HIGH EFFICIENCY COMPOUND SEMICONDUCTOR CONCENTRATOR PHOTOVOLTAICS

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SUMMARY

Work on compound semiconductor concentrator photovoltaics at Varian is reviewed. Special emphasis is given to projects that have achieved significant results in the last six months. These include the high yield pilot production of packaged AlGaAs/GaAs concentrator solar cells, using organometallic VPE for materials growth, the demonstration of a concentrator module using 12 of these cells which achieved 16.4% conversion efficiency at 50°C coolant inlet temperature, and the demonstration of a spectral splitting converter module that achieved in excess of 20% conversion efficiency. This converter employed ten silicon and ten AlGaAs cells with a dichroic filter functioning as the beam splitter. Finally, a monolithic array of AlGaAs/GaAs solar cells will be described.

INTRODUCTION

Varian has a number of ongoing programs related to the development and demonstration of high efficiency compound semiconductor concentrator photovoltaic devices at both the cell and module level. The purpose of this paper is to review some significant developments that have occurred during the last six months. These include the following:

- Organometallic vapor phase epitaxy (OM-VPE) has been successfully applied to the pilot production of AlGaAs/GaAs solar cells. This epitaxial growth technique has the advantages of exceptional control, uniformity, provides good surface morphology, and naturally lends itself to high throughput. As a consequence, production yields of packaged cells, measured at 50°C and 400 AM2 suns, are 87% greater than 18% efficiency, 67% greater than 20%, and about 45% greater than 22%, with the best cell to date running at 23.2% efficiency.

- A module of 12 AlGaAs/GaAs cell illuminated by 12 curved-groove fresnel lenses providing 400 suns has been built and tested. This module achieved a conversion efficiency of 16.4% with AM2 insolation. The coolant temperature was 50°C, and pumping losses have been subtracted from the output power.

- A spectral splitting module has also been built and tested. This achieved 20.34% at 839 W/m^2, with a 37°C coolant inlet temperature. Here, curved-groove fresnel lenses illuminated dichroic filters, which split the beam into a high energy component transmitted to AlGaAs cells with bandgaps of 1.65 eV and a low energy component reflected to silicon cells. The module had a total of 20 cells, ten of each type. In the test, they were wired together for a single output.

A high voltage AlGaAs/GaAs solar cell is being developed. This consists of an array of solar cells monolithically integrated onto a single substrate. Because of on-chip series interconnection, high voltage-low current terminal characteristics are obtained. The fabrication, rather than the bandgap, determines the operating voltage, so that the cell can be optimized for a number of applications.

In the following sections, each of these topics will be discussed individually.

OM-VPE AlGaAs/GaAs SOLAR CELLS

Varian is currently engaged in the pilot production of AlGaAs/GaAs solar cells. These devices are designed for use in point focus concentrator systems operating at 400 AM2 suns, with coolant temperatures up to about 150°C. Through this program, we have gained considerable experience in the fabrication, packaging and testing of AlGaAs/GaAs solar cells, and have demonstrated that they can be produced with high yield.

A principal reason for seeing good yields has been a switch from liquid phase epitaxy (LPE) to organometallic vapor phase epitaxy (OM-VPE). The OM-VPE cell structure is described in another paper [1]. From a processing standpoint, OM produces wafers with a minimum number of morphological defects. This translates into higher yields, especially during photolithography. Results of an extensive life test program have shown that degradation under stress is correlated to surface defects, so that the OM-VPE cells show a longer life than LPE devices. Significantly, since OM-VPE is a vapor phase process, it can be scaled up for high throughputs.

Figure 1 shows the grid structure appropriate for a concentrator cell. The chief design feature is a nearly constant grid line spacing to reduce emitter series resistance. The lines are spaced 60 microns; the diameter is .49 inches. The contact metal scheme is a Au-Mg-Au sandwich followed by a TiW barrier and a layer of gold. The back contact is similar, except that Sn replaces the Mg to provide contact to the n-type substrate.

A packaged cell is shown in Fig. 2. The alumina baseplate has a molymanganese pattern to which the cell die is vacuum soldered with a silver-tin solder. The leadframe is bonded to the top of the cell with lead-indium paste. Copper tabs brazed to the baseplate carry out the current.

Packaged cells are tested at one sun in a xenon-source solar simulator, and at concentration in a computer-controlled xenon source flash tester. The latter unit consists of a photographic strobe mounted above the cell. A computer triggers the flash, then captures the peak voltage and current on peak detectors. By varying an active load, the computer plots the cell IV curve and finds the cell short circuit current, open circuit voltage, fill factor and efficiency. By varying the power and strobe-cell spacing, a concentration range from a few suns to several thousand suns can be obtained. The flash spectrum does not exactly match the sun's; we have found, however, that measured efficiencies at room temperature in the flash tester compare within the error of the system to tests with an AM2 spectrum and the cell at 50°C.

Typical pilot production yield data on packaged cells measured at 400 AM2 suns by flash testing shown in Fig. 3. For comparison, the yield on a batch of LPE cells appears. The difference in performance can be attributed to the better doping and thickness control, and better morphology obtained with OM-VPE.

A life test program is currently in progress [2]. It began before the OM-VPE cell was well developed, and has focused largely on unpackaged LPE cells. These devices use magnesium as a p-type dopant in the emitter, and have proven stable at one sun in a variety of tests. These include storage at 400°C in a N_2 ambient and thermal cycling between room temperature at 425°C, also in nitrogen. The short circuit currents of the test cells are plotted in Figs. 4 and 5 for these two tests. Note that in the thermal storage experiment, significant degradation sets in after about 600 hours and failure of the entire batch occurs only after 3000 hours. The primary failure mode appears to be delamination of the silicon nitride AR coating. Other storage tests at 425°C in nitrogen and 250 and 350°C in air are presently underway to better identify failure mechanisms and to estimate the time to failure at normal operating temperatures.

12-CELL CONCENTRATOR MODULE

As part of a program sponsored by DOE and Sandia [3], Varian has built and tested a module consisting of 12 AlGaAs/GaAs cells illuminated at 400 suns with 12 curved-groove fresnel lenses. Figure 6 shows a breakdown of the module. From top to bottom, it consists of a parquet of 12 lenses. A heat shield, made of aluminum, protects plastic components from damage during off-track operation. The cells are connected in a four in parallel-three in series arrangement, and fit in the base of a housing made of foamed lexan. An integral cooling manifold uses a jet impingement technique to cool the backs of the cells. The completed module is shown in Fig. 7, mounted on a tracker for testing.

Module performance as a function of insolation at 28 and 50°C is shown in Fig. 8. Coolant pumping losses have been subtracted from these data. The AM2 performance of 16.4% at 50°C considerably exceeds the best reported performance of about 12% for modules using silicon cells and operating at about the same coolant inlet temperature and insolation level.

10-UNIT SPECTRAL SPLITTER MODULE

Under sponsorship of Sandia [4], a spectral splitter module has been designed and built. The module is shown schematically in Fig. 9. One of the units is shown in Fig. 10. The entire module consists of 10 units supported with an I beam. Each unit has a f4.2 hexagonal curved groove fresnel lens focusing light onto a dichroic filter. This filter ideally has a cutoff of 1.65 eV, reflecting light below this energy to a silicon cell and transmitting light above this energy to a 20% AlGaAs cell with a bandgap of 1.65 eV. The effective concentration (that is, the ratio of lens area to spot size on the AlGaAs cell with the filter removed) is 477 suns. The system is actively cooled; all 20 cells are mounted in plastic jet-impingement coolers, using water as a cooling fluid.

Both types of cell have been made and packaged at Varian. A grid mask, similar to that shown in Fig. 1 but with a 1/3-inch diameter, is used. The package is the same as that shown in Fig. 2. The silicon cell has a .07-micron deep diffused p-type emitter; a deep emitter is acceptable since low emitter resistance is more important than blue response in this application. The substrate is 111 n-type FZ silicon, with a diffused back surface field. Such cells, packaged, have been tested at 15-16% full spectrum 400-sun AM2 efficiency.

The AlGaAs cells are grown by LPE and otherwise processed in a manner identical to the AlGaAs/GaAs solar cell. The bandgaps vary from 1.58 to 1.68 eV as a consequence of the extreme sensitivity of aluminum incorporation into the solid to aluminum concentration in the LPE melt. These cells, as well as the silicon cells, have cover glasses to protect from environmental degradation and allow cleaning.

The completed module appears in Fig. 11. This is wired for a single output by connecting all silicon cells in one series string and forming two series strings with five AlGaAs cells in each. Since the operating voltage of the AlGaAs cells is nearly twice that of the silicon, these three strings are then connected in parallel.

Testing is presently underway. The best results to date, 20.34% efficiency with 839 W/m^2 insolation and a cooling water temperature of 37°C, appears in Fig. 12. It should be noted that the filters in the present system have a cutoff of 1.55 eV, due to design compromises made between the manufacturer and Varian. Also, losses in the fresnel lens are 15-20%. Taking these into account, the performance of this module matches or exceeds the results reported by Varian in 1978 for a single converter [5].

A comparison of the spectral splitting and GaAs concentrator modules gives a measure of the advantages and drawbacks of going to a spectral splitting approach, given the present state-of-the-art. The obvious advantage is a 25% increase in conversion efficiency (about 16% compared to about 20%). The drawbacks are the cost of the filter, which must necessarily consist of multiple dielectric layers to achieve a sharp enough cutoff, and the increased complexity of the optical system which makes alignment and optimization of performance more difficult. A longer focal length system with the spectral splitter increases the cost of materials. We have noted no problems with reliability of the cells, filters, or lenses; the module has remained on the laboratory roof in the weather for about four months to date. The optics, however, have required realignment from time to time.

HIGH VOLTAGE CELLS

In work sponsored by SERI [6], we are developing monolithic series-connected arrays of AlGaAs/GaAs solar cells, or "High Voltage Cells". The device structure, shown in Fig. 13, consists of a number of subcells grown on an insulating GaAs substrate, isolated with etched grooves, and interconnected with metal lines. Because the device has a high voltage-low current output (by virtue of its series connection), grid line widths can be reduced -- indeed, with n-on-p structures, with higher emitter mobilities, grid lines may not be needed. This compensates for obscuration introduced by the interconnects, so that these devices can have efficiencies comparable to planar solar cells. An advantage of working with GaAs is the short absorption length, allowing the use of shallow structures that are simple to fabricate by standard monolithic processes.

Use of these devices should considerably facilitate array design, since the cell terminal voltage can now be decided by the designer rather than the material bandgap. An obvious application is in spectral splitters, where the oft-imposed constraint of matching the short circuit currents of the high and low bandgap cells could be removed. Another application is in the design of high voltage photovoltaic systems which use long strings of cells. Because the performance of the entire string is affected by the degradation of even one cell, it is desirable to use as many strings as possible, each covering as little a fraction of the total array area as possible. Use of high voltage solar cells obviously allows minimization of the array area occupied by each series string.

A four-cell device has been fabricated and tested; Fig. 14 shows the IV characteristic at about 1 AM2 sun and, for comparison, the IV characteristic of a single-junction AlGaAs/GaAs solar cell. The details of the performance of this device are described elsewhere [7]; note that the open circuit voltage is about four times that of the single-junction device. Work in the lab is proceeding toward the demonstration of an optimized 10-subcell device.

CONCLUSION

Since initial demonstration of a high-efficiency AlGaAs/GaAs solar cell, the thrust of the Varian program has been to produce a reliable, high-efficiency packaged device that is not a laboratory experiment, but a device that can be readily used in photovoltaic systems and can be cheaply produced in large quantities. The development of OM-VPE epitaxial growth and the ceramic base-plate package configuration, and the demonstration of high yield in pilot production have been significant accomplishments in this direction.

At the module level, recent results with a GaAs module and a spectral splitter module have demonstrated the state-of-the-art efficiency advantage of GaAs over other technologies, and the advantages accrued by pursuing a spectral splitting approach. The latter is of relevance to work on cascade cells, since it represents, in some ways, an "ideal" approach, because effects due to individual components of the system can be isolated and the cells can be carefully chosen and matched.

REFERENCES

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3. Varian Associates reports on contract SAND 42-7248.
4. Varian Associates reports on contract SAND 13-0308.
5. Varian Associates reports on contract SAND 13-6953 and 13-6953A.
6. Varian Associates reports on contract SERI XS-0-9010-10.
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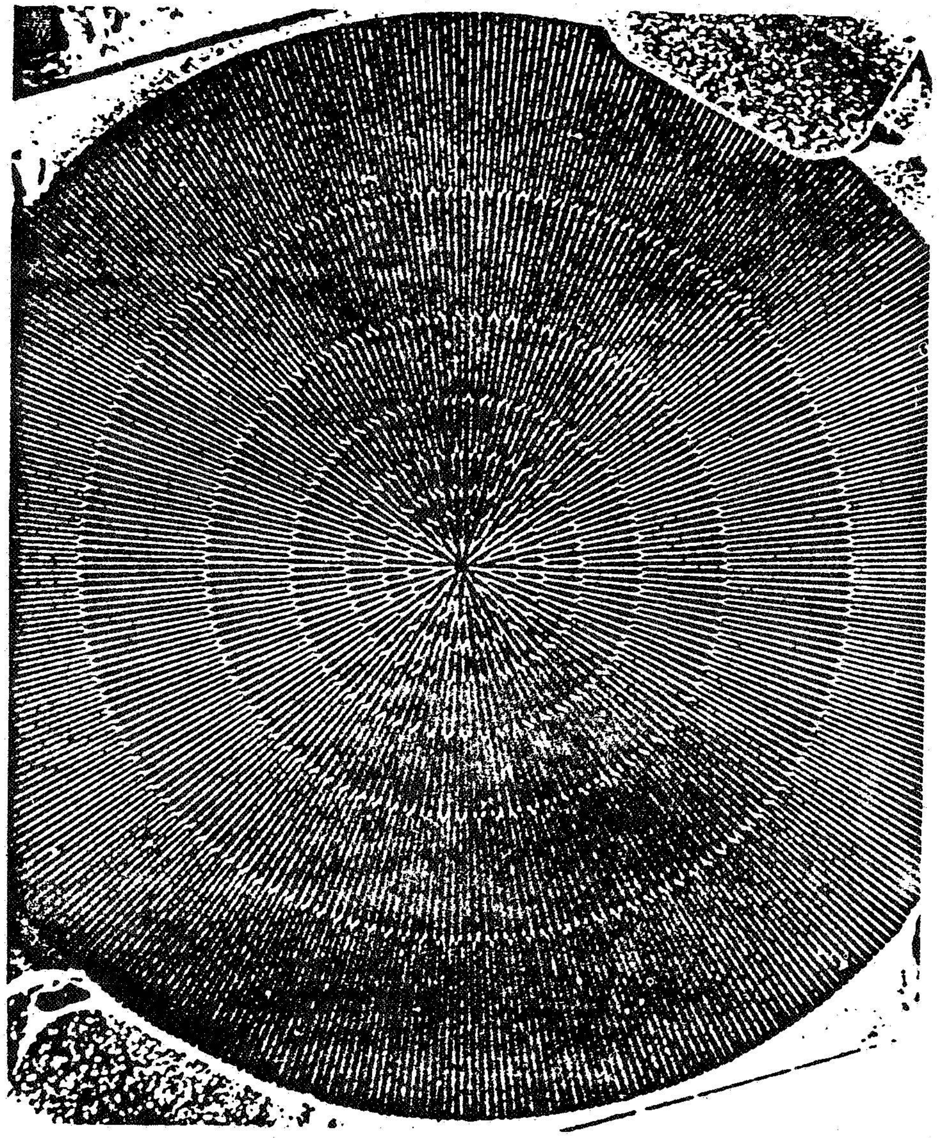


Fig. 1 Grid structure for AlGaAs/GaAs concentrator solar cell.

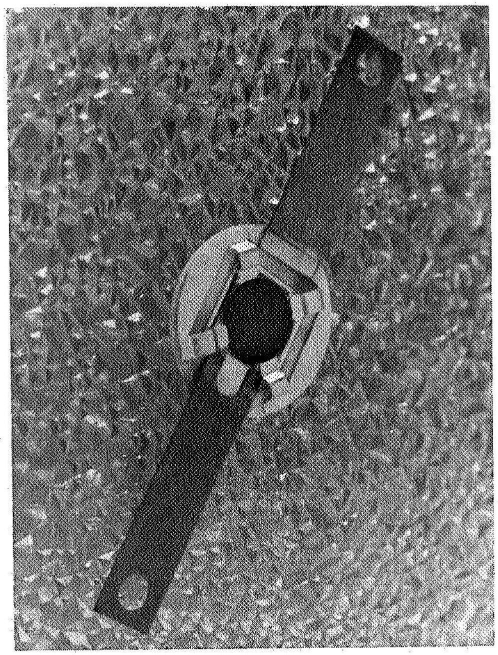


Fig. 2 A packaged AlGaAs/GaAs concentrator solar cell. Active area is .49" in diameter.

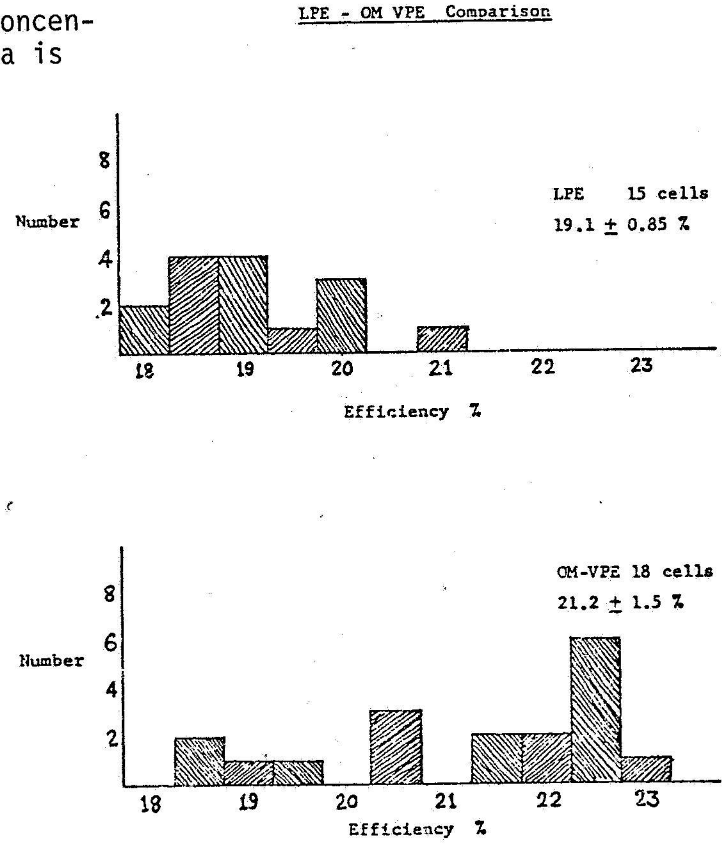


Fig. 3 Pilot production yields at 400 AM2 suns/50°C for packaged OM-VPE and LPE solar cells, fabricated by the same process.

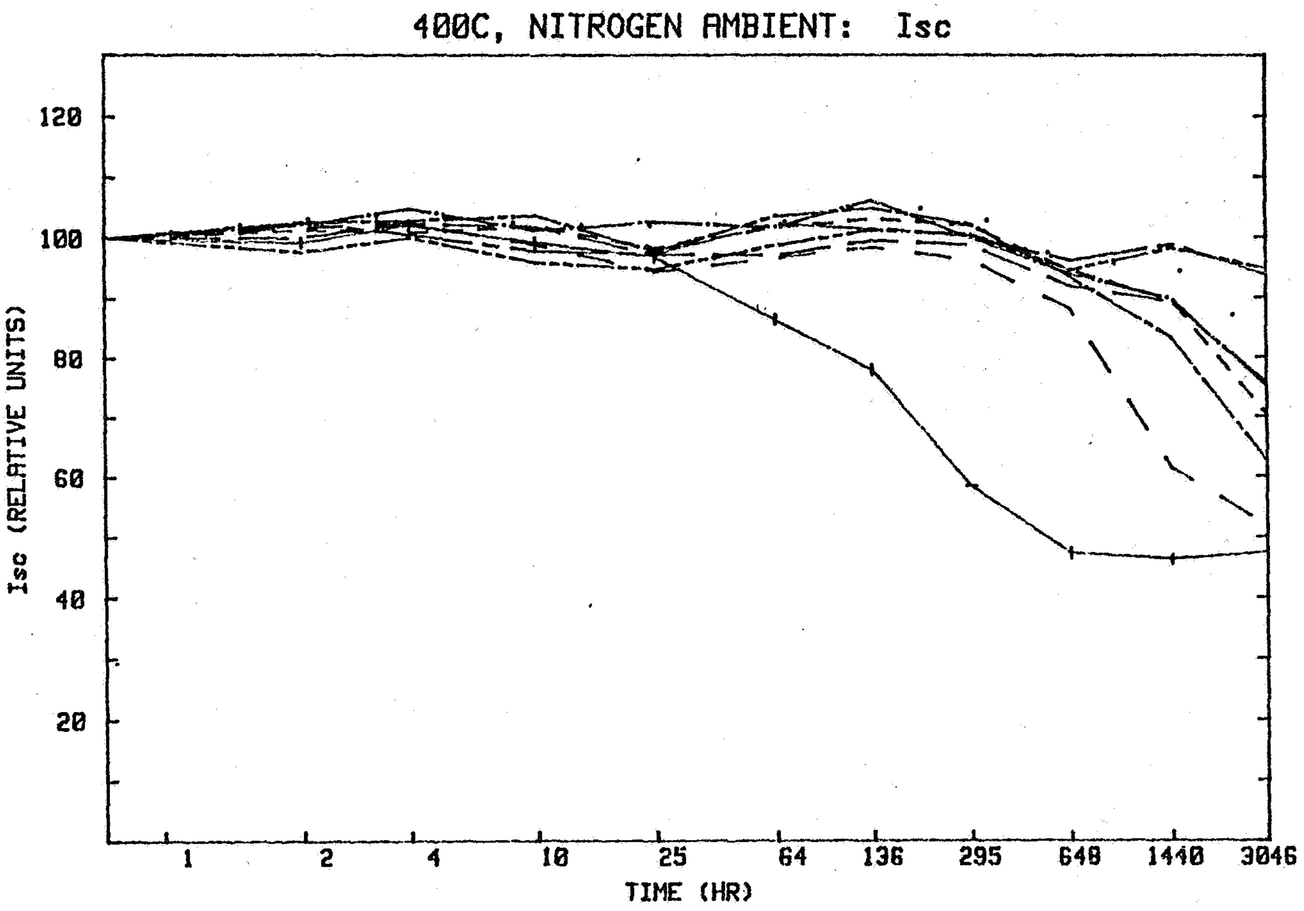


Fig. 4 Normalized AM1 short circuit currents for 9 unpackaged cells stored at 400°C in nitrogen plotted as a function of time. The cells were unpackaged and tested at AM1 conditions.

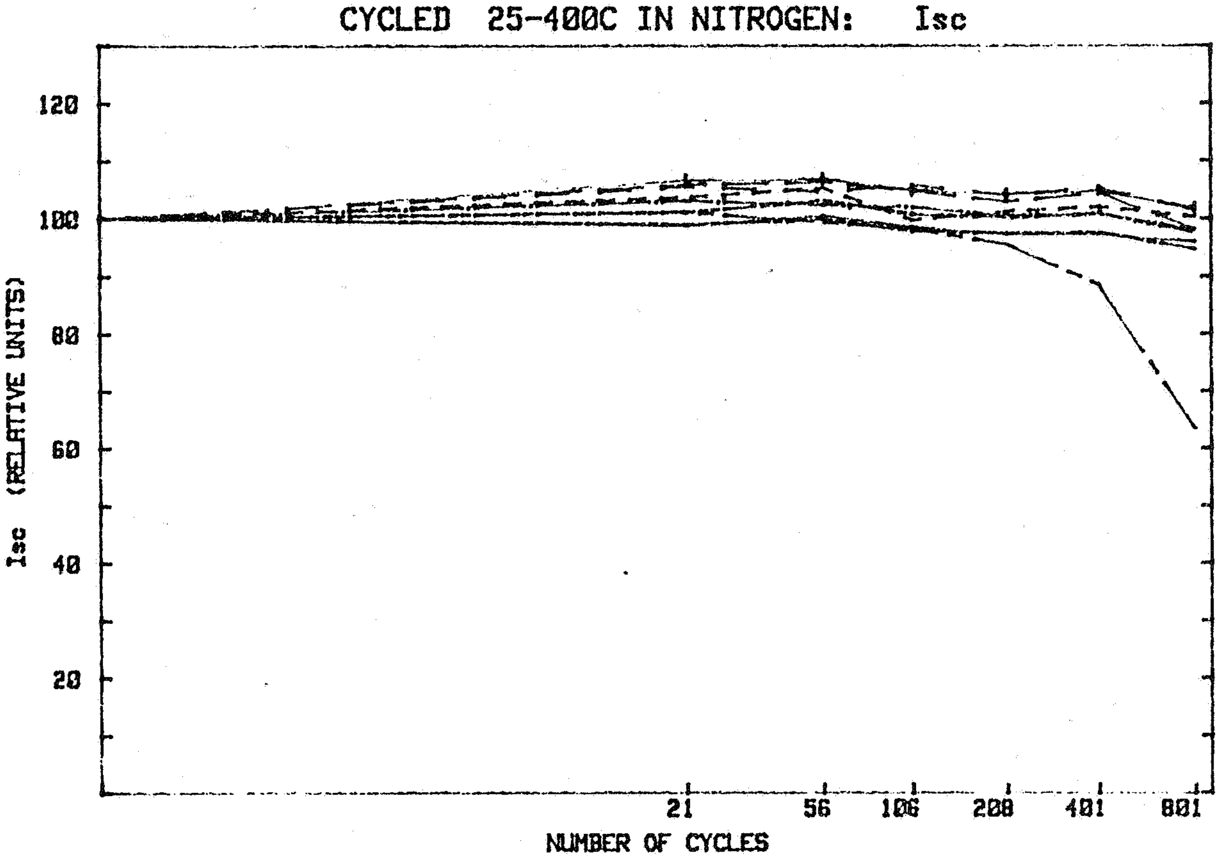
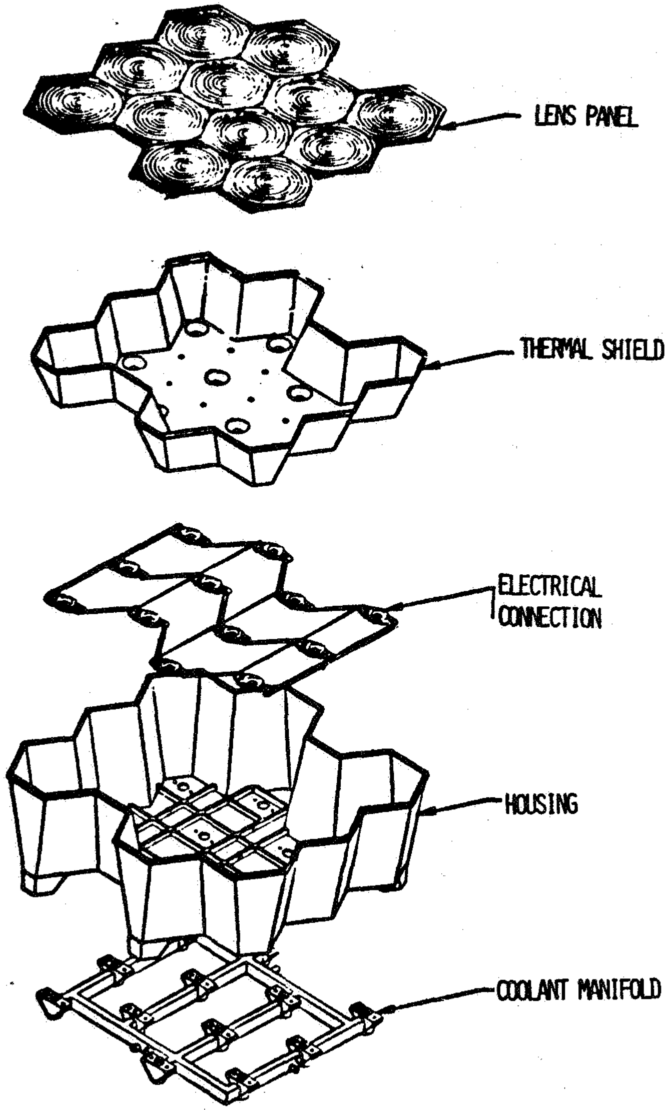


Fig. 5 Normalized short circuit currents for 9 unpackaged cells thermally cycled between room temperature and 400°C at 30 minutes per cycle.



SOLAR MODULE

Fig. 6   A breakdown of 12-cell solar module.

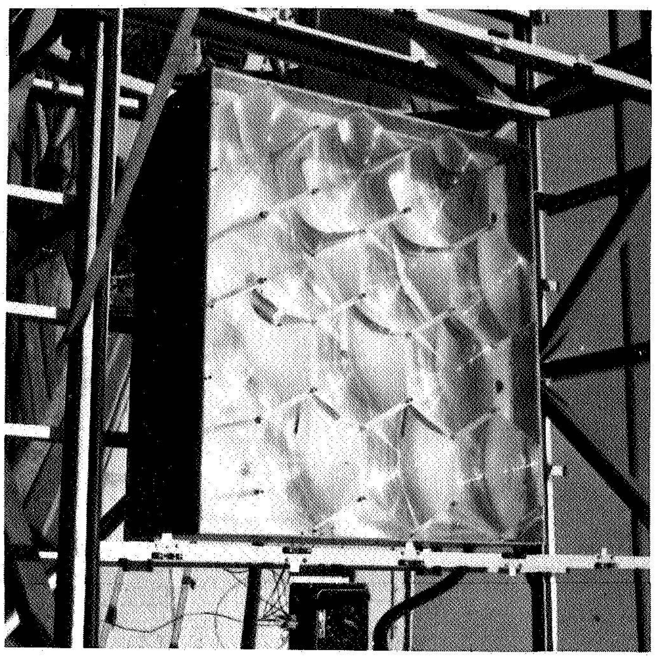


Fig. 7 The prototype module mounted on a solar tracker.

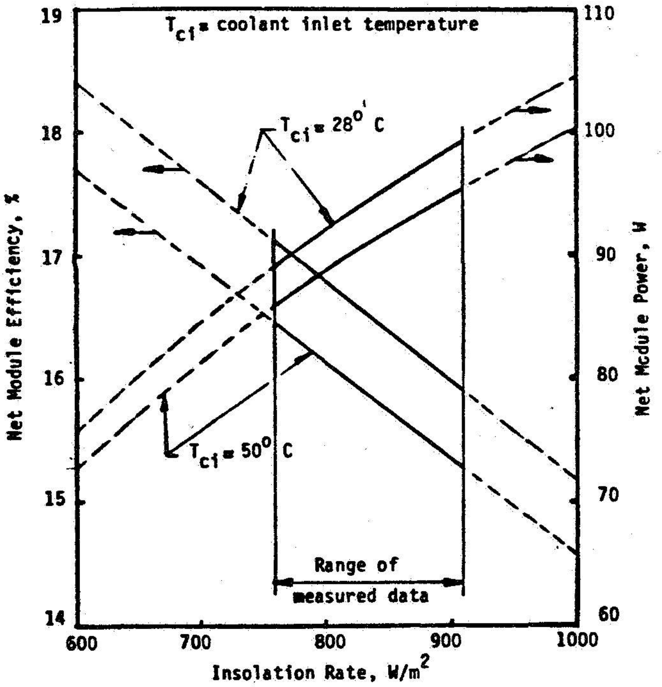


FIGURE 8- MEASURED MODULE PERFORMANCE

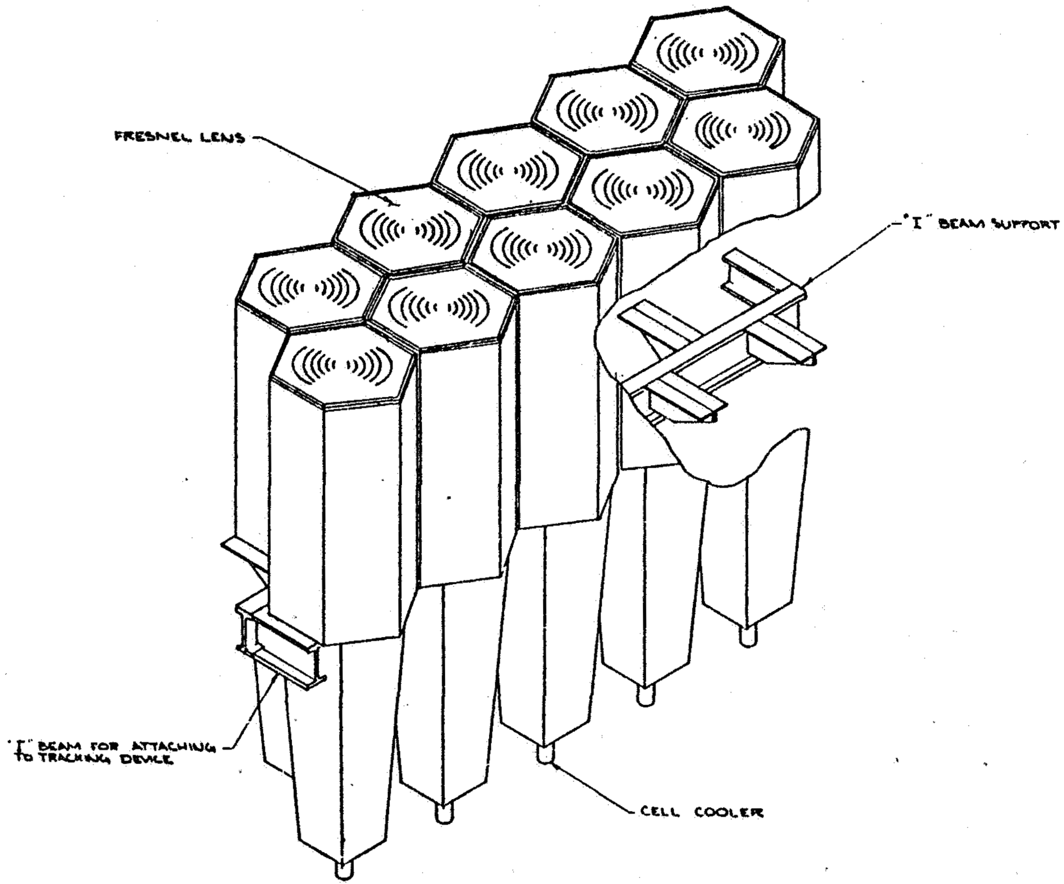


Fig. 9 A drawing of the spectral splitter module.

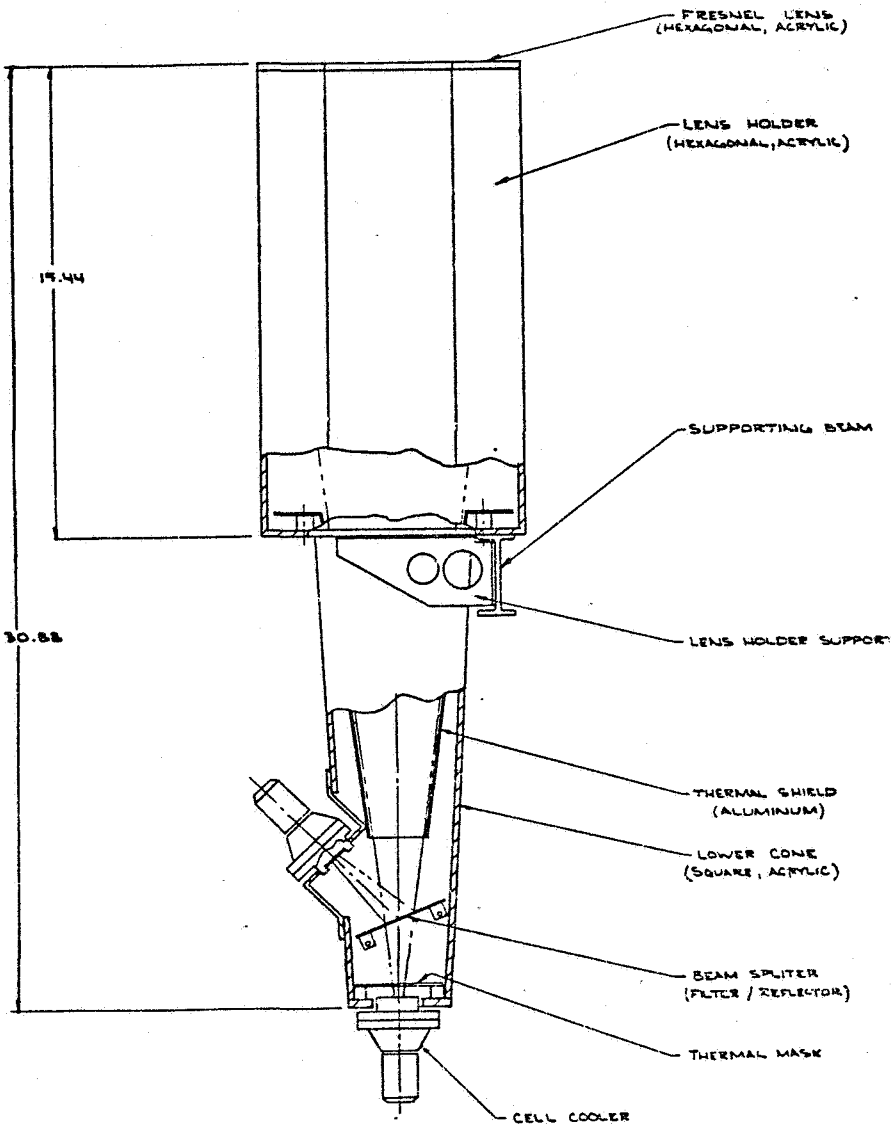


Fig. 10 Cutaway drawing of one unit of spectral splitter module.

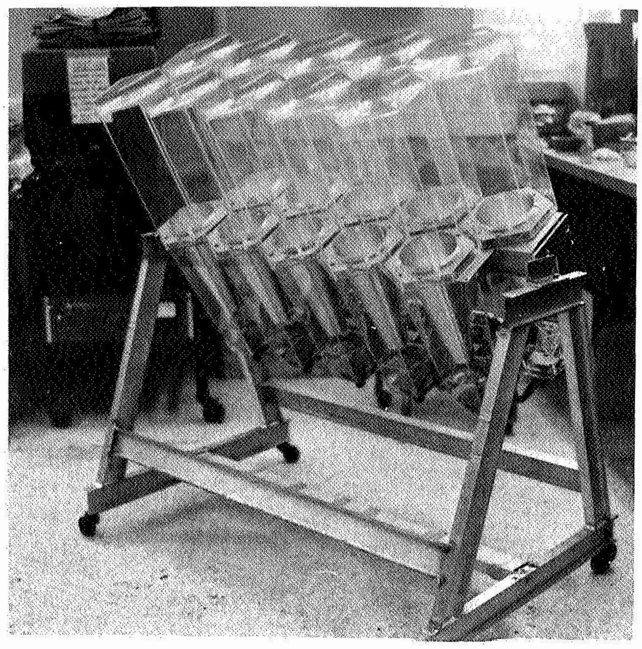


Fig. 11 A photograph of the completed spectral splitter module.

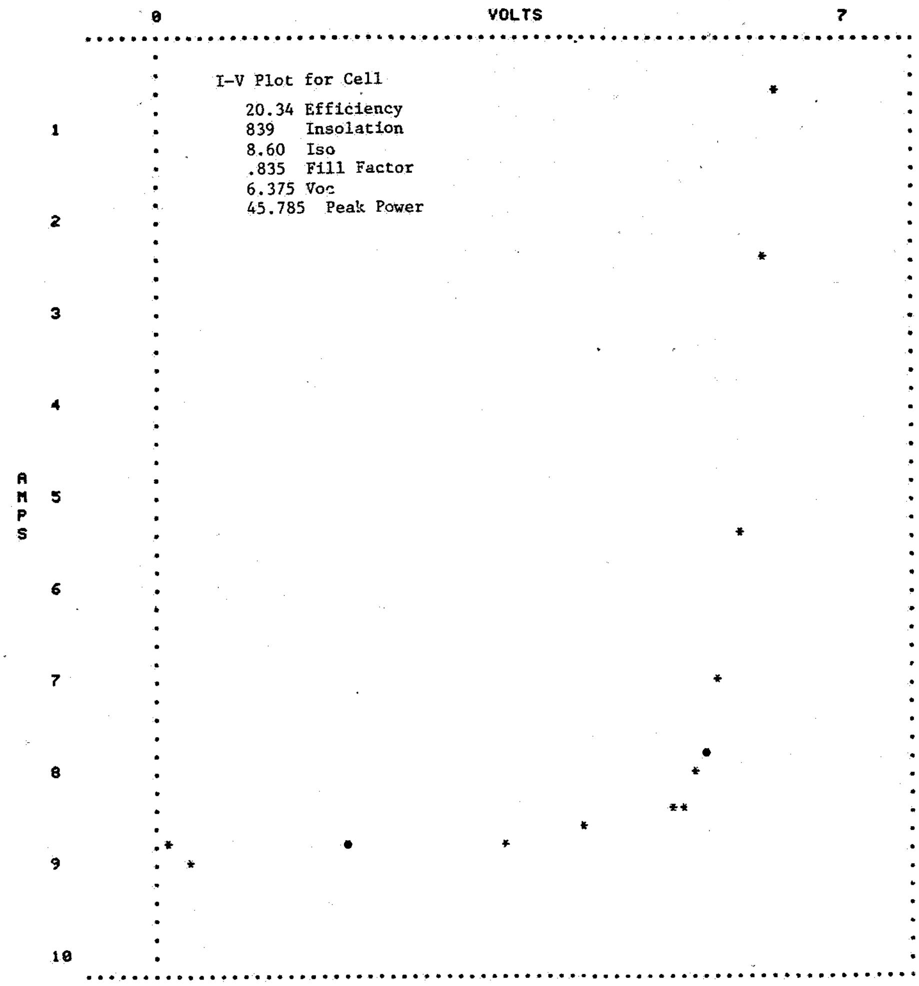


Fig. 12 A measured IV curve from the spectral splitter module.

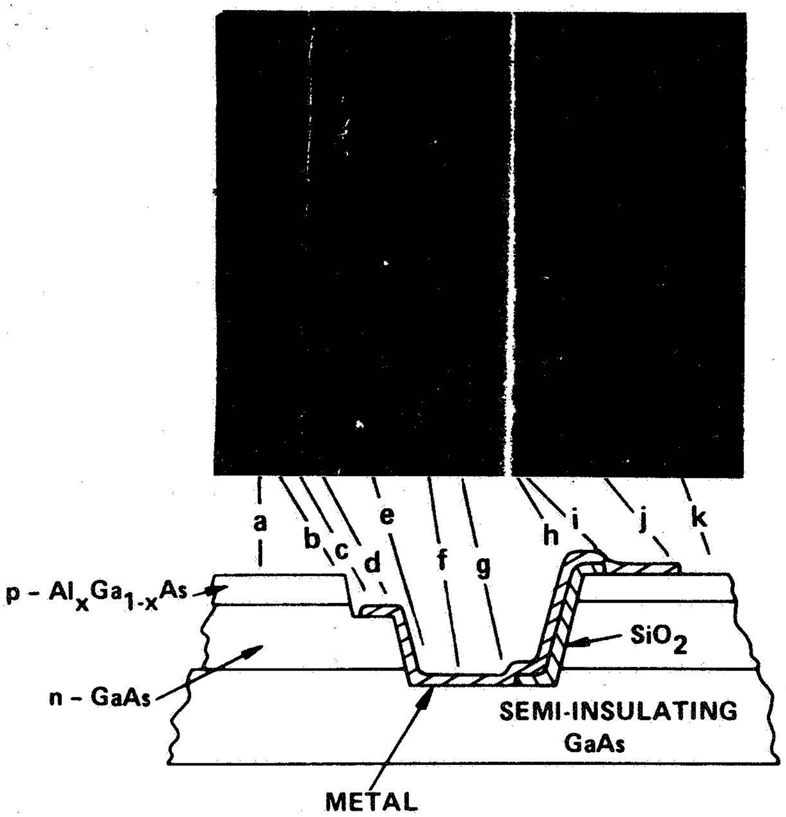


Fig. 13 High voltage cell device structure.

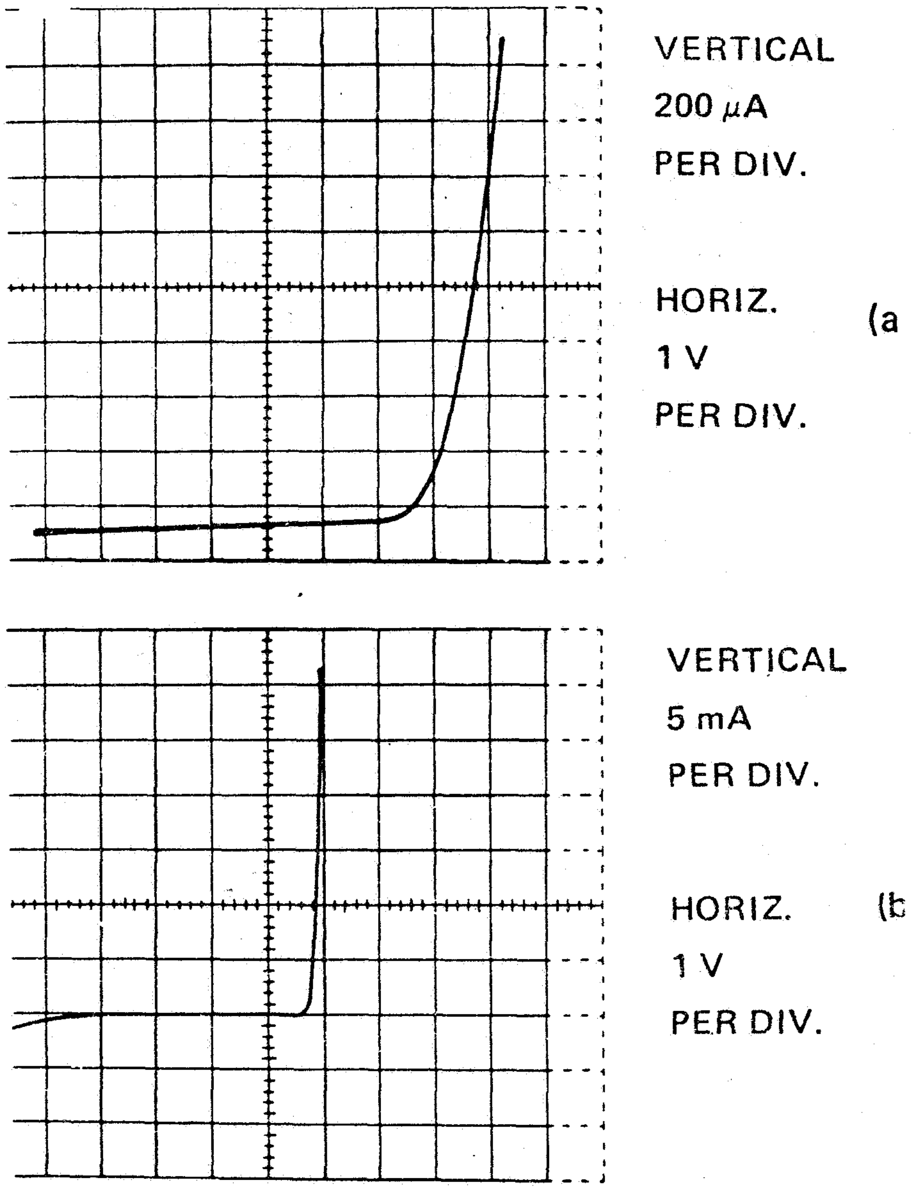


Fig. 14 IV characteristic of a 4-subcell high-voltage solar cell at about 1 AM2 sun and, for comparison, the IV characteristic from a single-junction AlGaAs/GaAs solar cell.