ABSTRACT: Tandem cell approaches offer the opportunity to increase silicon cell efficiency. Four terminal approaches provide the flexibility to freely choose the bandgap of the top cell without compromising the system efficiency. By using the top cell as a reflector of sub-bandgap light, a simple tandem approach has been demonstrated that has the potential for strong system efficiencies. Efficiency of 27.8% was achieved in a system comprising a 24.6% GaAs top cell and 20.3% bottom cell. Improvements in either the GaAs cell or the Si cell could increase efficiency beyond 30% with combined improvements leading to a realistic potential of 34%. Combination with single axis roll trackers offers potential for reflective tandems to be practicable.

Keywords: Tandem, Silicon, High-Efficiency

1 BACKGROUND

Efficiency is a major driver for cost reduction in photovoltaics, decreasing modularization and balance of systems costs. While silicon continues to dominate the photovoltaics market, the efficiency of the best laboratory devices has been locked between 25% and 26% for 15 years [1, 2]. Large area cells with efficiency of 25% have also been recently demonstrated [3]. However, for photovoltaic performance to exceed 30%, silicon cells need to be combined with another, ideally higher bandgap, cell.

Most tandem cells to date have been based on the two terminal approach, with similar area cells connected in series. Non-silicon based tandem cell concepts based on III/V semiconductors devices have demonstrated the potential of this approach. The best performances vary from 31.1% for a two junction device under 1 sun global illumination [4] to 44.7% for a four junction device under high concentration [5]. However, with these concepts based on series connection of the two cells, high efficiency is only possible when the cell characteristics match the illuminating spectrum.

In contrast, this work focuses on four terminal tandem devices with silicon as the low bandgap device. White et al. [6] recently reported modelling that showed a broad range of semiconductor materials are capable of delivering efficiencies >30%. This work looks at a practical implementation of this modelling to demonstrate the potential of four terminal tandems with silicon as the bottom cell. Rather than requiring devices that are transparent to sub-bandgap light or expensive optics, the high bandgap cell is used as a reflector of the sub-bandgap light onto the silicon cell.

The photovoltaics group at the Australian National University is exploring the use of tandems based on silicon devices, building on our strong silicon capabilities and the strong market position of silicon devices.

2 FOUR TERMINAL, SILICON BASED TANDEMS

For this work, the bottom cell is assumed to be silicon based. Silicon is currently the cheapest high efficiency photovoltaic device, dominates the PV market and is capable of tandem cell efficiencies >30%.

In two terminal tandem approaches, the current of the top cell needs to match the current of the bottom cell as the cells are connected in series. The two terminal approach significantly constrains the bandgap of the top cell to approximately 1.7V. While some semiconductors such as antimony sulphide Sb2S3 and amorphous silicon (a-Si:H) have near ideal bandgaps, their efficiencies are currently too low and would result in lower efficiency than a silicon device would be capable of in isolation.

Performance of the system also depends on the spectrum of the light that is incident on the cells. Changes in the spectrum throughout the day can lead to mismatch between the cell currents and reduced performance.

In contrast, the four terminal tandem system provides the flexibility in the choice of top cells to enable high efficiencies. Four terminal approaches provide freedom to choose the bandgap, lattice constant and thermal expansion coefficient of the second cell for best system performance enabling a wide variety of bandgaps capable of achieving >30% performance. This flexibility comes at the expense of more complicated circuitry to manage the two electrical power streams.

3 REFLECTIVE TANDEM ARRANGEMENT

A less obvious advantage of the four terminal approach is that it provides additional flexibility in the design and arrangement of the cells. In particular, the two cells no longer need to be stacked and therefore the top cell does not need to be transparent. This alleviates the need for transparent conductive oxides or contact grids on the rear of the top cells to enable sub-bandgap light to penetrate to the bottom cell. Cells can have a more traditional architecture that maximizes efficiency.

Figure 1. Schematic of reflecting tandem arrangement.
An alternate approach is to reflect light from the top cell onto the bottom cell. This is shown schematically in Figure 1.

Light is directed onto a top cell mounted at 45 degrees to the silicon bottom cell. Light with energy greater than the bandgap (represented by the green and blue arrows) are absorbed in the top cell. Sub-bandgap light (represented by the red arrow) is reflected from the top cell by the rear metal of the top cell onto the silicon cell. This reflection is achieved from the rear metal contacts which should extend across the entirety of the top cell. Light which is reflected from the front surface of the cell is also directed towards the silicon cell reducing reflection losses. That said, it is always better for light to be absorbed in the top cell if it has a higher voltage at maximum power than the bottom cell as required for a net increase in efficiency with the tandem arrangement.

![Figure 2. Test jig for demonstrating reflective tandem.](image)

A suitable jig for testing cells in this configuration was built. A schematic of this system can be seen in Figure 2 and Figure 3. The top cell is shown in purple. 45 degree supports (green) are used to mount the cell. The silicon cell is positioned vertically on a sliding mount (black). This enables the appropriately sized silicon cell to be positioned adjacent to the bottom cell to efficiently capture the reflected light. An appropriately sized aperture (blue in Figure 3) is placed on the jig so that the light entering the system is constrained to the top cell. The width of the aperture is \( \sqrt{\frac{1}{2}} \) width of the top cell to account for the 45 degree mounting.

![Figure 3. Test jig with aperture.](image)

4 GaAs – Si TANDEM

Initial trials of this system were undertaken with a gallium arsenide (GaAs) cell and silicon (Si) cell tandem. The reflection from the GaAs cell was measured at an angle of 45 degrees (Figure 4). The bandgap of GaAs and Si are 1.42eV and 1.11eV and are not well matched to a two terminal approach with the GaAs cell taking the dominant share of light absorption in natural sunlight.

![Figure 4. Reflection from GaAs solar cell. Reflection averaged ~70% for sub-bandgap photons and ~5% for photons above the bandgap.](image)

The GaAs cell was not designed for this application and shows significant absorption in the sub-bandgap region. Approximately two thirds of the photons with energy less than the bandgap are reflected from the GaAs cell. The sine wave appearance of the reflection above 900nm is due to interference effects from the thin GaAs layer. There are no transmission losses through the cell due to the presence of a continuous rear metal contact. Rear reflection losses (red area in Figure 4) are caused by absorption at the interface between the GaAs and the rear metallization. This could be reduced with the choice of a more reflective rear metal and/or the introduction of an intermediate dielectric over most of the rear.

The parasitic losses could also be reduced with a suitable spectral reflector in front of the cell. Suitable reflectors exist but the cost is too high for this to be practical.

Prior to placement in the system, the GaAs cell and the Si cell were measured at efficiencies of 24.6% and 20.3% at the equivalent of 1 sun AM1.5G. Measurements were made on a Photo Emissions Tech SS150 AAA rated simulator with light intensity adjusted using an externally calibrated silicon reference cell. The one sun current-voltage curves for the devices can be seen in Figure 5.

![Figure 5. Current-voltage curves for the Si (red) and GaAs cells (green) at one sun (solid) and in the tandem arrangement (dashed).](image)
The cells were then mounted in the system shown in Figure 2 and the aperture and the silicon cell were positioned to maximise the performance of the GaAs and the silicon cells respectively. The light intensity was adjusted to 1 sun using the reference cell placed at the height of the aperture in Figure 3. Efficiencies are then reported relative to the aperture area. The current-voltage curves of the cells measured in the tandem arrangement can be seen as the dashed lines in Figure 5.

The resulting efficiency of the combined system was 27.8%, exceeding the performance of either of the individual cells. As expected, the efficiency of the GaAs cell remains high at greater than 24% given it receives the full one-sun illumination. The slight drop in efficiency was due to a decrease in the short circuit current density from 29.2 mA/cm$^2$ to 28.1 mA/cm$^2$ offset by a slight increase in FF from 80.0% to 82.0%. The drop in current can be attributed to a combination of the increased reflection at 45 degrees and light falling outside the cell due to separation of the aperture from the cell. The performance of the silicon cell is reduced much more significantly to 3.75%, due to a large drop in current density from 40.2 mA/cm$^2$ to 8.3 mA/cm$^2$. This is due to the higher energy photons being absorbed in the GaAs (as desired) and the parasitic losses in the rear reflector. Combined current across the two cells is 36.4 mA/cm$^2$ which is 10% less than for the Si cell alone. The reduced current also led to a 10% decrease in the open circuit voltage of the silicon cell.

4 TARGETING >30% EFFICIENCY

Improvement in the GaAs cell performance is largely equivalent to improving the one sun cell performance. The high bandgap cell receives near full 1 sun illumination (70% due to 45 degree inclination). Introduction of the best reported one sun GaAs cell (28.8% Alta Devices [7]) would increase system performance by about 4.2% to 32%.

Scope for improving the relative performance of the silicon cell is much greater. Improving the sub-bandgap reflectance of the GaAs cell could dramatically increase the Si cell current. This is simulated in Figure 6. Including realistic external quantum efficiencies, it is expected that the current of the Si cell could increase by up to 40%. This would result in a further increase in efficiency of 1.5%.

Replacing the existing silicon cell with a higher performance cell would also increase performance. High voltage and excellent IR response is critical to maximise the value of the silicon cell in the system. The cells in this application were cut down from larger cells. This resulted in excessive edge recombination which limited open circuit voltage and fill factor. ANU has recently manufactured 4 cm$^2$ IBC cells with efficiency of 24.4% [8] (independently confirmed) with similar dimensions to the current system (6 cm$^2$ aperture). The increase in voltage and fill factor by using these cells at 1/4 current should boost the efficiency of the silicon cell in the system to about 5.5% and the potential tandem system efficiency to >34%.

5 PRACTICAL IMPLEMENTATION

The reflective tandem arrangement would lead to considerably different architecture than for a conventional module. Any configuration is likely to require the range of directions on the light to be constrained in one axis. Fortunately, one axis roll trackers are capable of meeting this requirement. Such systems are already cost effective for flat plate modules due to the increase energy collection and are economic even for moderate efficiency modules such as those produced by First Solar [9]. The cost position would be even stronger for high efficiency tandems.

One potential approach would be to have a 45 degree saw tooth superstrate on which the high bandgap cells are placed (Figure 7). The high bandgap cells could be deposited directly on the superstrate or formed separately and then mounted. Bifacial silicon cells, such as SLIVER cells, would be placed in slots formed at the peaks of the saw tooth. Light reflected from the high bandgap cells would then strike the silicon devices as per the arrangement in the earlier measurements. One advantage of this arrangement is that the light intensity on the silicon cell is doubled, requiring only half the silicon cell area and increasing light intensity closer to one sun.

The use of narrow (of the order of 1mm) silicon cells such as SLIVER cells ensures that the module thickness would be similar to conventional modules. Given that the entirety of the module is covered with the high bandgap material, it would be best suited to lower cost thin film approaches.

Another approach better suited to enabling more expensive high bandgap cells such as GaAs to have lower electricity costs is represented in Figure 8. A linear concentrating element is placed in front of the cells.
reducing the area of cells required. By using a linear concentrating element, the use of the same relatively simple one axis rolling tracker option mentioned earlier is still practical. This approach is best suited to regions with high ratios of direct to global light insolation.

Even moderate levels of concentration can bring significant increases in the amount that can be spent on the high bandgap cells compared to that which can be spent on a flat plate tandem. This greatly increases the range of cells which could be a viable partner to the silicon devices.

6 CONCLUSION

Four terminal tandems provide the opportunity to increase silicon cell efficiency without the material constraints of two terminal tandems. This work also presented a simple reflecting arrangement for the cell which alleviates the need for expensive optics.

The potential of this approach was shown through the use of standard GaAs and Si cells which would not be well matched for two tandem devices. Using good quality cells, efficiencies of 27.8% were demonstrated with the potential to achieve >34% with higher performing cells.

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References


