounts for at least 8% of global electricity consumption and is doubling every decade.

The current, silicon-based technology (CMOS) is over 60 years old and has almost reached the limits of its efficiency.

It is predicted that without a seismic shift in efficiency, global computing capacity will be strongly limited by energy in the next couple of decades.

Computing makes every other industry more sustainable, and is key to solving the largest future challenges.

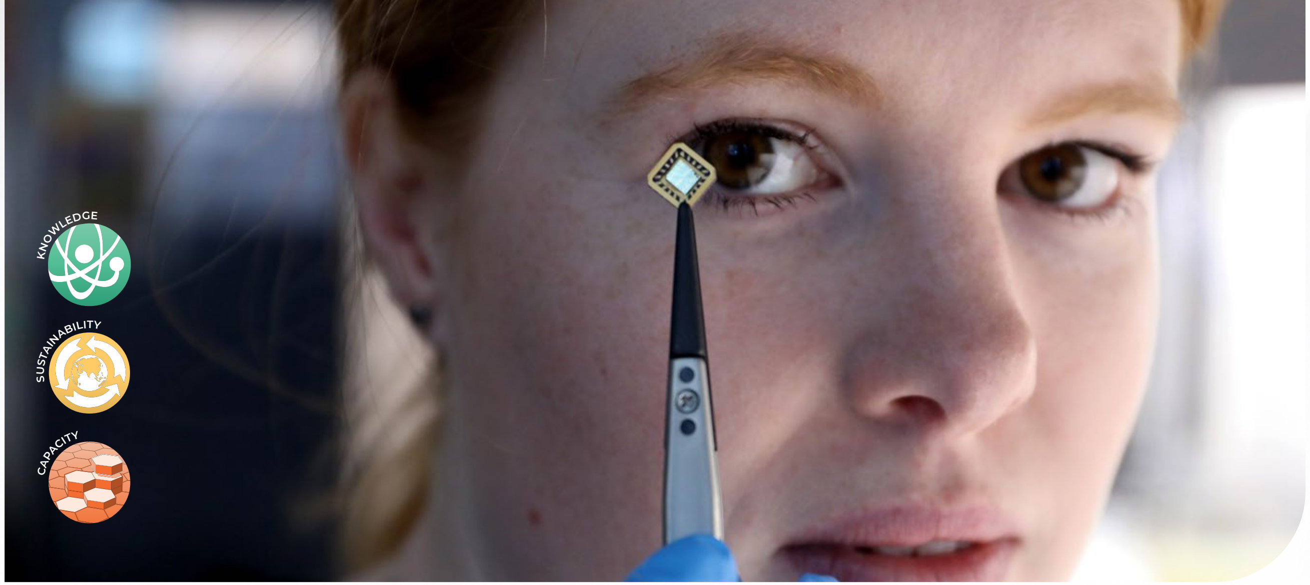


We want to use computers to better model the results of climate change, to create better drugs, and to better understand how viruses reproduce.

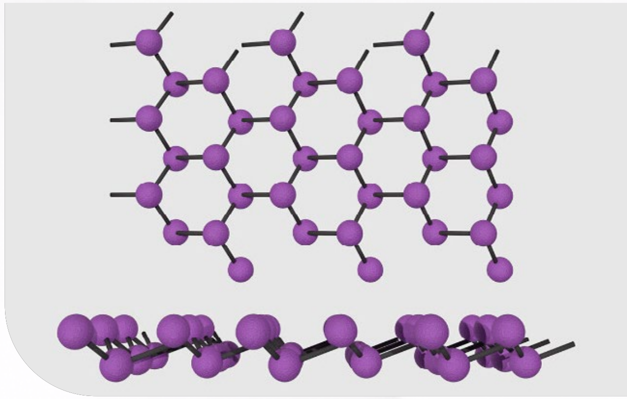
But without new technology that switches at much lower energy, we won't be able to do these things.

Direct advances at FLEET towards lower-energy electronics include highly energy-efficient topological transistors (described in the case study on page 10).

Meanwhile, liquid-metal-based 'spin off' technologies discovered along the way promise other advances towards a more-sustainable future (see case study on page 11).



Bismuthene, a candidate 2D material studied in the 2021 theoretical study (UNSW, University of Wollongong, Monash)



CASE STUDY 1:

Future topological electronics

Switching topological state off and on a step towards low-energy topological transistors.

FLEET's search for a viable room-temperature topological transistor was bold at the outset of the Centre's funding. But now – via combined efforts in materials, experimentation and theory across the Centre – the low-energy topological transistor is a reality.

FLEET researchers achieved a world first in 2018: successfully 'switching' a topological material, via application of an electric field.

This success represented the first step in creating a functioning topological transistor – a key FLEET goal.

In a topological insulator's edge paths, electrons can only travel in one direction. This means there is no 'backscattering' of electrons, which is what causes electrical resistance in conventional electrical conductors.

Unlike conventional electrical conductors, these topological edge paths can carry electrical current with near-zero dissipation of energy, meaning that topological transistors could burn much less energy than conventional electronics. They could also potentially switch between conducting and non-conducting much faster.

Topological materials would form a transistor's active 'channel' component, and would switch between open (0) and closed (1) to accomplish the binary operation used in computing.

The electric field induces a quantum transition from topological insulator to conventional insulator.

To be a viable alternative to today's silicon-based technology (CMOS), topological transistors must function at room temperature, without the need for expensive supercooling. And must be able to be 'switched' extremely rapidly between electrically conducting (1) and non-conducting (0), by application of an electric field.

While switchable topological insulators had been proposed in theory, FLEET's experiment was the first to prove a material could switch at room temperature, which is crucial for any viable replacement technology.

FLEET theoretical studies in 2021 confirmed that topological insulators transistors could reduce transistor gate voltage by half, and reduce transistor switching energy by a factor of four, defeating 'Boltzmann's tyranny', which puts a lower limit on operating voltage.

Applying negative capacitance (via a ferroelectric material) connecting the topological material to the gate terminal allowed for significantly lower switching voltage.

The resulting device, the NC-TQFET (negative-capacitance topological-quantum field effect transistor) was been patented, and a spin-off company TQFET was launched in 2024.

FLEET's efforts saw topological electronics added to the IEEE International Roadmap for Devices and Systems in 2020, ensuring awareness among industrial semiconductor R&D leaders. Thus FLEET's breakthroughs will be considered among other leading potential solutions for future low-energy electronics, fulfilling the Centre's mission.

FLEET.org.au/topologicalelectronics

CASE STUDY 2:

Liquid-metal technologies opening pathways to sustainable science

Serendipitous 'once in decade' liquid-metal advance has flow-on effects.

Centres of Excellence, which bring scientists together from different fields – such as material science, electronics, chemical engineering and theoretical physics – with common purpose, inevitably spark discoveries that weren't even considered at the outset.

As a consequence of ongoing collaborations within FLEET, researchers made a series of liquid-metal discoveries.

Interfaces between liquid metals were discovered to form a successful reaction environment for synthesising the two-dimensional materials FLEET was investigating for future low-energy electronics.

An entirely new process was born that allows access to previously unattainable novel materials.

This 'once in a decade' advance was described as so cheap and simple it could be done on a kitchen stove.

Metals that are liquid at room (or relatively low) temperatures include gallium (with a melting point of 30°C), indium (157°C), tin (232°C) and bismuth (271°C). Material synthesis technologies using these metals allow:

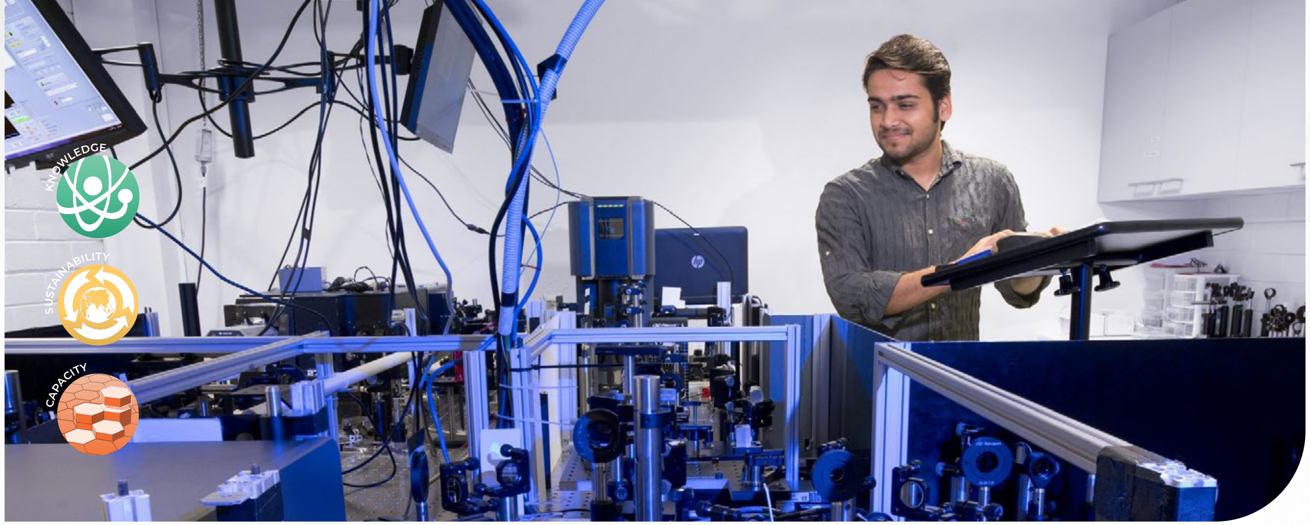
- Liquid-metal touch printing of new electronic materials
- Manufacture of protective layers for delicate novel materials, allowing integration into functioning devices (for example, allowing room-temperature exciton trapping – see the case study on page 12)
- Creation of never-before synthesised materials that offer new applications.

And those new materials are just the start...

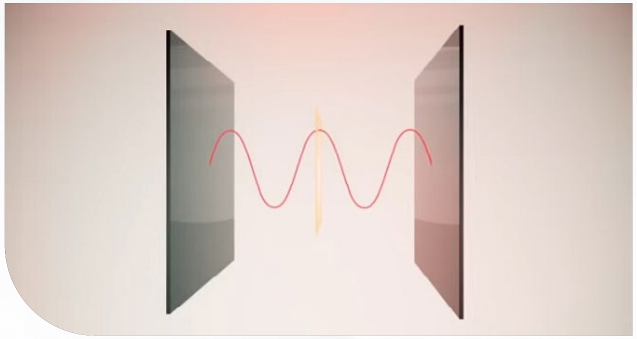
The new liquid-metal processes allow advances that will have direct benefits for our environment and for a more-sustainable future, including innovative carbon-capture technologies, water filtering, and low-energy hydrogen catalysis for alternative energy systems.

These technologies have all sparked further research, attracting external funding, and at least one spin-off company has been formed.

FLEET.org.au/liquidmetal



Exciton-polaritons are a hybrid particle composed of a trapped photon (light) and an exciton (a bound electron-hole pair)



CASE STUDY 3:

Exciton snapshot, a fundamental physics discovery

FLEET researchers achieved the first-ever 'snapshot' of Bose-Einstein condensation excitons in a semiconductor, the quantum state known as the fifth state of matter.

Previously, observations of the hybrid particles known as 'exciton-polaritons' in a Bose-Einstein condensate had been limited to statistical averaging over millions of condensation events.

'Snapshot' imaging of polaritons forming a condensate in a typical inorganic semiconductor was considered impossible.

However, in 2018, FLEET researchers at ANU led an international study imaging exciton-polaritons for the first time as a 'single shot', rather than averaging.

This offers a unique opportunity to understand the details of Bose-Einstein condensation of exciton-polaritons.

Such fundamental advances also significantly advanced FLEET's research on excitonic condensation and superfluidity as a mechanism for electronic conduction without wasted dissipation of energy.

'Exciton-polaritons' are hybrid quantum particles that are part matter and part light, bound together by strong coupling of photons and electron-hole pairs (excitons) within a semiconductor microcavity.

However, because exciton-polariton lifetimes are measured in picoseconds (trillionths of a second), previous observations of their behaviour had always necessitated averaging over a million lifetimes of many, many exciton-polaritons.

This is like taking a long exposure of moving objects: you get a blurred image.

The ANU team made sure that, instead of the blurred image, their sensitive camera captured only one lifetime or 'single shot' of the condensate. This let them observe behaviour of exciton-polaritons that had never been seen before.

The single-shot imaging was performed by analysing photoluminescence caused by the decay of exciton-polaritons, a technique thought to be impossible in inorganic microcavities because emissions simply weren't bright enough.

Usually, the density of exciton-polaritons trapped in inorganic microcavities is too low to be detected in single-shot mode, partly because exciton-polaritons do not live long enough for the density to build up.

To get a better signal, the team used ultra-high-quality samples designed and made by collaborators in the USA, extending the lifetime of polaritons by an order of magnitude and pushing the density high enough for the sensitive camera to detect.

The imaging revealed that, contrary to the smooth condensate observed in averaged experiments, the condensate actually forms filaments whose orientation varies from shot to shot.

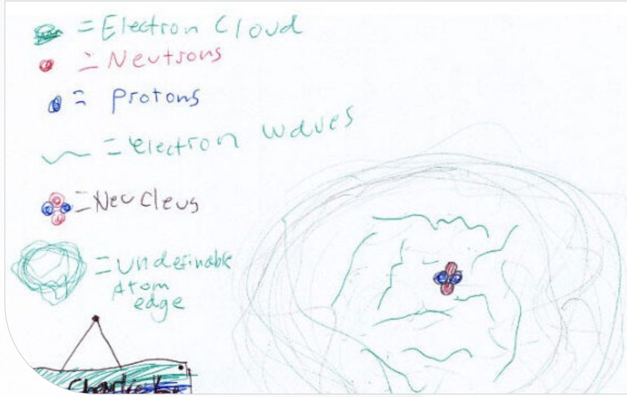
The study found remarkable agreement between experiment and numerical simulations, validating the background theory of exciton-polariton condensate dynamics.

The work paves the way for further fundamental studies of quantum phase transitions and non-equilibrium condensation in solid-state systems.

These single-shot experiments could prove critical for our understanding of the fundamental (and still debated) nature of the condensed phase in these systems.

FLEET.org.au/excitons

'Bohr' type idea of atoms, hard, 'certain' electrons, before discussions towards models that have indistinct 'clouds' of electrons, instead of hard dots.



CASE STUDY 4:

Making quantum and science more accessible

From levitating superconductors to home-science experiments and card games, FLEET built a diverse and engaging set of outreach tools and resources to engage students, teachers and the public.

New science-outreach resources We used 1500 neodymium magnets to build a giant levitating superconductor in the form of a Möbius strip, took FLEET scientists and science demonstrations into primary schools and kindergartens, developed teacher resources linked to FLEET research and combined the brains trust of all FLEET members to produce hands-on home science experiments.

The superconducting, supercooled Möbius track was the natural star of FLEET science outreach, allowing demonstration and discussion of topology, superconductivity, magnetism and low-temperature physics.

FLEET developed curriculum-linked teacher resources containing information, hands-on activities and worksheets in light, electricity, forces and energy.

FLEET's 80+ home science experiments introduced younger students to easy, fun science experiments using accessible, everyday items. Each was ground-tested with simple instructions written for a non-science audience, including a description of the underlying scientific concepts.

The participation of FLEET members drove the Centre's success in outreach FLEET members performed science shows at kindergartens, primary and secondary schools, demonstrating physics with equipment not typically available to students.

The program brought scientists to the students, allowing them to ask questions about science, careers in science and any other burning questions they had such as why aren't you wearing a lab coat?

These face-to-face conversations with practicing scientists most-effectively 'shifted the dial' in engaging school students as a personal, relatable, inspirational and trusted face of working scientists.

Having scientists engaged in one-on-one (rather than 'broadcast mode'), and face-to-face conversations with students and public allowed deeper, more effective communication.

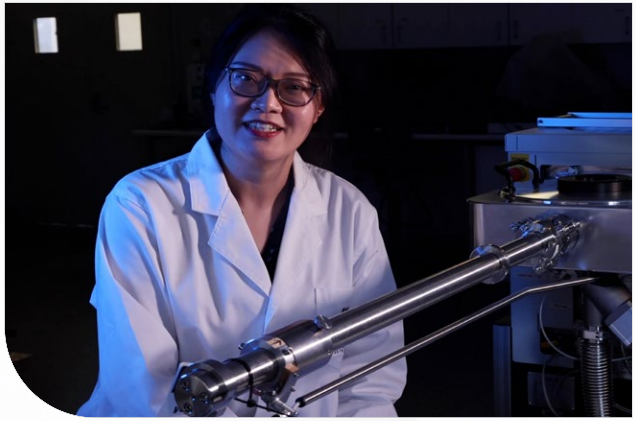
Accessible quantum Australia's future industries will include a higher proportion of quantum technologies, and FLEET's part towards building the workforce to support such a future includes an impressive 240 quantum-skilled PhD and postdoctoral graduates.

But we believe there is more we can do towards building a quantum-savvy workforce, and quantum-savvy community. We believe that process begins well before 'quantum 101' in a university physics degree.

FLEET's hands-on quantum workshops were designed to engage primary and lower-secondary school students with quantum physics, while the Centre's secondary school 'quantum 101' lesson aimed to develop a 'low maths', intuitive level of quantum understanding.

FLEET.org.au/outreach

FLEET has also recognised the power of putting women forward as the face of science.



CASE STUDY 5:

Women in FLEET and Diversity in FLEET

Improving equity in science: the Women in FLEET and Diversity in FLEET programs

A significant legacy of FLEET will be the increase in participation of women in STEM research, and improved 'best practice' in seeking equity.

FLEET pioneered Women in FLEET Fellowships, open to women across all areas of FLEET research rather than targeting specific areas.

Subsequently the Centre broadened this strategy to other groups that are also under-represented in STEM, appointing Diversity in FLEET Fellows representing women, LGBTIQA+ and disadvantaged backgrounds.

Through this and other initiatives, FLEET achieved a strong upward trajectory in the proportion of women in the Centre from 2017 to 2020.

FLEET had set out to change the culture by significantly increasing the representation of women in electronic materials research – a field traditionally among the very lowest.

Women in FLEET Fellowships were introduced as an innovative new approach to 'shift the dial' in terms of improving the percentage of women recruited.

Recruitment up to that point had drawn from the existing physics pool, which (along with related fields such as engineering and material science) unfortunately features a relatively low percentage of women.

FLEET's innovative new Fellowships allowed the Centre to begin increasing the percentage of women above the average in these fields.

The Fellowships allowed for improved flexibility in the location and type of position on offer. FLEET's previous recruitments had been highly-focused research roles with specific expertise criteria, which has resulted in maintaining 'status quo' in gender balance.

The new Fellowships allowed applicants to nominate which FLEET investigators they wanted to work with, effectively matching applicants' skills and interests with any research area within FLEET. This broader search allowed FLEET to find excellent researchers who may have been missed in previous, narrowly-targeted searches.

The flexibility of offering whichever field suited the best applicants available allowed the widest choice of applicants, ensuring the best possible candidates were hired.

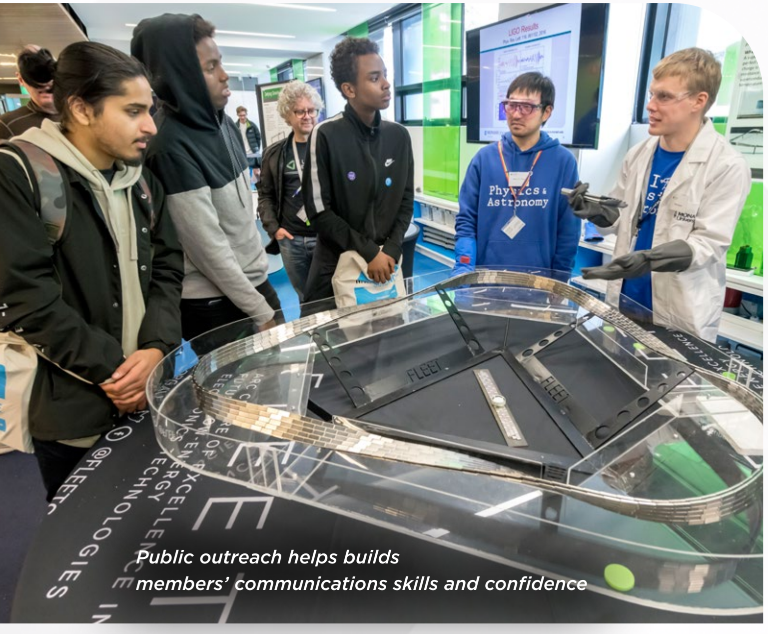
The very first round of recruiting demonstrated the effectiveness of this new approach. FLEET received almost 70 applications. In comparison, 15 previous, more tightly-targeted, searches had received fewer than 30 women applicants in total.

We believe that these broad-based searches more effectively allow applicants from under-represented groups to find a place in a science organisation.

FLEET's white paper on the experiences learned from the program, will facilitate take-up by other large science and engineering organisations.

FLEET.org.au/equity

100+ FLEET members stories have been published on external scientific platforms



Public outreach helps builds members' communications skills and confidence

CASE STUDY 6:

Empowering members to communicate their own scientific work

A key focus for FLEET was building our members' self-sufficiency in communicating their own scientific discoveries.

While members are in a Centre of Excellence, they have access to a communications coordinator who can help them share their research. But this will almost certainly not be the case for most of a scientist's career.

FLEET devoted significant effort into building researchers' skills in 'DIY sci-comms'.

FLEET's members gained the skills and confidence to share their research through several channels, including effectively leveraging university communications teams, online scientific platforms and social media.

In addition to undertaking structured communication training, members were trained, coached and encouraged to write articles aimed at the general public (in contrast to peer-reviewed scientific papers).

An unexpected benefit in communications skills also came from the Centre's science-outreach efforts:

FLEET's ambitious goal of every member (from Director to students) doing at least 20 hours of science-outreach each year had unexpected benefits for FLEET members.

In explaining their science to school students and members of the public, members developed science communications skills that were just as useful in explaining their work to colleagues, members of Faculty, or possible collaborators or investors.

"Our experience doing science-outreach to schoolkids is an opportunity for us to think and practice how to explain science to the public."
Dr Peggy Zhang

"Doing school outreach helped me get the right tone for a subsequent research pitch to MPs and policymakers. I used exact descriptions and examples that we'd developed presenting at a college in Sydney." Harley Scammel

FLEET allowed a wide array of outreach activities to 'count' as outreach hours, allowing members to find an activity that matched their skill-set and preferences.

For example, FLEET members from PhD students through to Chief Investigators developed teaching resources for the Year 10 Future Electronics unit at John Monash Science School. For most junior Centre members, this was their first exposure to teaching – and a valuable addition to their skill set and their CV.

FLEET.org.au/scicomms

FLEET PARTNERS

FLEET was an Australian Research Council Centre of Excellence linking a highly interdisciplinary team of high-profile Australian and international researchers.

Australian Government Australian Research Council

MONASH University

Australian National University

RMIT UNIVERSITY

SWINBURNE UNIVERSITY OF TECHNOLOGY

UNSW SYDNEY

THE UNIVERSITY OF QUEENSLAND AUSTRALIA

UNIVERSITY OF WOLLONGONG AUSTRALIA

ANSTO

Australian Synchrotron

University of Maryland

The MacDiarmid Institute for Advanced Materials and Nanotechnology

MPQ

JOINT QUANTUM INSTITUTE

NUS National University of Singapore Centre for Advanced 2D Materials

University of Colorado Boulder

CSRC

TEXAS The University of Texas at Austin

UNIVERSITÄT WÜRZBURG

Wrocław University of Science and Technology

Università di Camerino

universität mainz

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Caltech