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Cost-Effective GaAsP Top Solar Cell Grown On A High Performance, Low Cost Silicon Solar Cell

Project results and lessons learnt

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*****Please use plain English – no jargon or unnecessary technical terms*****

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Executive Summary and Project Overview

This project is a partnership among UNSW Australia, AmberWave Inc., Veeco, Inc., Yale University, the University of Delaware and Arizona State University. The goal of this project is to develop a cost-effective and high performance GaAsP/SiGe tandem solar cell on Si substrate with an efficiency over 33%.

Silicon solar cells dominate the Photovoltaic (PV) market due to their performance, reliability and relatively low cost. However, the efficiency of the best silicon solar cells has stayed at around 25% for the last 17 years. Solar cells made of materials in the 3rd and 5th column of the periodic table (III/V materials) are known to yield the highest efficiencies, but the high cost of lattice-matched substrates and metal organic chemical vapor deposition (MOCVD) of the active device layers makes them prohibitively expensive for large scale terrestrial applications.

This programme combines the affordability of silicon substrates with limited III-V material thickness to increase the overall efficiency at an affordable cost. The greatest challenge is lattice-mismatch when developing III-V on Si tandem devices. Lattice match is required to achieve high efficiency. This has been addressed by a metamorphic silicon:germanium (SiGe) buffer grown between the silicon substrate and the gallium-arsenide phosphide (GaAsP) active device layers.

A cost-effective and high performance GaAsP/SiGe tandem solar cell grown on silicon substrate has achieved an efficiency of 23.8%. This is the highest efficiency achieved for any III-V on silicon solar cell. We have also demonstrated the pathways to an efficiency higher than 35%.

The system cost can be reduced by 28% with one-axis tracking and a 4X non-imaging concentrator. This low level of concentration can collect the global radiation in high direct normal incidence regions such as northern New South Wales where the Moree Solar Farm is located.

In the course of this project, we developed the design for the 21-layer structure. Working with our collaborators, the required structures were grown and the solar cell devices were fabricated. We analysed each layer and modified the characteristics to achieve the desired results. In the course of this project, we learnt to grow and analyse a complex tandem structure with 21 layers. We also learnt the best methods to produce high quality materials, characterise the individual sub cells using a three terminal (3T) method, test materials and device parameters using test structures, and improve the bottom cell device design and structure including applying light trapping techniques to increase its output current to further improve the tandem device efficiency.

Project Outcomes

Solar cell and module efficiency is a significant electricity cost driver [a]. To develop a cost-effective and high performance GaAsP/SiGe tandem solar cell grown on silicon, a range of research has been conducted using a design cycle that started with modelling and was followed by solar cell device design, fabrication and analysis of the measured performance. After each cycle, new and relevant information was selected and used to gradually and steadily improve the performance of the solar cells. The outcomes of this project are listed below:

- A detailed numerical model was developed to assess the potential and then the design rules for an efficient III-V/SiGe tandem device. The theoretical efficiency of a GaAsP/SiGe tandem solar cell on silicon is 40%.

- SiGe material growth recipes were developed and improved. The resultant threading dislocation density (TDD) was as low as $2.1\times10^5 cm^{-2}$. A TDD less than $10^6 cm^{-2}$ is required from the epitxial growth to achieve high performance III/V solar cell material.
- Growth recipes and growth conditions were tested and modified. A high quality GaAsP/SiGe tandem structure with 21 layers has been successfully grown. The measured TDD of the III/V active layers was as low as $2.8\times10^6 cm^{-2}$. This leads to a relatively high Voc of the top cell with the corresponding increase in the power output of the tandem cell. The ultimate goal is to achieve a TDD less than $10^6 cm^{-2}$.
- The bottom cell structure and its corresponding SiGe composition have been re-designed based on the analysis of the initial device results, which led to changing the SiGe layer thickness, doping level, as well as the SiGe concentration. The performance of the bottom cell with the new structure was improved significantly. The best bottom cell efficiency at one sun was 3.4% and at 20 suns was 4.9%.
- Tandem solar cells were designed with optimised metal grid patterns. Solar cells of various sizes along with bespoke test structures were used to obtain the best possible performance. Test patterns and structures were designed as well to extract device parameters and improve the better controllability of the fabrication process. The fabrication process was developed and improved to achieve better device results. The best top cell efficiency at one sun was 18.4% and at 7.2 suns was 19.6%.
- A three terminal (3T) concept was conceived and validated for this tandem device. This structure allows separate analysis of the top cell and the bottom cell in a tandem structure. The three terminal design not only provides current-voltage characteristic for both sub cells simultaneously, but also facilitates the detailed analysis of current-limiting and current-matching cases as well as the extraction of cell's parameters used for device modelling. This is a leveraging technique developed during this project and can also be applied to other projects on tandem solar cells. With the new proposed bottom cell, improved fabrication process and this 3T method, the measured tandem efficiency was increased from 18.9% to 20.6% at one sun and 23.8% at 7.2 suns.
- Material properties were carefully studied because there was limited information published for the III/V and SiGe material alloys of this tandem solar cell. Optical constants and electrical parameters were extracted using optical and electrical techniques and were published in scientific journals.
- New designs and processes were conceived and implemented to further improve the tandem device efficiency based on presently available materials. GaAsP top cell and SiGe bottom cell were fabricated independently, to measure the efficiency of the combined best individual sub-cells from our presently available materials. The best combined efficiency of 23.8% was achieved under 7.2× concentrated light intensity.
- Pathways to achieve higher efficiency for this tandem device on silicon were developed. Non-ideallities in the devices and the material itself discovered during the course of this project are now included in our numerical model. Our latest simulations indicating that an efficiency of 33% and 35.8% can be achieved under 20× and 400× concentrated light intensities, respectively.
- The particular solar cell structure investigated in this project will be cost effective for modules for low-X utility scale systems, unlike other high performance multi-junction solar cells technologies, due to 4 factors (i) AmberWave's SiGe compositional graded buffer technology, with new cost breakthroughs allowing low defect density SiGe virtual substrates to be produced for more than 100X cheaper than Ge or GaAs substrates used for

multi-junction cells today; (ii) adaptation of cell fabrication processes from the Si PV industry to III-V solar cells; (iii) limiting total III-V growth to 1.5um or less; and (iv) MOCVD tool optimization based on Veeco's TurboDisc platform [b].

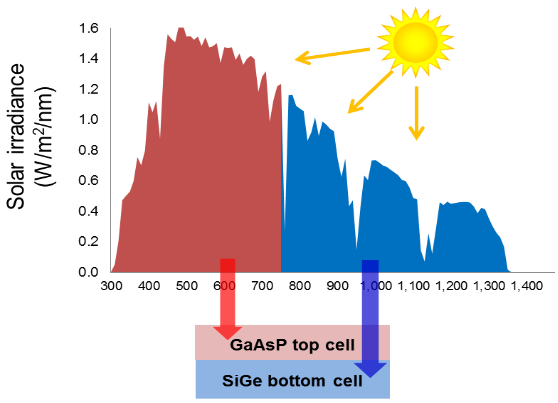
- The cost of the PV system can be reduced by 28% with one-axis tracking and a 4X non-imaging concentrator. This low level of concentration can collect the global radiation in high direct normal incidence area such as northern New South Wales where the Moree Solar Farm is located. Detailed analysis was adapted from the 2016 NREL report [c].
- Identification of the requirements for utility scale markets and premium value markets which can lead to early commercial market entry – within 2 years.

References

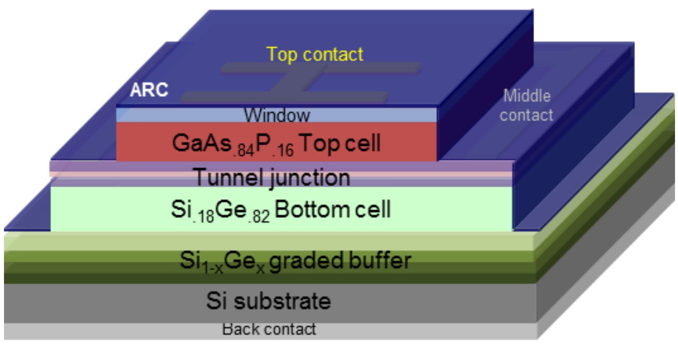
[a] Wang, X., Kurdgalashvili, L., Byrne, J., & Barnett, A. (2011). The Value of Module Efficiency in Lowering the Levelized Cost of Energy of Photovoltaic Systems. Renewable and Sustainable Energy Reviews, 15(9), 4248-4254

[b] Module cost analysis done by AmberWave in cooperation with other industry collaborators.

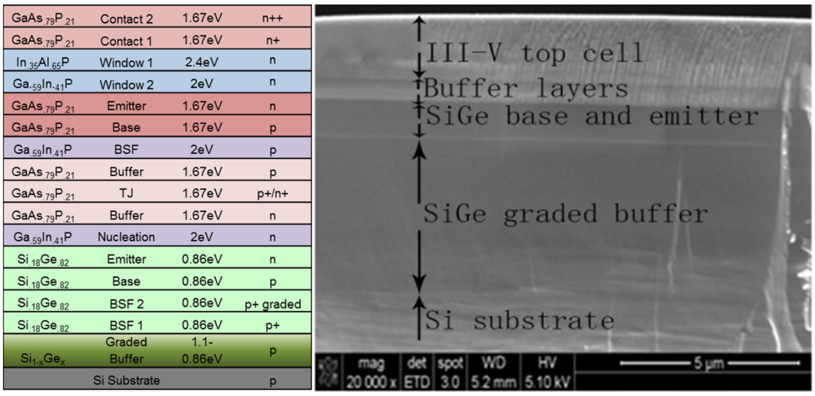
[c] U.S. Solar Photovoltaic System Cost Benchmark: Q1 2016, National Renewable Energy Laboratory (NREL).



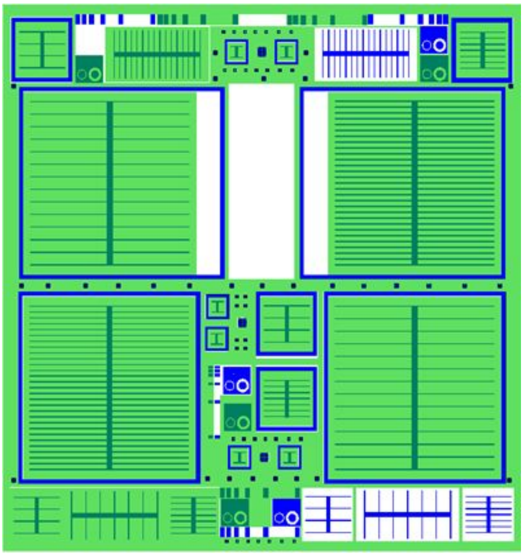
Spectrum to be absorbed by top cell and bottom cell, respectively.



Cross-section view of a fabricated 3T tandem device

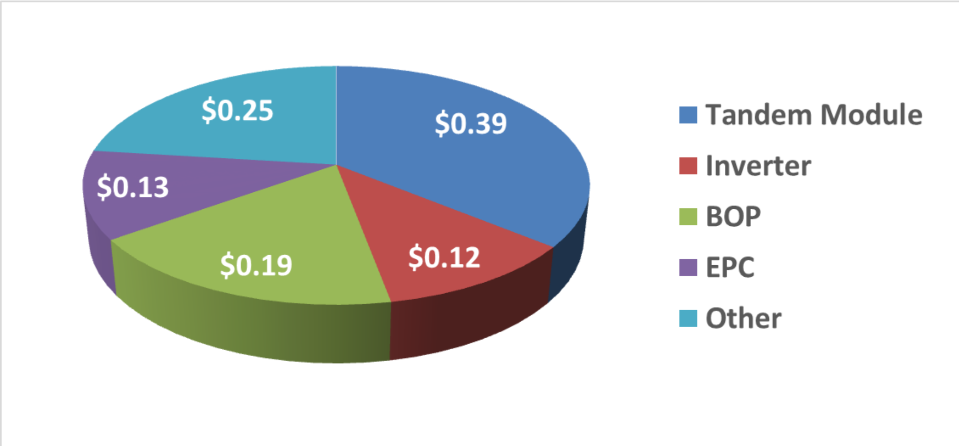


Cross section view of tandem structure and SEM micrograph



Top view of a 3cm by 3cm tandem wafer with solar cell and test structures.

Set up for outdoor efficiency measurements using a sun tracker



Cost to the user breakdown for $1.08/W PV system based on 4X modules with the GaAsP/SiGe tandem solar cell on Si. “BOP” refers to Balance of Plant (mounting system, wiring, connectors); “EPC” refers to Engineering, Procurement and Construction; “Other” consists of all components not included in the other categories, including site preparation, getting approvals, land cost, etc.

Transferability

The GaAsP/SiGe tandem solar cell being developed has a calculated potential production cost of \$0.78/Watt at one sun and \$0.20 at 4 suns. The system level savings due to the value of efficiency make the system competitive with today's silicon based systems for utility scale (grid) applications. It would be difficult to enter this large market if the only offer is cost parity. Following is a description of a cost-effective utility scale application and two identified "Premium Value Markets". These Premium Value Markets have recently emerged.

For these utility scale applications, the market is moving towards single axis trackers such as that used in the Moree Solar Farm. The GaAsP/SiGe on silicon at a selling price of \$1.56/Watt (2 times the cost) is a promising product for a low-X, non-imaging concentrator. At concentration of 4X this new solar cell module can lead to a 28% reduction in systems cost to \$1.08/Watt. Applying NREL's SAM model this leads to an electricity cost ¢6.35/kWh based on utility scale generation of electricity in the Moree region over 30 years. The calculation has not included any government incentives or tax benefits.

<u>Premium Value Market: Ultra-Light Solar Cells for UAVs</u>

Working with our lead commercial partner, AmberWave, we have identified several premium value markets for our high performance, lightweight solar cells. The largest of these is for High Altitude, Long-Endurance UAVs (Unmanned Aerial Vehicles), which require:

- High specific power (power-to-weight ratio) solar cells to enable long term / near-perpetual flight
- Robust and flexible solar cells to conform to the shape of the aircraft skin and withstand the elements
- Substantially lower price per W compared to the solar cells typically used in aerospace applications: III-V compound semiconductor based solar cells, which are highly efficient but also highly expensive (>\$100/W). The lightweight version of this GaAsP/SiGe on silicon solar cell of this program will have a cost well under \$2/Watt.

A host of companies are exploring solar powered long-endurance aircraft for deployment above 60,000 feet (above air-traffic and most weather patterns) as potential communications, surveying or observation platforms delivering the capabilities of traditional satellites for a fraction of the cost. Under names such as "atmospheric satellites", HAPS (High Altitude Pseudo Satellites) and HALE (High Altitude Long Endurance) aircraft. Companies involved include: **Facebook**, **Google**, **Solar Impulse** (the developer of the widely followed solar-powered piloted airplane that recently finished a global circumnavigation), **Airbus Defense & Space**, and many others

Private discussions with companies on the above list (and others), combined with publicly available information, suggest a market evolving to a total size of 50MW/year, or \$500M annually at \$10/W, by early in the next decade.

<u>Premium Value Market: Low Earth Orbit (LEO) Telecommunication Satellites</u>

Several high-profile companies--Elon Musk's **SpaceX**, **OneWeb** (funded by Richard Branson), and potentially **Samsung**--are pursuing low earth orbit satellites for similar next generation telecommunications applications. Distinct from geo-synchronous satellite orbits which travel around the earth at distances beyond 22,000 miles from the earth's surface, low earth orbit satellites operate like a swarm at distances of a few hundred miles above the earth's surface. **SpaceX** is in the early stages of developing advanced micro-satellites which operate in large formations. **OneWeb** has contracted **Airbus** to build and launch an initial 648 low earth orbit microsatellites and has secured $500 million in funding from **Virgin Galactic** and **Arianespace**. Current III-V based solar cells for satellites are highly efficient but exceed $100/watt cost, and are relatively heavy unless additional and costly thinning steps are employed.

Given the high expense of the traditional space cell alternatives, and the complete unsuitability of low-cost terrestrial solar cells for space applications, we believe this submarket will be less price sensitive than high altitude drones, and anticipate $20/W will be an acceptable price point.

Total Available Premium Value Markets – LEO

From direct confidential conversations with a major strategic partner of one of the leaders in this space, we have estimates of this market at 10MW of ultra-light solar cells annually, and a willingness to pay in the $10-20/W range. We believe a price at the top of this range is sustainable, corresponding to a total available market (TAM) of $200M/year.

To serve these markets we will need manufacturing partners. We are working with one of our present partners, AmberWave, and a new III-V manufacturing partner, Spectrolab a Boeing company, to commercialize this solar cell product.

Publications

There are 14 referred journal papers and 21 conference papers from this programme published as listed below:

Referred journal papers (14):

[1] B. Conrad et al., "Optical characterisation of III-V alloys grown on Si by spectroscopic elliposometry", Solar Energy Materials and Solar Cells. 162(2017), 7-12. Doi:10.1016/j.solmat.2016.12.023

[2] X. Zhao et al., "Short circuit current and efficiency improvement of SiGe solar cell in a GaAsP-SiGe dual junction solar cell on a Si substrate", 159 (2017) 86–93. doi:10.1016/j.solmat.2016.08.037

[3] A. Soeriyadi et al., "Increased Spectrum Utilisation with GaAsP/SiGe Solar Cells Grown on Silicon Substrates", MRS Advances, pp. 1–6, 2016. DOI: 10.1557/adv.2016.354

[4] D. Li et al., "Performance improvement for epitaxially grown SiGe on Si solar cell by optimizing the back surface field", Phys. Status Solidi RRL, 10 (2016) 735-738. doi:10.1002/pssr.201600231

[5] L. Wang, et al., "Current and efficiency improvement for a GaAsP/SiGe on Si tandem solar cell device achieved by light trapping techniques", Physica Status Solidi - Rapid Research Letters, 10(8), 596-599, 2016. doi:10.1002/pssr.201600157

[6] D. Li et al., “Optical absorption of graded buffer layers and short circuit current improvement in SiGe solar cells grown on silicon substrates”, Sol. Energy Mater. Sol. Cells, 157 (2016) 973-980. doi:10.1016/j.solmat.2016.08.019
[7] D. Li et al., “Optical constants of silicon germanium films grown on silicon substrates”, Solar Energy Materials and Solar Cells, vol. 140, pp. 69-76, Sep. 2015. doi:10.1016/j.solmat.2015.03.031
[8] L. Wang , B. Conrad, A. Soeriyadi, X. Zhao, D. Li, M. Diaz, A. Lochtefeld, A. Gerger, I. Perez-Wurfl, A. Barnett, "Current matched three-terminal dual junction GaAsP/SiGe tandem solar cell on Si", Solar Energy Materials & Solar Cells, 146, pp. 80-86 (2016). doi:10.1016/j.solmat.2015.11.037
[9] B. Conrad et al., “Window Optimization Enabling Broadband Double-Layer Antireflection Coating for GaAsP/SiGe Tandem on Silicon”, Solar Energy, vol. 127, pp. 216-222, April. 2016. doi:10.1016/j.solener.2016.01.019
[10] K. J. Schmieder et al., “GaAsP on SiGe/Si material quality improvements with in-situ stress sensor and resulting tandem device performance”, Materials Science in Semiconductor Processing, 39, 614-620. doi:10.1016/j.mssp.2015.05.058
[11] L. Wang et al., “Material and Device Improvement of GaAsP Top Solar Cells for GaAsP/SiGe Tandem Solar Cells Grown on Si Substrates”, IEEE Journal of Photovoltaics, 2015. 5(6): p. 1800-1804. doi:10.1109/JPHOTOV.2015.2459918
[12] Xin Zhao et al., “Material and device analysis of SiGe solar cells in a GaAsP-SiGe dual junction solar cell on Si substrate,” Solar Energy Materials & Solar Cells, vol. 134, pp. 114-121, Mar. 2015. doi:10.1016/j.solmat.2014.11.027
[13] D. Li et al., “Optical constants of silicon germanium films grown on silicon substrates”, Solar Energy Materials and Solar Cells, 140(2015), 69-76. doi:10.1016/j.solmat.2015.03.031
[14] M. Diaz et al., “Tandem GaAsP/SiGe on Si solar cells”, Solar Energy Materials and Solar Cells, 143 (2015), 113-119. doi:10.1016/j.solmat.2015.06.033

Conference papers (21):

[1] B. Conrad et al., “Improved GaAsP/SiGe Tandem on Silicon Outdoors and Under Concentration”, IEEE PVSC Jun. 2016
[2] A. Soeriyadi et al., “Spatially Resolved EL and PL Coupling of a Dual Junction Solar Cell”, In 43rd IEEE PVSC Jun. 2016
[3] A. Soeriyadi et al., “Solar cell parameters extraction of Subcells In a dual junction system through a three terminal device design”, In PVSEC-26 2016. Singapore
[4] X. Zhao et al., “Short Circuit Current Improvement of SiGe Solar Cell in a Gallium Arsenide Phosphide-Silicon Germanium Dual Junction Solar Cell on Silicon Substrate”, 42nd IEEE PVSC, Jun. 2015
[5] D. Li et al., “Optical and Electrical Analysis of Graded Buffer Layers in III-V/SiGe on Silicon Tandem Solar Cells”, 42nd IEEE PVSC, Jun. 2015
[6] L. Wang et al., “Current matched GaAsP/SiGe tandem device on Si over 20% efficiency under indoor measurement”, 42nd IEEE PVSC, New Orleans, Jun. 2015
[7] B. Conrad et al., “Analysis and improvement of GaAsP/SiGe tandem on Si by IQE data”, 31st EU PVSEC, Hamburg, Sep. 2015
[8] A. Soeriyadi et al., “A direct method of analysing the current matching condition in a multi-junction solar cell”, 31st EU PVSEC, Hamburg, Sep. 2015
[9] D. Li et al., “Optical and Electrical Analysis of Graded Buffer Layers in III-V/SiGe on Silicon Tandem Solar Cells”, 42nd IEEE PVSC, June 2015
[10] X. Zhao et al., “Short Circuit Current Improvement of SiGe Solar Cell in a Gallium Arsenide Phosphide-Silicon Germanium Dual Junction Solar Cell on Silicon Substrate”, 42nd IEEE PVSC, June 2015

[11]A. Soeriyadi et al., “GaAsP Hall mobility characterization for GaAsP/SiGe tandem solar cell on Si substrate”, PVSC 2014
[12]B. Conrad et al., “Analysis and improvement of GaAsP/SiGe tandem on Si by IQE data”, 31st EU PVSEC, Hamburg, Sep. 2015
[13]B. Conrad et al., “Double Layer Antireflection Coating and Window Optimization for GaAsP/SiGe Tandem on Si,” 40th IEEE PVSC, Denver, Jun. 2014.
[14]M. Diaz et al., “Dual-Junction GaAsP/SiGe on Silicon Tandem Solar Cells,” 40th IEEE Photovoltaic Specialist Conference, Denver, Colorado, Jun. 2014
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[16]M. Diaz et al., “Lattice Matched III-V/SiGe on Silicon Tandem Solar Cells”, In 29th European Photovoltaic Solar Energy Conference and Exhibition (pp. 1996-1998). Amsterdam.
[17]K. J. Schmieder et al., “GaInP window layers for GaAsP on SiGe/Si single and dual-junction solar cells,” 39th IEEE PVSC, Tampa, Florida, Jun. 2013.
[18]A. Barnett et al., “GaAsP on SiGe/Si Tandem Solar Cells”, In 23rd Photovoltaic Science and Engineering Conference. Taiwan 2013.
[19]K. J. Schmieder et al., “Progression of tandem III-V/SiGe solar cell on Si substrate,” in Proc. 27th European Photovoltaic Solar Energy Conf., (Frankfurt), Sept. 2012.
[20]K. J. Schmieder et al., “Analysis of tandem III-V/SiGe devices grown on Si,” 38th IEEE Photovoltaic Specialists Conf., Austin, Jun. 2012
[21]A. Barnett et al., “GaAsP/SiGe on Si Tandem Solar Cell Performance Predictions and Experimental Results”, 38th IEEE PVSC, Jun. 2013. Retrieved from http://www.ieee-pvsc.org/PVSC38/PVSC38-YB-SMALL.pdf

Intellectual Property: Patents / Licences

There was no patentable intellectual property.

Awards

There were no awards.

Conclusion and next steps

The efficiency of a GaAsP/SiGe tandem device on Si has been increased to 23.8% under 7.2X concentration. The previous best III-V on Si solar cell was 21.2% (active-area) under AM0 [d]. This achievement is based on the success of matching each project milestone. This consists of the improved material quality, optimized tandem cell structure, effective material property analysis, and an improved fabrication process. The knowledge, skills, concepts and techniques developed during this project are applicable to other tandem solar cell projects.

Next steps will be to continue improving the performance and reduce the cost of this product. Pathways to achieve efficiency results of 32.9% at 20X and 35.8% at 400X have also been demonstrated. Pathways to commercialise this new product including reduced cost utility scale PV generating systems have been identified and will be pursued.

Reference

[d] T. Soga, T. Kato, M. Yang, M. Umeno, and T. Jimbo, “High efficiency AlGaAs/Si monolithic tandem solar cell grown by metalorganic chemical vapor deposition," J. Appl. Phys., vol. 78, no. 6, pp. 4196-4199, 1995.

Lessons Learnt

Lessons Learnt Report: Design and implementation of test structures integrated with the tandem solar cell design which enables direct testing of materials and device parameters in addition to overall tandem solar cell performance.

Project Name: *Cost-Effective GaAsP Top Solar Cell Grown on a High Performance, Low Cost Silicon Solar Cell*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

Integrating test structures into the tandem solar cell design enables direct testing of the materials and device parameters. These test structures can be constructed simultaneously with solar cell fabrication. This allows detailed analysis, including the electrical and optical parameters, for each layer in this complex structure and leads to more advanced modelling and accurate prediction of the device performance.

Implications for future projects

We will design and integrate the test structures in parallel to the device design at each stage of the project, study the material parameters and use them to predict and improve the solar cell performance.

Knowledge gap

During the course of this project, we identified that some important optical constants and electrical parameters of III-V material relevant to this project had never been published. To fill this knowledge gap, we designed specific structures to obtain the parameters of III-V materials we needed. The extracted optical constants and electrical parameters were published in Reference [1] and [2], respectively, as shown in the supporting information below.

Background

Objectives or project requirements

The project at this stage required a more realistic modelling of the solar cell to predict the best performance that can be achieved. We set out to extract both optical and electrical material parameters to build such a model. More accurate parameters led to deeper understanding and analysis of the optical absorption as well as optical and resistive losses. Our model is now able to more accurately identify limitations and predict a more realistic tandem cell performance.

Process undertaken

We designed test structure to determine resistivity, thickness and mobility that were integrated into the solar cell mask set used in the photolithography process. The test structures were fabricated simultaneously with the solar cells and used to obtain the optical constants and electrical parameters of interest. Our findings lead to a detailed understanding of the material properties and consequently more advanced solar cell modelling.

Reference

[1] B. Conrad et al., "Window Optimization Enabling Broadband Double-Layer Antireflection Coating for GaAsP/SiGe Tandem on Silicon", Solar Energy, vol. 127, pp. 216-222, April. 2016. doi:10.1016/j.solener.2016.01.019

[2] A. Soeriyadi et al., "GaAsP Hall mobility characterization for GaAsP/SiGe tandem solar cell on Si substrate", PVSC 2014, doi:10.1109/PVSC.2014.6925126

Lessons Learnt Report: Three-terminal measurements to determine subcell device parameters leading to improved tandem performance

Project Name: *Cost-Effective GaAsP Top Solar Cell Grown on a High Performance, Low Cost Silicon Solar Cell*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

Three-terminal (3T) measurements allow separate analysis of top cell and bottom cell in a tandem structure. It can not only provide current-voltage characteristics for both sub cells simultaneously, but also facilitates the detailed analysis of current-limiting and current-matching cases, and the extraction of the cell parameters. This is a leveraging technique for this project and can also be applied to other tandem solar cell projects.

Implications for future projects

We will apply the 3T method to the tandem solar cell analysis first to obtain information for two terminal (2T) solar cell design and fabrication. This will reduce the unknowns and identify key aspects of the device to be improved at an early stage in the design of the structure.

Knowledge gap

N/A.

Background

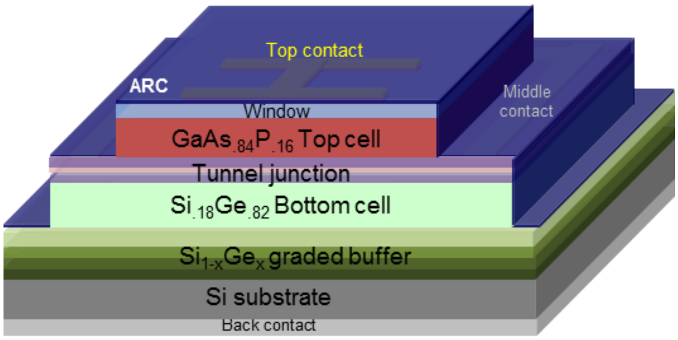
Objectives or project requirements

The requirement of this stage of the project was to develop a high efficiency 3T tandem device.

Process undertaken

We first designed a 3T method for this tandem device, consisting of a front metal contact on the top cell, a middle metal contact in between the sub cells, and a rear metal contact on the back surface of the silicon substrate, as shown in the figure below. Then we fabricated the 3T device with improved fabrication processes. Next, we applied circuit simulation to better understand the current flowing within this tandem device. In addition, with the assistance of an adjustable light source, we characterised the tandem performance under different current-limiting cases, and finally realised current-matching.

Supporting information



Three Terminal (top, middle and back metal contacts) tandem solar cell

Lessons Learnt Report: Requirement for in-situ optical stress sensor to enable high quality III/V material to attain the highest device voltages

Project Name: *Cost-Effective GaAsP Top Solar Cell Grown on a High Performance, Low Cost Silicon Solar Cell*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

Monitoring wafer bowing during the III/V materials growth is essential to producing high quality (low TDD) materials. Wafer bowing is a symptom of stress in the material (leading to increased TDDs) caused by changing atomic spacing during the epitaxial growth of III/V materials.

Implications for future projects

To achieve high quality III/V materials, the reactor to be used to grow these layers should be equipped with an in-situ optical stress sensor to detect wafer bowing.

Knowledge gap

Bandgap-voltage offset under open circuit condition (W_{oc}) is defined as the difference between the band gap and the open circuit voltage (V_{oc}) of a solar cell. It provides a simple metric to compare results among solar cells independent of material used. This is particularly important for III/V top cell, since its V_{oc} is strongly affected by the material quality.

Background

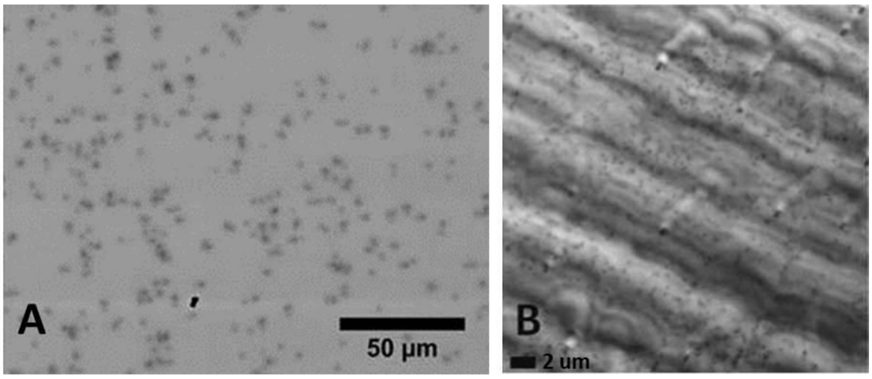
Objectives or project requirements

Critical to achieving high performance is an open circuit voltage from the GaAsP solar cell that is less than the bandgap minus 0.45 volts. One of the requirements was to grow high quality III/V material with threading dislocation density (TDD) below 10^6 cm^{-2}, which is a key parameter to evaluate the defects in the material.

Process undertaken

Using an in-situ optical stress sensor during the III/V material growth and adjusting the lattice-matching conditions at the growth temperature instead of at room temperature, the TDD of the III/V active layer was decreased from 7.8×10^7 cm^{-2} to 2.8×10^6 cm^{-2}. Subsequently, a 0.48V W_{oc} was achieved for the III/V top cell. This is the lowest W_{oc} (highest voltage) at one sun for ternary compound III-V solar cells grown on Si substrates. The W_{oc} at 7.2X was yy and at zzX was ---.

Supporting information



Micrographs of III/V active layer in the tandem structure (A) showing TDD of 2.8×10^{6} cm^{-2} (after using optical stress sensor during growth), and (B) showing TDD of 7.8×10^{7} cm^{-2} (before using optical stress sensor during growth)

Lessons Learnt Report: Silicon-germanium (SiGe) bottom cell structure including the design and implementation of an effective back surface reflector to increase the bottom solar cell performance.

Project Name: *Cost-Effective GaAsP Top Solar Cell Grown on a High Performance, Low Cost Silicon Solar Cell*

Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

The current of this dual junction tandem solar cell is limited by the SiGe bottom cell as the structure and composition of the bottom cell are not yet optimised. This also constrains the performance of the tandem solar cell due to the requirement of current matching for a 2T double junction tandem solar cell. Therefore, it is important to improve the structure design of the bottom cell and apply light trapping techniques to increase the bottom cell performance.

A silicon dioxide (SiO_2) dielectric layer between the Si substrate and the Al back contact can be used to improve the back-surface reflectance. This SiO_2 dielectric layer is called a back-surface reflector (BSR). A proper BSR not only increases the current output of the SiGe bottom cell by enhancing the light path lengths in the solar cell, but also boosts the voltage output due to its passivation effect.

Implications for future projects

Maximising the current of the bottom cell as much as possible should be prioritised as this will improve the overall tandem cell performance.

BSR should be included in the fabrication process at the early stage to increase the performance of the SiGe bottom cell.

Knowledge gap

During the course of this project, we identified that optical constants of SiGe alloy with the Ge concentration relevant to this project had never been reported, To overcome this limitation, we designed specific structures to obtain the optical constants of the required SiGe composition. The extracted optical constants were published in Reference [3] shown in the supporting information below.

Background

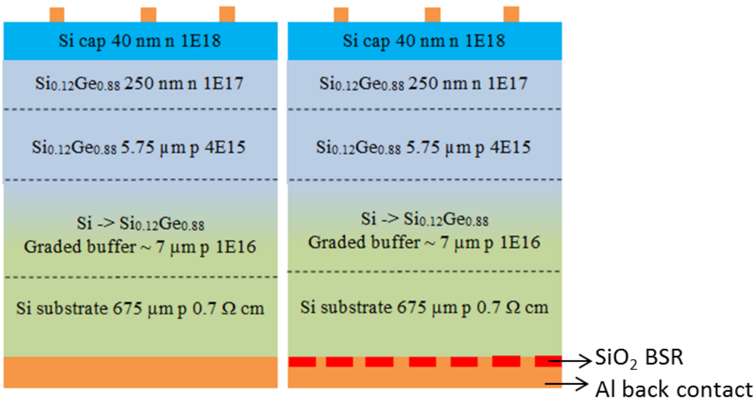
Objectives or project requirements

With the structure improvement, the current density of the bottom cell is expected to achieve 21 mA/cm^2. The requirement of this stage of the project was to achieve 21 mA/cm^2 for the bottom cell. This was predicted to be the result of an improved structure with the addition of light trapping techniques. By adding a proper BSR alone, we should observe an increase of both the short circuit current J_{sc} and open circuit voltage V_{oc}.

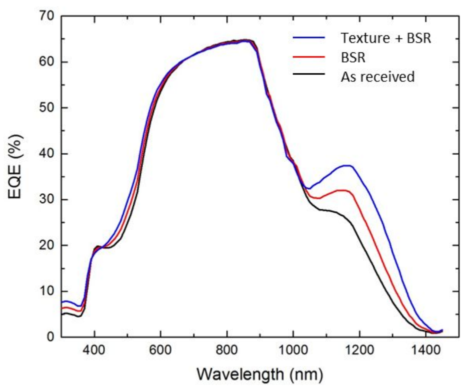
Process undertaken

We re-designed the SiGe alloy with higher Ge composition, reduced the thickness and doping level of the SiGe layer, applied light trapping techniques during the fabrication process, and added anti-reflection coating after device fabrication.An optimised SiGe bottom cell was grown and fabricated, and the best current density of 20.3 mA/cm^2 (close to the 21 mA/cm^2 target) has been achieved to date.
Two samples with the same structure were fabricated with and without BSR. These two devices are shown in below supporting information. The J_{sc} increase can be demonstrated in the external quantum efficiency (EQE) measurement. The measured EQE shows a clear improvement when adding BSR. In addition, BSR also lead to 19 mV Voc increase for this SiGe device.

Supporting information



Structure of SiGe bottom cell without (left) and with (right) BSR



Measured EQE of the three fabricated devices without (black curve) and with (red curve) BSR.

Reference

[3] D. Li et al., "Optical constants of silicon germanium films grown on silicon substrates", Solar Energy Materials and Solar Cells, vol. 140, pp. 69-76, Sep. 2015. doi:10.1016/j.solmat.2015.03.031

Appendix

Keywords

Cost-effective module, Gallium-Arsenide Phosphide, high efficiency, III/V on silicon, Silicon-Germanium, tandem solar cell, three-terminal device,

Glossary of terms and acronyms

Bandgap-voltage offset under open circuit condition: W_{oc}

External quantum efficiency: EQE

Gallium-Arsenide Phosphide: GaAsP

High Altitude Long Endurance: HALE

High Altitude Pseudo Satellites: HAPS

Levelised cost of electricity: LCOE

Metal organic chemical vapor deposition: MOCVD

Open circuit voltage: V_{oc}

Short circuit current density: J_{sc}

Silicon-Germanium: SiGe

Threading dislocation density: TDD

Three-terminal: 3T

Total available market: TAM

Unmanned Aerial Vehicles: UAVs