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ELECTRON-IRRADIATED TWO-TERMINAL, MONOLITHIC InP/$Ga_{0.47}In_{0.53}$As TANDEM SOLAR CELLS AND ANNEALING OF RADIATION DAMAGE

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ABSTRACT

Radiation damage results from two-terminal monolithic InP/$Ga_{0.47}In_{0.53}$As tandem solar cells subject to 1 MeV electron irradiation are presented. Efficiencies greater than 22 % have been measured by the National Renewable Energy Laboratory from 2×2 cm^2 cells at 1 sun, AM0 (25 °C). The short circuit current density, open circuit voltage and fill factor are found to tolerate the same amount of radiation at low fluences. At high fluence levels, slight differences are observed. Decreasing the base dopant level of the $Ga_{0.47}In_{0.53}$As bottom cell improved the radiation resistance of J_{sc} dramatically. This in turn, extended the series current flow through the subcells substantially up to a fluence of 3×10^{15} cm^{-2} compared to 3×10^{14} cm^{-2}, as observed previously. The degradation of the maximum power output from the tandem device is comparable to that from shallow homojunction (SHJ) InP solar cells, and the mechanisms responsible for such degradation is explained in terms of the radiation response of the component cells. Annealing studies revealed that the recovery of the tandem cell response is mostly dictated by the annealing characteristics exhibited by SHJ InP solar cells.

INTRODUCTION

In the past few years, tandem solar cells have been the center of much research as an alternate source of generating electrical power in space applications (refs. 1-4). However, for a solar cell to be suitable for this application, it must tolerate the harsh radiation environment of space. Such a cell is the two-terminal, monolithic InP/$Ga_{0.47}In_{0.53}$As tandem solar cell grown by the National Renewable Energy Laboratory. In collaboration with the Naval Research Laboratory (NRL), the tandem cell program has been directed toward optimizing the radiation resistance of the tandem cells by improving the device structure. To date, this has lead to the fabrication of two-terminal, monolithic prototypes as large as 2×2 cm^2 with beginning of life (BOL) efficiencies greater than 22% (1 sun, AM0, 25 °C). Several of these cells will be tested in the STRV 1 space experiment soon (ref. 5).

An InP-based approach has been integrated into the tandem technology mainly because of the proven higher radiation resistance of shallow homojunction (SHJ) InP cells than other types such as Si and GaAs (ref. 6). A key issue in the development of the two-terminal tandem device is to design each subcell so that the series current flow through both junctions is matched end-of-life (EOL) after irradiation. Preliminary studies on InP/$Ga_{0.47}In_{0.53}$As tandem cells irradiated with successive fluences of 1 MeV electrons have already shown promising results (ref. 2). The subcell currents remained equal at relatively high fluences, and the degradation of the photovoltaic (PV) parameters occurred at a slow rate. By varying the base dopant level of the $Ga_{0.47}In_{0.53}$As bottom cell, it was found that the rate of decay of the short-circuit current density (J_{sc}) and the open-circuit voltage (V_{oc}) is more pronounced for the heavily-doped case by the former parameter but less pronounced by the latter (ref. 7). As a first step in the optimization procedure for the tandem cell, the base dopant level of the bottom cell was reduced.

The ability of a solar cell to recover from radiation damage is also an important aspect of the overall cell performance. The recovery of irradiated tandem cells due to thermal annealing in the dark is presented, and the recovery is analyzed in terms of the annealing characteristics of the individual cells.

The tandem cells were tested with successive fluences of 1 MeV electrons. Illuminated current-voltage (I-V) measurements and annealing results are presented for InP/$Ga_{0.47}In_{0.53}$As solar cells. The results are compared with previous studies on InP/$Ga_{0.47}In_{0.53}$As cells and with each component cell, all with a similar structure.

CELL DESCRIPTION

The tandem cells were grown by the atmospheric-pressure metal organic vapor phase epitaxy (APMOVPE) technique for which the details have been described elsewhere (ref. 8). The cell structure consists of an InP top junction, a $Ga_{0.47}In_{0.53}As$ bottom junction and a $Ga_{0.47}In_{0.53}As$ tunnel junction to provide the electrical connection between the subcells, as shown schematically in Fig 1. The component cells are lattice-matched by adjusting the Ga and In compositions. The total area of the tandems in this study were 1×1 cm^2.

EXPERIMENTAL PROCEDURE

The cells were irradiated with incremental fluences of 1 MeV electrons at NASA Goddard, and the fluence was measured with a Faraday cup. The irradiations were performed in ambient conditions at room temperature under open circuit. The beam current was usually kept in the nanoamp regime to avoid heating the device, and the electron fluence ranged from 1×10^{13} to 2.4×10^{16} cm^{-2}. Measurements of the I-V characteristics were made within three hours after each irradiation. The results were obtained under one sun, AM0 at 25 °C using a 2500 W SpectroLab, Mark III solar simulator. The efficiency is measured using an InP reference cell calibrated by NASA Lewis Research Center. Since the band gap of $Ga_{0.47}In_{0.57}As$ is 0.75 eV, it should be pointed out that the IR portion of the simulator in this energy region is somewhat stronger than what it should be. This is characteristic of the uncorrected Xe sources employed, and the overall effect this has on the I-V curve is to enhance the fill factor by a very small percentage (ref. 9). Annealing of the radiation damage was carried out in the dark and in the air up to 500 K.

RESULTS

The effects of radiation damage on the cell I-V curves are illustrated in Fig. 2. The main feature of importance from the I-V curve is the smooth kink which begins to develop at low voltages as a result of the current mismatch between the top and bottom cells. The kink appears at a fluence of about 3×10^{15} cm^{-2}, and becomes more pronounced as the irradiation increases. This feature has been associated with the reverse-bias breakdown of the $Ga_{0.47}In_{0.53}As$ bottom cell, which has been observed before in $InP/Ga_{0.47}In_{0.53}As$ devices (ref. 2). (Not related to radiation damage, however, a mismatch in the currents between the subcells at BOL has been seen due to the spectral content of different light sources (ref. 9).) This allows the larger generated current from the top subcell to pass through the tandem. The data also show excellent radiation resistance in these partially optimized cells despite the presence of a slight BOL current mismatch between the subcells.

Figure 3 depicts the change of the PV parameters with electron fluence for a tandem cell. At low fluences, the degradation of the maximum power (P_{max}) output of the cell was primarily due to the reduction of J_{sc} and V_{oc}. The power loss at a fluence of 1×10^{15} cm^{-2} was about 20% relative to the BOL power. An additional plot of the degradation of the efficiency of a SHJ InP solar cell is included in the figure for comparison. The degradation of the tandem cell efficiency is comparable to that of the SHJ InP cell. It should be noted that for GaAs/Ge solar cells the FF has been reported to be affected by the infrared portion of the excitation source (ref. 9). Since the infrared content of the Xe source used in this study has not been entirely suppressed to simulate the sun's true IR spectrum, the FF considered here is that of an effective FF. Although this should boost the cell efficiency by a small percentage, the radiation response and the annealing behavior of the solar cells are the issue of importance and not the absolute values of the PV parameters.

Illustrated in Fig. 4 are two I-V curves measured after irradiation with 1 MeV electrons at a fluence of 3×10^{15} e^-/cm^2 for the tandem cell in this work, and a tandem cell from a previous study for comparison. The present cell is offset by 0.25 for clarity. At this fluence, P_{max} from the early tandem is suppressed by the radiation-induced kink which appears as a result of the current mismatch. The present tandem cell does not show a pronounced current mismatch at this fluence, and in consequence, P_{max} is considerably higher. Therefore, the devices studied here show a dramatic enhancement of the radiation resistance compared to the previous cell. This is known to be due to the reduced carrier concentration in the base of the bottom cell (ref. 2), and is discussed below.

A desirable feature of space solar cells is the ability to thermally anneal the radiation damage while being subject particle irradiation. Annealing of $InP/Ga_{0.47}In_{0.53}As$ cells exposed to 2.4×10^{16} cm^{-2} electron irradiation was carried out to examine the recovery of the cell response. Fig. 5 depicts a few I-V curves that were isochronally and isothermally annealed, both in 30-minute increments. As illustrated in the figure, the I-V curves gradually recover from the post-rad curve but fall short from recovering completely. The behavior of PV parameters as a function of annealing temperature is shown in Fig. 6. The pre-annealed value of each parameter is normalized with respect to the corresponding pre-rad value. Partial recovery of J_{sc} is seen to begin at 350 K and begins to level off near 450 K and stays constant up to 500 K. At this temperature, the sample was annealed isothermally to check whether more recovery was possible. All parameters except for Eff% showed no further appreciable recovery. At 500 K for 1.5 hours, P_{max} has recovered by 16% from its pre-anneal value.

DISCUSSION

Recent studies on prototype, two-terminal, monolithic InP/$Ga_{0.47}In_{0.53}As$ solar cells demonstrated that these devices perform very well when exposed to 1 MeV electrons. It has been shown that the degradation of the PV response is similar to that observed in SHJ InP cells up to a fluence of 3×10^{14} e/cm^2. The results were very encouraging considering that the previous tandem cells were not optimized for radiation resistance. The present study reports on the work of a first step in optimizing the tandem cell structure for radiation resistance.

In an effort to optimize the InP/$Ga_{0.47}In_{0.53}As$ tandem solar cells so that the subcell currents remain matched at EOL in a space environment, the PV response of the component cells must be adjusted. Particularly, J_{sc} must be designed to be highly tolerant to radiation. Work dealing with the effects of base dopant level on J_{sc} from $Ga_{0.47}In_{0.53}As$ and InP solar cells suggest that the radiation hardness of J_{sc} is improved by decreasing the base dopant concentration (refs. 2, 7, 10). Similar results have been obtained from GaAs single junction solar cells (ref. 11). In view of this, the base dopant level of the bottom subcell was reduced by an order of magnitude (to about 10^{17} cm^{-3}) which caused the resistance of J_{sc} to increase. In consequence, the onset of the current mismatch between the subcells was extended to substantially higher fluence levels. From previous tandem cells, the mismatch occurs at 3×10^{14} e$^-$/cm^{-2} whereas in this study it occurs at 3×10^{15} e$^-$/cm^{-2}, which is a dramatic improvement. The improved current matching which is, in turn, due to the radiation-hardening of J_{sc}, is a result of the decreased sensitivity of charge collection to the radiation-induced degradation of the minority carrier diffusion length (or its lifetime) in the bottom cell (ref. 10).

It is interesting to note that the fill factor is only reduced by 8% relative to the BOL value at a fluence of 10^{15} e$^-$/cm^2. Using a technique developed by Handy (ref. 12), intensity-dependent measurements of the I-V curves for the tandem cells show that the series resistance is in the order of a few milliohms for the fluence range studied. In addition to this, analysis of dark I-V fits suggest that the series resistance may not even play a role in the degradation of $Ga_{0.47}In_{0.53}As$ devices at a fluence of 10^{16} e/cm^2 (ref. 13). This would seem to suggest that the overall series resistance has almost a negligible effect on FF, and thus the device performance. The low series resistance is probably due to the heavily doped base of each subcell thus decreasing the overall material resistivities.

Partial recovery is seen in the irradiated tandem cells. The annealing characteristics exhibited by J_{sc} and V_{oc} are similar to those reported elsewhere (ref. 14) on SHJ InP solar cells and they seem to be consistent with this type of cell. Particularly, in that study, no notable recovery of J_{sc}, V_{oc} and P_{max} is further seen at temperatures above 400 K. This appears to be consistent with other SHJ InP cells where a similar trend is observed (ref. 15, 16). The annealing behavior of the tandem cell can be described in terms of the minority carrier diffusion length of each component cell. The recovery of J_{sc} under thermal annealing can be attributed to annealing of defects formed in the neutral regions of the device where J_{sc} is mostly affected. This, in turn, results in an increase of the minority carrier diffusion length thus allowing the collection of charge carriers to be more efficient. A point worthy of mention is that according to unpublished results obtained at NRL, the recovery of J_{sc} from the $Ga_{0.47}In_{0.53}As$ bottom cell occurs at a faster rate than the InP top cell. This suggests that the recovery of J_{sc} from the tandem cell is mainly characteristic of the recovery from the InP top cell. Likewise, V_{oc} from InP solar cells does not recover as fast as that from $Ga_{0.47}In_{0.53}As$ solar cells. This is an interesting result because it shows that unless the recovery rate of the PV response of the top subcell is the same as that of the bottom subcell, the tandem cell will not recovery effectively under thermal annealing.

A final remark about the degradation of J_{sc} and V_{oc} can be made on the basis of their normalized pre-annealed values in Fig. 6. At a fluence of 2.4×10^{16} e$^-$/cm^2, J_{sc} and V_{oc} have decreased to 62% and 78% from their pre-rad values, respectively. The modeling results from reference 10 combined with the results of references 2 and 7 suggest that a more optimized cell design for the radiation resistance of J_{sc} and V_{oc}, the efficiency would be expected to increase by several percent at EOL.

CONCLUSIONS

High-performance, partly optimized InP/$Ga_{0.47}In_{0.53}As$ tandem solar cells have been achieved, and have shown excellent radiation response. Efficiencies greater than 22% have already been obtained from 2×2 cm^2 cells. After 1 MeV electron irradiation, the tandem cells with a BOL efficiency of over 20% have shown an efficiency of approximately 10% at a fluence of 10^{16} e^-/cm^2. This is higher than Si and GaAs, both with efficiencies of about 7.5% at the same fluence. Furthermore, the results described here show that the radiation resistance of J_{sc} and V_{oc} can be further optimized by fine-tuning the device structure, specifically, the base dopant level of the $Ga_{0.47}In_{0.53}As$ bottom cell.

The annealing results revealed that the tandem cell annealing characteristics are mainly controlled by the InP top cell. This indicates that if annealing of tandem solar cells are viable while in earth orbit, then not only is the degradation rate of importance but also the annealing rate. That is, J_{sc} in each subcell must recover at the same rate so that current matching can be maintained throughout the mission life.

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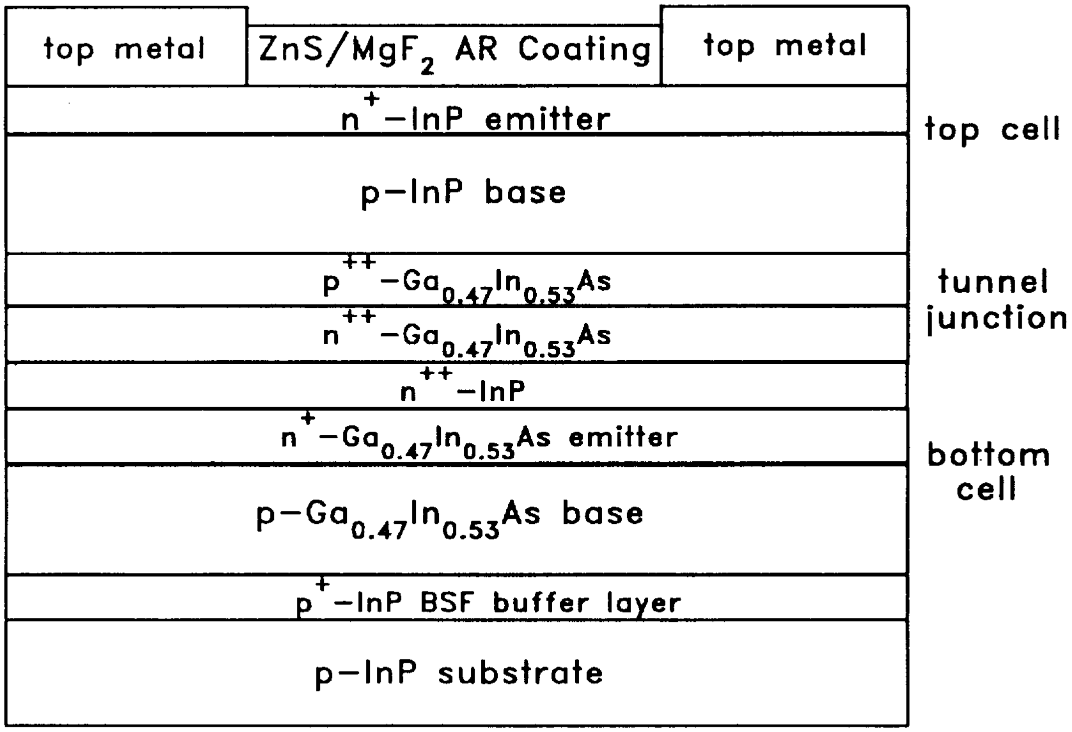

Figure 1: Schematic diagram of the InP/Ga$_{0.47}$In$_{0.53}$As tandem solar cell structure.

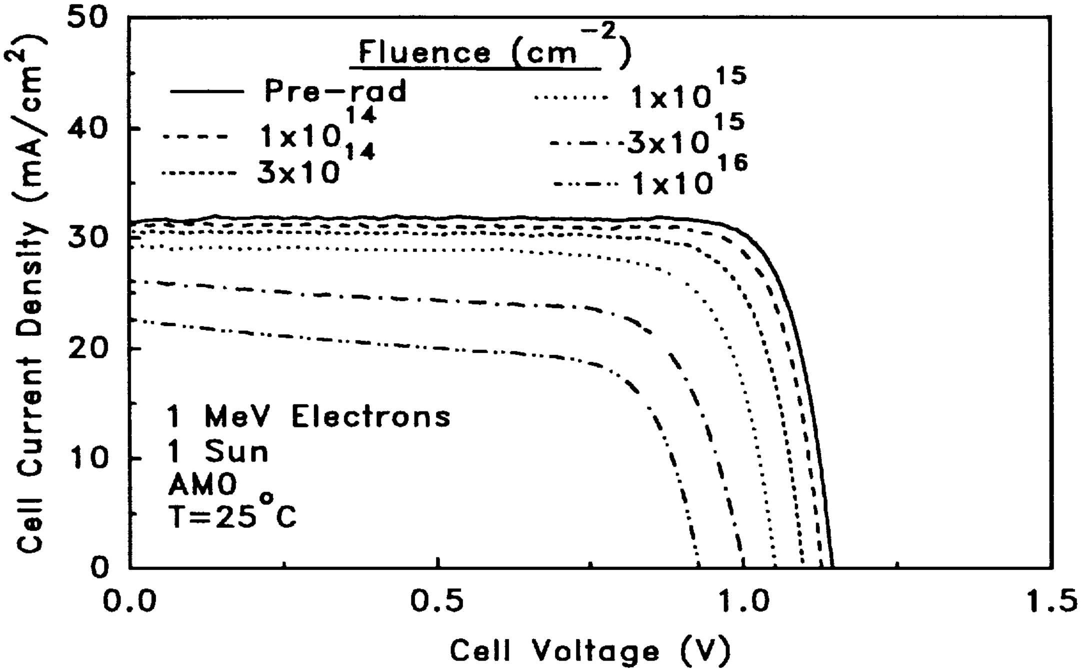

Figure 2: The effects of 1 MeV electron irradiation on the InP/$Ga_{0.47}In_{0.53}As$ tandem solar cell I-V curves. A kink is shown at low voltages.

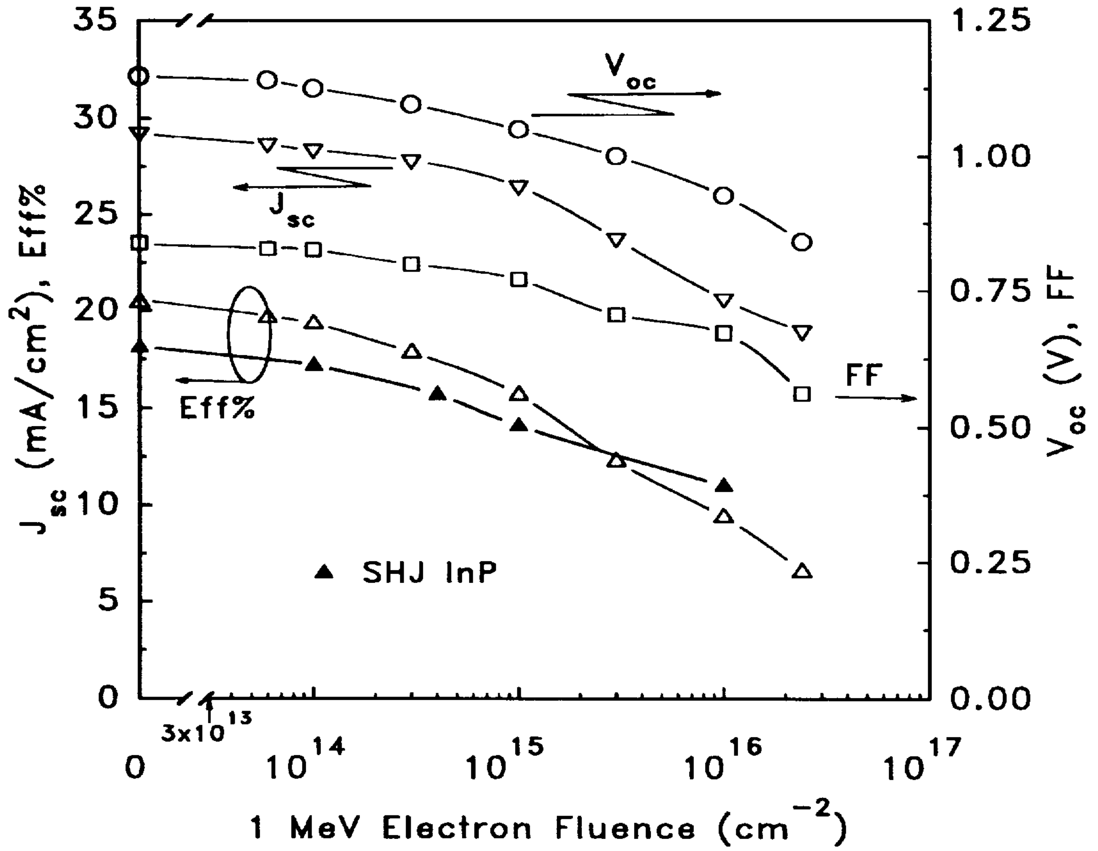

Figure 3: The degradation of the cell response for the InP/$Ga_{0.47}In_{0.53}As$ device shown in Fig. 2. The n^+p SHJ InP data was obtained from reference 15.

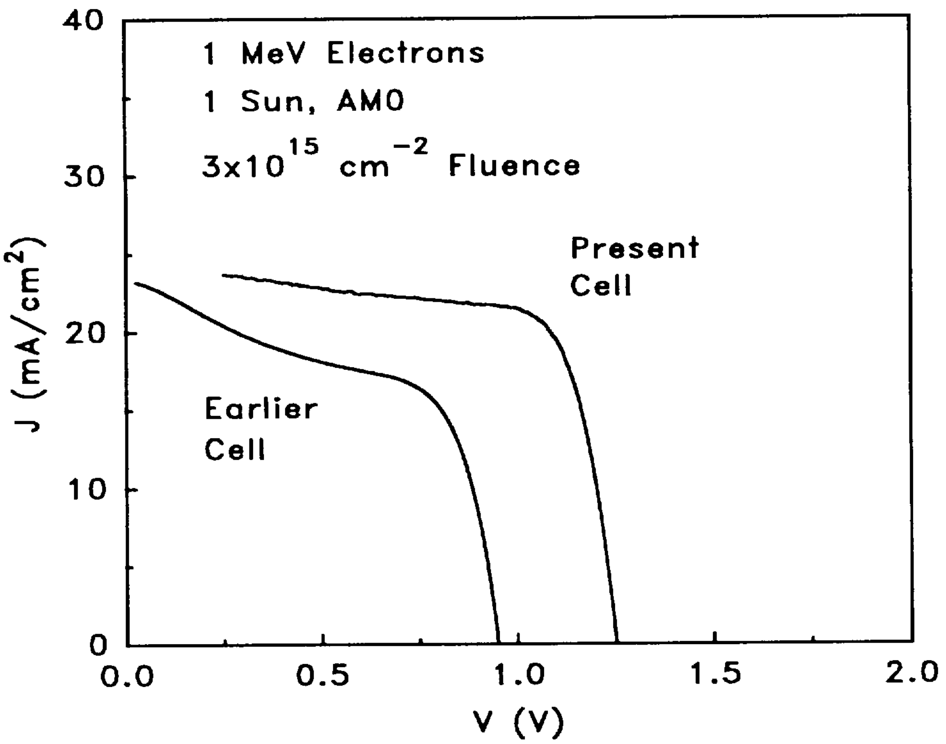

Figure 4: Comparison of the I-V curves for the tandem cell in this study with a tandem cell from a previous study (ref. 2). The present cell curve has been displaced by 0.25 V for clarity.

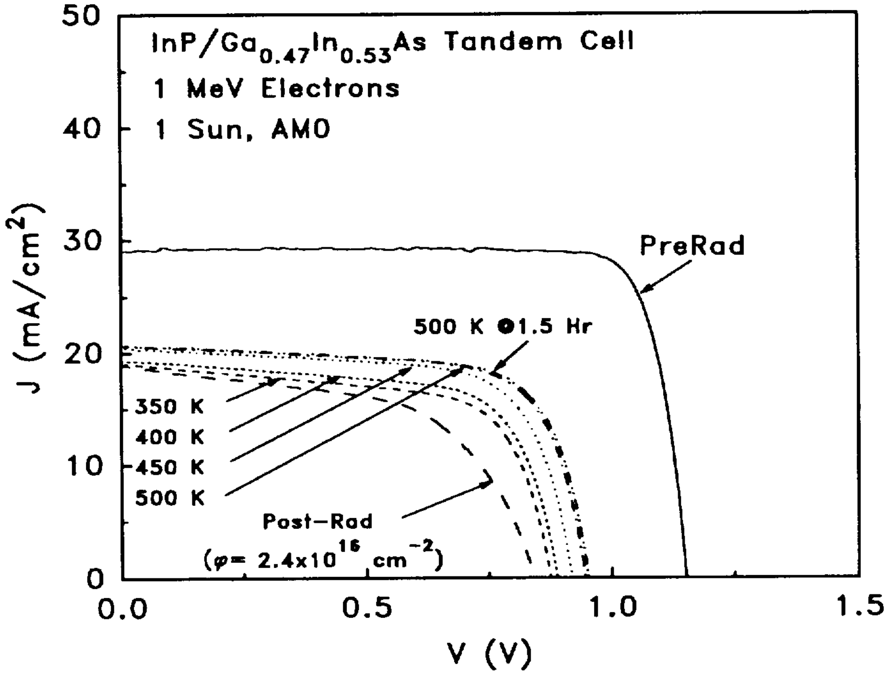

Figure 5: Annealing of 1 MeV electron-irradiated I-V curves for the InP/Ga$_{0.47}$In$_{0.53}$As tandem solar cell shown in Fig. 2.

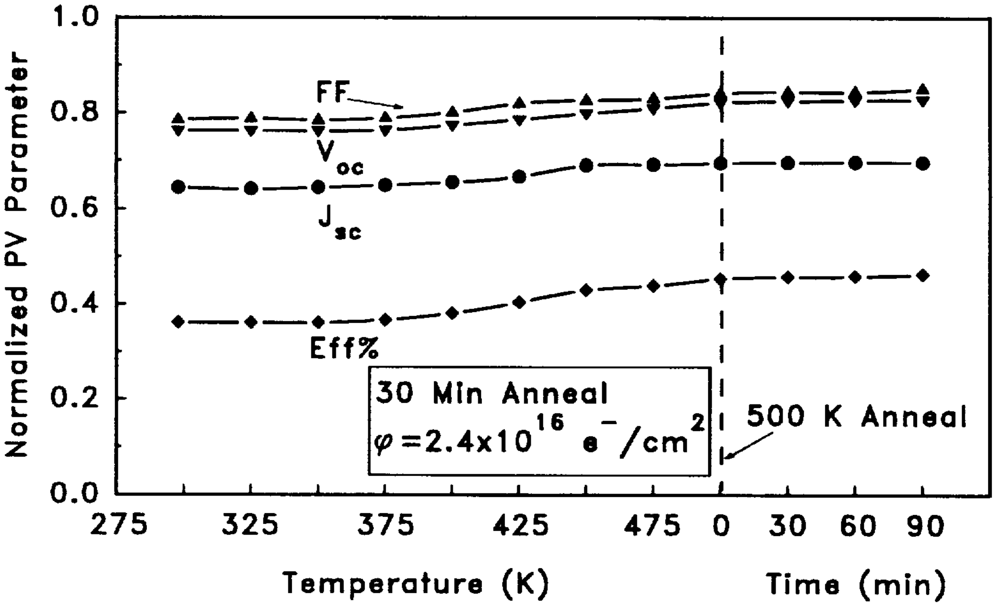

Figure 6: The recovery of the PV parameters of the $InP/Ga_{0.47}In_{0.53}As$ solar cell irradiated with 1 MeV electrons. Partial recovery is seen up to 475 K. Only V_{oc} continues to recover gradually above this temperature.