N91-30230

HIGH-EFFICIENCY HETEROEPITAXIAL InP SOLAR CELLS

M.W.Wanlass, T.J.Coutts, J.S.Ward and K.A.Emery
Solar Energy Research Institute (SERI), Golden, CO, 80401, U.S.A.

ABSTRACT

High-efficiency, thin-film InP solar cells grown heteroepitaxially on GaAs and Si single-crystal bulk substrates are being developed as a means of eliminating the problems associated with using single-crystal InP substrates (e.g., high cost, fragility, high mass density and low thermal conductivity). A novel device structure employing a compositionally graded $Ga_xIn_{1-x}As$ layer (~8 μm thick) between the bulk substrate and the InP cell layers is used to reduce the dislocation density and improve the minority carrier properties in the InP. The structures are grown in a continuous sequence of steps using computer-controlled atmospheric-pressure metalorganic vapor phase epitaxy (APMOVPE). Dislocation densities as low as $3x10^7$ cm^{-2} and minority carrier lifetimes as high as 3.3 ns are achieved in the InP layers with this method using both GaAs or Si substrates. Structures prepared in this fashion are also completely free of microcracks. These results represent a substantial improvement in InP layer quality when compared to heteroepitaxial InP prepared using conventional techniques such as thermally cycled growth and post-growth annealing.

The present work is concerned with the fabrication and characterization of high-efficiency, thin-film InP solar cells. Both one-sun and concentrator cells have been prepared from device structures grown on GaAs substrates. One-sun cells have efficiencies as high as 13.7% at 25°C. However, results for the concentrator cells are emphasized. The concentrator cell performance is characterized as a function of the air mass zero (AM0) solar concentration ratio (1-100 suns) and operating temperature (25-80°C). From these data, the temperature coefficients of the cell performance parameters are derived as a function of the concentration ratio. Under concentration, the cells exhibit a dramatic increase in efficiency and an improved temperature coefficient of efficiency. At 25°C, a peak conversion efficiency of 18.9% (71.8 suns, AM0 spectrum) is reported. At 80°C, the peak AM0 efficiency is 15.7% at 75.6 suns. These are the highest efficiencies yet reported for InP heteroepitaxial cells. Approaches for further improving the cell performance are discussed.

INTRODUCTION

InP solar cells are particularly attractive for space applications due to their resistance to radiation damage and demonstrated high energy conversion efficiency under the AM0 spectrum [ref. 1, 2]. Single-crystal InP wafers, however, have characteristics which make them generally undesirable for solar cell fabrication and operation. These include high cost, high fragility, high mass density and low thermal conductivity. Thus, in order to promote the widespread use of InP cells in space it is critical that techniques are developed for fabricating high-efficiency, thin-film InP cells. Three approaches are currently under investigation for solving this problem and they include CLEFT [ref. 3] using a bulk InP wafer, chemical separation [ref. 4] from an InP wafer and heteroepitaxy onto single-crystal materials with more desirable characteristics. Of the three options, heteroepitaxy may prove to be the preferred choice since, ultimately, large-area thin films of InP may be too difficult to handle and process on a large scale. Furthermore, it is uncertain whether the InP bulk substrates used in the CLEFT and chemical separation processes will actually be reusable. Heteroepitaxial cells have the advantage of being fully compatible with existing cell processing technologies as well as being based on mature single-crystal wafer technologies in materials such as GaAs, Ge and Si.

Due to the large differences in lattice constant and thermal expansion coefficient between InP and the above-mentioned materials, problems generally arise which inhibit the growth of high-quality InP heteroepilayers. For example, the lattice constant mismatch is 3.7% between InP and GaAs and 7.5% between InP and Si. Such large mismatches result in high mechanical stresses in the resulting epilayers which, in turn, lead to the generation of a high density of defects. The defects include dislocations, stacking faults and even microcracks. Several techniques have been investigated for reducing the density of defects in the InP layers, thereby reducing their deleterious effects. These have included thermally cycled growth, post-growth annealing and inclusion of an intermediate GaAs layer for the case of InP grown on a Si substrate. Limited success has been realized with these procedures and InP epilayers with dislocation densities of $\sim 3 \times 10^8$ cm^{-2} and minority carrier lifetimes of ~1 ns or less in undoped material are reported for the best cases when grown on GaAs substrates [ref. 5]. Unfortunately, InP layers with these properties are of insufficient quality for the fabrication of high-efficiency solar cells. Using post-growth annealing, the highest efficiency for InP cells grown directly on GaAs substrates is 10.8% (one-sun, AM0, 25°C) [ref. 6]. Even lower efficiencies have been reported for InP cells grown on Si substrates [ref. 7].

In previous work [ref. 8], we reported on the use of a novel structure for the growth of high-quality InP epilayers on substrates such as GaAs, Ge and Si. A full description of the device structure concept is given in [ref. 9]. The structure utilizes a compositionally graded $Ga_xIn_{1-x}As$ layer disposed between the bulk substrate and the InP device layers. This serves to reduce the dislocation density in the InP device layers substantially when compared to the conventional techniques discussed above. In this work, substrates of GaAs and GaAs/Si were placed side by side in the growth reactor and identical structures were deposited on each. The resulting InP epilayers were then characterized using transmission electron microscopy (TEM), electron-beam-induced current (EBIC) and photoluminescence-decay (PL-decay) lifetime techniques to assess the defect density and minority carrier lifetime. n^+/p shallow homojunctions were grown into the InP layers and solar cells with grids designed for one-sun operation were processed from the structures grown on the GaAs substrates only. Additionally, structures with three different $Ga_xIn_{1-x}As$ graded layer thicknesses (8, 12 and 20 μm) were grown and characterized; however the InP material and solar cell quality was essentially independent of the thickness chosen in this range. With this structure, dislocation densities of 3×10^7 cm^{-2} and minority carrier lifetimes of over 3 ns were achieved in the InP layers using either GaAs or GaAs/Si substrates. Furthermore, the InP epilayers were completely free of microcracks in both cases, which is an extremely important result for high-quality solar cell fabrication. InP solar cells with one-sun efficiencies of 13.7% (AM0, 25°C) and 15.7% (global, 25°C) were fabricated on GaAs substrates using an 8μm-thick $Ga_xIn_{1-x}As$ graded layer. Unfortunately, pinholes in the InP layers grown on the GaAs/Si substrates resulting from surface contamination prior to growth precluded the fabrication of cells in this case. However, it seems reasonable to assume that InP cell efficiencies similar to those achieved using GaAs substrates should be possible on Si substrates due to the similar dislocation densities and minority carrier lifetimes observed in the InP layers grown on either substrate type.

In the remainder of this paper, we describe the epitaxial growth, fabrication and characterization of concentrator heteroepitaxial InP solar cells grown on GaAs substrates using a compositionally graded intermediate structure similar to that described above. The cell performance has been determined as a function of the concentration ratio and the operating temperature. We have also investigated the behavior of the cell performance parameter temperature coefficients as a function of the concentration ratio. The details of this work are described in the sections which follow. Support for this work was provided by the U.S. Department of Energy under contract No. DE-AC02-83CH10093 through an award from the SERI Director's Development Fund.

DEVICE STRUCTURE

A schematic diagram of the heteroeopitaxial (HE) InP solar cell structure grown on a GaAs substrate is given in figure 1. The structure is initiated with a thin buffer layer of p-GaAs which is then followed by the p-$Ga_xIn_{1-x}As$ linearly graded layer (LGL) which has a thickness of 8 μm for the results reported here. The LGL is followed by a buffer layer of $Ga_{0.47}In_{0.53}As$ which is lattice matched to InP. The InP solar cell layers are finally deposited at the top of the structure and these comprise a high-efficiency n+/p shallow homojunction (SHJ) cell structure (in figure 1, "BSFL" is an acronym for "back-surface field layer"). A back contact of pure Au is applied to the exposed bottom surface of the GaAs substrate. The top grid contact on the surface of the InP cell emitter is also composed of pure Au. A 2-layer antireflection coating is deposited on the front surface of the cell structure and an Entech prismatic cover is also incorporated into the structure to allow for a high top-contact-metallization coverage (~20%). Further details of the device structure are discussed below.

EXPERIMENTAL

The heteroepitaxial solar cell structures were grown by atmospheric-pressure metalorganic vapor-phase epitaxy (APMOVPE) using a specially designed, RF-heated vertical reactor vessel [ref. 10] which yields highly uniform epilayers. The growth system is a home-built, run-vent type and uses palladium-purified hydrogen as the carrier gas through the main mixing manifold and through each of the metalorganic source cylinders. The primary reactants used in the growth process included trimethylindium, trimethylgallium, pure phosphine and pure arsine. The sources for p- and n-type doping were diethylzinc and 500 ppm hydrogen sulfide in hydrogen, respectively. Zn-doped p+-GaAs wafers oriented 2° off the (100) were supplied by Sumitomo Electric, Inc. and used as substrates. These were loaded directly into the growth reactor as received from the vendor (i.e., without any pre-growth cleaning or etching steps). Prior to growth, the GaAs substrates were heated to 700°C for 10 minutes with arsine flowing into the reactor vessel. Growth was then carried out at a constant temperature of 650°C. The structures were grown at a rate of 75 - 175 nm min.$^{-1}$ in a continuous sequence of steps (i.e., without stop-growth periods at the heterointerfaces). A typical growth run takes about 2.5 hours, including the time required for warm-up and cool-down of the reactor vessel. The entire process is controlled and monitored using a home-built, PC-based control system.

The epitaxial structures were then processed into completed concentrator solar cells using conventional techniques. Ohmic, low-resistance contacts were made to both the back surface of the p^+-GaAs substrate and the n^+-InP emitter surface using electroplated Au as deposited. The back surface of the GaAs substrate was etched in 1% by volume bromine in methanol for 5 minutes at room temperature prior to applying the metallization. The top contact and device mesa geometries were defined by photolithographic techniques using positive photoresist. The top contact grids were specially designed to accomodate an overlying Entech prismatic cover which was originally designed for concentrator GaAs solar cells [ref. 11]. A center-to-center grid line spacing of 127 μm was used and the individual gridlines have a cross-sectional area of ~125 μm^2 (~25 μm wide by ~5 μm high). A busbar is included at both ends of the grid lines in this design to allow for the simultaneous placement of test probes at both ends. This aspect of the grid design results in better performance under concentration. Through the use of the Entech cover, it is possible to cover ~20% of the cell surface with the grid metallization without incurring any photocurrent losses due to grid obscuration. This allows for ample grid metallization on the cell which results in low electrical power losses within the top contact. As such, the Entech cover has proven to be a very important component in the fabrication of high-efficiency concentrator cells. Electrical isolation of the individual cells was accomplished by etching moats through the n^+/p InP junction with concentrated HCl. A two-layer antireflection coating of ZnS (~55 nm) followed by MgF_2 (~95 nm) was then deposited on the front surface of the device wafer. The concentrator cells were completed by installing the Entech cover. A typical array of completed heteroepitaxial InP concentrator cells is shown in figure 2. The effect of the Entech cover is also illustrated in this figure. Each individual cell has an area of 0.0746 cm^2 which is computed by subtracting the areas of the two busbars from the total device mesa area (this is a standard area definition for concentrator solar cells [ref. 12]).

The performance of the concentrator cells was characterized by measuring the absolute external quantum efficiency (AEQE) as a function of temperature as well as the illuminated current-voltage characteristics as a function of the temperature and the concentration ratio. The latter data sets were used to calculate the dependence of the cell performance parameter temperature coefficients on the concentration ratio. The measurement techniques have been described previously [ref. 13]. All of the results reported here are referenced to the AM0 spectrum [ref. 14]. A discussion of the cell performance is given in the following section.

RESULTS AND DISCUSSION

Initially, the current-voltage characteristics for the cells were measured as a function of temperature under one-sun AM0 conditions in order to obtain the necessary information for evaluating the efficiency under concentration (i.e., the one-sun short-circuit current (I_{sc}) is needed to calculate the concentration ratio for concentrator measurements). To within experimental error, we found I_{SC} to be independent of temperature. The AEQE data shown in figure 3 illustrates why I_{SC} is temperature independent. As expected, the InP band edge shifts to longer wavelengths as the temperature increases and one would normally expect an increase in I_{SC} due to this effect. However, a concomitant decrease in the short- and mid-wavelength response is also observed for these devices as the temperature increases which offsets any increase in I_{SC} due to the band gap shift. Thus, I_{SC} remains essentially constant as the temperature is increased. Note that the blue response for these cells is relatively low. This characteristic is typical of shallow-homojunction solar cells which have a high surface recombination velocity. We have shown in previous work that graded emitter doping profiles can be used to improve the blue response in these cells [ref. 15]. However, a technique for effectively passivating the emitter surface needs to be developed in order to realize InP cells with near-theoretical performance characteristics.

The HE InP cell performance was then tested as a function of the temperature and the AM0 concentration ratio and the results from these measurements are shown in figures 4 and 5. The AM0 efficiency (figure 4) increases rapidly at low concentration ratios and then reaches a broad plateau for concentration ratios of ~40 or more. At 25°C, the cells have efficiencies of close to 19% over a broad range of concentration ratios. This value decreases to ~16% as the temperature is increased to 80°C. The broad plateau in efficiency can be understood by examining the open-circuit voltage (V_{OC}) and fill factor (FF) *versus* concentration ratio data given in figure 5. The behavior of V_{OC} is as expected. In fact, when the V_{OC} data are plotted against *ln*(concentration ratio) a straight line is obtained. However, the FF data indicate that the cells quickly become series-resistance limited as the concentration ratio is increased beyond ~20 suns. Additionally, this effect appears to be enhanced as the operating temperature is increased. An analysis of the resistance components contributing to the overall series resistance for these cells shows that the emitter sheet resistance is primarily responsible for limiting the concentrator cell performance. A lower emitter sheet resistance or a smaller grid line spacing will be necessary in order to improve this aspect of the cell performance. The broad plateau in efficiency *versus* concentration ratio is seen to be due to offsetting effects of the V_{OC} and FF as the concentration ratio increases.

Current-voltage data for an HE InP concentrator cell at peak efficiency are shown in figure 6. At 25°C, the efficiency reaches 18.9% under the AM0 spectrum at 71.8 suns. As shown in figure 4, the peak efficiency at 80°C is 15.7% at 75.6 suns. These values are very encouraging and demonstrate that HE InP cells have the potential to reach high efficiencies at high concentration ratios and high temperatures. Additionally, these results show that the HE cell efficiencies improve dramatically when operated under concentration.

Using the data shown in figures 4 and 5, we have calculated the temperature coefficients for the HE InP cell performance parameters as a function of the concentration ratio. As a basis for comparison, we have also fabricated homoepitaxial (HO) InP concentrator solar cells on single-crystal InP substrates with junction structures which are similar to those used in the HE InP cells. Similar concentrator measurements and temperature coefficient calculations have been performed for the HO InP cells. In figure 7, we compare the V_{OC} temperature coefficients for the two types of cells as a function of the concentration ratio. At low concentration ratios, the HO cells clearly out-perform the HE cells. However, at high concentrations, the HE cell temperature performance improves substantially and approaches that of the HO cells. This result highlights an additional advantage of operating the HE cells under concentration.

Efficiency and FF temperature coefficient data for the HE InP cells as a function of the concentration ratio are plotted in figure 8. The data indicate that the temperature performance of the FF actually degrades with increasing concentration. This behavior is linked to the series resistance problems discussed previously. Nevertheless, the temperature performance of the conversion efficiency actually improves as the concentration ratio is increased due to the behavior of the V_{OC} temperature coefficient (shown in figure 7). The temperature coefficient of efficiency would improve much more rapidly with concentration if the cell series resistance were reduced. This problem remains as an important one to solve for these devices in order to realize higher efficiencies at high concentration ratios.

SUMMARY

High-efficiency heteroepitaxial InP solar cells have been fabricated on GaAs substrates using a novel compositionally graded intermediate layered structure. One-sun cells have AM0 efficiencies as high as 13.7% at 25°C. The concentrator cell performance has been characterized as a function of the temperature and the AM0 concentration ratio. Peak concentrator AM0 efficiencies of 18.9% at 71.8 suns, 25°C and 15.7% at 75.6 suns, 80°C have been obtained with these cells, which are the highest efficiencies yet reported for InP heteroepitaxial solar cells. It has also been shown that the conversion-efficiency temperature coefficient for these cells improves substantially as the concentration ratio is increased. The advantages of operating the HE InP cells under concentration include reduced cell area, higher conversion efficiencies and improved temperature performance.

The cell performance is presently limited by three main loss factors including 1) recombination at the surface of the emitter layer, 2) a high emitter-layer sheet resistance leading to reduced FF values at high concentration and 3) a high density of threading dislocations in the active cell layers. Improvements in any of these areas will lead to increased cell efficiencies.

Technologically, it would be important and immediately useful if the results obtained in this work for InP cells grown on GaAs substrates could be duplicated using Si substrates. Such a result would make HE InP cells a viable contender for space power applications and efforts toward this goal are currently underway.

REFERENCES

1) Yamaguchi, M. et al.; Jap. J. Appl. Phys., **23**, 302, 1984.

2) Keavney, C.J. et al.; Conf. Record 21st IEEE Photovoltaic Specialists Conference, 141, 1990.

3) McClelland, R.W. et al.; Appl. Phys. Lett., **37**, 560, 1980.

4) Spitzer, M.B. et al.; Conf. Record 21st IEEE Photovoltaic Specialists Conference, 196, 1990.

5) Vernon, S.M. et al.; Proc. Mat. Res. Soc. Symp., **198**, 163, 1990.

6) Keavney, C.J., Spire Corp.; private communication, Mar. 1991.

7) Keavney, C.J. et al.; Conf. Record 20th IEEE Photovoltaic Specialists Conference, 654, 1988.

8) Al-Jassim, M.M. et al.; Proc. Mat. Res. Soc., 1990 Spring Meeting, San Francisco, CA, April 16-21, 1990.

9) Wanlass, M.W. et al.; U.S Patent No. 4,963,949, Oct. 16, 1990.

10) Wanlass, M.W.; U.S. Patent No. 4,649,859, Mar. 17,1987.

11) O'Neill, M.J.; U.S. Patent No. 4,711,972, Dec., 1987.

12) Terrestrial Photovoltaic Measurement Procedures, Report ERDA/NASA/102277/16, June, 1977.

13) Wanlass, M.W. et al.; Proc. 10th Photovoltaic Advanced Research and Development Meeting, Lakewood, CO, U.S.A., Oct.23-25, 1990. To be published in *Solar Cells*, 1991.

14) Wehrli, C.; Extraterrestrial Solar Spectrum, Physical Meteorological Observatory and World Radiation Center, tech. rep. no. 615, Davos-Dorf, Switzerland, July 1985.

15) Wanlass, M.W. et al.; Proc.1st Int. Conf. on InP and Rel. Mat., Norman, OK, U.S.A., March, 1989, **1144**, 445-458, SPIE (1989).

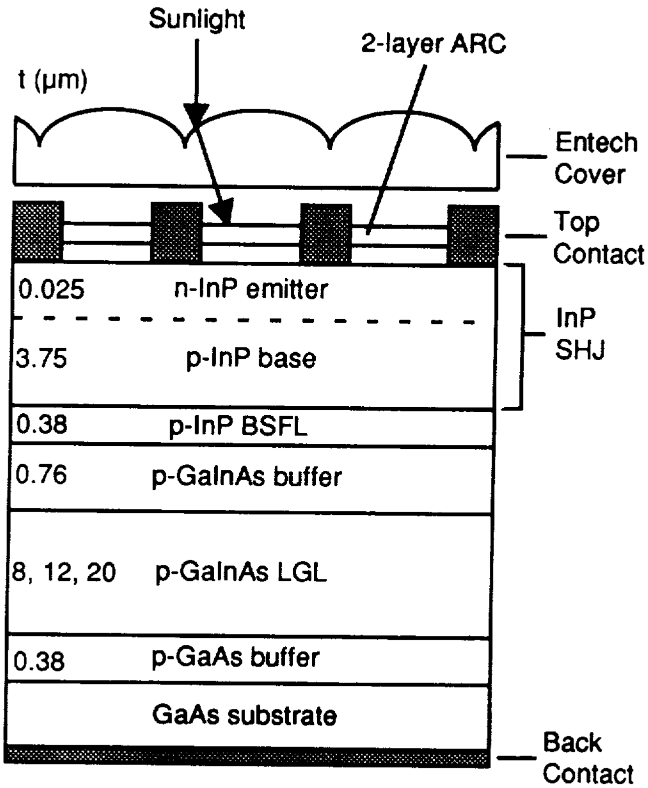

Figure 1. Schematic diagram of the HE InP concentrator solar cell structure on a GaAs substrate.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

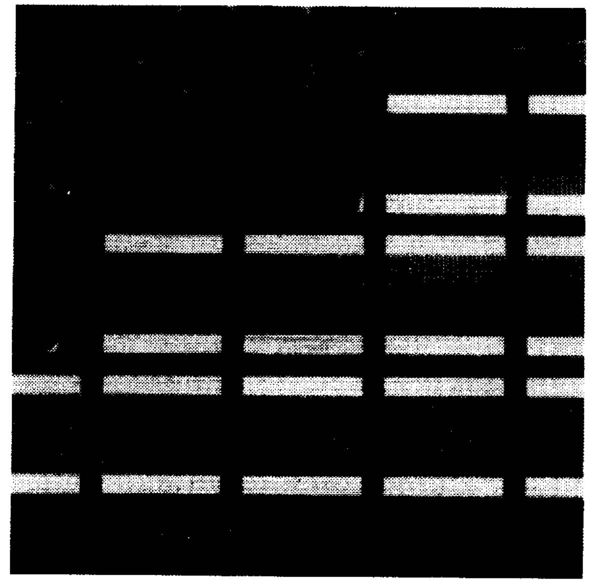

Figure 2. Plan-view photomicrograph of a typical array of HE InP concentrator cells. The cell in the center of the micrograph has an Entech cover properly installed.

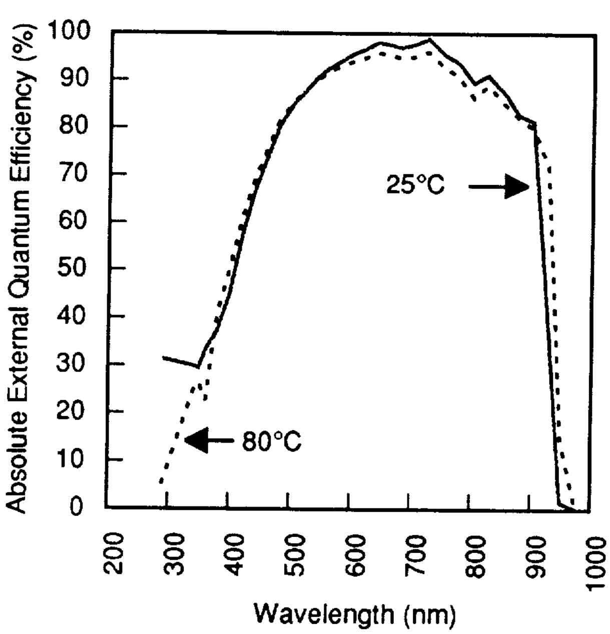

Figure 3. AEQE data for an HE InP concentrator cell at 25°C and 80°C.

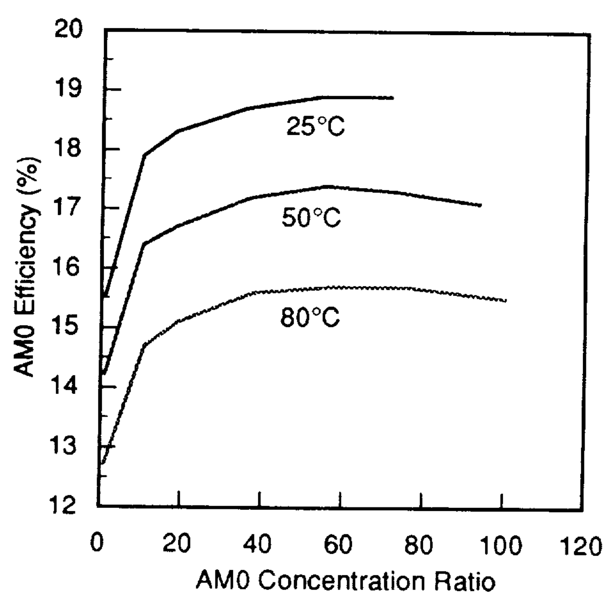

Figure 4. AM0 conversion efficiency data for an HE InP concentrator cell as a function of the operating temperature and AM0 concentration ratio.

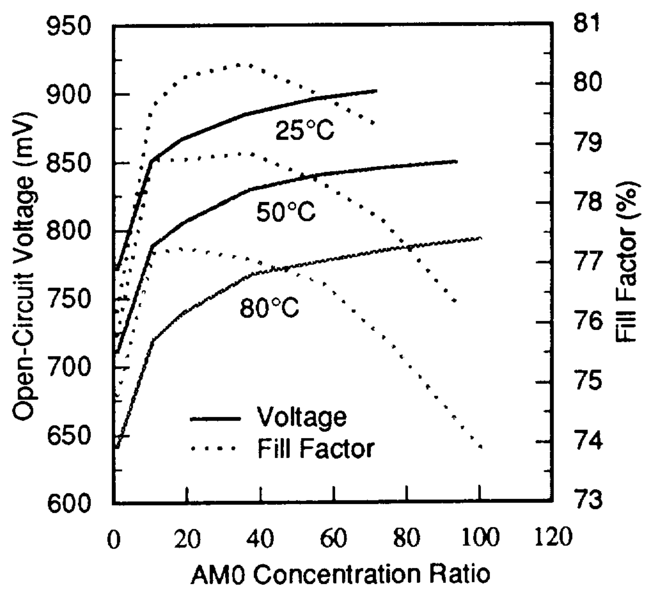

Figure 5. Open-circuit voltage and fill factor data for an HE InP concentrator cell as a function of the operating temperature and AM0 concentration ratio.

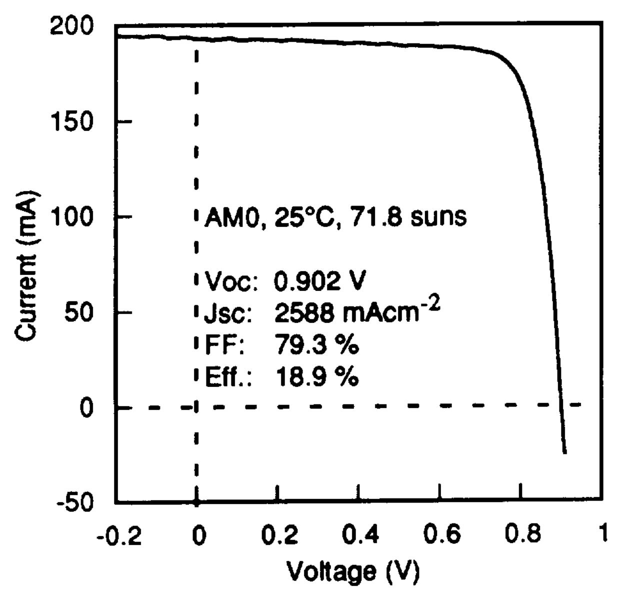

Figure 6. Current-voltage data for an HE InP concentrator cell at peak efficiency under concentrated AM0 illumination.

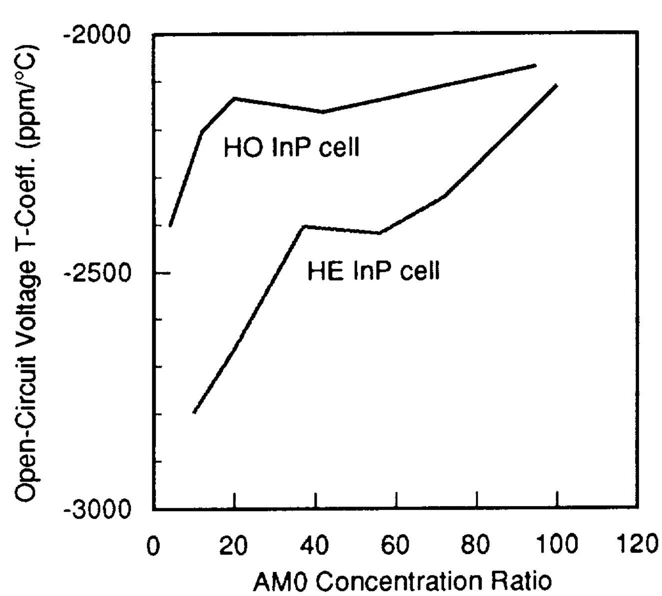

Figure 7. Open-circuit voltage temperature coefficient data as a function of the AM0 concentration ratio for HO and HE InP concentrator cells.

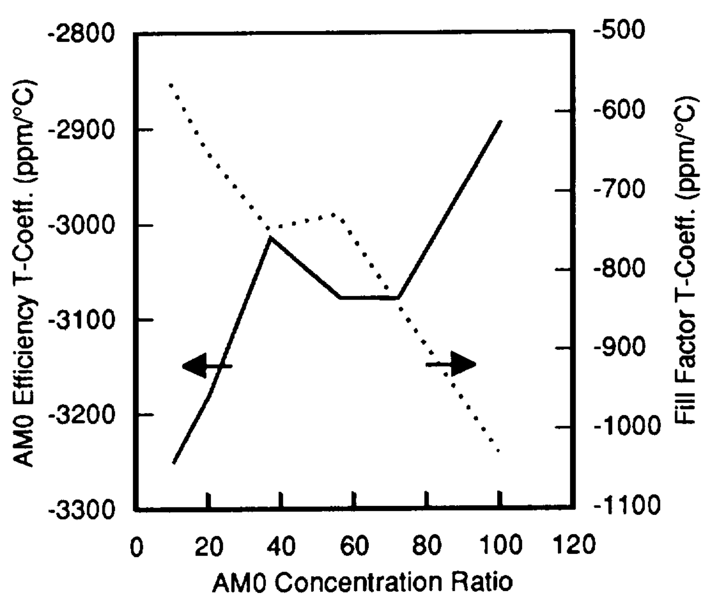

Figure 8. AM0 conversion efficiency, and fill factor, temperature coefficient data as a function of the concentration ratio for an HE InP concentrator cell.