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RECENT ADVANCEMENTS IN MONOLITHIC AlGaAs/GaAs SOLAR CELLS FOR SPACE APPLICATIONS

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ABSTRACT

High efficiency, two-terminal, multijunction AlGaAs/GaAs solar cells have been reproducibly made with areas of 0.5 cm^2. The multiple layers in the cells were grown by OMVPE on GaAs substrates in the n-p configuration. The upper AlGaAs cell has a bandgap of 1.93 eV and is connected in series to the lower GaAs cell (1.4 eV) via a metal interconnect deposited during post-growth processing. A prismatic coverglass is installed on top of the cell to reduce obscuration caused by the gridlines. The best 0.5 cm^2 cell has a two-terminal efficiency of 23.0 % at 1 sun, air mass zero (AM0) and 25 °C. To date, over 300 of these cells have been grown and processed for a manufacturing demonstration. Yield and efficiency data for this demonstration will be presented. As a first step toward the goal of a 30 % efficient cell, a mechanical stack of the 0.5 cm^2 cells described above, and InGaAsP (0.95 eV) solar cells was made. The best two-terminal measurement to date yields an efficiency of 25.2 % AM0. This is the highest reported efficiency of any two-terminal, 1 sun space solar cell.

INTRODUCTION

In terms of space qualified photovoltaic cells, the most important variables to control are: weight, cost, efficiency, operating lifetime, and radiation resistance. This paper will address the efficiency of space photovoltaic cells. To get to very high efficiencies (i.e. 25 - 30+ %) without the additional complexity of concentrating optics, one must utilize two or three junctions in tandem. The additional junctions increase the energy range that is usefully absorbed by the cell, and therefore, increase the efficiency. In order to reduce the weight and complexity of a panel of multijunction cells, a monolithic structure is ideal. Up until now, two junction monolithic solar cells have been in the research phase, but in this paper we report the first manufacturing demonstration of these devices. A monolithic three junction cell has never been made. However, attempts at mechanically stacking three junctions have been successful, and will be discussed below.

A computer model, described in detail in reference 1, has been used to determine the optimal design parameters for III-V materials based single and multijunction photovoltaic cells. The program can optimize such structural parameters as doping levels, concentration gradients, layer thicknesses, indices of refraction for anti-reflective (AR) coatings, and gridline aspect ratio and spacing to achieve the highest efficiency for the given solar concentration, air mass and operating temperature. Predictions of efficiency for one, two, and three junction cells as a function of temperature are shown in Fig. 1. At 25 °C, the predicted efficiency for a single junction GaAs cell is approximately 22 %. This value has been achieved with our single junction GaAs cell, and a pilot line for manufacturing has been installed. The expected efficiency for a 1.93 eV AlGaAs on 1.42 eV GaAs two junction cell is approximately 25 % . Currently we have achieved 23.0 % efficiency using a metal interconnect cascade cell (MICC) (ref. 2). There are other two junction cells which have higher predicted efficiencies than the line shown, but they involve lattice mismatched material structures (i.e. AlGaAs/InGaAs), or quaternary materials which are quite difficult to grow repeatably and uniformly. The three junction line shows the optimized efficiency for the same AlGaAs/GaAs cell as the two junction line, but includes a low bandgap (1.0 eV) InGaAs lower cell. This structure has the potential to achieve efficiencies of up to 31% at 25 °C (1 sun, AM0).

DEVICE GROWTH AND PROCESSING

The metal interconnect cascade cell (MICC) consists of an upper 1.93 eV AlGaAs cell and a lower 1.42 eV GaAs cell (both in the n on p configuration) which are connected in series by a metal interconnect deposited during post-growth processing. These cells are grown by atmospheric pressure OMVPE on p-type GaAs substrates, as described in reference 3. The schematic cross section of an MICC is shown in Fig. 2. The base and emitter of the GaAs lower cell are grown first. A highly doped AlGaAs window is grown on top of the emitter to reduce the surface recombination velocity at this interface. Next, p+ and n+ contact layers are grown which will be shorted together during later processing to eliminate the intrinsic p-n junction formed by the two solar cells, and to connect the two cells in series. The AlGaAs base and emitter of the upper cell are grown next, followed by another highly doped AlGaAs window layer. Finally, a GaAs cap layer is added to ensure good ohmic contact to the top metal grid, and to protect the device during processing.

Fig. 3 shows the processing sequence used to fabricate the MICC devices. During processing, the front and back metalizations are deposited by evaporation. The metalization contact to n-type material includes Au/Ge/Ni/Au layers with additional Pt/Au layers on the top metal grid for easy soldering or welding. The p-type metalization contacts are Au/Zn/Au. A wide and a subsequent narrow trench are etched in the upper cell to expose the p+ and n+ contact layers of the device. The metal interconnect consists of two evaporated metal layers deposited in the trench areas which form good ohmic contacts to the p+ and n+ contact layers. Contact resistance after a 400 °C anneal is typically very good, with values below 1×10^{-5} Ω-cm^2. An isolation etch is performed to allow electrical testing of the devices before they are scribed and separated into individual cells. The n+ GaAs cap layer is selectively etched away between the gridlines prior to the deposition of the AR coating. The two-layer AR coating which includes TiO_2 and MgO is sputtered onto the exposed AlGaAs window layer. The indices of refraction of the two layers are designed to minimize reflection when a prismatic coverglass is applied to the surface. This coverglass, supplied by Entech, is a series of lenses which bends light in toward the active area of the cell and away from the gridlines. This effectively eliminates the obscuration caused by the gridlines.

DEVICE TESTING

The testing of the devices always involves a spectral response measurement of both the upper and lower cell. A separate integrated current density is obtained for the upper and lower cell based on the AM0 spectrum. Current-voltage (I-V) measurements are obtained using a two-color simulator which includes two light sources as shown in Fig. 4. The use of two light sources allows the current in each junction to be controlled independently. The light source for the AlGaAs junction has a short-pass filter, and that for the GaAs junction has a long-pass filter. The intensity of each light source is set so that the current density out of each junction matches the integrated current density obtained from the spectral response measurement of the corresponding junction. After the lamps are set to the appropriate intensity, computer controlled I-V measurements are made. The reason for using this test method is that any AM0 simulator introduces errors because of "spikes" at various wavelengths. By using empirical data for the AM0 spectrum and obtaining the integrated current density from the spectral response, the I-V measurements will be more accurate and the current densities of the two junctions can be realistically compared.

RESULTS AND DISCUSSION

Our best MICC cell has an efficiency of 23.0 %. An I-V curve for this device is shown in Fig. 5. In addition to this best result, a manufacturing demonstration has been completed for 0.5 cm^2 AlGaAs/GaAs MICCs. Twenty-two wafers were grown with the device structure of an MICC. Each wafer contains either fourteen or sixteen 0.5 cm^2 cells (depending on whether a D-shaped or a square wafer is used. These 22 wafers resulted in 342 cells grown. During processing and scribing, 45 of the cells were broken. We hope to reduce this breakage rate of 13 % by using a more pointed scribing tip. All of the cells were put through a screening test in wafer form to get an estimate of their performance. The test method was simply to choose one cell on the wafer, set the lamp current so that 15.5 mA/cm^2 was obtained out of each junction at short circuit, and then test all the devices on the wafer at that lamp intensity. By doing this we get a wafer map of the expected efficiencies for each cell. After the wafers were scribed, 297 cells were available for individual efficiency measurements.

115 cells which had screening "efficiencies" of at least 20 % were tested with an "electronic" coverglass. When a prismatic coverglass is applied to an MICC the measured increase in device current is 21 % for the upper AlGaAs cell and 9 % for the GaAs cell. We therefore simulated the coverglass effect during testing by multiplying the corresponding integrated current densities by 21 % (AlGaAs) and 9 % (GaAs). This simulation of the coverglass saves installation time, and allows the MICCs to undergo subsequent radiation testing. Seventy-four of the MICCs had actual efficiencies of at least 20 %. Therefore, the yield for good cells is 25 % as compared to the 297 testable cells, and 21.6 % as compared to the 342 cells grown. A histogram showing the efficiencies of these 115 cells is shown in Fig. 6. These results do not show a large number of cells approaching our best MICC efficiency of 23 %. However, this is the first manufacturing demonstration of monolithic two junction cells, and

improvement in both efficiency and yield is to be expected with further process refinements and manufacturing experience.

In addition to the 0.5 cm^2 devices we have made, a scale-up to 2x2 cm^2 MICC devices is in progress. Our very first attempt at fabricating the devices indicated that our material growth quality was very good, but a problem with one of the metalization steps prevented them from operating properly. Several additional wafers have been grown and the devices are currently being processed using a method which will prevent the metalization problem encountered earlier. If successful, these will be the first monolithic two junction solar cells to be made on an area as large as 4 cm^2. They will then me made into a panel of six cells to be flown in a space based experiment.

As a proof of concept project for the near term, a method was developed for stacking a MICC above a low bandgap third junction. Several low bandgap solar cells were used, but the best result was obtained from a InGaAsP cell (ref. 4) which was processed at Varian. The mechanical fixture allowed electrical access to the third junction so that it could be measured independently, and the MICC has the capability to be measured in either a two or three terminal configuration. Table I shows the device parameters of each cell in the stack and the results of a two terminal measurement of the entire stack. The efficiency obtained at 1 sun, AM0 is 25.2 %. This represents the highest 1 sun, AM0 efficiency ever reported. The sum of the efficiencies of each component cell is 25.48 %. This is higher than the two-terminal measurement of the entire stack because the GaAs cell is current limiting the other two cells, thus bringing their efficiencies down slightly. In general, the GaAs component cell has a lower current density than the AlGaAs cell. To remedy this we suggest increasing the bandgap of the AlGaAs cell slightly to allow more light into the GaAs cell. With better current matching, the efficiency of the two terminal configuration will rise. In addition, the MICC cell used had a two terminal efficiency of only about 21 %; this is 2% lower than our best MICC cell so further efficiency gains can be expected. Fig. 7 shows the external quantum efficiency of the three junctions in the stack.

CONCLUSIONS

Because both component cells can be measured independently, the MICCs have an advantage over tunnel junction based devices in terms of testing and diagnostics. With tunnel junction devices, only two terminal measurements can be made. However, with the MICC one can measure the efficiency of each component cell, determine which cell degrades the most during radiation experiments, and find the current limiting cell. Ultimately, the tunnel junction concept is preferred because it reduces post-growth processing complexity and does not involve reducing the active area of the upper junction. For this reason, tunnel junction development is currently proceeding in parallel with the MICC work.

It is clear that a monolithic integration of three junctions is superior to mechanical stacking if the devices are to actually be used in space. Efficiencies higher than 30 % have been predicted for monolithic three junction devices. Future work in this area should concentrate on monolithic integration of three junctions using grading layers or a superlattice to compensate for the lattice mismatch between GaAs and InGaAs or other low bandgap materials.

REFERENCES

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2). B-C. Chung, G. F. Virshup, S. Hikido, and N. R. Kaminar; "27.6% efficiency (1 sun, air mass 1.5) monolithic $Al_{0.37}Ga_{0.63}As/GaAs$ two-junction cascade solar cell with prismatic cover glass"; Appl. Phys. Lett. **55**, p. 1741; (1989).

3). B-C. Chung, G. F. Virshup, and J. G. Werthen, High-efficiency, one-sun (22.3% at air mass 0; 23.9% at air mass 1.5) monolithic two-junction cascade solar cell grown by metalorganic vapor phase epitaxy"; Appl. Phys. Lett. **52**, p. 1889; (1988).

4). InGaAsP material grown by M. Wanlass at the Solar Energy Research Institute.

Table I. - Device parameters for the three junction mechanical stack of an MICC on an InGaAsP cell.

	Efficiency (%)	V_{oc} (V)	Fill Factor	J_{sc} (mA/cm^2)
AlGaAs	12.00	1.398	0.75	15.77
GaAs	9.09	0.994	0.78	15.63
InGaAsP	4.39	0.521	0.72	15.98
Efficiency Sum	25.48			
Stack	25.20	2.882	0.77	15.63

All measurements are two terminal, and made at 25 °C under 1 sun, AM0 illumination.
Device area 0.5 cm^2

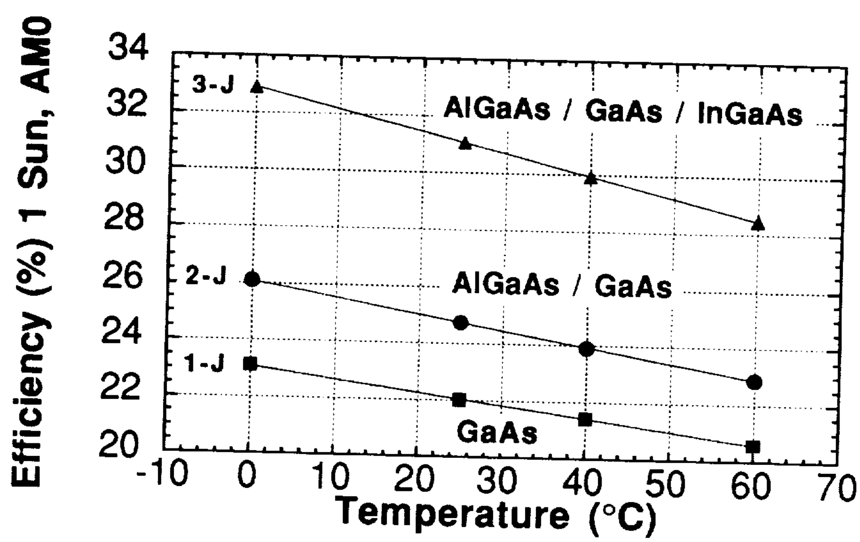

Figure 1. - Predicted efficiency vs. temperature for selected one-, two-, and three-junction solar cells.

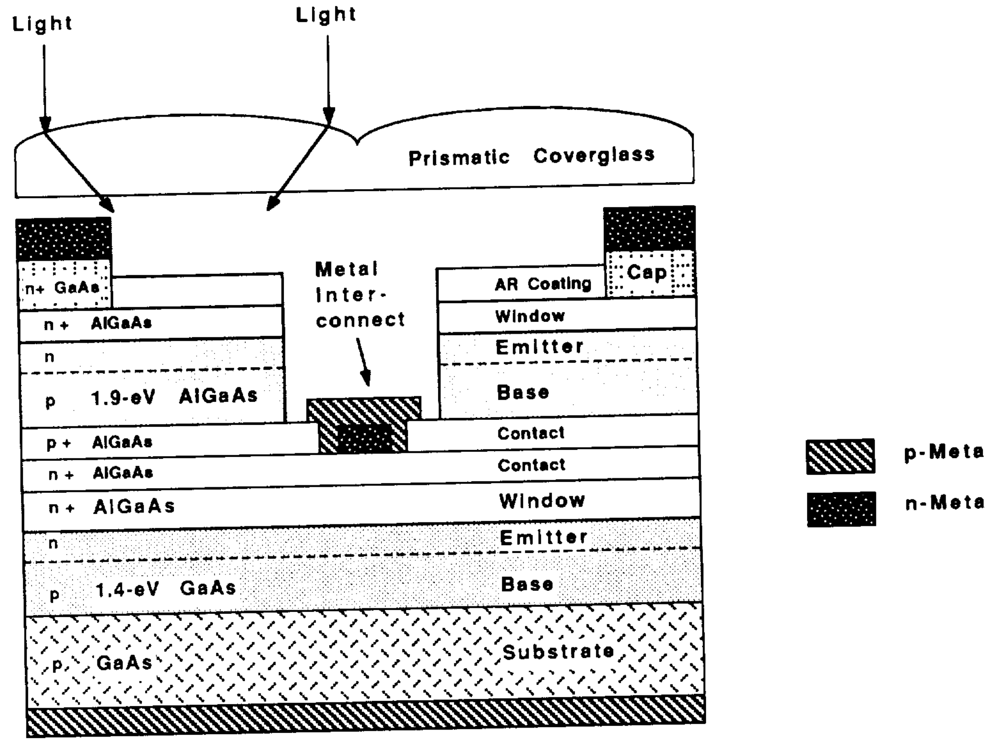

Figure 2. - Schematic cross section of the MICC (not to scale).

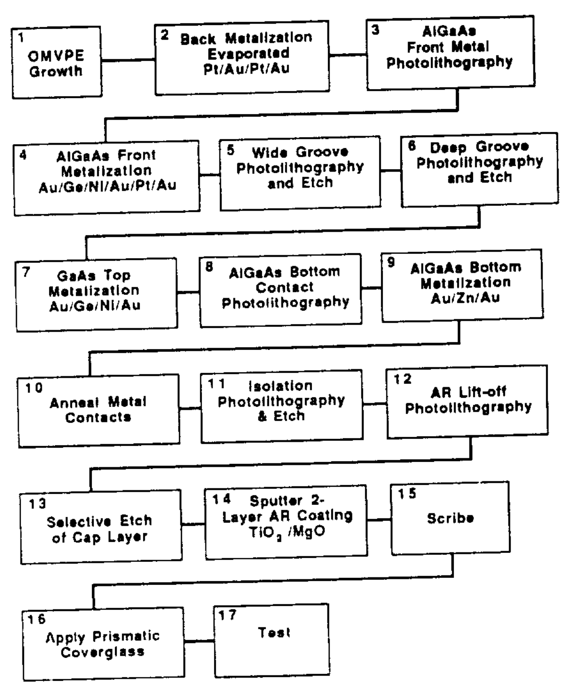

Figure 3. - MICC device processing flow chart

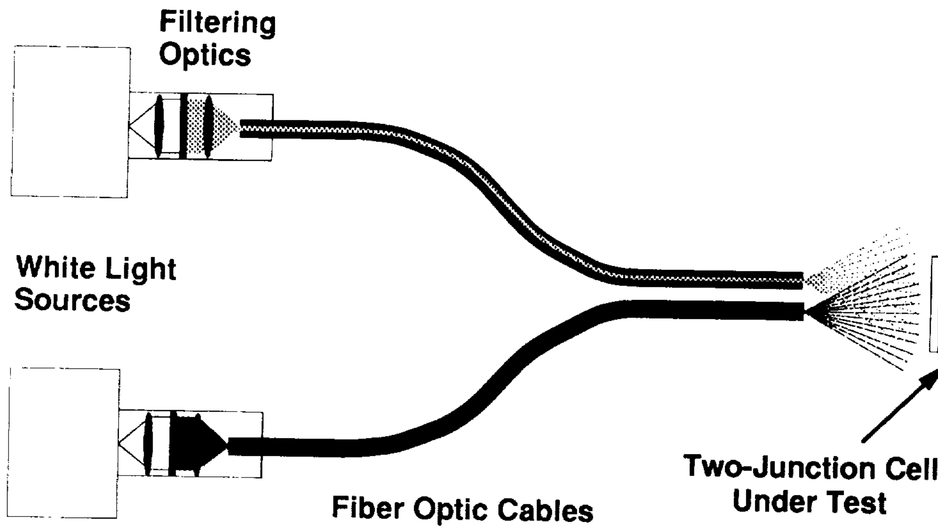

Figure 4. - Testing configuration for I-V measurements of two junction MICCs.

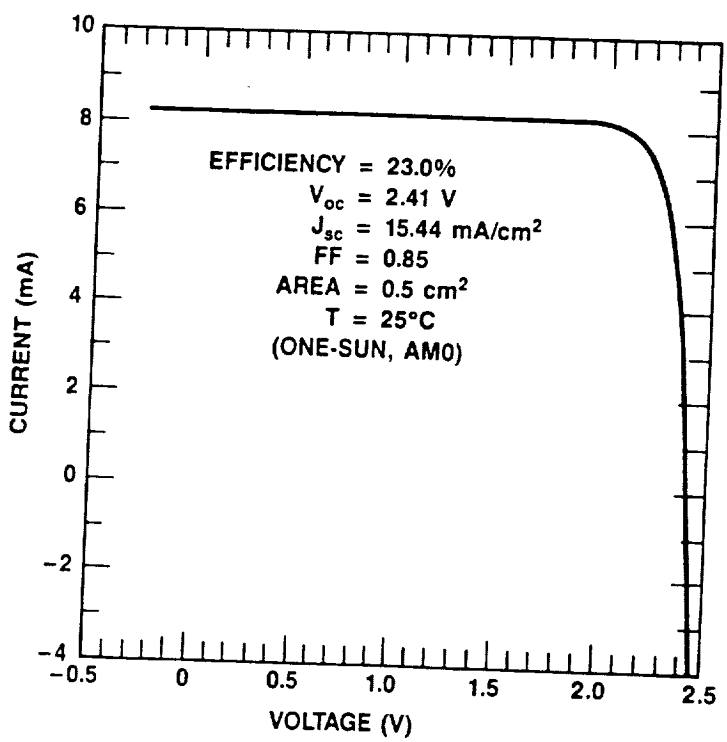

Figure 5. - An I-V curve of the best 0.5 cm^2 MICC, showing the measured device parameters.

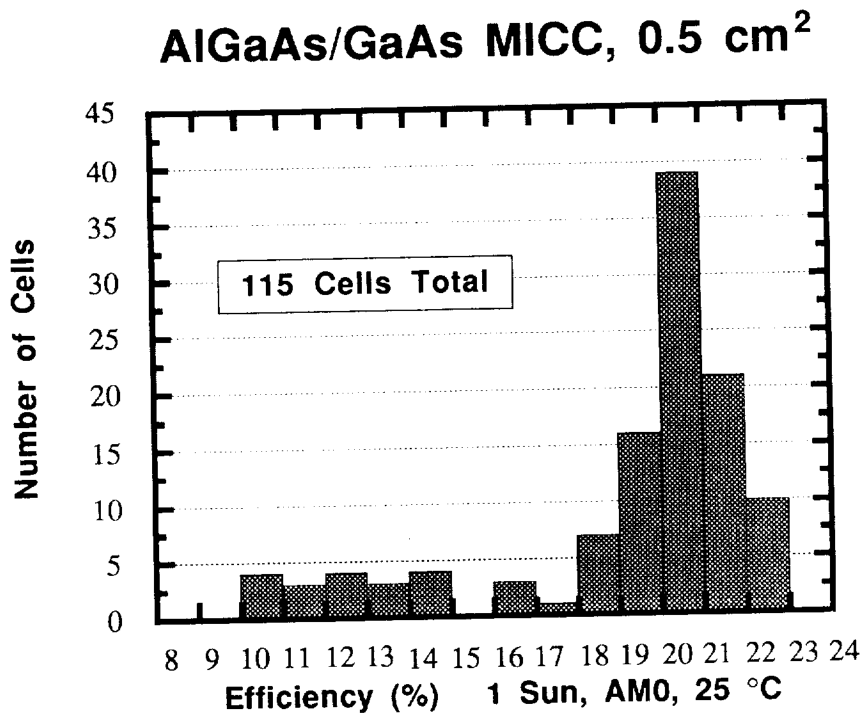

Figure 6. - Efficiency Histogram for 115 of the best 0.5 cm^2 MICC cells produced in the manufacturing demonstration.

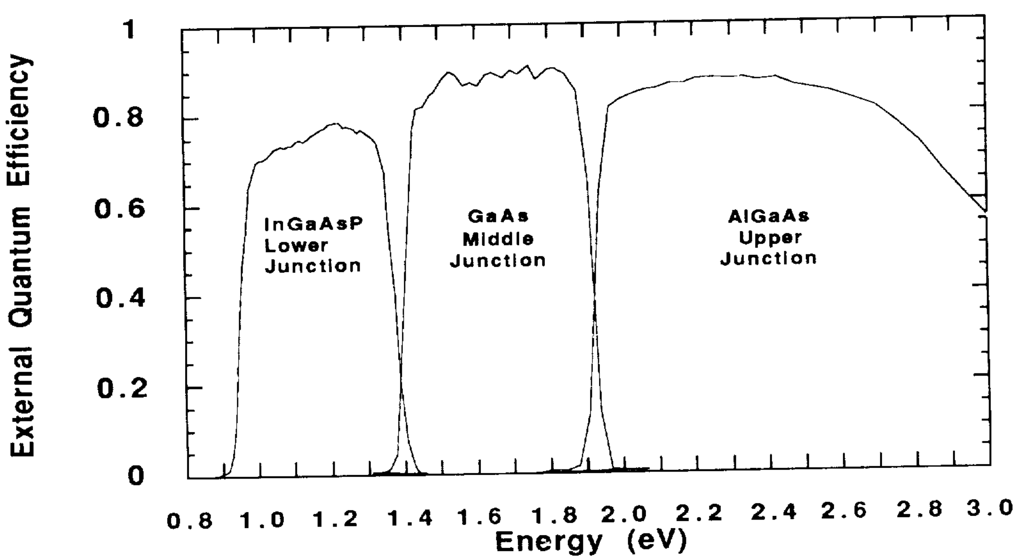

Figure 7. - Spectral Response of the three junction mechanical stack. The stack includes a 0.5 cm^2 MICC above a 0.5 cm^2 InGaAsP solar cell.