A GaAs/Silicon Mechanically Stacked, Multijunction Solar Cell*

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ABSTRACT

A GaAs/silicon mechanically stacked, multijunction solar cell has been experimentally and theoretically investigated. Theoretical calculations predict efficiencies over 30% for this cell and indicate that the penalty for using a non-optimal combination of bandgaps is small when the cells are operated independently. Preliminary experiments achieved 24.7% at 70X. A detailed analysis of the experimental results allowed estimation of the various loss mechanisms in the stack and projection of the performance of an optimized stacked cell. An optimized GaAs/silicon MSMJ cell should be able to achieve efficiencies near 30% under concentration.

INTRODUCTION

In order to obtain photovoltaic conversion efficiencies of 30% or more, it will be necessary to use tandem cells. A tandem cell consists of several photovoltaically active junctions (cells) with different bandgaps that are stacked in optical series. The higher theoretical efficiencies of tandem cells compared to single junction cells arises from the better match to the broad solar spectrum that can be achieved with multiple bandgaps than with a single bandgap. Recent studies have indicated that efficiencies around 30% are practical for a two junction tandem cell (1,2). In order to achieve these very high efficiencies, each junction of the tandem cell must be optimal in the sense that it is operating near its intrinsic limiting efficiency. There has been considerable effort towards demonstrating a tandem cell with good progress (3,4,5). However, the best tandem cell is still less efficient than the best single junction cell. The lower performance of experimental tandem cells to date is due to the use of semiconductor alloys which have the required bandgaps for optimal conversion efficiencies but are not well developed.

We have adopted an approach which avoids the material difficulties of relatively new semiconductor alloys by using the two best developed photovoltaic materials available, GaAs and silicon, and by using a mechanically stacked, multijunction (MSMJ) tandem cell approach. An MSMJ cell is a tandem cell which is fabricated by mechanically stacking two (or more) cells with transparent adhesives. Because each cell incorporated into the stack is first fabricated on its own substrate, each cell can be fabricated using conventional single junction cell technology and optimized separately. Hence, a GaAs/silicon MSMJ cell can use state-of-the-art GaAs and silicon cells. Furthermore, each cell in the stack can be contacted separately and thereby be operated independently. Current matching is not necessary when the cells are operated independently, in which case a much wider selection of bandgaps may be used for the two junctions (1,2).

Preliminary experiments with a GaAs/silicon MSMJ cell have been reported by another research group. These researchers reported an efficiency of 20% (1X,AM1), with the GaAs cell providing 18% and the silicon cell providing 2% (6). They have also reported an efficiency of 19.5% (1X, AM1), with the GaAs cell providing 16.5% and the silicon cell providing 3% (2). This group, however, considered their work as a preliminary experiment towards demonstration of a tandem cell with an optimal bandgap for the top cell of 1.75 to 1.8 eV. One of the purposes of this paper will be to demonstrate the potential of a GaAs/silicon MSMJ cell for high efficiencies.

In this paper, we will describe our work on a GaAs/silicon MSMJ cell. We will first present calculations which show that the penalty for selection of a non-optimal combination of bandgaps is relatively small when the cells in the tandem cell

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are operated independently. We will then present experimental results of a GaAs/silicon MSMJ cell operated under concentration. Next, we will describe an experiment which simulated the performance of a GaAs/silicon MSMJ cell and allowed us to calculate the various loss mechanisms in the stack; from these calculations we were able to make projections on the potential performance from a GaAs/silicon MSMJ cell.

THEORY

Many researchers have theoretically examined tandem cells (1,2,6,7). For our calculations, we will use the same models as used in Reference 2. These calculations assume a quantum efficiency of one and no optical losses in the stack. We calculated the performance of a stacked cell with a silicon (1.12 eV) bottom cell as a function of the top cell bandgap. The calculations were performed for one-sun illumination (AM1.5, 72.7 mW/cm^2). The photogenerated current in each junction is shown in Figure 1. The current shows the expected behaviour; as the top cell bandgap is increased, the current from the top cell decreases while the current from the bottom cell increases. For the spectrum used in our calculations the currents are matched at a top cell bandgap of about 1.65 eV.

The efficiency of the tandem cell with the two cells operated in series and independently is shown in Figure 2. As is expected, the performance of the stacked cell with the two cells operated in series decreases dramatically when the photocurrents of the two cells are not matched. Independent operation of the two cells is much less sensitive to the top cell bandgap since photocurrent matching is no longer required. The optimal bandgap for the top cell for either series or independent operation would require a high bandgap semiconductor with a bandgap between 1.65 and 1.8 eV. Hence, much of the experimental work on tandem cells has featured development of a high bandgap semiconductor for solar cells (4,5,8).

For independent operation of the two cells, the peak efficiency is 35.1% with the top cell bandgap at 1.8 eV. The calculated efficiency for a GaAs top cell (1.424 eV) is 32.5%, of which 25.6% is provided by the GaAs cell and 6.9% is provided by the silicon cell. The silicon cell provides about 21% of the GaAs/silicon tandem cell output. The penalty for using GaAs rather than a semiconductor with the optimal bandgap is only 1.6 percentage points. Other researchers have also noted the small penalty for selection of GaAs for an MSMJ cell with a silicon bottom cell when the cells are operated independently (1). In order to estimate the potential performance of a realistic cell, it is necessary to estimate the optical losses and the effect of a non-unity quantum efficiency. Even after accounting for these losses, the projected efficiency of a GaAs/silicon cell under concentration still exceeds 30%

EXPERIMENT

A schematic diagram of a GaAs/silicon MSMJ concentrator cell is given in Figure 3. A commercial silicon concentrator cell (Applied Solar Energy Corp.) was used for the bottom cell. It is a conventional silicon concentrator cell with an n^+p planar junction and a low resistivity base (.3 ohm-cm). Cells from the same lot have achieved efficiencies near 21% at 100X, AM1.5 (9). The GaAs cell was fabricated at Hughes Research Laboratories using their

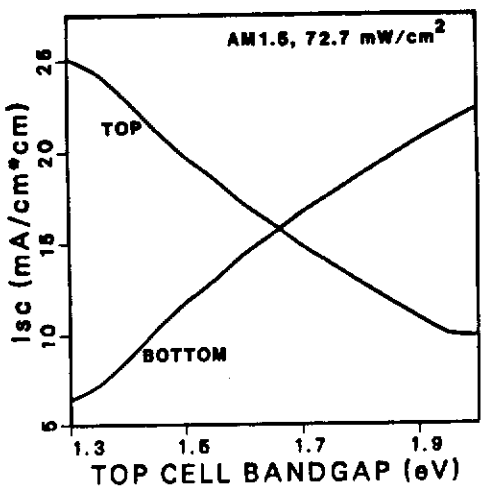

Figure 1. Photocurrents of the top and bottom cells for a tandem cell with a silicon bottom cell.

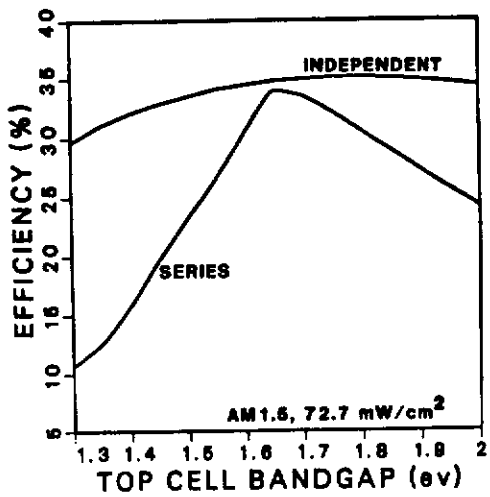

Figure 2. Tandem cell efficiency with a silicon bottom cell for independent and series operation.

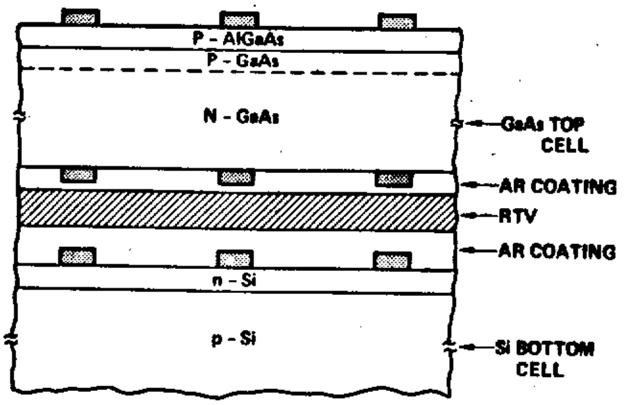

Figure 3. A schematic diagram of the GaAs/silicon MSMJ cell.

infinite melt LPE growth technique (10). The cell structure is a conventional p^+n structure with an AlGaAs heteroface window layer to minimize front surface recombination.

In order to maximize transmission of solar photons with energy below the bandgap of GaAs, a grid and AR coating was used on the back surface of the GaAs cell. Although the grid pattern used for the top and bottom surface of the GaAs cell is the same, no attempt was made to align the front and back grid metallizations. Also, no attempt was made to optimize the AR coatings. The GaAs wafers are polished on both sides, are about 300 µm thick, and are doped to about 1E18 cm^{-2} (Te). No attempt was made to thin the substrate in order to minimize the free carrier absorption in the GaAs. The area of both cells was 1 cm^2 as defined by the busbars. The grid patterns for the GaAs and silicon cells are different and no attempt was made to align them during the stacking process. Also fabricated at Hughes was a GaAs filter so that an experiment to simulate the performance of our MSMJ cell could be performed. The filter consisted of a GaAs wafer similar to the substrates used for cell fabrication with AR coatings applied to both the front and back surfaces. The filter was thus an accurate representation of an actual cell.

The tandem cells were assembled and all measurements were performed at Sandia. The GaAs filter or cell was stacked onto the silicon cell with a silicone adhesive (GE RTV 615A). The curing agent was not added to the adhesive so that the stack could be disassembled. Illuminated IVs at one-sun and under concentration were taken. A pulsed solar simulator was used for the concentration measurements so that heating of the cell, which may be a significant factor for the top cell, is limited. The cell measurement procedures employed at Sandia have been described elsewhere (11). All one-sun measurements were made at AM1.5, 100 mW/cm^2. Measurements of the cell hemispherical reflectance and external spectral response were made of the silicon cell by itself and with the GaAs filter stacked on top. An example of these measurements is given in Figure 4, which shows the quantum efficiency of the silicon cell both with and without the filter. The cutoff of the silicon cell response with the GaAs filter is not sharp, which may indicate that there is substantial absorption of sub-bandgap photons in the GaAs filter. (Sub-bandgap photons have an energy less than the semiconductor bandgap.) The absorption of the GaAs filter was also measured.

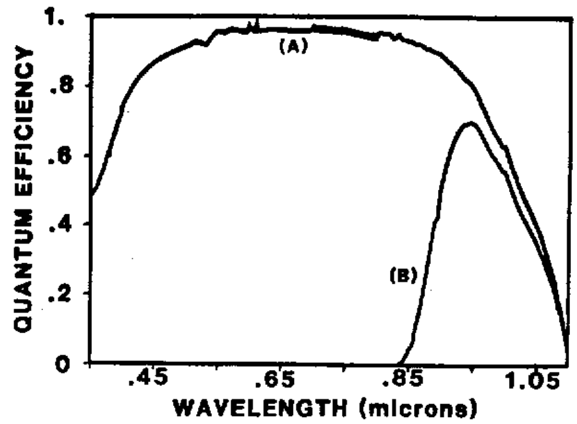

Figure 4. The quantum efficiency of the silicon cell (A) by itself and (B) with the GaAs filter stacked on top.

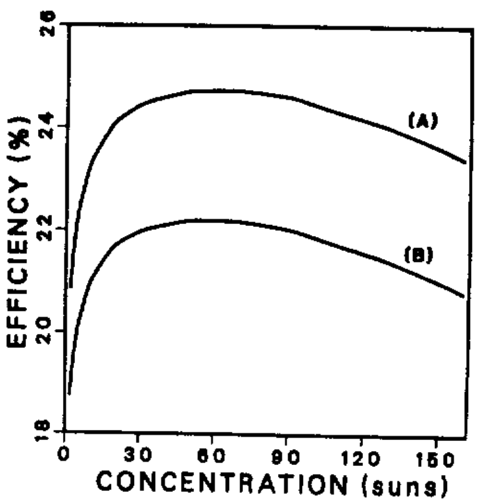

Figure 5. The efficiency of (A) the GaAs/silicon MSMJ cell and (B) the GaAs cell by itself.

Conc.	Cell	Isc	Voc	FF	Eff.
1X	Silicon	4.61	.553	.748	1.90
	GaAs	24.0	.973	.745	17.4
	Tandem	n/a	n/a	n/a	19.3
67X	Silicon	311	.683	.824	2.55
	GaAs	1615	1.109	.833	22.2
	Tandem	n/a	n/a	n/a	24.7

Isc = mA, Voc = volts, Eff. = %,
n/a = not applicable.

Table 1. Cell parameters at one-sun and at the peak efficiency concentration.

The GaAs and the MSMJ cell performance is given in Figure 5. The peak efficiency of the MSMJ cell was 24.7% at 70X, with the silicon cell providing about 10% of the output. This is believed to be the highest reported efficiency for any multi-junction device. The performance characteristics followed the performance of the GaAs cell since the GaAs cell provided about 90% of the output. The grid design of the GaAs cell was not optimized and the GaAs cell could be improved. GaAs concentrator cells with 26% efficiency under concentration have been recently reported (12). The parameters of the GaAs/silicon MSMJ cell at one-sun and at the peak efficiency concentration of 70X are presented in Table 1.

DISCUSSION

The largest discrepancy between the experimental results and the theoretical calculations was in the performance of the silicon cell. Our calculations indicated that the silicon cell should provide about 21% of the tandem cell output while the measured contribution was only 10%. This lower output was due to a low short-circuit current from the silicon cell. There are several optical loss mechanisms in the MSMJ cell which will reduce the current of the silicon cell. These loss mechanisms include the following: alignment of the grids of the top and bottom cells, sub-bandgap absorption in the top cell, reflection at the various interfaces, and recombination losses within the silicon cell itself. The simulated MSMJ cell (silicon cell with the GaAs filter stacked on top) allows estimation of these various loss mechanisms.

The effective grid obscuration to the silicon cell will include both its own grid and the two grids on the GaAs cell. The grid coverage on the silicon cell is about 5%. The effective grid obscuration due to GaAs cell grids may be estimated by comparing the short-circuit currents from the silicon cell with the filter and with the GaAs cell stacked on top. These values are, respectively, 5.28 and 4.61 mA/cm^2. This represents a 14.5% reduction in current due to the grids on the top cell. The GaAs cell grid design presents about 10% obscuration; misalignment of the front and back grids on the GaAs cell accounts for the additional obscuration loss. The total effective obscuration is about 20% (14.5% from the GaAS cell and 5% from the silicon cell). To minimize grid obscuration losses, all the grids should be aligned as depicted in Figure 1. Alignment of the grids would reduce the obscuration loss to the obscuration of the GaAs grid, which is about 10% for a concentrator cell.

The output of the silicon cell with the filter stacked on top is still substantially below the calculated current of 13.7 mA/cm^2. The reflectivity and spectral response measurements of the silicon cell, both with and without the filter stacked on top, and the optical characterization of the GaAs filter allows a detailed analysis of the short-circuit current of the silicon cell. Figure 6 presents the equations used in our analysis to calculate the absorption, reflection, and recombination losses. The derivation of these equations is given in Reference 13. All the quantities appearing in these equations are measured values. Also, the losses are calculated as a relative loss so that relative measurements of the reflectance and spectral response are adequate.

$$\text{ABS. LOSS} = \frac{1}{K}\int_{\lambda_c} \frac{A_{STK}(\lambda)}{1 - R_{SI}(\lambda)} SR_{SI}(\lambda)\, I(\lambda)\, d\lambda$$

$$\text{REFL. LOSS} = \frac{1}{K}\int_{\lambda_c} \frac{R_{STK}(\lambda)}{1 - R_{SI}(\lambda)} SR_{SI}(\lambda)\, I(\lambda)\, d\lambda$$

$$\text{REC. LOSS} = 1 - K \Big/ \int_{\lambda_c} SR_{IDEAL}(\lambda)\, I(\lambda)\, d\lambda$$

$$\text{WHERE} \quad K = \int_{\lambda_c} \frac{1}{1 - R_{SI}(\lambda)} SR_{SI}(\lambda)\, I(\lambda)\, d\lambda$$

$SR(\lambda)$ ≡ SPECTRAL RESPONSE
$A(\lambda)$ ≡ ABSORPTIVITY
$R(\lambda)$ ≡ REFLECTIVITY
$I(\lambda)$ ≡ SOLAR SPECTRAL IRRADIANCE, AM 1.5
λ_c ≡ cutoff wavelength

Table 2. The equations used in the analysis. Subscripts "SI" and "STK" refer to the silicon cell by itself and with the GaAs filter stacked on top. The subscript "IDEAL" refers to a silicon cell with a quantum efficiency of one.

The relative reduction in current due to reflection for the simulated MSMJ cell is 17.5%. The reflection loss is rather high and shows that the AR coatings have not been optimized. A single layer AR coating is used on the front surface of the GaAs cell, which is adequate for single junction GaAs cells but not for a tandem cell which responds to a broader spectrum. Siegel has thoroughly investigated the optical properties of MSMJ cells and estimates that the reflectance losses could be kept below 10% (14).

The relative reduction in current due to absorption of sub-bandgap photons in the GaAs filter is 15.5%. The measured absorption of the GaAs filter at 1 micron was 12.2%. This absorption corresponds to an absorption coefficient of about 4.3 cm^{-1}, which is consistent with other measurements in heavily doped GaAs that have been attributed to free carrier absorption (15). The absorption loss may be reduced by two different methods. In the first method, a less heavily doped substrate is used. For instance, the absorption at 1 micron of two substrates doped to 1E18 and 2E17 cm^3 with Te was measured to be 11.4 and 3.9%, respectively. The doping of the substrate can be reduced in GaAs cells since the series resistance is dominated by the grids and emitter and not by the base. The other method to reduce absorption losses in the GaAs would be to use a thin cell. Thin GaAs cells are under development for space applications where weight is an important concern (16), and for terrestial cells where material costs is an important concern (17). For example, the calculated absorption loss for a 75 micron thick GaAs cell is 8.8%. The absorption losses could easily be reduced to below 10% and probably below 5% with the above two methods.

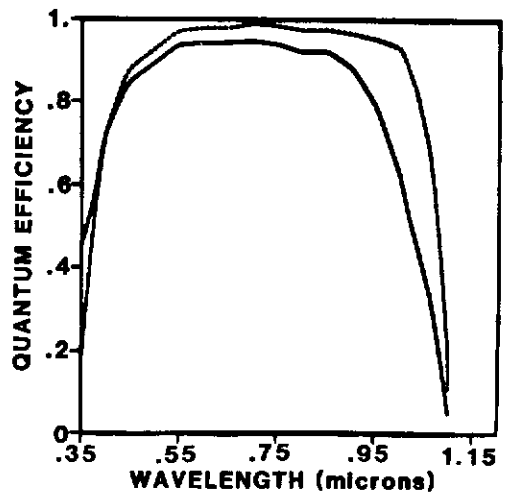

Figure 6. The internal quantum efficiency of the silicon concentrator cell (solid line) and of the red enhanced silicon cell (dashed line).

Recombination losses are the reduction in current due to an internal quantum efficiency less than one. For our concentrator silicon cell, the recombination losses are 38.3%. This large loss is due to the relatively poor red responses of silicon concentrator cells, which use low resistivity bases in order to minimize base resistance and maintain Voc (18). Stacked cell applications will require new silicon cell designs with enhanced red response. Figure 6 compares the quantum efficiencies of the silicon concentrator cell and a red-enhanced silicon cell. Such cells typically will use a high resistivity base (10 ohm-cm in this case) in order to obtain long minority carrier diffusion lengths. The calculated recombination losses for the red-enhanced silicon cell is only 17%.

Figure 7 shows a bar chart which illustrates the contributions of the various loss mechanisms for our MSMJ cell and for an improved design. The improvements are conservative estimates of present technological capabilities as explained in the preceding paragraphs. The assumed losses for the improved design are 17%, 7.5%, 10%, and 10% for the recombination, absorption, reflection, and obscuration losses, respectively. With these improvements, the silicon cell component of the tandem cell efficiency will approach 5% under concentration, which would correspond to nearly 15% of the tandem cell

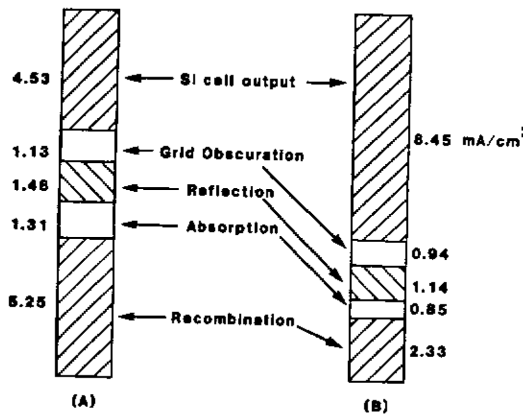

Figure 7. The reduction of the silicon cell current from its ideal value by the various loss mechanisms is illustrated with bar charts. Chart (A) is the experimental cell and chart (B) is for an improved cell (see text). Also quoted are the currents associated with each loss component. Note that the calculated output current is within 2% of the measured value.

total output. This scenario assumed the availability of a red-enhanced silicon concentrator cell. With a conventional silicon concentrator cell and the other improvements, the silicon cell component of the tandem cell efficiency should reach 3.5%. Hence, with an optimized GaAs cell, a GaAs/silicon MSMJ cell should be able to achieve an efficiency of around 30% under concentration.

CONCLUSIONS

The GaAs/silicon MSMJ cell has been shown to be a viable option for high efficiencies. Both theoretical calculations and a detailed analysis of experimental results indicate that efficiencies around 30% are practical under concentration for this cell. The primary advantage of a GaAs/silicon MSMJ cell is that the component cells are the best developed photovoltaic cells available. Preliminary experiments achieved an efficiency of 24.7% at 70X.

The silicon cell will provide nearly 15% of the tandem cell output in an optimized tandem cell. The cost of the MSMJ cell ($/watt) will be less expensive than the GaAs cell alone if the cost of the silicon cell ($\$/cm^2$) is less than 15% of the cost of the GaAs cell ($\$/cm^2$), which is presently the case for commercial GaAs space cells and commercial silicon concentrator cells (19). Hence, we believe that this cell is an excellent option for applications which require very high efficiencies.

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