Tandem PV Micro Concentrator

Project results and lessons learnt

Lead organisation:	Australian National University		
Project commencement date:	01/12/2017	**Completion date:**	01/03/2021
Date published:	19/02/2021		
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This project received funding from the Australian Government through ARENA, the Australian Renewable Energy Agency.

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Executive Summary

The project funded the development of a novel tandem solar photovoltaic (PV) micro concentrator module. The lightweight, thin-form linear PV tandem micro concentrators are capable of being mounted on standard PV single axis tracking support systems that are being deployed in large quantities around the world.

The best commercial and laboratory silicon-only solar cells have efficiencies in the range 23-27%. In order to reach efficiencies of 30% and beyond, tandem solar cells comprising of two or more different materials must be used. Silicon (Si) is often used as the rear cell in tandem devices along with a higher bandgap top cell.

III-V materials such as gallium arsenide (GaAs) are promising candidates as high bandgap top cell due to their excellent efficiency and stability. However, these materials are expensive. In order to develop a commercially competitive GaAs/Si tandem solar cell system, the cost of the GaAs component must be reduced. This project aims to achieve this by using the ANU developed Sliver technique for creating GaAs solar cells, in conjunction with a micro concentrator system.

Individual measurements of the GaAs solar cells under concentrated light, combined with simulated performance measurements of the underlying silicon cell, indicate a tandem efficiency ≥ 30 % could be achieved using this system.

The integration of the micro concentrator, GaAs and Si cells into an improved tandem PV micro concentrator module capable of being mounted on a solar tracker has been completed, demonstrating that all the components can function together effectively. The underlying efficiency of the GaAs/Si cells combined was 30%. Accelerated lifetime testing of the tandem PV micro concentrator module demonstrated its high durability and stability.

The creation of narrow grooves through the GaAs wafer (an integral part of the SLIVER process) has been achieved using both a dicing saw and plasma etching. The former enabled the formation of GaAs SLIVER cells with a pitch (groove + GaAs SLIVER) of less than 50 µm. Inductively coupled plasma reactive ion etching (ICP/RIE) has been investigated for further improving the pitch and quality of the groove etching. A working thin GaAs SLIVER cell was also demonstrated. The production of narrow GaAs grooves, a working GaAs SLIVER cell and the demonstration of a fully functioning tandem PV micro concentrator module are important steps towards achieving a high efficiency and potentially commercially competitive tandem PV micro concentrator.

The main impediment to progression of GaAs/Si tandem cells is the high cost of GaAs. A concentrator system such as the one described above substantially ameliorates this cost. However, it is very difficult to obtain reliable estimates for the cost of GaAs wafers when produced at very large scales. It will certainly be much lower than at present, but whether it is sufficiently low could not be ascertained.

Project Overview

Project summary

The project aimed to develop a potentially commercially competitive GaAs/Si tandem system based upon a GaAs cell placed at the focus of a liner concentrator, and an underlying non-concentrator Si cell that collects diffuse light and sub-bandgap light that is not absorbed by the GaAs cell. This report details the testing and integration of working GaAs and silicon cells into an improved tandem PV micro concentrator module and formation of GaAs SLIVER cells.

Project scope

The Project was designed to develop a tandem PV micro concentrator module with a high efficiency and reliability while keeping material costs to a minimum. Currently, the world's highest efficiency solar cells are made of expensive III-V materials in tandem or multi-junction arrangements.

In order to reduce the materials cost, the Project aims to utilise the SLIVER technique (developed at ANU for silicon solar cells) and apply it to GaAs. The SLIVER technique will allow for GaAs wafers to be processed in a way that increases the surface area per wafer that is available for light collection. This, in conjunction with the micro concentrators, will reduce the total amount of GaAs material required for the tandem device.

The other novel feature of the tandem device is having a standard large-area silicon solar cell on the rear as the bottom cell. This allows the silicon cell to receive concentrated direct light that passes through the GaAs cell, as well as collecting diffuse sunlight that is not concentrated by the micro concentrators. The device is designed to be mounted on standard single-axis PV trackers that are used in most ground-mounted PV power stations.

The ANU tandem micro-concentrator utilises two physically and electrically separate solar cells with the GaAs solar cell bonded to an optical concentrator and behind it a silicon solar cell, as shown in Figure 1. In this design, GaAs is used as the top solar cell, which absorbs the concentrated sunlight up to wavelength of about 870 nm. The concentrated sunlight with wavelength longer than 870 nm passes through the GaAs cell and is absorbed by the bottom large-area silicon solar cell. This configuration allows the silicon solar cell to absorb diffuse light that is not focused by the micro concentrators as well as concentrated light that is not absorbed by the GaAs solar cell. The diffuse sunlight collected by the concentrator may account for between 10-50% of the total sunlight depending on the atmospheric conditions. The entire module is designed to be mounted on a single-axis tracking system.

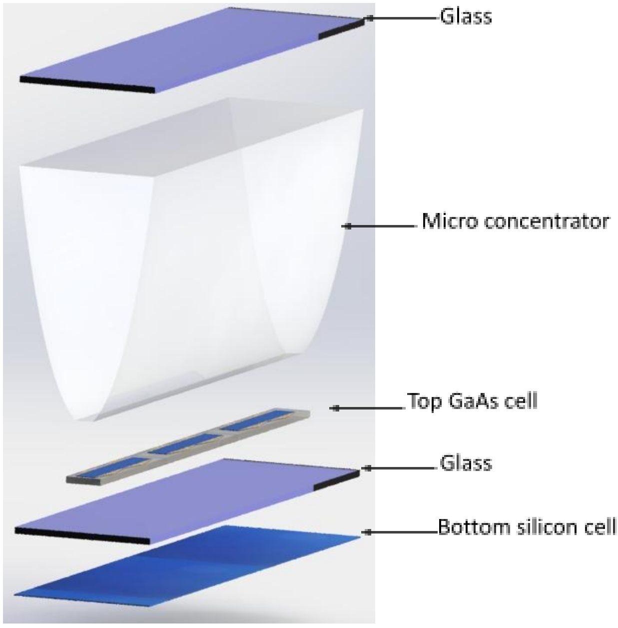

Figure 1: Representation of all the parts of the ANU micro-concentrating solar photovoltaic collector.

Outcomes

Demonstration of GaAs SLIVER cells

The ability to form grooves and SLIVERs with a pitch (groove + SLIVER) of less than 50 µm through a GaAs wafer is critical to the feasibility of a GaAs SLIVER system. Narrow deep grooves were formed using either mechanical dicing or inductively coupled plasma/reactive ion etching (ICP/RIE).

It could be possible to etch very high aspect ratio grooves into a GaAs wafer with the ICP/RIE method. The most important factor to maintain is the vertical and constant shape of the groove. So far, the ICP/RIE method has shown promising results as shown in Figure 2 for groove widths of about 20, 15, and 10 µm. The deepest grooves so far achieved with ICP/RIE are 100 µm deep. Further optimisation of the ICP/RIE method could potentially etch all the way through a GaAs wafer.

Figure 2: Grooves in GaAs after 30 minutes of ICP/RIE method for groove widths of about 20 (left), 15 (centre) and 10 µm (right).

The mechanical formation of the grooves using a mechanical dicing saw is a relatively simple method. However, there are limitations such as the dicing blade shape and thickness that affects the groove width/pitch, kerf losses, cracks and chipping at the top/bottom surfaces of the GaAs and the overall mechanical stability of the GaAs during dicing. Nonetheless, it enable the formation of GaAs SLIVERs with a thickness of less than 16 µm, groove of 25 µm (pitch of less than 50 µm) and length of 2 cm as shown in Figure 3.

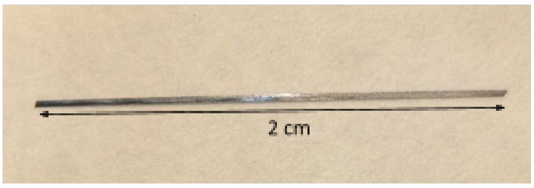

Figure 3: GaAs SLIVER lateral view (left) and thickness from the top view close-up (right).

Mechanical dicing of GaAs SLIVER provides a useful and simple method. However, it is extremely challenging to produce high efficiency SLIVER GaAs solar cells and/or scale up this process because of the limitations of this method in terms of pitch, groove width and rough finish.

Improved Tandem Concentrator Module

The integration of working GaAs and silicon solar cells into a tandem concentrator module consists of bonding (optically and mechanically) all the components that make the tandem concentrator module.

The ANU tandem PV micro concentrator module prototype is composed of the front glass, one micro concentrator made of acrylic, GaAs solar cells and one silicon solar cell as was shown in Figure 1. These components were bonded mechanically and optically using transparent durable materials such as epoxy and silicone gels. Electrical connections to the GaAs and silicon cell were done by attaching wires to the cells. The complete tandem concentrator module assembly is housed inside a weatherproof box for mounting outdoors on a solar tracker as shown in Figure 4.

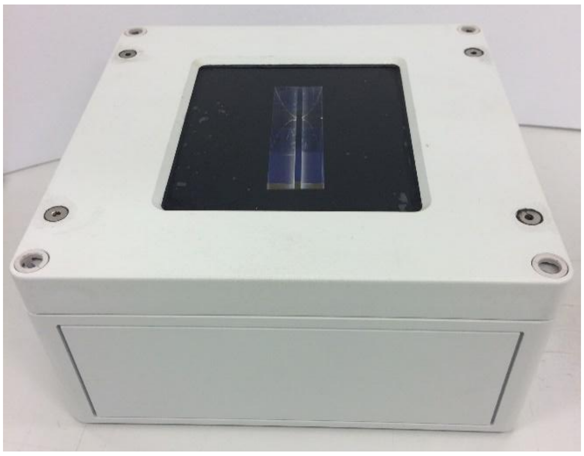

Figure 4: Tandem micro concentrator module improved prototype.

Measurements of the tandem micro concentrator module in a sunny day of January in Canberra are summarized in Table 1. The 25% tandem module efficiency is the addition of the efficiencies of the GaAs and silicon cells embedded in the tandem module. The GaAs cells in the module had a maximum of 22% efficiency and the silicon cell 3% efficiency. The efficiency of the silicon cell is underestimated because with only one acrylic micro concentrator of dimensions 7.5 cm x 2.2 cm only a small fraction of the standard large-area silicon cell (12.5 cm x 12.5 cm) is under illumination. In a commercial module, the full area of the silicon cells would be covered with micro concentrators so the efficiency of the silicon cell would be higher than in this prototype tandem module. It is expected that the efficiency of the silicon cell would increase by about 1% absolute once its full area is covered with micro concentrators. Further optimisation of the tandem module components could increase the efficiency of the tandem micro concentrator module to 30%.

Table 1: Results summary for GaAs solar cells fabricated at ANU.

Tandem Micro Concentrator	V_{OC} (mV)	J_{SC} (mA/cm^2)	FF	Efficiency (%)	Tandem Module Efficiency (%)
GaAs cell	1072	24.6	0.83	22	**25**
Silicon cell	561	6.8	0.77	3	

The accelerated lifetime testing of a tandem micro concentrator module involved thermal cycling from 0°C to 80°C, then from −20°C to 80°C and finally from −40°C to 80°C, with 30 cycles for each temperature range. The overall efficiency of the module only decreased by 10% relative to the initial efficiency. A degradation in the electrical contacts to the GaAs cell are the likely cause for the reduction in efficiency. The electrical contacts can be made more robust and reliable. Overall, the module can be highly reliable and stable as silicon and GaAs cells are mature cell technologies.

Underlying GaAs/Silicon Tandem Solar Cell System

The GaAs/silicon tandem cell efficiency is the addition of the efficiencies of the GaAs and silicon cells when they are stacked on top of each other. The GaAs is placed on top of the silicon solar cell without any other components unlike the module, which has an acrylic micro concentrator, front glass and glass of the laminated silicon cell. The efficiencies of the GaAs top cell, silicon bottom cell and the GaAs/silicon tandem under non-concentrated sunlight are summarised in Table 2.

Table 2: Summary of the GaAs top cell, bottom silicon cell and GaAs/silicon tandem performance.

	V_{OC} (mV)	J_{SC} (mA/cm^2)	FF	Efficiency (%)	GaAs/Si tandem efficiency (%)
GaAs top cell	1061	27.6	0.85	25	**30**
Silicon bottom cell	663	9.0	0.83	5	

The efficiency of the GaAs/silicon tandem cell system as a function of light intensity is shown in Figure 5. The GaAs/silicon tandem cell efficiency peaks at 32.6% at 10 suns or 10x concentrated sunlight. These results show that under concentrated light tandem efficiencies above 30% are achievable by combining the GaAs and silicon cells made at ANU.

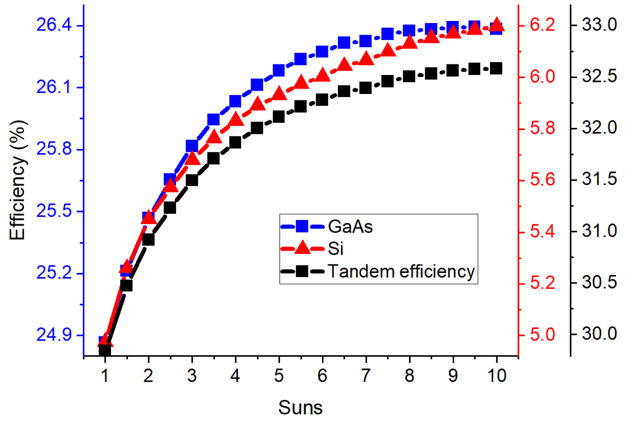

Figure 5: GaAs/silicon tandem cell efficiency as a function of concentrated light.

Transferability

The tandem PV micro concentrator was carefully designed to be compatible with existing single-axis PV tracking systems. Most new installed utility scale silicon PV systems in Australia employ single-axis tracking and the tandem PV micro concentrator can be directly used in these systems. The tandem micro concentrator can maintain its high efficiency despite any error in the tracking or deviation from the ideal angle due to wind loading. With the use of 500 µm wide GaAs SLIVER solar cells, such as those produced via the SLIVER process, a geometric concentration ratio of 10× may be achieved with a micro concentrator with a total height of only 10 mm.

Tandem solar cells are currently widely studied, as they are the pathway to higher efficiencies. Many projects are investigating the potential of perovskite/Si tandems as well as III-IV/Si systems both at ANU and worldwide. There is potential for some technology transfer between these projects, particularly in areas unrelated specifically to the concentrator or SLIVER components i.e. bonding, mounting, and connectors.

The etching of the GaAs SLIVERs may also find applications in other areas of GaAs technology, for example in the formation of through-vias or diffraction gratings.

Publications

Conference presentation “A GaAs/Silicon Tandem Microconcentrator Module”, 47th IEEE Photovoltaic Specialist Conference (PVSC), Calgary, Canada, 15 June-21 Aug 2020

Conference Poster: “GaAs SLIVER solar cells for linear microconcentrator applications”, 47th IEEE Photovoltaic Specialist Conference (PVSC), Calgary, Canada, 15 June-21 Aug 2020

Conference Proceedings: “GaAs SLIVER solar cells for linear microconcentrator applications” 47th IEEE Photovoltaic Specialist Conference (PVSC), Calgary, Canada, 15 June-21 Aug 2020

Conference Proceedings: “GaAs/Silicon Tandem Micro-Concentrator Module” 47th IEEE Photovoltaic Specialist Conference (PVSC), Calgary, Canada, 15 June-21 Aug 2020

Journal article: “Deep, vertical etching for GaAs using Inductively Coupled Plasma/Reactive Ion Etching.”

Intellectual Property: Patents / Licences

N/A

Awards

N/A

Conclusion and next steps

The project has the potential to benefit the Australian energy system through the introduction of a novel, high efficiency solar cell system. The system is designed to be easily integrated into existing single-axis tracking system for simple large-scale deployment.

A prototype tandem PV micro concentrator module was developed with a GaAs/Si underlying cell efficiency of 30%. This demonstrates the potential of the novel combination of non-imaging micro concentrators with GaAs and silicon cells for single-axis tracking systems. Further work could improve the overall efficiency of the tandem module.

The fabrication of GaAs SLIVER cells was demonstrated, which is a pathway to decrease the cost of GaAs cells. Improvements in GaAs SLIVER cell design and fabrication methods could further improve the efficiency. Use of the SLIVER process in combination with optical concentration has the potential to significantly reduce the cost of high efficiency GaAs/Si tandem PV systems.

Lessons Learnt

Lessons Learnt Report: Improved tandem concentrator capable of being mounted on single-axis PV tracker

Project Name: *Tandem PV Micro Concentrator*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	N/A

Key learning

The tandem PV micro concentrator was demonstrated to function effectively as a fully integrated package. All components (micro concentrator, GaAs cell and Si cell) were bonded together and encapsulated in a weatherproof box for measurement and testing. Further improvements in efficiency of the module can be achieved by reducing the reflectance and by increasing the transmittance of light through all the module components. Every component and interface could be further optimised for maximising the efficiency of the tandem module.

The ANU tandem concentrator system utilises non-imaging micro concentrators in order to improve the tolerance of the system to errors in the sun-tracking system, thus enabling less accurate but much cheaper sun-trackers to be used. This is in contrast to other solar concentrators that require very precise and very expensive sun-trackers.

In recent years, single-axis trackers have become widespread in utility scale photovoltaic installations. These systems move the solar module throughout the day in order to follow the sun, keeping the module within a few degrees of its optimum angle perpendicular to the sun, thus allowing the photovoltaic system to operate at close to its peak power for longer periods compared with a fixed angle module, leading to lower overall energy costs. The worldwide PV industry has adopted single-axis trackers for many ground-mounted conventional systems because they add 15-20% to energy output and allow greater kWh/kW (thus reducing power-related BOS costs) because of longer operating hours, but add only 5-10% to cost. The availability of reliable mass produced low cost single-axis trackers presents opportunities for tamed PV micro concentrators mounted on such trackers to confer greater output using the same single-axis PV tracker.

Implications for future projects

The use of non-imaging micro concentrator optics in this configuration enables the system to be paired with a simple single-axis tracking system that is required to be accurate to only a few degrees of optimum, but does not need to be nearly as precise as for concentrators operating at 100 suns and above. Concentrations of 5 to 30 times are required to be able to afford the highly efficiency but more expensive GaAs cells.

When considering the ANU concentrator, the pairing of non-imaging optical elements and active tracking enables high concentration to be achieved for all peak sunlight hours provided the error of the tracking system is within the tolerance of the non-imaging micro concentrators. For the ANU concentrator this is typically in the range of 5° ± 1°. Future projects can extend this work and further develop the ANU concentrator design, including possibly other cell materials/combinations and the incorporation into an existing active tracking device.

Knowledge gap

The combination of non-imaging micro concentrators and single-axis tracking has yet to be investigated experimentally with a commercially available system. As a result, it is unclear as to what will be the ideal pairing of non-imaging micro concentrator design with the commercially available single-axis sun-trackers. As a rule, there is a trade-off between concentrating more light onto the solar cells and reducing the tolerance of the system to errors in sun-tracking system. Experimental evidence from a commercially available system will be required in order to optimise the design of the micro concentrator system.

Background

Objectives or project requirements

This project aimed to take a new approach to solar photovoltaic concentrators by using non-imaging micro concentrators. The aim was to demonstrate that all of the components of the tandem PV micro concentrator can function together effectively for use with single-axis sun-trackers which have become widespread in the past few years to the point that the majority of the projects in the recent ARENA large scale solar PV funding round used single-axis sun-tracking.

Process undertaken

The module components (glass, micro concentrator, solar cells) were bonded together using silicone gel, encapsulants and epoxy. Electrical connections using wires were made to the solar cells. The components were then housed in a weatherproof box for indoor and outdoor measurements. Optical losses in the micro-concentrator were analysed and minimised where possible by using a different silicone gel. Loss mechanisms were identified with realistic optical models for all materials using OptiCAD and the Module Ray Tracer available on PV Lighthouse. The results showed that further improvements could produce a tandem PV micro concentrator module with an efficiency close to 30%.

Lessons Learnt Report: GaAs SLIVER Solar Cells

Project Name: *Tandem PV Micro Concentrator*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	N/A

Key learning

Grooves in GaAs wafers with a width of 23.5 µm ± 3 µm were produced by dicing the GaAs wafers with a narrow (17.5 ± 2.5 µm) blade. However, there was some chipping on both surfaces as well as roughness on the SLIVER sidewall to contend with. A post-dicing acid etch was demonstrated to decrease the roughness of the sidewall surface. The minimum pitch (groove + GaAs SLIVER) which could be produced was about 45 µm.

In order to reduce the groove width and the damage by the blade, ICP/RIE was investigated as an etching method. Using SiO_2 as an etch mask, grooves up to 100 µm deep have been etched in a GaAs wafer with a groove width of 13 µm. Ultimately, grooves of at least 250 µm depth will be required. These results suggest that the mask durability of the SiO_2 will be suitable for this process. Grooves with the required width and depth could be obtained using the ICP/RIE method.

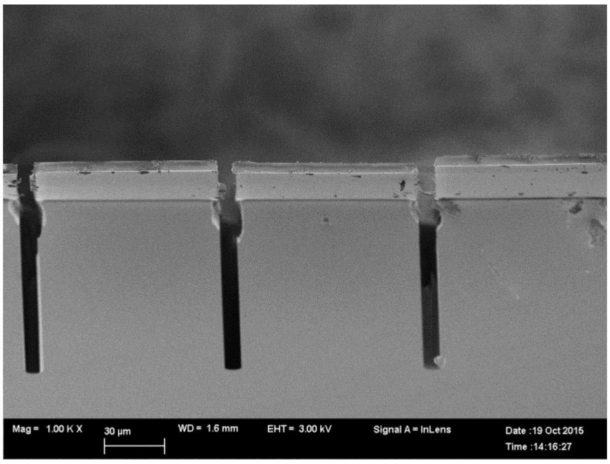

Figure 6: SEM image of GaAs etching masked by SiO_2 with excellent directionality and uniformity of etching.

These results demonstrate a path towards developing a SLIVER process that is compatible with GaAs.

Implications for future projects

This progress towards a micromachining process is crucial in developing a commercial SLIVER process that is compatible with GaAs. The cost reductions that are enabled by the SLIVER process and the high, stable efficiency of GaAs solar cells combine to make an attractive option for a high efficiency tandem photovoltaic module.

Knowledge gap

The promising results achieved here for the micro machining of GaAs need to be further developed into a repeatable high-throughput process that is able to achieve consistent, clean groove etching. From there, the process would have to be expanded to produce high efficiency GaAs cells.

Background

Objectives or project requirements

The objectives of this section of the Project were to develop a method to create SLIVER grooves in a GaAs wafer with a pitch of <50 µm. Ideally, the method will produce a minimum amount of damage to all surfaces. The SLIVER process has demonstrated that it is able to significantly reduce the material costs of solar cells.

Process undertaken

Dicing: Experiments were conducted using a dicing saw with a 17.5 ± 2.5 µm wide blade. Parameters such as spindle speed and cut speed were varied in order to obtain the narrowest possible grooves with minimal tapering and chipping. The GaAs SLIVERs were diced with spindle speeds of 30,000 rpm and a cut speed of 0.1 mm/s.

ICP/RIE: Etching of grooves was conducted using a 10 µm-thick SiO_2 mask. An example of grooves etched using ICP/RIE was shown in Figure 6. The etch of highly vertical grooves demonstrates good selectivity for the GaAs over the masking material. This is a promising method for the creation of narrow, high quality GaAs SLIVERs cells.

Appendix

Keywords

Solar concentrators
Non-imaging optics
Single-axis sun-tracking
Acrylic concentrators
GaAs solar cells
SLIVER solar cells

Glossary of terms and acronyms

GaAs Gallium arsenide is an efficient but expensive photovoltaic material.

Si Silicon is an abundant, low-cost and efficient photovoltaic material.

Non-imaging optics A class of optical element, which reflect light to focus it onto a receiver. Non-imaging optics have the characteristic of being able to accept 100% of light for a range of angles. The acceptance angle range is selected during the design stage.

SLIVER solar cells The SLIVER solar cell process significantly reduces the material cost of solar cells by forming solar cells through the thickness of a wafer rather than just at the surface.

Solar concentrator The use of optical elements to reflect light onto a receiver, which reduces the amount of solar cell area that is required. This can reduce costs by replacing the costly solar cells with comparatively inexpensive mirrors or lenses.