PROGRESS TOWARD CASCADE CELLS MADE BY OM-VPE*

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SUMMARY

OM-VPE has been used to make a sophisticated monolithic cascade cell, with a peak AM0 efficiency of 16.6%, not corrected for 14% grid coverage. The cell has 9 epitaxial layers. The top cell is 1.35 microns thick with a 0.1 micron thick emmitter. Both cells are heteroface n-p structures. The cascade cell uses metal interconnects. Details of growth and processing are described.

INTRODUCTION

This paper describes the design, fabrication, and testing of a high efficiency monolithic cascade cell made using Organometallic Vapor Phase Epitaxy (OM-VPE), and interconnected using the MIC^2 structure. A number of significant results have been obtained, including

- 16.6% AMO efficiency at a concentration of 10.7 suns, uncorrected for the 14% obscuration (19.3% active area efficiency).
- .5 cm^2 active area (.71 cm by .71 cm), with wafer yields in excess of 4 cm^2 per processed wafer.
- A 1.35 micron thick 30% AlGaAs heteroface top cell with an emitter only 0.1 microns thick.
- An n-on-p heterface GaAs bottom cell stable enough to endure the 20 minute, 780 °C growth of the top cell.

The cell design and structure will be described first. The fabrication process follows, followed by a presentation of experimental results.

Cell Design

The cell structure is listed in Table 1. It is based on a computer optimized design for 400 suns AM2 and experimental iterations to optimize the quantum yield of the top cell. As can be seen, heteroface structures are used for both the top and bottom cells. The entire structure contains nine layers. These are formed in continuous sequence under computer control in the OM-VPE reactor. Uniformity over a 1.5 x 2 inch wafer is typically ± 7.5%.

An n-on-p structure is used for the bottom cell, Typically, n-type dopants are slow diffusers in GaAs; this gives the GaAs cell an inherent stability during the growth of the top cell. The n-on-p structure has other advantages for space applications, including long base diffusion lengths for better radiation hardness[1]. The low resistivity of the n-type emitter reduces emitter sheet resistance, an important consideration in cells using MIC^2 interconnects.

The top cell is composed of six layers, the junction occurring in 30% AlGaAs, with a bandgap of 1.82 eV. From the top down, these are a GaAs contact layer, used in the contacting process. Next is an 80% AlGaAs window layer and an emitter 0.10 microns thick. This is the thinnest emitter ever reported for a heteroface cell, and is required because of the relatively short diffusion length in n^+ 30% AlGaAs. The p-type base is about 1 micron thick, and collects most of the photons used by the top cell. Below the base is a back surface field (BSF) layer, required to prevent carriers from leaking out the back of the thin base. The remaining layer is used for contacting during the interconnect process.

Note that the top cell is extremely thin, and is, to the knowledge of the authors, the thinnest single crystal solar cell ever reported. The motivation is as follows: To properly current match an AlGaAs/GaAs cascade cell, the top cell should have a bandgap of about 1.9 eV. The problem is that key properties of AlGaAs, such as mobility and diffusion length, degrade rapidly as the direct-indirect transition at 1.95 eV is approached. An alternative strategy is to make the top cell so thin that it is semi-transparent, allowing some of the near gap photons to penetrate through to the bottom cell. In this manner, a current matched structure with a lower gap top cell is possible. A careful tradeoff of practical material parameters, bandgap, and efficiency places an optimum gap for the top cell at about 1.82 eV.

Figures 1 and 2 show quantum yields for top and bottom cells made with this design strategy. Figure 1 shows the quantum yield of a 1.82 eV AlGaAs cell. This is corrected for both AR coating reflection and grid coverage. The downward slope of the red response is partially due to the semi-transparency. Figure 2 shows the quantum yield of a GaAs bottom cell. This is corrected for AR coating reflection, but not grid coverage. Note the sharp cut-off at the bandgap of the top cell. But note also that some light above the top cell bandgap energy leaks through.

Figure 2 attests to the stability of the bottom cell. This plot is not corrected for the 14% grid obscuration, so that the internal quantum yield is flat at about 90%. This cell has been exposed to a temperature cycle of 780°C for 20 minutes.

FABRICATION PROCESS

The MIC^2 interconnect process has been used with this cell. This has been described elsewhere[2], and will be summarized here. In this process, narrow grooves are etched through the top cell to the emitter of the bottom cell. Metal deposited in these grooves shorts the emitter of the bottom cell to the base of the top cell. This interconnect is particularly useful in the development of cascade cells because it requires no tunnel junction and allows divert probing of the top and bottom cells.

Figure 3 outlines the MIC^2 process. Two selective etches are used. One etch attacks GaAs and 30% AlGaAs, but not 80% AlGaAs. HF etches 80% AlGaAs, but not the other materials. The process proceeds as follows: Following masking, the two etches are used to etch down to the contact layer below the top cell BSF. The cell is remasked, and a narrower groove etched in the bottom of the first groove through to the emitter of the bottom cell. The same mask is used to deposit an n-type ohmic contact on the top of the cell and the emitter of the bottom cell. Finally, a p-type contact placed in the groove connects the n-type contact metal to the buried contact layer. The cell is alloyed, cap stripped, and AR coating applied.

The grooves are nominally 13 microns wide, on 202 micron centers. The top contact stripes are nominally 7 microns wide on the same centers, for an obscuration of 10%. This design is appropriate for 400 suns AM2. Low concentration or 1 sun designs have contacts spaced typically 5 or more times further apart, and obscuration is negligible. In practice, the grooves and grids are 19 and 10 microns wide respectively, increasing obscuration to 14%. This can be reduced considerably through further process enhancements.

We have used AuGa/Ni/Au for n-type contacts and Al/Mg/Au contacts for p-type. These are chosen because they alloy at the same temperature and time, and thus amenable for use in a two-layer contact.

Anti-reflection coating is applied by selective etching of the GaAs cap layer, followed by plasma deposition of a single layer of Si_3N_4. Two-layer coatings will significantly improve performance. The single layer has been used at this stage of development because of its simplicity and yield.

PERFORMANCE RESULTS

Cells are typically made on 1.5 x 2 inch wafers, with the mask providing 6 devices per wafer. Each device has an active area 0.5 cm^2, with dimensions .71 x .71 cm. The entire chip active area measures .77 cm^2, with two large contact busses taking up the remaining area. This is an optimized design for 400 suns, AM2. The cells have a single Si_3N_4 AR coating. The top contact grid is not plated.

Cells have been tested in a Spectrolab XT-10 simulator with an AM0 filter set. Intensity is set to one sun, using a GaAs calibration cell. A glass lens provides concentration. The cell has no cooling, and the nominal ambient temperature is 24°C. The concentration is measured by taking the ratio of the cascade cell short circuit current at concentration to the one sun short circuit current.

Table 2 shows the efficiency at various concentrations. Table 3 lists other cell parameters. Figure 4 shows the cell IV characteristics. The efficiency assumes a 0.5 cm^2 cell area. In Table 2, three columns tabulate the measured efficiency (14% obscuration), the internal efficiency (no obscuration) and efficiency corrected to 5% obscuration, as might be typical for a 1 sun cell. The efficiency at 10.7 suns is close to that of a very good GaAs cell.

This cell has about 17% current mismatch, with the bottom cell short circuit current greater than the top. This can be determined by illuminating with a He-Ne laser. Such light, which is absorbed in the top cell alone, improves the short circuit current by about 35%. This mismatch is due to the cell being an AM2 design, that we are only using a single layer AR coating, and that more work is needed to optimize the top cell thickness to properly exploit its semi-transparency.

CONCLUSION

This work has demonstrated that cascade cells can be made with areas approaching those required for space applications, and that high efficiencies are realizable. To achieve these efficiencies, several design techniques have been employed, including:

- use of thin, semi-transparent top cells to enhance current matching while maintaining top cell quantum yield.
- use of n-p cells to maintain stability of the bottom cell during growth of the top cell.
- use of top cell BSF to prevent carriers from spilling out the back of the base.

It is anticipated that considerable improvements are possible through such steps as use of a 2-layer AR coating, plating of grids to improve fill factor, and better current matching through an optimized AR coating and proper thickness top cell. Improvements of this sort, none of which require new technology development, should increase efficiency well beyond that of the best GaAs cell.

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REFERENCES

1. Flood, D. J., Swartz, C. K. and Hart, Jr., R. E., GaAs Homojunction Solar Cell Development, In Space Photovoltaic Research and Technology 1980, NASA Conference Publication 2169, p. 239.

2. Borden, P. G., LaRue, R. A., Ludowise, M. J., Saxena, R. and Gregory, P. E., A Metal-Interconnected Cascade (MIC^2) Solar Cell, IEDM Technical Digest, 150 (1981).

TABLE I.-CELL STRUCTURE

LAYER	PURPOSE	TYPE	MATERIAL	THICKNESS
9	Contact	n^+	GaAs:Se	0.5 μm
8	Window	n^+	$Al_{.8}Ga_{.2}As$:Se	0.15
7	Emitter	n^+	$Al_{.3}Ga_{.7}As$:Se	0.1
6	Base	P	$Al_{.3}Ga_{.7}As$:Zn	1.0
5	BSF	P	$Al_{.8}Ga_{.2}As$:Zn	0.1
4	Contact	P^+	$Al_{.32}Ga_{.68}As$:Zn	0.2
3	Window	n	$Al_{.8}Ga_{.2}As$:Se	0.1
2	Emitter	n	GaAs:Se	0.5
1	Base	p	GaAs:Zn	2.0
0	Substrate	p	GaAs:Zn	12 mils

TABLE II.-MIC^2 AM0 EFFICIENCY

Concentration (suns)	Efficiency at Obscuration of		
	14%	5%	0%
1	13.2%	14.6%	15.3%
3.97	15.4%	17.0%	17.9%
8.79	16.5%	18.2%	19.2%
10.67	16.6%	18.3%	19.3%

14% obscuration (grooves, top contact)
.5 cm^2 active area (.71 x .71 cm)
30% AlGaAs top cell
GaAs bottom cell

TABLE III.- CELL PERFORMANCE

Conc. (Suns)	V_{oc}(V)	I_{sc}(mA)	FF	η (%)
1	2.15	6.1	.681	13.2
3.97	2.27	24.2	.753	15.4
8.79	2.32	53.6	.786	16.5
10.67	2.33	65.1	.782	16.6

.5 cm^2 active area
14% obscuration
AMO, simulated
Single layer Si_3N_4 AR coating

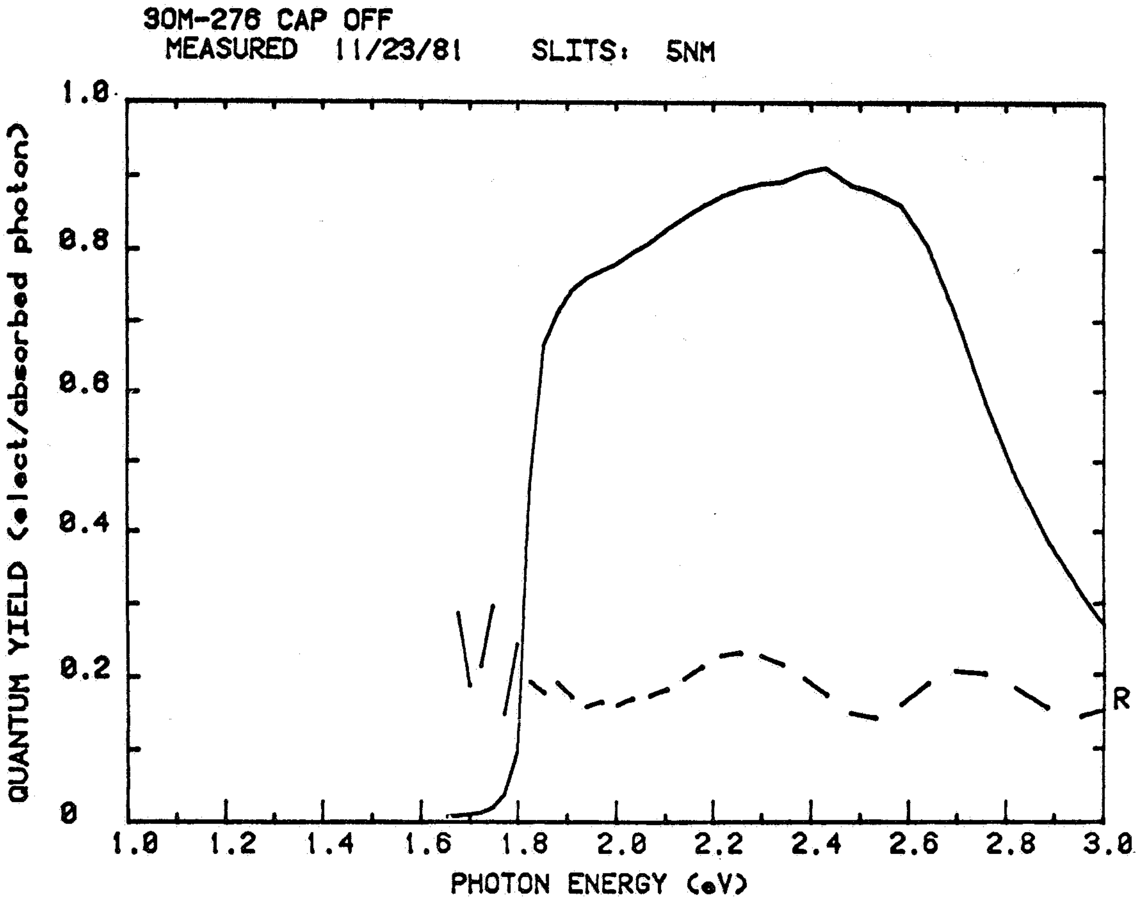


Figure 1

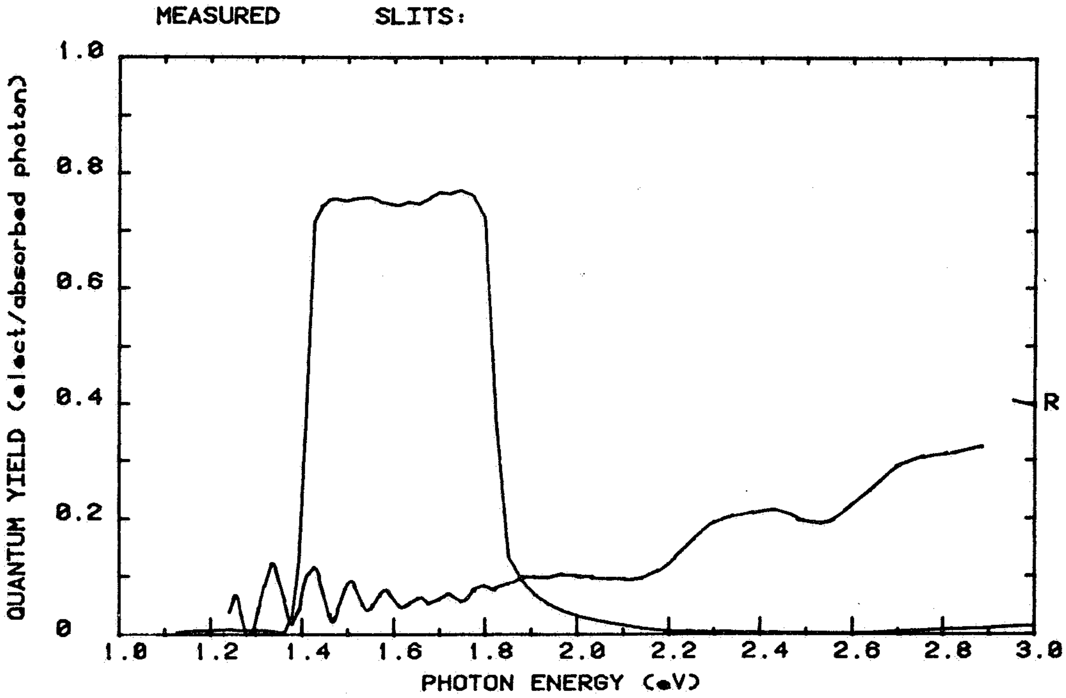
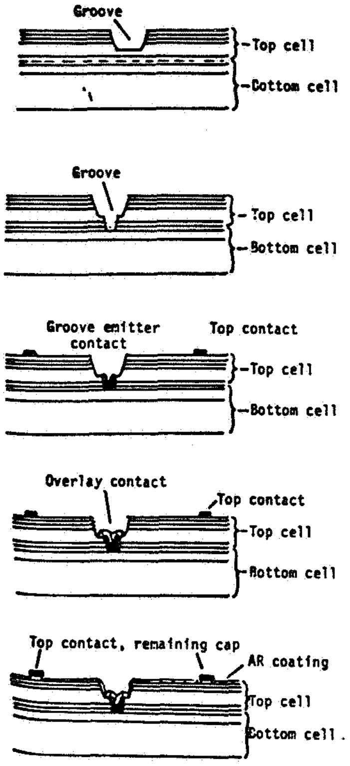


Figure 2

MIC^2 CELL PROCESS

NOTE: Drawings are not to scale. Top cell layers are about 1.5 microns thick in total, bottom cell is about 2.5 microns thick. Top grid bars are spaced about 150 microns for a concentrator cell, about 1000 microns for a 1 sun cell. Top groove is about 10 microns wide.



A) Etch first groove

B) Etch groove to emitter of bottom cell, etch out stop layers

C) Deposit emitter contacts

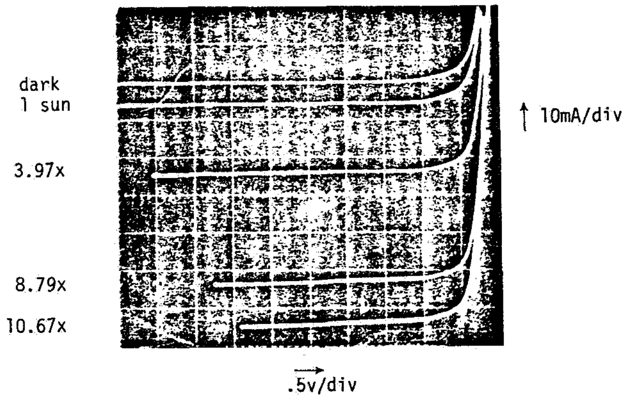
D) Deposit base contact in groove

E) Etch cap, AR coat

Bottom cell layers, from bottom up, are base, emitter, and window. Top cell layers, from bottom up, are back barrier, base, emitter, window and cap.

Figure 3

CASCADE CELL IV AT VARIOUS CONCENTRATIONS



.5 cm^2 active area
14% grid coverage
Single layer AR coating
AM0, simulated.

Figure 4

PRESENT STATUS OF AIR FORCE AlGaAs/GaAs CASCADE CELL PROGRAM

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ABSTRACT

The status of the AF AlGaAs/GaAs cascade cell program is summarized. Recent results show that liquid phase epitaxy is a superior fabrication approach. Specific technical difficulties are addressed and approaches to solve them are described. The plans for follow-on programs based on these results are also described.