Report for 2009
April 2010

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Highlights of 2009

- The Centre’s funding position for 2009 benefitted from the outstanding success in obtaining external funding throughout 2008-10. The value of external grants currently held by Centre members is $21 million.
- The Government established the Australian Solar Institute (ASI) under the auspices of the Federal Department of Resources, Energy and Tourism, partly as a result of representations by Centre members during 2006 and 2007. $100 million has been committed to the formation and operation of ASI. The Australian National University (ANU), the University of New South Wales (UNSW) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) are the three Core Participants, reflecting their pre-eminent positions in solar research in Australia.
- In 2009 an award of a $5 million Foundation Grant was made by ASI to upgrade and extend our laboratories, and to acquire a greatly expanded range of process and characterisation equipment. Work will be completed in June 2010.
- An ASI grant of $5 million and an ARC Linkage grant of $0.9 million was recently made jointly to the Centre and to Origin Energy Solar to further develop SLIVER solar cell technology.
- A comprehensive new agreement (2009–21) was reached between ANU and Origin Energy Solar in respect of SLIVER technology. It replaces the 1998 Agreement, and much more clearly specifies the benefits and obligations of the parties.
- Origin Energy Solar and Micron (a large US semiconductor memory manufacturer) have formed a joint venture called Transform Solar to bring together Origin’s SLIVER capability and Micron’s large scale production and manufacturing capability. This is an exciting development in the commercialisation process. Successful commercialisation will spark strong scientific and commercial interest in adapting non-concentrator SLIVER technology for concentrator applications.
- The concept of engineering the properties of silicon nitride surface coating has been demonstrated. This may allow the films to be used in a wider range of applications.
- We continued our optical studies into silicone and ethylene vinyl acetate, both of which are used to encapsulate solar cells in modules and concentrator systems. The work was conducted within an ongoing collaboration with Dow Corning (USA).
- We developed a method to grow oxides on silicon at room temperature. The passivation offered by these oxides is close to that attained by oxides grown at 1000°C by conventional semiconductor processing. Our low-temperature oxides provide an opportunity to reduce the expense of fabricating high-efficiency solar cells.
- Significant improvements were made in the design of plasmonic structures for efficient light trapping in solar cells including concentrator solar cells.
- Development of nano-imprinting as a reliable large scale patterning technique for fabrication of light trapping structures on thin solar cells including concentrator solar cells.
- An ARC Linkage grant of $237,348 was recently awarded to the Centre for the continued development of Micro-concentrator receiver technology.
- Substantial progress was made towards the development of second generation concentrator cells for Combined Heat and Power Solar (CHAPS) receivers based on elongate solar cells
- Substantial progress has been made with a prototype design for integrating the electrical and thermal requirements of hybrid PV-thermal micro-concentrator receivers.
- The Centre organised the Singapore-Australia solar workshop at ANU, a gathering of 40 senior solar energy researchers
The Centre

The ARC Centre for Solar Energy Systems was established in 2003. Following ARC reviews in 2006 and 2007, it will receive funding until the end of 2010. An extension of operation of the Centre beyond its funding life, until 2013, is foreshadowed. The core research of the Centre is in the area of advanced silicon concentrator solar cells. The Centre is located within the College of Engineering and Computer Science at the Australian National University. The ARC Centre works in association with the Centre for Sustainable Energy Systems.

The Centre website is at http://solararc.anu.edu.au/

Personnel

Principal Researchers

Professor Andrew W. Blakers (RD)  Director
Dr. Vernie A. Everett (CI)  Deputy Director
Associate Professor Klaus J. Weber (CI)  Principal Researcher
Dr. Kylie Catchpole  Principal Researcher
Dr. Keith R. McIntosh (CI)  Principal Researcher
Dr. Sudha Mokkapati  Principal Researcher
Dr. Elizabeth A. Thomsen  Principal Researcher

Chief Operating Officer and Centre Manager

Ray Prowse (until June 2009)
Dr. Barry Fordham (from November 2009)

PhD Candidates

Simeon Baker-Finch, commenced Q1 2009; Dielectrics for the front surface of high-efficiency solar cells
Fiona Beck, commenced Q1 2007; Increasing light absorption in silicon using metallic nanoparticles and photonic structures
Kean Fong Chern, commenced Q1 2008; Ultra-thin elongate solar cells,
Nicholas Grant, commenced Q1 2008; Low-cost passivation of silicon surfaces
Bijaya Paudyal, commenced Q1 2006; Application of temperature and injection dependent lifetime spectroscopy to surface passivation of silicon semiconductors
Lisa Ren, commenced Q2 2008; Optimising charge in silicon nitride films
Andrew Thomson, commenced Q1 2006; Studies of silicon oxide ageing and titanium oxide passivation of silicon for use in solar cells
Er-Chien (Eric) Wang, commenced MPhil Q3 2008, transferred to PhD Q4 2009; Controlled fabrication of nanophotonic structures for photovoltaic applications
Chun Zhang, commenced Q2 2007; The influence of hydrogen on surface passivation of silicon-silicon dioxide interfaces
Ngwe Soe Zin, commenced Q2 2007; Concentrator silicon solar cells for tandem packages

Masters (by Research)

Natalita Nursam, commenced Q3 2008; Electrical properties of boron diffused emitters
Other people working in areas relevant to the Centre during 2009

Research Staff
Maureen Brauers – Research Officer
James Cotsell – Technical Officer
Erin Davies – Research Assistant
Dr. Jin Hao – Postdoctoral Fellow
Judy Harvey – Research Officer
Anke Lemke – Research Assistant (June–November)
Rowena Mankilow – Research Assistant
Dr. Jelena Muric-Nesic – Research Officer
Ruud van Scheppingen – Research Assistant
Chris Samundsett – Research Officer
Dr. Sachin Surve – Research Engineer
Dr. Peter Surwaski – Research Officer (to March)
Dr. Marta Vivar – Research Fellow
Daniel Walter – Research Officer
Dr. Huanhuan Zhao – Research Officer

Technical Staff
Neil Kaines – Laboratory Manager
Nina De Caritat – Process Manager
Bruce Condon – Technical Officer
Glen Cecil – Technical Assistant
Hamidreza Riazi-Nejad – Technical Officer
John Musladin – Technical Assistant

Administrative Staff
Dr. Igor Skryabin – Business Development Manager
Janette Garland – Administrator (January–July)
Milisa Haberschusz – Senior Administrator (July–November)
Alena Almassy – Senior Centre Administrator (from November)
Caroline Ashlin – Administrative Assistant (December)
Centre Funding

Centre funding received in 2009 was $574,129, comprising:

1. ARC Centre Funding, $442,279
2. ANU Central Areas, $43,350

Grants, Consultancies and other income

Centre members are Chief Investigators on external grants totalling $21 million over the period 2008–12. In addition, substantial royalties (from SLIVER technology) are flowing to ANU, at a rate of more than $1 million per year. R&D funding from the Australian Solar Institute (ASI) will not flow until Q2 2010. Current and announced grants are:

New in 2009

- ASI Foundation Grant, Blakers, $5M, 2009–10: improved solar laboratories.
- Not active until 2010:

On-going

- Origin Energy, SLIVER technology transfer, $0.9M ($3M received to date). $1.1M due September 2010.
- Department of Defence (Capability and Technology Demonstrator program), *Elongate solar cells for energy generation*, Blakers, Everett, Skryabin, and Weber, $2.2M (2008–2010). This contract stems directly from foundation work undertaken with ARC Centre funding.
- Asia Pacific Partnership on Clean Development and Climate (APP), *Increasing the efficiency of linear concentrators to capture solar energy*, Blakers and Everett, $1.6M, 2009–10. This contract stems directly from foundation work undertaken with funding from the ARC Centre and two ARC Linkage grants (LP0669751 and LP0454195). The aim is to further develop and commercialise hybrid PV–thermal concentrator receivers utilising upgraded one sun solar cells. The project includes a contractual agreement with a commercial collaborator (Chromasun, USA) and a research collaboration (with Tianjin University, China).
- Australia–India Special Research Fund, *Technical and economic assessment of improved solar photovoltaic linear concentrators and determination of market potential in India*, Blakers and Skryabin, $380,000, 2008–10. This project is related to the $1.6M APP project.
• International Science Linkage, *Immersed linear concentrator receivers*, Blakers and Skryabin, ANU and Tianjin University, $350 000, 2009–11. This project is related to the $1.6M APP project.


• ARC Linkage LP0989593, *Spray-on hydrogenated films for solar cells*, McIntosh and Weber, Cuevas (School of Engineering), Karkkainen (BraggOne), and McCann (Spark Solar), $370 000 ARC + $200 000 industry, 2009–11.

• ARC Linkage LP0883613, *Minimising charge carrier recombination at silicon surfaces with improved dielectric coatings*, Weber, McIntosh, and Jin, McCann (Spark Solar), and MeInyk and Fath (GP Solar GmbH), $420 000 ARC + $230 000 industry, 2009–11.

• ARC Discovery DP0880017, *Photonic structures for high efficiency, low cost solar cells*, Australian Research Fellowship, Catchpole, $600 000, 2008–13.

• ANU–Dow Corning commercial research contract, *Silicone for photovoltaic modules*, McIntosh and Norris (Dow Corning), $90 000, 2007-09.

**Impact of the ARC Centre**

The ARC Centre for Solar Energy Systems was funded modestly but consistently from 2003 to 2010. During difficult financial years in 2005–07 this funding was sufficient to keep our core staff together, which positioned us for strong growth from 2008. Much of the project funding arising from 2008 onwards stems directly from ideas and capabilities developed with Centre funding in 2003–07.

Since 2008, Centre staff have secured $21 million in external funding. Modest-scale centres such as our Centre can have substantial outcomes, quite out of proportion to the amount of ARC funding received.

We are very grateful to the ARC for its support.
Research Projects

Introduction

The worldwide photovoltaic industry continues to rapidly expand despite the worldwide financial problems of 2008–10. Concern over anthropogenic climate change sets the scene for long term rapid growth of the solar energy industry. The establishment of the Australian Solar Institute is a significant development in placing solar energy technology development in this country on a sound footing.

Asia Pacific Partnership Program

Researchers: Dr Vernie Everett, Prof Andrew Blakers, Mr James Cotsell, Ms Judy Harvey, Mr Ruud van Scheppingen, Mr Dan Walter

The key objective of the APP Project is to resolve the remaining barriers to the widespread deployment of photovoltaic trough concentrator systems. Principal barriers include (1) the difficulty of supply of high-performance, low cost solar cells suitable for parabolic trough concentrator systems, (2) the technical problem of moving shadows cast by gaps between mirrors and structural elements on strings of solar cells, and (3) the integration and qualification of the system. Project outcomes will include the resolution of technical, scientific, and engineering impediments to the deployment of photovoltaic linear concentrator systems.

Figure 1. Prototype receiver samples illustrating a range of test cell configurations.

The Project has now been running for over two years and is making good progress with meeting the above objectives. At the technical level, suitable cells have been identified and methods have been developed for reducing performance losses associated with dicing, upgrading and handling to allow operation at 20-30 suns concentration. Work is continuing on improving the mounting techniques and methods for establishing modified electrical connections, and improving heat-sinking methods and materials, as shown above in Figure 1. A commercial partner, Chromasun Inc., in the US has developed a low-cost, ultra light weight mirror and tracking system for the improved micro-concentrator receivers, as well as the structural enclosure for the micro-concentrator system.
Preliminary results to date on micro-concentrator sub-modules constructed from commercially available one-sun solar cells are shown below in Table 1. For sub-modules operating at up to 10X concentration the design can achieve better than 20% aperture efficiency, with efficiencies dropping to 19.8% at 20X and 19.3% at 30X, corresponding to the yellow and light blue IV curves respectively, shown in Figure 2 above.

The micro-concentrator sub-module electrical efficiency achieved to date is a remarkable result, given that these one-sun cells achieve around 92% the performance of a leading 21% efficient concentrator silicon cell at less than 10% of the cost of the concentrator cells.

Table 1. An example sub-module IV curve for illumination concentration ratios of 5, 10, 20, and 30 suns.

<table>
<thead>
<tr>
<th>Performance Characteristics at 20x</th>
<th>Performance Characteristics at 30x</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Circuit Current (A)</td>
<td>Short Circuit Current (A)</td>
</tr>
<tr>
<td>1.7</td>
<td>2.6</td>
</tr>
<tr>
<td>Open Circuit Voltage (V)</td>
<td>Open Circuit Voltage (V)</td>
</tr>
<tr>
<td>2.9</td>
<td>3.0</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>Fill Factor</td>
</tr>
<tr>
<td>0.71</td>
<td>0.67</td>
</tr>
<tr>
<td>Efficiency</td>
<td>Efficiency</td>
</tr>
<tr>
<td>19.8%</td>
<td>19.3%</td>
</tr>
</tbody>
</table>

While improved methods for preparing, mounting, and heat sinking these adapted one-sun cells, and improved receiver designs are still being investigated, the prototype integrated hybrid design is largely complete, and functional prototypes are being constructed in 2010.

Thorough performance and qualification testing of designs and materials are presently under way, as is the development of a Commercialisation Plan and technology transfer to other

Figure 2. An example sub-module IV curve for illumination concentration ratios of 5, 10, 20, and 30 suns.
partner countries for use in demonstration systems. Thermal management is a critical aspect of concentrator systems; design and testing in this area is well advanced.

Figure 3. The linear Fresnel ultra light-weight mirror array test bed.

A prototype linear Fresnel mirror array is shown in Figure 3. This array is approximately 3.2 metres long by 0.6 metres wide. Mirror design elements such as curvature and width are being optimised for performance and manufacturability. Because the system is fully enclosed, the mirrors do not have to withstand wind-loading, allowing a very low power, balanced tracking system. Furthermore, this design ensures high performance from clean mirrors for the life of the system.

The present design is a hybrid PV-thermal system, but several variations are possible, which are easily optimised for localised conditions. For example, a thermal-only micro-concentrator design can provide solar thermal energy sources for applications ranging from domestic hot water, low-grade industrial heat, space heating, and solar air conditioning. Purpose-designed integrated electrical, heating, and cooling domestic or industrial systems can be readily constructed from identical base units simply by interchanging receiver designs as required.

Tooling and construction of prototype enclosures is shown in Figure 4 with a complete prototype micro-concentrator shown in Figure 5. Future work includes on-sun testing and qualification of the entire system, with design refinements incorporated for B-stage production and testing. Commercial test units are expected to be manufactured in late 2010.
Figure 4. Tooling up for prototype enclosure construction.

Figure 5. A complete prototype micro-concentrator.
Silicon oxide grown at room temperature

Researchers: Dr Keith McIntosh, Mr Nick Grant

In 2009, we explored ways to grow silicon dioxide layers (SiO₂) on silicon (Si) at room temperature. Such SiO₂ layers provide “passivation” to the surface of Si solar cells, making them more efficient, which is particularly important for concentrator cells.

In high-efficiency solar cells—and in almost all microelectronic devices—the SiO₂ layers are grown at 1000 °C over an hour or so. This “thermal” SiO₂ is of a very high quality. In fact, the resulting interface between the SiO₂ and the Si contains fewer than one defect for every 10,000 Si atoms (at the centre of the forbidden band-gap). The problem with thermal SiO₂ is, of course, that it must be grown at such high temperatures. These temperatures make the procedure expensive, and the silicon more susceptible to being infused with metal impurities.

We are therefore exploring methods to grow SiO₂ at low temperatures. In this regard, we are the first to closely examine the density of interface defects and the surface recombination velocity of such oxides. In particular, we have examined SiO₂ grown by submerging Si into nitric acid, with and without the application of a high electric field. We find that the electric field does not greatly affect the quality of the interface but it does greatly increase the growth rate of the SiO₂. In fact, we have grown SiO₂ at room temperature at a similar rate as a thermal SiO₂ grown at 1000 °C.

In 2009, we found that the interface quality of our room-temperature SiO₂ was inferior to that of thermal SiO₂. It possesses about 10 times as many defects, but this was partly compensated by the SiO₂ having a higher positive charge. Nevertheless, as the year progressed, we were glad to have determined ways to attain repeatable and uniform SiO₂, and to have attained progressively better interfaces.

Our results have been published in two journal articles and at one international conference. We will continue to work on low-temperature SiO₂ in 2010, aiming to grow layers with interfaces that are compatible with high-efficiency solar cells. Should we succeed, we will have found a method to reduce the fabrication cost of such cells.

Optical study of encapsulants used in PV modules

Researchers: Dr. Keith McIntosh, Mr James Cotsell

The majority of photovoltaic modules employ ethylene vinyl acetate (EVA) to bond solar cells to glass. While EVA is highly transparent, silicones are even more so. This year, we continued our extensive investigation into the optical properties of silicones and EVA in collaboration with Dow Corning (USA). In 2008, we were the first to accurately measure the refractive index and absorption coefficient of EVA and silicone over a wide range of wavelengths (200–1600 nm). In 2009, we measured how those optical properties were affected by exposure to humidity, UV light, and concentrated sunlight.

We found that both PDMS silicone and modern EVA withstood UV exposure but degraded slightly under humidity exposure. The degradation due to humidity was small (~1%) and insufficient to cause modules to fail standard reliability testing. But when exposed to sunlight that is concentrated by 30 times, as occurs in the ANU trough concentrator systems, the EVA
deteriorated markedly, heating so much that it charred like a burnt sausage. Under the same conditions, all silicones survived with a small degree of deterioration after 6 months.

In addition to optical degradation, we also examined the capacity of these materials to store water vapour. We showed that the EVA stores 10 times the quantity of water vapour after exposure to humidity than silicone, as determined by the change in their weight (Figure 6). We also showed that the water vapour causes scattering of incident light, which reduces the transmission of light to the cells. The extent of that reduction is the subject of future research and is of interest to solar cells operating in humid climates, such as the tropics.

![Sample weight as a fraction of its final weight after exposure to 1000 hours of 85 °C and 85% relative humidity. After 24 hours of measurement at room temperature (RT), the samples were placed in an oven at 85 °C to hasten the desiccation.](image)

These results are important to Dow Corning’s commercialisation of silicones for use in photovoltaic modules. They also provide the ANU with valuable information for its commercialisation of concentrator systems. The results were presented at two international conferences in 2009 and have been submitted for publication in a high-impact scientific journal.

**Charge Engineering of Silicon Nitride**

Researchers: A/Prof Klaus Weber, Dr Jin Hao, Lisa Ren

Silicon nitride is a widely used material in the production of commercial silicon solar cells. It combines a variety of desirable optical and electronic properties, and allows the specific film properties to be tuned over quite a wide range. Silicon nitride films typically contain positive charge. This charge is beneficial in some circumstances but detrimental in others. As an example, while silicon nitride films are commonly applied on the front surface of solar cells, they do not provide good results when applied to the rear (p type) surface. This is because on the rear surface these films cause the formation of an inversion layer, which introduces a virtual shunt to the cell and substantially reduces its performance. Here, films containing negative charge are able to provide far superior performance.

We have studied the possibility of changing the charge state of silicon nitride films, so that they can be used for applications requiring both positive and negative charge. The charge state of silicon nitride films can be easily manipulated, and we have demonstrated high negative
The key question to be addressed is whether this charge will be sufficiently stable for photovoltaic applications.

We have commenced extensive investigations of the charge stability of silicon nitride films, focussing in particular on how the charge stability is affected by silicon nitride deposition parameters and post deposition treatments. An example of these results is shown in Figure 7.

**Figure 7.** Experimental and modelling results of the decay of negative charge in silicon nitride films. Red and blue data points are the experimental results from samples stored at 150°C, while green and black are the modelling results. The results show that for suitable prepared samples (red data and green model) the charge is sufficiently thermally stable to be used in PV applications.

Results to date have shown that both the charge storage ability and charge stability are significantly better of nitrogen rich films than for silicon rich films. Further, high temperature annealing seems to enhance both properties. These promising results provide the basis for a further, more detailed investigation of charge storage in silicon nitride, and the application of the results to solar cells, including high performance concentrator cells.

**The role of hydrogen at the silicon-silicon dioxide interface**

Researchers: A/Prof Klaus Weber, Dr Jin Hao, Chun Zhang

The Si-SiO₂ interface is very important in crystalline silicon solar cell devices, and particularly for high performance devices such as concentrator solar cells. Due to the excellent surface passivation it affords, surface coatings featuring an interfacial oxide, such as oxide/PECVD silicon nitride stacks, are under active investigation. Hydrogen (H) is needed to terminate the majority of dangling bonds at the Si-SiO₂ interface. Atomic H atoms can passivate the Si-SiO₂ interface, and the process occurs with no or a negligible energy barrier. However, atomic H can also be detrimental. It has been shown that atomic H at low temperatures can introduce additional interface defects, which lead to substantially increased...
recombination. Atomic H can be created in a number of ways and is likely to play a key role in various different degradation mechanisms including UV and humidity degradation, which are particularly relevant for concentrator solar cells.

The detailed role of atomic hydrogen at the interface is quite poorly understood. Our recent work, building on the results reported previously, has focussed on studying the annealing behaviour of H induced interface defects, in order to determine fundamental parameters (activation energy and pre-factors) from the results. An example of the results is shown in Figure 8. It is apparent that the H-induced defects are not governed by a single activation energy, but by a spread of activation energies, indicating that the defects are not homogeneous in their structure. Future work will aim to extend the work to obtain a clearer understanding of the UV and humidity degradation mechanisms.

![Figure 8](image)

**Figure 8.** Annealing of interface defects with time, at different temperatures. The emitter saturation current density $J_{0e}$ is an indirect measure of the defect density.

**Nanophotonics**

Researchers: Dr. Kylie Catchpole, Dr. Sudha Mokkapati, Ms. Fiona Beck, Mr. Er-Chien Wang

In order to reduce the cost of photovoltaics, there is a worldwide trend to decrease the thickness of solar cells, and hence the consumption of expensive, highly purified silicon. However, as the thickness is reduced, the absorption of sunlight by the solar cell decreases, reducing the efficiency of the solar cell. To overcome this, surface textures are used to change the direction of light coming into the solar cell, trapping light within the cell. Traditional methods of light trapping use pyramid-shaped surface textures formed by alkaline etching, which are
effective for cells made from single-crystal silicon, but are less effective for cells made from multi-crystalline silicon or thin-film solar cells such as SLIVER solar cells.

Researchers in the nanophotonics group have developed a novel method of trapping light in solar cells based on nano-sized particles of silver. When light strikes the nanoparticles it creates a resonant oscillation of the electrons in the nanoparticle, known as a surface plasmon. The particles then re-radiate the light at high angles into the solar cell, where it is trapped by total internal reflection. This leads to increased absorption in the solar cell, and hence increased cell efficiency. A thin layer of dielectric like silicon dioxide or silicon nitride or titanium dioxide separates the metal nanoparticles from the silicon surface, to prevent degradation of the voltage produced by the solar cell. The process has been developed for silicon solar cells, but it is a very simple, versatile process that can be applied to solar cells based on any type of semiconductor.

The technique has attracted the attention of researchers worldwide, and has also been applied to organic solar cells. Work in our research group has thus far been focussed on obtaining a detailed understanding of the underlying mechanisms and optimizing the design of the nanoparticles. We have recently demonstrated the best light trapping achieved to date using plasmonics by designing the solar cell geometry based on our comprehensive understanding of the mechanism involved.

**Figure 10.** A scanning electron micrograph showing a 2 dimensional grating formed by nano-imprinting.

**Figure 11.** A scanning electron micrograph showing a silver nanoparticle grating formed by nano-imprinting.

The nanophotonics research group is also actively investigating dielectric/metallic gratings with feature sizes of few 100 nm for light trapping in solar cells. We have successfully developed nano-imprinting for easy, reliable and large scale patterning of solar cells to form light trapping dielectric and metallic grating structures.

**Very High Efficiency Solar Cells**

Researchers: Mr Soe Zin and Prof Andrew Blakers

Miniature silicon solar cells (8 x 2.0 mm²) are being fabricated for use in the VHESC six-junction tandem concentrator solar cell stack. The VHESC program initiated by the Defense Advanced Research Projects Agency program comprises around 20 contributors, and has adopted a multi-junction concentrator tandem approach. The involvement of ANU in this
program was to design and develop high efficiency silicon solar cells, which are to be used in conjunction with other high-band gap and low-band gap solar cells, for 50% efficient multi-junction concentrator solar cells.

Several factors combine to make the achievement of high efficiency problematical. These include surface, bulk and edge recombination. Surface recombination in the cells is caused by the loss of passivating hydrogen beneath a conformal LPCVD SiNx antireflection coating, induced by high temperature annealing. Bulk carrier lifetime degradation mechanisms that we have encountered include silicon crystal damage induced by laser scribing of the cells, which affects a relatively large proportion of the volume of the cell. Edge recombination in the cells is caused by the detachment, where this detachment is realized by dicing on the cell’s depletion region, of the cells out of the host wafer. Characterisations of the surface, bulk and edge recombination were undertaken to narrow down the possible factors that caused the low carrier lifetime degradation, affecting the high efficiency potentials in the miniature silicon solar cells.

Miniature silicon solar cells used a stack of oxide and nitride as passivation and anti-reflection layers. In the fabrication of miniature silicon solar cells, the oxide and nitride stack was subjected to high temperature anneals for prolonged hours. This prolonged high temperature anneals could have adverse effects on the carrier lifetime of samples. An experiment, carried out on the oxide and nitride stack samples subjected to high temperature anneals for long hours, revealed that the passivation quality of the oxide and nitride stack was degraded drastically, resulting in low carrier lifetime after the anneal as shown in Figure 12a. Subsequent hydrogenation of the samples in forming gas environment failed to recover the degraded lifetime. However, degraded carrier lifetime was recovered only after removing the annealed SiNx film in hot phosphoric acid, which selectively removed SiNx layer but leaving the oxide layer still passivating to the silicon. This recovery was further evidenced by the carrier lifetime recovery of post nitride-stripped oxide-grown samples as shown in Figure 12b.

![Figure 12. a) Behaviour of samples grown with the oxide and nitride stack after having subjected to high temperature anneals for long hours and forming gas annealing, following the nitride layer removal in hot phosphoric acid. b) Lifetime of samples grown with the oxide and nitride stack before and after the hot phosphoric acid etch.](image)

Shaping of the miniature silicon solar cells was accomplished by infrared laser scribing, which uses a Nd:YLF (1024 nm) pulsed laser, as shown in Figure 13a. Laser processing was used in our cells as it offers the capability to form the desired shape of cells on the wafer in a faster and more convenient way than alternatives such as wet etching or a dicing saw. An experiment, carried out to compare carrier lifetime of samples processed by the laser, wet etch and dicing, showed that samples processed by the laser scribing to shape the cells suffered the most carrier lifetime degradation as compared to the other samples as shown in Figure 13b.
Edge recombination in small solar cells is a problem since small cells need to be processed in the host wafer before detachment for practical reasons of wafer handling. Edge recombination is particularly significant if the pn junction extends to the cell’s edge, where the edge cut occurs, resulting in high dark saturation current, which is an equivalent of ideality factor 2. The silicon solar cells that we developed are rather small, and an experiment was undertaken to fabricate cells with different pn junction designs that minimize the chances of the edge cut occurring on the pn junction, where the significant recombination exists. The designs of cell with different pn junctions are shown in the Figure 14. Following the fabrication, cells will be tested for current-voltage measurement to compare the edge recombination effects.

The results that we achieved for the surface recombination induced by the loss of passivating hydrogen beneath a conformal LPCVD SiNx coating due to high temperature anneals, and bulk recombination caused by the laser-induced crystal damage; coupled with forthcoming results from the edge recombination study on different cell designs, we believe that a subsequent batch of cells fabricated would meet the targeted efficiency requirements.
Elongate Solar Cells for Energy Generation

Researchers: Dr Elizabeth Thomsen, Prof. Andrew Blakers, Dr Vernie Everett, Ms Maureen Bauers, Ms Erin Davies, Ms Jelena Muric-Nesic, Mr Tom Ratcliff, Mr Chris Samundset, Dr Igor Skryabin, Dr Sachin Surve, Dr Huanhuan Zhao

A $2.2 million Capability Technology Demonstration Project (CTD grant) was awarded to the Centre by the Australian Defence Department. The grant arose from ARC Centre funded work on elongate and SLIVER solar cells for one-sun and concentrator applications.

The key objective of the CTD grant is to demonstrate elongate solar cells embedded into a flexible substrate, which can be integrated with a soldier’s ensemble. These flexible modules should be lightweight (150 W/kg), operate over a wide range of temperatures (-40°C to +65°C) and light conditions, and be in the form of a roll-out module with a maximum radius of curvature of 5 cm. An example of how a small module may look is shown in Figure 15.

The PV cells required for these modules must be highly efficient as only a small area may be available for capturing light. The cells must be lightweight, and they also need to be flexible. The approach taken in this project is to use elongate solar cells. Flexible elongate cells are long, narrow, and thin. These cells are fabricated using mono-crystalline silicon, ensuring highly efficient and durable cells.

Much of the work on cell development has focussed on modifying commercially available rear-contact solar cells. All mono-crystalline silicon solar cells which are commercially available in large quantities are too thick to satisfy the flexibility requirements for this project. Hence, they need to be thinned in order to be of use. Most solar cells have contacts on both faces of the cells, making it very difficult to thin the silicon without destroying the cell. Rear-contact cells have both positive and negative contacts on the back of the cell, with light absorbed from the front of the cell.

A process has been established to successfully thin and cut commercially available cells to the required thickness and elongate dimensional profiles whilst maintaining power conversion efficiencies of up to 16%. This process involves removing the electrodes, light trapping, and passivation components of the cell, followed by thinning the silicon, then reconstructing the cell by reintroducing electrodes, light trapping, and passivation. The cells can then be cut to the desired elongate size for module fabrication. Tests on the cells have included power conversion efficiency measurements under a variety of irradiances, and cell and module flexibility tests. The cells are thinned to less than 65 μm which results in cells which can be repeatedly flexed to a small (<5 cm) radius of curvature without a noticeable deterioration in their performance.

The unusual size and shape of elongate solar cells allows for innovative design of circuit interconnects. This includes designs that minimise the impact of puncturing or shading effects that would be impractical for conventional, large area solar cells. One approach is known as “series-parallelizing”. Smaller series connected sub-modules build voltage, and these sub-modules are then connected in parallel with other sub-modules of common voltage to build current. Due to the small width of the elongate cells, voltage can be rapidly built over a small distance. In the case of puncturing or shadowing to an individual sub-module, only the power...
contribution of that sub-module is lost or reduced. The electrical circuits are realised using a
variety of techniques including ink jet printing, etching of metal layers on flexible substrates,
and conductive pastes. Small demonstration modules show efficiencies of greater than 14% at
1 sun, as shown in Figure 16.

Figure 16. Performance of a small demonstration module as a function of illumination
intensity

The small amount of silicon used in the cells means that almost all the weight of the module is
in the protective packaging. As the cells are highly efficient and silicon can survive many
terrestrial environments with minimal protection, very high power to weight ratios, exceeding
150 W/kg, are achievable with this technology. Cell interconnection and packaging are
formidable issues in modules designed to be flexed. The modules can be fabricated using a
number of approaches including constructing the circuitry separately to the packaging, or
using the packaging as both a protective layer and a base for circuitry. The total module
thickness of demonstrated prototype modules is less than 0.5 mm.

Facilities Available to the Centre

The ARC Centre for Solar Energy Systems has full access to the solar laboratories in the
School of Engineering, as well as facilities elsewhere in the University.

CSES was awarded a $5M Foundation Project by the Australian Solar Institute which is
funding a major restructure with extended laboratories, new equipment and an outdoors test
facility. Much of the new equipment is already operational, and by mid year the restructure
will be complete. Total laboratory floor area is 520m2 plus an outdoors facility of 320m2. At
present the immediate needs of researchers are being met while at the same time facilitating
construction work.

Upon completion the facilities will include:

Laboratories E122, 123, 124, and 114 are combined by the removal of all doors to provide an
unimpeded suite of semiconductor processing space. Capabilities include:

- Ten fume cupboards of various sizes and used for a variety of both specialised and
general purposes. Services are in place to accommodate another 4 cupboards as
demand grows
- Eighteen silicon processing furnaces of various sizes and functions. These include P and N type doping, oxidation, annealing and rapid thermal annealing.
- 4 chemical vapour deposition systems including atmospheric pressure, low pressure and plasma enhanced low pressure.
- Metal deposition under high vacuum conditions using two cryogenically pumped Varian deposition systems.
- Three laser dicing system with IR, Green and UV wavelengths.
- Supporting equipment including spin rinsers, etching stations, silver plating, laminar flow benches, lab ware washer.
- Equipment used for device characterisation activities. Sheet resistance, mercury probe, ellipsometer (film thickness and refractive index), photoluminescence imaging, photoluminescence spectroscopy.
- Measurement and inspection equipment including scales, microscopes and cameras.

![Figure 17. a: Research meets construction: Makeshift services to equipment crowded into Room E122, one of the old laboratories. b: The new ASI Lab taking shape: The service duct which will ultimately hide services being delivered to equipment in the room. Markings on the floor denote where equipment will be placed.](image)

E126 is a clean room with photolithographic facilities (resist spinner, HMDS & baking ovens, cassette to cassette spin coat and bake system, mask aligner). Corrosive chemical proof spin coater, flammables proof spin coater and a contra-rotating lid spin coater. Three fume cupboards and laminar flow benches.

E127 is a class 4 laser room with two independent laser systems. A UV/red/green station used for machining or surface patterning and a water jet system with dicing and doping capabilities.

E131 contains downstream processing and module/receiver assembly: three dicing saws, 2 stencil printers, hand soldering station, vapour phase soldering, automated selective soldering,
Encapsulation apparatus, vacuum chambers, multi-sun tester, accelerated life testing ovens, 3 humidity and temperature controlled environmental chambers, UV chambers, measuring microscope, workbenches.

E137 & 138 are characterisation rooms with a solar simulator, spectral response system, spectrophotometer, angle resolved spectrophotometer, IV characterisation workstations, corona discharge, temperature-dependent photo-conductance and Kelvin Probe instruments, minority carrier lifetime systems, photoconductive decay lifetime testers.

Rooftop platform: A versatile 360m² facility used for teaching and the installation of prototype and demonstration systems, to be situated on the 2nd storey of Building 32 placing it in close proximity to the laboratories and offices of the Centre for Sustainable Energy Systems. Extensive weather and radiation monitoring including global horizontal radiation, direct beam radiation, ambient temperature, relative humidity, barometric pressure, wind speed and direction, and sunlight spectral radiation. All this information is available through a networked data takers to facilitate long term testing and monitoring. There is also a 10m² tracking parabolic trough system delivering solar intensities of 30-40 kW/m² for the testing of prototype receivers.

Bruce Hall: 300m² of parabolic troughs.

E129 & 130 house the electronics workshop, jobbing area and support offices.

Mechanical Workshop: Full workshop facilities with sheet metal, machining, welding and fabrication facilities shared with Department of Engineering

Other facilities at ANU: Access to extensive facilities in other Departments, including electron microscope, PECVD, RIE, lasers, ion implanters, MOCVD and an extensive array of characterisation facilities.

**Future goals and objectives**

We are interested in both fundamental R&D and commercial R&D. The activities of the Centre are predominantly in areas that could be realistically commercialised in the 3-7 year time frame. Centre researchers aim to achieve the following research outcomes over 2008-2012:

- Be one of the top two solar research groups in Australia, and be viewed as an excellent research group on a world scale
- Continue a substantial outreach program
- Increase our involvement in education activities to train engineers and scientists for a solar future
- Continue the development of advanced characterization tools and process options for silicon.
- Continue the development and commercialization of high performance silicon solar cells for concentrator (and non-concentrator) applications
- Continue the development of SLIVER and other elongate silicon solar cells for linear concentrators, and commercialise the technology, in conjunction with partners.

**Financial stability**

An important goal of the Centre is to be in a position to carry on our work following cessation of Centre funding.

One strategy for achieving this goal is to have a prominent national and international research profile through excellent research that will allow us to maintain diversified income sources,
including income from Government and private research funds, royalties, and education (undergraduate, masters and short courses).

Large royalty income streams are flowing from commercialisation of Centre research. So far, ANU has received $3 million in royalties from Origin Energy Solar in respect of SLIVER commercialisation, with a further $1.1 million being due in August.

Activity plan for the next twelve months
Activities planned for 2010 include the following:

1. Progress contractual and technical relationships with Origin Energy Solar–Transform Solar, Chromasun and other commercial partners
2. Develop a streamlined Sliver cell process capable of delivering 22% efficient SLIVER solar cells.
3. Develop improved methods to adapt SLIVER solar cells for use under concentration.
4. Continue to improve the performance and versatility of surface coatings for reflection control
5. Further improve the understanding of, methods for suppressing, surface recombination, including the investigation of the possibility of embedding static charge within insulating layers.
6. Develop a prototype micro-concentrator receiver using modified one-sun solar cells. Integrate the prototype receiver into a micro-concentrator PV-thermal proof-of-concept test system.
7. Investigate the remaining barriers to direct liquid-immersed concentrator cell cooling, and develop a prototype direct liquid immersed PV-thermal hybrid receiver to proof-of-principle stage
8. Development of design of plasmonic solar cells for increasing the light absorption in thin solar cells
9. Optimize the nano-imprinting technique for different materials like TiO2, Al2O3 etc.
10. Develop conceptual understanding and design of nanometer sized dielectric grating structures for optimal light trapping.
11. Develop a prototype flexible module, and integrate with selected applications.

Education and Training
Researchers associated with the Centre delivered lectures and tutorials in undergraduate courses ENGN2224 (Semiconductors) and ENGN3227 (Analogue Electronics). Also Dr. Klaus Weber was convenor for the BE R&D degree, an elite Engineering degree for academic high achievers. Several final year Engineering students undertook projects in the Centre during the year.

Advisory Board of the Centre
The Advisory Board met in May, August, and November 2009. Substantial interactions between Centre researchers and members of the Advisory Board continued throughout the year.

The role of the Advisory Board is to provide strategic advice on the research focus of the Centre, to provide an independent perspective on Centre structure and operating principles, to
provide advice on intellectual property and commercialisation management and to assist with external contacts, linkages and relationships as the opportunity arises.

The Board played a major role in resolution of issues relating to the relationship between the University, the Centre and Origin Energy Solar. It also provided strategic advice in relation to technology directions and commercial opportunities.

The advice of the Board is highly valued.

Mr Ian Farrar – Chair of the Board
Ian Farrar has a distinguished career in senior management in CSIRO and the coal industry. He has a Bachelor of Commerce from ANU.

From 2002 until his retirement in 2005 he was Managing Director/CEO of Coal Services Pty Limited (CSPL), Coal Mines Insurance Pty Limited (CMI) and Mines Rescue Pty Limited, as well as Chairman of Coal Services Health and Safety Trust and Injury Prevention and Control Australia Limited.

From 1992-2002 he was Chairman/CEO of the Joint Coal Board, Coal Mines Insurance Pty Limited and the Joint Coal Board Health and Safety Trust

From 1964 to 1992 he held a range of senior management position within CSIRO, including General Manager (Corporate Resources) and Senior Principal Advisor (Special Projects).

Professor Chris Baker
Professor Chris Baker commenced an appointment as Dean of the College of Engineering and Computer Science in September 2008 and replaced the Acting Dean, Professor Mick Cardew-Hall on the advisory board. Previously he held the Thales-Royal Academy of Engineering Chair of intelligent radar systems based at University College London. He has been actively engaged in radar system research since 1984 and is the author of over one hundred and fifty publications. His research interests include Coherent radar techniques, radar signal processing, radar signal interpretation, Electronically scanned radar systems, natural echo locating systems and radar imaging. He is the recipient of the IEE Mountbatten premium (twice), the IEE Institute premium and is a fellow of the IEE. He is also currently chairman of the IEE Radar, Sonar and Navigation systems professional network. He is a visiting Professor at the University of Cape Town, Cranfield University, University College London and Adelaide University.

Mr Merv Johnston
Merv Johnston (B.Eng (Syd), FIEAust) has more than thirty years experience in industry, including multinational private sector organisations; management consulting; as founder and principal shareholder of a small computer sales and service company; and in the public sector. He is currently Managing Director of CVC REEF Limited, which specialises in providing Venture Capital to businesses which are commercialising innovative Renewable Energy technologies, Managing Director of Magma Pty Limited, a management consultancy, specialising in the innovation and commercialisation processes, and early stage businesses, and a Director of Windcorp Australia Limited.

Ms Susan Neill
Susan Neill has a tertiary background in mathematics and modern languages.

Susan commenced working in the renewable energy industry at a wholesale level in 1986, obtained PV System Design Accreditation and completed postgraduate Applied PV certificate from UNSW. She became involved in the development of the Solar Energy Industry Association of Australia (SEIIA) in 1990 through to its present status as part of the Business Council for Sustainable Energy, fulfilling the role as National President of SEIIA through the mid 1990s. Susan is currently a member of the PV Directorate for BCSE.
Susan was formerly Managing Director of Quirk's Victory Light Co. Pty. Ltd. - Energy Today. This company specialised in stand-alone and grid-connected wind and solar systems. In 2005 Quirks was acquired by Conergy. Sue is now Conergy Australia’s Business Development Manager for off-grid and on-grid products and services.

Susan has broad experience in industry development issues and a wide network of contacts at industry level.

**Dr Hugh Saddler**

Hugh Saddler, BSc (Hons) Adelaide, PhD Cantab., FAICD, is the Managing Director of Energy Strategies, a consultancy company he established in 1982, specialising in the fields of energy, environment and technology economics and policy. He has been fully engaged in the analysis of major national energy policy issues, with a strong and consistent emphasis on energy system sustainability, in the UK and Australia as an academic, government employee and consultant, since 1973. He is the author of a book on Australian energy policy and of over 70 scientific papers, monographs and articles on energy, technology and environmental policy. He is also a regular commentator in the electronic and print media. He was a member of the Board of ACT Electricity and Water (ACTEW) from 1991 to 1995.

**Award**

Dr Kylie Catchpole, NSW/ACT Young Tall Poppies in Science Award, from by the Australian Institute of Policy and Science: “Kylie investigates how light interacts with semiconductors, so that better, cheaper solar panels can be designed. She is part of a world-class research team looking at all aspects of how solar energy can become a major part of the world’s energy supply. Through their research we have discovered that covering solar cells with tiny particles of silver helps to absorb light better.”

Kylie Catchpole (ARC Centre for Solar Energy Systems, ANU; middle right) and Nicholas Robins (Department of Nuclear Physics, ANU; middle left) and receive their awards from Professor John Close (Research School of Physics and Engineering, ANU; far left) and Professor Robin Stanton (Pro Vice-Chancellor, E-Strategies, ANU; far right), 29 October, 2009. Kylie: “I’m very pleased to receive this award for the work that my colleagues and I are doing on new ways to improve the efficiency of solar cells. I’m also grateful for the opportunity to share how much fun science is with school students as part of the Young Tall Poppies outreach program.”
Publications

The commercial value of solar cell intellectual property developed by the Centre is large. In the absence of substantial Government basic R&D funding programs, it has been necessary to rely substantially upon commercial income from applied R&D projects. These two factors, together with the associated legal and commercial constraints, continue to heavily restrict output from publications.

Book Chapters


Papers in refereed scientific and technical journals


S. Mokkapati, F.J. Beck, A. Polman and K.R. Catchpole, "Designing periodic arrays of metal nanoparticles for light-trapping applications in solar cells", Applied Physics Letters 95,


Conference papers

Singapore-Australia Solar Energy Workshop, Canberra, 30–31 March 2009


34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia, 7–12 June 2009


47th Australian and New Zealand Solar Energy Society Conference, Townsville, 29 September–2 October, 2009


19th Photovoltaics Science and Engineering Conference and Exhibition, ICC Jeju, South Korea, 9–13 November 2009


International Photovoltaic Solar Energy Conference, Beijing (China), 18–20 November 2009


Articles

Invited Addresses


K. Catchpole, “Light trapping with metal nanoparticles for solar cells”, Invited Address, 3rd Nanophotovoltaics Workshop, Foundation for Fundamental Research on Matter (FOM) Institute for Atomic and Molecular Physics (AMOLF), Amsterdam, 20 June 2009

Seminars

A. Blakers, "Solar energy is special", The Australian National University, Canberra, Australia, March 2009

Igor Skryabin, “Solar Energy in Australia”, Presentation to staff and students of Anna University, Chennai, January 2009


Collaborating Institutions and Companies

Institute for Atomic and Molecular Physics (AMOLF), Amsterdam
Anna University, Chennai, India
BraggOne, Finland
Caltech, USA
Centrotherm, Germany
Chromasun, Inc, USA
Defense Science and Technology Organisation, (DSTO)
Dow Corning, USA
Energy Research Centre of the Netherlands (ECN), Petten, The Netherlands
Fraunhofer Instituts für Solare Energiesysteme (ISE), Freiburg, Germany

Heriot-Watt University, Edinburgh, Scotland
Institut für Solarenergieforschung Hameln (ISFH), Germany
Origin Energy Solar – Transform Solar
SierraTherm, USA
Sinton Consulting, USA
Spark Solar
SunPower, USA
Tianjin University, Tianjin City, People’s Republic of China
University of New South Wales

Contractual Partners

Asia Pacific Partnership Program
Defense Science and Technology Organisation, (DSTO)
Australian Research Council
BraggOne, Finland
Chromasun, Inc, USA
Defence Advanced Research Project Agency

Department of Environment & Water
Department of Innovation, Industry, Science and Research
Dow Corning, USA
GP Solar–Centrotherm, Germany
Origin Energy Solar – Transform Solar
Spark Solar
Visits: Research Partners, Stakeholders, and Peers

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<td>Griffith Hack (Patent Attorneys And Intellectual Property Lawyers), 5 Feb</td>
<td>Tim Staley (Principal)</td>
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<td>Singapore Polytechnic, 20 February</td>
<td>Dr Jiang Fan</td>
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<td>French Scientific Delegation and French Embassy, 27 February</td>
<td>Yves Le Bars and Sebastien Velut; Pr Michel Thibier</td>
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<td>National University of Singapore, 5 March</td>
<td>Prof Tan Chorh Chuan (President)</td>
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<td>Anna University, India, 23 March</td>
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<td>Commonwealth Department of Innovation, Industry, Science and Research, 27</td>
<td>Markus Gorondi, Diane Wilson, Shane Baker (Industry Government</td>
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<td>Consultative Committee)</td>
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<td>Singapore-Australia Solar Energy Workshop, Canberra, 30–31 March 2009:</td>
<td>40 senior solar energy researchers</td>
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<td>organised by Centre</td>
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<td>Anna University, Chennai, 20 April–19 May</td>
<td>Joseph Daniel</td>
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<td>Commonwealth Department of Defence, 28 April</td>
<td>Delegation from Capability and Technology Demonstrator program</td>
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<td>Commonwealth Department of Innovation, Industry, Science and Research, 8 May</td>
<td>Penny Sackett (Chief Scientist)</td>
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<td>Chinese Scientific Delegation and Chinese Embassy, 26 May</td>
<td>Chinese Ambassador with a group of 24 senior officials</td>
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<td>Australian Solar Institute, 6 June</td>
<td>Establishment Committee</td>
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<td>Silex Systems Limited, 16 June</td>
<td>Michael Goldsworthy</td>
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<td>A*Star Singapore, 16 June</td>
<td>Jeff Obbard (A/P)</td>
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<td>King Saud University, 7 July</td>
<td>Dr Khaled Al Farahan (Vice-Dean, College Of Science)</td>
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<td>Environment ACT, 24 July</td>
<td>David Papps (Executive Director)</td>
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<td>Commonwealth Parliament, 14 August</td>
<td>Bob McMullan (MP)</td>
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<td>Tianjin University and Commonwealth Department of Innovation, Industry,</td>
<td>Launch of Tianjin University–ANU DIISR International Science</td>
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<td>Science and Research</td>
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<td>Tianjin University, Tianjin City, People’s Republic of China, 1 July–30</td>
<td>Prof Li Zhu, Dr Qunwu Whang</td>
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<td>Sunergy, Pty Ltd, 28 September</td>
<td>Phil Connor</td>
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<td>Politecnico di Torino, Turin, Italy, November 2009–March 2010</td>
<td>Cristina Scarzella (Visiting Scholar)</td>
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<td>Copper Development Centre , 13 November</td>
<td>John J Fennell (CEO)</td>
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<td>Fraunhofer Instituts für Solare Energiesysteme (ISE), Freiburg, September</td>
<td>Jan Benick, Philip Granek</td>
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<td>DSTO, Air Vehicles Division, 9 December</td>
<td>Geoff Brian</td>
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<td>From the Centre</td>
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<td>International PV Conference PVSEC 18, Kolkata, India, 19 January</td>
<td>Igor Skryabin</td>
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<td>ADC Future Summit in Melbourne, 19 May</td>
<td>Andrew Blakers (Invited Panellist and Discussion Leader)</td>
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<td>Launch of ERIAN at NTU, Singapore, 3 June</td>
<td>Andrew Blakers (Invited Speaker)</td>
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<td>34th IEEE Photovoltaic Specialists Conference (PVSC), Philadelphia, 7–12 June 2009</td>
<td>Keith McIntosh, Bijaya Paudyal, Zhang Chun, Soe Zin</td>
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<td>ANU Climate Change Institute open day, 27 July</td>
<td>Andrew Blakers (Invited Presentation)</td>
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<td>Switch to Green Conference, Canberra</td>
<td>Andrew Blakers (Workshop Leader)</td>
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<td>Fraunhofer Instituts für Solare Energiesysteme (ISE), Freiburg, September</td>
<td>Klaus Weber</td>
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<td>Tianjin University, Tianjin City, People’s Republic of China</td>
<td>Vernie Everett, Daniel Walter</td>
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<td>Surface Plasmon Polaritons 4 Conference, Amsterdam, June</td>
<td>Kylie Catchpole</td>
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<td>3rd Nanophotovoltaics Workshop, Amsterdam, June</td>
<td>Kylie Catchpole</td>
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<td>DSTO Air Vehicles Division, 31 August</td>
<td>Igor Skryabin</td>
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<tr>
<td>Fraunhofer Instituts für Solare Energiesysteme (ISE), Freiburg, September</td>
<td>Jin Hao</td>
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<td>International Solar Centre Konstanz, Germany, September</td>
<td>Jin Hao, Erin Davies</td>
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<td>Korea-Australia Renewable Energy and Policies, Korean Embassy, Canberra</td>
<td>Igor Skryabin (Invited Presentation)</td>
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<tr>
<td>24th European Conference on Photovoltaic Solar Energy Conversion (EUPVSEC), Hamburg, 21–25 September 2009</td>
<td>Kean Fong, Nicholas Grant, Jin Hao, Teng Kho, Keith McIntosh, Bijaya Paudyal, Maria Talló, Andrew Thomson, Marta Vivar, Klaus Weber, Zhang Chun, Soe Zin</td>
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<td>47th Australian and New Zealand Solar Energy Society Conference, Townsville, 29 September–2 October, 2009</td>
<td>Vernie Everett, Elizabeth Thomsen, Soe Zin</td>
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<td>19th Photovoltaics Science and Engineering Conference and Exhibition, ICC Jeju, South Korea, 9–13 November 2009</td>
<td>Natalita Nursam</td>
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<td>International Photovoltaic Solar Energy Conference, Beijing, 18–20 November 2009</td>
<td>Marta Vivar</td>
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<td>Defence Housing Association (Peter Howman, COO), 24 November</td>
<td>Igor Skryabin</td>
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<td>Materials Research Society (MRS) Annual Fall meeting, Boston, November</td>
<td>Sudha Mokkapati</td>
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### Outreach activities

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<td>11 March</td>
<td>2 April</td>
<td>7 May</td>
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<tr>
<td>Large article with photo in the Canberra Times about solar and ASI</td>
<td>Clean Energy for Eternity, meeting of technical committee</td>
<td>ABC Radio Victoria interview on solar power</td>
<td>Submission to the Senate inquiry into climate policy</td>
<td>ANU Exchange - the Green Centre workshop</td>
<td>Eco investor magazine June issue featured our CHAPS system</td>
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<td>Interview, ABC Radio (Canberra) about ASI</td>
<td>ACTPLA energy workshop, University House, advisory role</td>
<td>Dr Maxine Cooper (ACT Commissioner for the Environment)</td>
<td>ABC Radio National Bush Telegraph interview and talk back about solar power</td>
<td>Careers advisors – lab tour and presentation</td>
<td>Quoted in an article in the Canberra Times about Australian solar innovation</td>
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<td>A follow-up article with photo in the Canberra Times about solar and ASI</td>
<td>Presentation on solar energy to the U3A community group</td>
<td>Interview, ABC Radio (Canberra) on solar power facility</td>
<td>Dickson College IT Class Visit</td>
<td>The Age newspaper, report on energy panel discussion (ADC Future Summit)</td>
<td>St Francis Xavier College Sustainable Careers Expo</td>
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<td>Spark Solar/ANU media release re. 2 ARC Linkage projects</td>
<td>Interview, Australian Financial Review: projects with Spark Solar</td>
<td>Hon. Gerry Brownlee (Minister of Energy &amp; Resources, New Zealand)</td>
<td>Invited talk at the IPOS launch, Sydney University</td>
<td>Interview, ABC Radio: projects with Spark Solar</td>
<td>Interview with reported from Canberra Times</td>
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<td>Interviews, ABC Radio and Luna media, following media release about 2 Linkage grants with Spark Solar</td>
<td>Meeting with the ACT Greens MLAs to discuss energy efficiency options for housing</td>
<td>Invited talk at the IPOS launch, Sydney University</td>
<td>Celebrate Sustainability Day, Union Court, ANU</td>
<td>Submission to the Inquiry into ACT greenhouse targets</td>
<td>Quoted in an article in the Canberra Times about solar rebates</td>
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<tr>
<td>July</td>
<td><strong>Radio interview with ABC Goulburn Murray on solar rebate</strong></td>
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<td></td>
<td><strong>Visit of two ACT Greens MLAs</strong></td>
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<td><strong>Quoted in an article in the Canberra Times about solar rebates</strong></td>
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<td></td>
<td><strong>Guest on ABC Radio “Australia talks” discussing rooftop PV systems</strong></td>
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<td></td>
<td><strong>Instigated high-level ACT Govt forum: Reducing GHG Emissions through Retrofitting Buildings</strong></td>
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<tr>
<td>August</td>
<td><strong>ABCTV, ABC radio, discussing domestic solar systems</strong></td>
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<td></td>
<td><strong>Letter in the Canberra Times in support of a solar feed in tariff</strong></td>
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<td></td>
<td><strong>Submission to the Senate inquiry into the 20% renewable energy target</strong></td>
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<td><strong>Invited oral evidence to the ACT Legislative Assembly Inquiry into ACT greenhouse targets</strong></td>
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<td></td>
<td><strong>Quoted in Canberra Times in respect of solar power</strong></td>
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<td>August</td>
<td><strong>Visit of Bob McMullan MP</strong></td>
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<td></td>
<td><strong>2 TV, 2 radio and 1 newspaper interview on the ANU–Tianjin University project</strong></td>
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<td></td>
<td><strong>19 separate media items arising from ANU–Tianjin University project press release of 20 August</strong></td>
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<td></td>
<td><strong>ABC Radio National Breakfast panel: solar power</strong></td>
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<td><strong>Canberra Times, Photo and text on the ANU–Tianjin University project</strong></td>
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<td><strong>ABC Radio SE interview on solar power</strong></td>
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<td></td>
<td><strong>“Energy Futures” session panel member, Australian Leadership Retreat, Hayman Is</strong></td>
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<td>September</td>
<td><strong>Participation in the ANU Media Program, spending 90 min with a dozen senior journalists</strong></td>
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<td><strong>EcoInvestor magazine, article on solar power</strong></td>
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<td><strong>Workshop leader, Switch to Green Conf, Canberra</strong></td>
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<td><strong>Attending function- the Embassy of China</strong></td>
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<td>October</td>
<td><strong>EcoGeneration (Sept–Oct issue), article on Centre Innovation ACT: participation and support</strong></td>
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<td>November</td>
<td><strong>Interview, ABC Radio (Wodonga), feed in tariffs</strong></td>
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<td>December</td>
<td><strong>Canberra Times article and photo on solar IP</strong></td>
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<td><strong>Centre featured in movie, “Eye of the Future”, shown at COP, Copenhagen</strong></td>
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</table>
### Key Result Areas and Performance Measures

<table>
<thead>
<tr>
<th>Performance measure</th>
<th>Target</th>
<th>Outcome</th>
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<tbody>
<tr>
<td><strong>Research findings</strong></td>
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<tr>
<td>Publications</td>
<td>2/yr in general journals such as Applied Physics Letters, Journal of Applied Physics, Electron Device Letters</td>
<td>12 refereed journal articles</td>
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<td>2/yr in solar energy journals such as Progress in Photovoltaics and Solar Energy Materials and Solar Cells</td>
<td>6 non-refereed in solar energy journals, 5 seminars</td>
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<td>2/yr in international conferences</td>
<td>25 international conf. papers</td>
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<td>2/yr in local conferences</td>
<td>7 local conference papers</td>
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<tr>
<td>Number of patents</td>
<td>Two over 5 years</td>
<td>0 patent applications (total of 13 to date)</td>
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<tr>
<td>Invitations to address and participate in national and international conferences</td>
<td>Five per 5 years</td>
<td>2 invitations (total of 8 to date)</td>
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<td>Number and nature of commentaries about the Centre’s achievements</td>
<td>1/year in quality lay publications</td>
<td>Hundreds – see the lists of publications and outreach activities</td>
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<td>1/year in electronic media</td>
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<td><strong>Research training and professional education</strong></td>
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<tr>
<td>Number of postgraduates recruited</td>
<td>Three per 5 years</td>
<td>Simeon Baker-Finch, PhD commenced Q1 2009; Dielectrics for the front surface of high-efficiency solar cells</td>
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<td>Fiona Beck, PhD commenced Q1 2007; Increasing light absorption in silicon using metallic nanoparticles and photonic structures</td>
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<td>Kean Fong Chern, PhD commenced Q1 2008; Ultra-thin elongate solar cells,</td>
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<td>Nicholas Grant, PhD commenced Q1 2008; Low-cost passivation of silicon surfaces</td>
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<td>Natalita Nursam, MPhil commenced Q3 2008; Electrical properties of boron diffused emitters</td>
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<td>Bijaya Paudyal, PhD commenced Q1 2006; Application of temperature and injection dependent lifetime spectroscopy to surface passivation of silicon semiconductors</td>
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<td>Lisa Ren, PhD commenced Q2 2008; Optimising charge in silicon nitride films</td>
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<td>Andrew Thomson, PhD commenced Q1 2006; Studies of silicon oxide ageing and titanium oxide passivation of silicon for use in solar cells</td>
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<td>Er-Chien (Eric) Wang, MPhil commenced Q3 2008, transferred to PhD Q4 2009; Controlled fabrication of nanophotonic structures for photovoltaic applications</td>
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<td>Chun Zhang, PhD commenced Q2 2007; The Influence of Hydrogen on Surface Passivation of Silicon-Silicon Dioxide Interfaces</td>
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<td>Ngwe Soe Zin, PhD commenced Q2 2007; Concentrator silicon solar cells for tandem packages</td>
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<tr>
<td>Performance measure</td>
<td>Target</td>
<td>Outcome</td>
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| Number of postgraduates completions | Three per 5 years | Wendy Jellett, PhD completed Q1 2009; *Characterization of boron diffused n-type silicon as an emitter*  
David Barton, PhD completed Q1 2008; *Social issues of sustainable technologies*  
Luke Johnson, MPhil completed Q1 2008  
Jin Hao, PhD completed Q3 2007; *Semiconductor processes*  
Evan Franklin, PhD completed in 2006  
Joe Coventry, PhD completed in 2004 |
| Number of Honours students or Summer Scholars | Two per year | Averaging 6 per year |
| Number and level of undergraduate and high school courses in the priority area of solar energy | At least two relevant undergraduate courses delivered per year | 3 relevant undergraduate courses delivered |
| Number and nature of commercialisation activities | Per 5 years: Two substantial; many minor commercial interactions | Major commercialisation of Sliver cells in progress (Origin Energy)  
Major commercialisation of PV/thermal hybrid concentrators in progress (Chromasun) |
| International, national and regional links & networks | | |
| Number of international visitors | Two per year | 46 |
| Number of national and international workshops and conferences attended | Two per year | 13 |
| Number of visits to overseas laboratories | Two per year | 4 |
| Examples of relevant social science and humanities research supported by the Centre | At least one significant program supported most of the time | Robin Tennant-Wood continued a study of the history of solar research at ANU, incorporating oral and written history from the Australian solar pioneers.  
David Barton, PhD scholar, investigated the technical and social issues curtailing application of renewable energy on Norfolk Is.  
Christian Bast (a Diplomarbeit student) investigated commercialisation processes in Australian Universities using Centre research as an example  
Active in promoting reductions in greenhouse gas emissions (see Outreach section) |
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<tr>
<th>Performance measure</th>
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<th>Outcome</th>
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<tr>
<td>Number of Centre associates trained/ing in technology transfer and commercialisation</td>
<td>3 (either formally or by experience)</td>
<td>Many staff are acquiring commercial experience through active collaborations with a dozen companies</td>
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<td>Number and nature of public awareness programs</td>
<td>One substantial media program on a particular theme per year</td>
<td>Sliver cells</td>
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<td>Solar energy solutions to climate change</td>
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<td>Number of government, industry and business briefings</td>
<td>3 per year</td>
<td>Many – see Outreach list above</td>
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<tr>
<td>Networking contributions to the solar energy industry</td>
<td>Substantial non-technical contributions to solar energy industry development</td>
<td>Many – see Outreach list above</td>
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<td>Organisational support</td>
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<tr>
<td>Annual cash contribution from collaborating organisations</td>
<td>ANU: at least $90,000 per year cash</td>
<td>Received.</td>
</tr>
<tr>
<td>Annual in-kind contributions from collaborating organisations</td>
<td>ANU: provision of the salary of the Research Director and Deputy Research Director</td>
<td>Director’s salary received</td>
</tr>
<tr>
<td>Level and quality of infrastructure provided to the Centre</td>
<td>ANU: Full access to ANU research facilities, including CSES laboratories</td>
<td>Achieved</td>
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</table>
| Acquisition of additional support for Centre activities                              | Additional grants or commercial investment at ANU that make use of Centre IP directly or indirectly. | ASI Foundation grant, $5 million to develop improved solar laboratories, 2009-10.  
ASI grant for Plasmonics for high efficiency solar cells, $1.6 million, 2010-12  
ASI grant for Next generation SLIVER solar cells, $5 million, ANU and Origin Energy Solar, 2010-12  
(improved processing technology for production of competitive SLIVER solar cells)  
ARC Linkage LP100100741, Advanced Sliver solar cells, ANU and Origin Energy Solar, $938,000, 2010-12 (fabrication of 22% efficient SLIVER cells)  
ARC Linkage LP100100808, Efficient PV-Thermal Micro-concentrator, ANU and Chromasun, $237,000, 2010-12  
Australia-India Special Research Fund grant for “Indo-Australian Workshop on Solar Energy”, Skryabin, $50,000, 2010.  This project is related to the $380,000 AISRF project.  
LIEF grant and Major Equipment grant to purchase a 4-stack furnace  
APP grant of $1.6 million  
Defence CTD grant of $2.2 million  
ISL grants of $0.7 million                                                                 |
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<th><strong>Governance</strong></th>
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<td>Breadth and experience of the members of the advisory board</td>
<td>Membership by senior academic and commercial people</td>
<td>Senior academic, Government and commercial people have accepted positions on the Advisory Board. Biographies attached to the Annual Report.</td>
</tr>
<tr>
<td>Frequency and effectiveness of advisory board meetings</td>
<td>Two per year; effective Board briefings; effective interaction between the Board and Centre</td>
<td>Board meetings were held in May, August and November. Regular contact was maintained with Board members between meetings.</td>
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<td>Quality of the Centre strategic plan</td>
<td>Effectively guides Centre activities; reviewed and updated regularly</td>
<td>Reviewed during the year</td>
</tr>
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<td>The adequacy of the Centre’s key performance measures</td>
<td>Reflect Centre focus; are challenging but achievable with available resources; are updated as required.</td>
<td>Reviewed during the year</td>
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<tr>
<th><strong>Performance measure</strong></th>
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<th><strong>Outcome</strong></th>
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<td><strong>National benefit</strong></td>
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<tr>
<td>Measures of expansion of Australia's capability in the priority area of solar energy</td>
<td>Good research outcomes; good research training outcomes</td>
<td>Centre personnel had a major role in the provision of $100 million for the Australian Solar Institute (ASI). The Australian National University is one of three Core Participants, reflecting their pre-eminent positions in solar research in Australia. In 2009 an award of a $5 million Foundation Grant was made by ASI to upgrade and extend the Centre’s laboratories, and to acquire a greatly expanded range of process and characterisation equipment.</td>
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<tr>
<td>Contributions to economic, social, cultural and environmental benefits of solar energy</td>
<td>Good commercial outcomes; good outcomes from outreach activities</td>
<td>Origin Energy Solar and Micron (a large US semiconductor memory manufacturer) have formed a joint venture called Transform Solar to bring together Origin’s SLIVER capability and Micron’s large scale production and manufacturing capability. This is an exciting development in the commercialisation process. Successful commercialisation will spark strong scientific and commercial interest in adapting non-concentrator SLIVER technology for concentrator applications. Highly visible Outreach program.</td>
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