N91-30240

Radiation Resistance of Ge, $Ge_{0.93}Si_{0.07}$, GaAs, and $Al_{0.08}Ga_{0.92}As$ Solar Cells*

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Solar cells made of Ge, $Ge_{0.93}Si_{0.07}$ alloys, GaAs and $Al_{0.08}Ga_{0.92}As$ have been irradiated in two experiments with 1-meV electrons at fluences as great as 1×10^{16} cm^{-2}. Several general trends have emerged. Low-band-gap Ge and $Ge_{0.93}Si_{0.07}$ cells show substantial resistance to radiation-induced damage. $Al_{0.08}Ga_{0.92}As$ cells have shown in the two experiments that degradation is less than for GaAs cells similarly irradiated. Compared to homojunctions, cells with graded-band-gap emitters did not show the additional resistance to damage in the second experiment that had been seen in the first. The thickness of the emitter is a key parameter to limit the degradation in GaAs devices.

Introduction

Radiation damage to devices is a key factor for space photovoltaics since the end-of-life (EOL)/beginning-of-life (BOL) ratios largely determine how much extra array area must be launched to meet EOL mission requirements. At the previous SPRAT, we presented preliminary radiation exposure data using 1-meV electrons at fluences as high as 5×10^{15} cm^{-2} for $Al_{0.08}Ga_{0.92}As$ and GaAs solar cells[1]. In that study, the AlGaAs emitter configurations were varied and included homojunctions, grade compositions, and heterojunctions. GaAs cells grown on Ge (with inactive GaAs/Ge interfaces) were included. All of these cells were grown in production-type reactors.

The preliminary data showed that AlGaAs cells, regardless of emitter configuration, degraded less than GaAs cells. But beyond this, the graded-emitter cells degraded the least of all in the experiment.

In this paper, we describe a second experiment that extends the results presented previously. The 1-meV electron fluence has been increased to 1×10^{16} cm^{-2}, and Ge and $Ge_{0.93}Si_{0.07}$ alloy cells have been added. Again, AlGaAs and GaAs cells form the major focus of the study.

* This work was funded by the Department of the Air Force under Contract Nos. F33615-87-C-2804 and F33615-88-C-2847. Mr. K. Reinhardt and Mr. J. Scofield are the respective Project Engineers.

Experimental

All the $Al_{0.08}Ga_{0.92}As$ cells used in this study were grown at RTI in a research-type reactor. This reactor is horizontal and operates at atmospheric pressure. Trimethylgallium (TMG), trimethylaluminum (TMA), and arsine (AsH_4) are the sources of Ga, Al, and As, respectively, and Se from a 50 ppm H_2Se/H_2 mixture and Zn from dimethylzinc (DMZ), and diethylzinc (DEZ) are the n- and p-type dopants, respectively. The AlGaAs layers were grown at 780 ° C using a V/III ratio of about 35 to 40. The RTI GaAs cells were grown at 700 ° C.

The Ge and $Ge_{0.93}Si_{0.07}$ cells were grown in a vertical low pressure reactor. The reactor was operated at 250 Torr and at 700 ° C for Ge and 900 ° C for $Ge_{0.93}Si_{0.07}$. Mixtures of germane (GeH_4), disilane (Si_2H_6), AsH_4, and diborane (B_2H_6) in H_2 were the source and dopant gases. The junctions evaluated in this study, using p-on-n polarity, were all epitaxially grown.

The RTI-grown devices were also processed at RTI. The current-voltage (I-V) characteristics were measured under a xenon-lamp solar simulator. The devices were sent to ASEC where the I-V measurements were repeated; generally, there was good agreement between the two sets of measurements. Several AlGaAs cells were evaluated by deep-level-transient spectroscopy (DLTS) at SERI, under the direction of Dr. R.K. Ahrenkiel, to establish a baseline deep defect level prior to irradiation. The only observed level was the DX center, present in most AlGaAs DLTS data, and the defect densities were low.

As in the first experiment, ASEC added several GaAs cells grown on Ge with inactive GaAs/Ge interfaces. These cells have an emitter thickness of about 0.5 μm compared to the 0.25-μm-thick emitters found in the GaAs and AlGaAs cells grown at RTI.

The irradiation of the devices was effected at JPL under the direction of Dr. B.E. Anspaugh. The cells, those grown and processed at RTI and GaAs/Ge cells from the ASEC process line, were divided into three groups. One group was irradiated at a fluence of 10^{15} cm^{-2}, the second at 5×10^{15} cm^{-2}, and the third at 10^{16} cm^{-2}. Unfortunately, there was no sequential irradiation with measurement after each level of exposure.

After irradiation, workers at ASEC remeasured the I-V characteristics and the quantum efficiencies at wavelengths of 450 and 800 nm. The cells were then returned to RTI, where they were also remeasured. There was again good agreement between the two sets of measurements. Several of the AlGaAs and GaAs samples were returned to SERI for remeasurement of the defect content by DLTS.

The BOL efficiencies for the cells used in the second experiment were typically higher than those of the cells from the first experiment. The Ge-cell efficiencies ranged from 4 to 6 percent, and $Ge_{0.93}Si_{0.07}$ efficiencies were about 5 percent. These values were measured under a xenon-lamp simulator and may be slightly high because of high currents. $Al_{0.08}Ga_{0.92}As$ homojunction cells varied from 15 to 19 percent, and graded-emitter cells varied from 14 to 17 percent. AlGaAs cells for which the emitter changed composition in discrete steps had BOL efficiencies of 14 to 17 percent. GaAs cell efficiencies were 17 to 20 percent, and cells with AlGaAs graded-composition emitters and GaAs bases had 13 to 19 percent efficiencies. The BOL efficiencies of these cells are high enough to extract useful information and are important because cells with lower efficiencies will generally show less effects of radiation damage.

Results

While, overall, the experiment went smoothly, some difficulties were encountered. A decision to test separate groups of cells at different fluences, rather than using sequential irradiation, was made to reduce the risk of damaging the cells during repeated measurements between irradiations, but this decision also reduced the sample size for each fluence. These smaller sample sizes prevented resolution of some discrepancies in the observed degradation data. Attempts to extract quantitative damage coefficients were hampered by the spread in the initial quantum efficiency values. The relatively small changes in quantum efficiencies at lower fluences made determination of the diffusion lengths L_n difficult. And since the damage coefficient K and L_n are related usually by the expression

$$\frac{1}{L_{n\phi}^2} = \frac{1}{L_{no}^2} + K\phi$$

where $L_{n\phi}$ and L_{no} and the diffusion lengths after and before irradiation, respectively, at the fluence of ϕ, uncertainty in L_n produces uncertainty in K.

Despite these difficulties, several conclusion about the trends in the data can be made.

1. Ge and $Ge_{0.93}Si_{0.07}$ cells show substantial resistance to radiation damage even at the highest fluences, confirming predictions made in our original proposal.

2. Although having lower beginning values for the product of J_{sc} and V_{oc}, the AlGaAs cells, regardless of emitter configuration, degrade less than the GaAs and GaAs-on-Ge cells.

3. Within the AlGaAs group, the graded-band-gap cells fail to show the performance advantage that was observed in the first experiment, i.e., shallow homojunction cells performed as well or better.

4. The GaAs cells with the 0.25-μm-thick emitters degrade less than the cells with 0.5-μm-thick emitters, which is a trend generally observed for cells.

These trends can be seen in Figure 1 that shows the post-irradiation efficiencies normalized to pre-irradiation values as a function of fluence. The data points are the averages of the cells irradiated at that fluence, and because of dividing the samples that is mentioned above, each point represents usually no more than three to four cells, which, unfortunately, is a small sampling size.

From the data shown in Figure 1, the performance of the Ge and $Ge_{0.93}Si_{0.07}$ cells is clearly outstanding. Even at a fluence of 10^{16} electrons/cm^2, these cells have retained 85 percent of the BOL efficiency. And a single Ge cell, upon which a 3-μm-thick $Al_{0.08}Ga_{0.92}As$ layer had been grown, performed even better, retaining about 94 percent of the BOL efficiency. This latter cell represents the structure of an AlGaAs/Ge cascade cell and clearly indicates that this cascade cell, or any other using Ge as the bottom junction, will likely by limited by the radiation resistance of the top cell.

Since cell fill factors changed by no more than two to five percent for all of the cells in the test, the differences in the normalized GaAs and AlGaAs data must reflect differences in V_{oc} and/or J_{sc}. For the GaAs and AlGaAs cells, the ratios of pre- and post-irradiated V_{oc} and J_{sc} are plotted versus the fluence in Figure 2. The data show that the voltage degrades comparably for both GaAs and AlGaAs, indicating that the changes in the normalized efficiencies must come from changes in the current collection, i.e., changes in diffusion length and minority-carrier lifetime. The AlGaAs cells retain about 70 to 75 percent of the current. The thickness of the GaAs cell emitters significantly impacts current collection. The 0.25-μm-thick-emitter cells retain about 50 percent more current than the cells with the thicker emitters at 10^{16} electrons/cm^2.

The change in the current collection in the GaAs and AlGaAs cells was examined further by considering the spectral response of these cells. This is shown in Figures 3 and 4. The data in Figure 3 were gathered with ASEC's two-source (tungsten and xenon) simulator, using the sources separately to illuminate the samples. For the AlGaAs cells, the "red" and "blue" responses from tungsten and xenon, respectively, degrade at about the same rate although the normalized ratio is lower for the "red". For the GaAs cells with thin emitters, the degradation is only slightly greater than for the AlGaAs cells. The thick-emitter GaAs cells show an initial rapid decrease in both the "red" and "blue" regions followed by a slowing of the degradation rate, but still greater than for the AlGaAs cells.

Figure 4 shows measured quantum efficiencies at wavelengths of 450 and 800 nm as a function of fluence for the AlGaAs and GaAs cells and confirms the simulator data shown in Figure 3. The higher starting values for the GaAs-based cells indicate longer diffusion lengths, but the slower rate of decrease for the AlGaAs-based cells supports the conclusion that the diffusion length changes less, producing the observed higher current ratios for those cells. And since this is the case for both short and long wavelengths, we infer qualitatively that the degradation coefficient is lower in AlGaAs than GaAs for both the base and emitter regions.

Normalized data present only part of the necessary information to evaluate radiation damage characteristics. Efficiency data must also be considered. Since the fill factor changes were small, plotting the J_{sc} V_{oc} product provides the additional information. This is shown in Figure 5. The key result here is that, while initially having lower J_{sc} V_{oc} products than GaAs cells, the AlGaAs-cell performance equals the GaAs-cell performance at an EOL fluence of 10^{16} electrons/cm^2, and, because the AlGaAs degradation proceeds at a slower rate, will outperform GaAs at higher fluences. This may be pivotal for long-duration flights or high-radiation-intensity orbits. In Figure 6 also note the stability of the output of the Ge and GeSi cells.

The DLTS data for the cells are currently being analyzed and will be reported at a later date.

Conclusions

In summary, a second radiation-resistance experiment has shown qualitatively that AlGaAs solar cells degrade more slowly the GaAs cells. We were somewhat disappointed that clear evidence favoring graded-band-gap emitters over homojunction emitters could not be concluded from the data. Because of the slower degradation, the performance of the AlGaAs cells equalled that of GaAs at a 1-MeV electron fluence of 10^{16} cm^{-2}. Because of some discrepancies in the data, we were unable to determine quantitative damage coefficients for AlGaAs to compare with the published data for GaAs.

Ge and GeSi cells, added for this experiment, showed remarkable resistance to damage. Both Ge and $Ge_{0.93}Si_{0.07}$ cells demonstrated BOL/EOL ratios of about 0.85 at 10^{16} electrons/cm^2. A Ge junction with a 3-μm-thick AlGaAs cap showed a BOL/EOL ratio of 0.94 at that fluence.

And, finally, thin emitter GaAs cells outperformed thicker-emitter cells. While this is not unexpected, it may suggest that there are processing optimizations yet to be done to examine the trade-offs between emitter thickness influence on yield versus the resistance to radiation-induced damage. It was clear that the thinner emitter cells produced at RTI were more susceptible to probing damage during I-V and spectral measurements.

References

1 M.L. Timmons, R. Venkatasubramanian, T.S. Colpitts, J.S. Hills, J.A. Hutchby, P.A. Iles, and C.L. Chu, *Graded Bandgap AlGaAs Solar Cells for AlGaAs/Ge Cascade Cells*, Proceedings of the Space Photovoltaic Research and Technology Conference, 1989, (NASA Conference Publication 3107), p. 48.

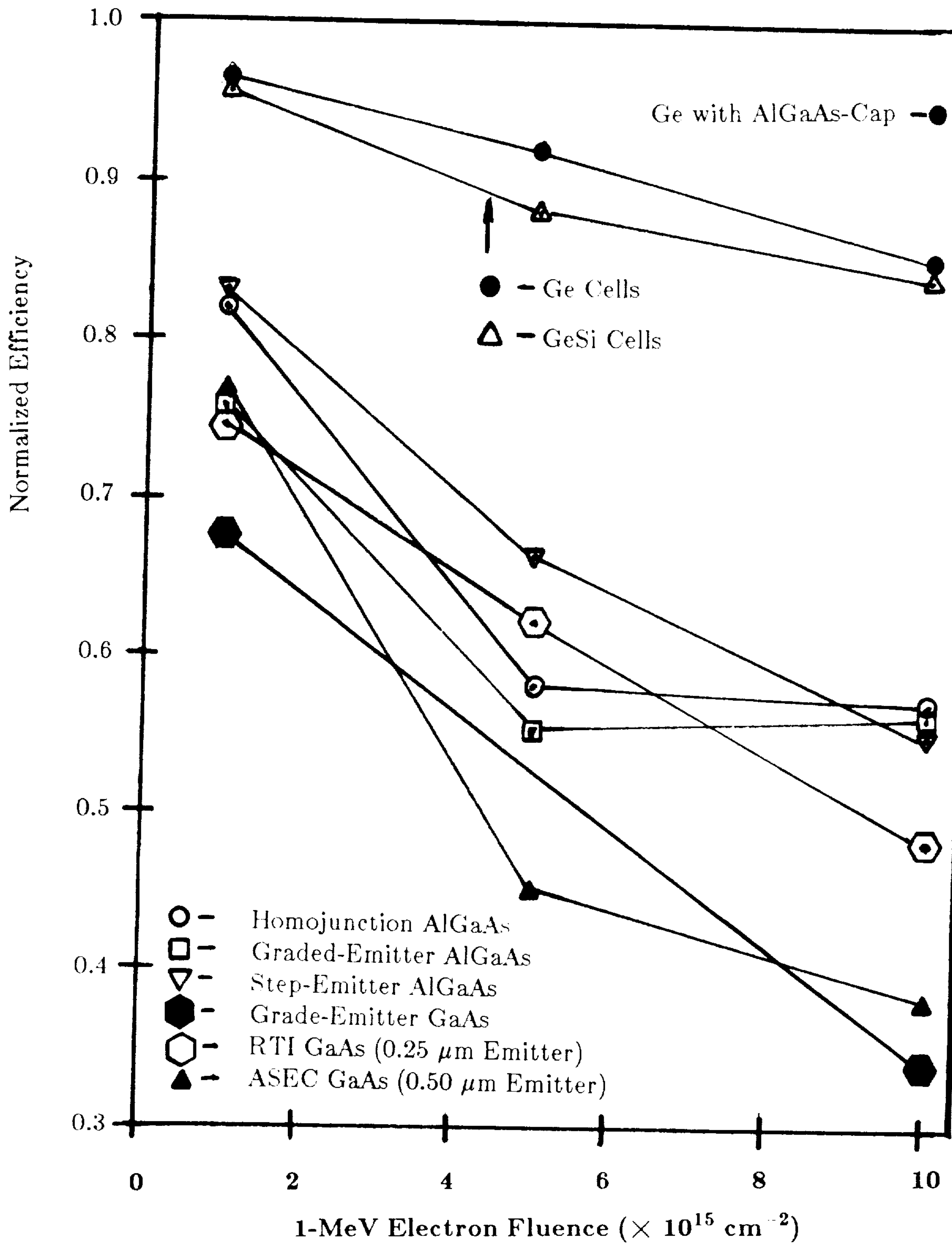

Figure 1. Normalized efficiencies versus fluence for the AlGaAs, GaAs, Ge, and GeSi solar cells after irradiation with 1-MeV electrons.

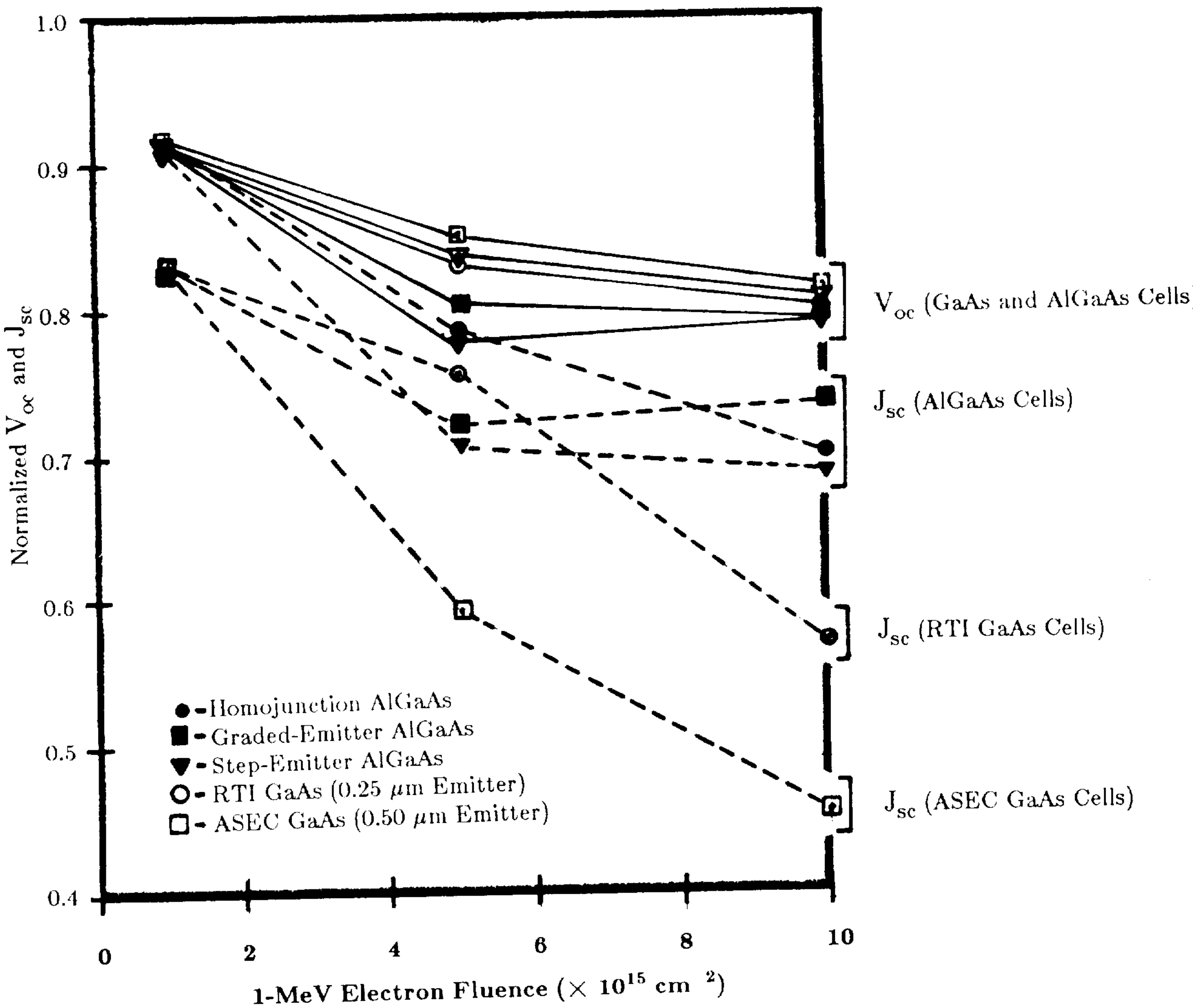

Figure 2. Normalized values of J_{sc} and V_{oc} versus fluence for the GaAs and AlGaAs solar cells that were part of this experiment. The dashed lines show current, and solid lines show voltage.

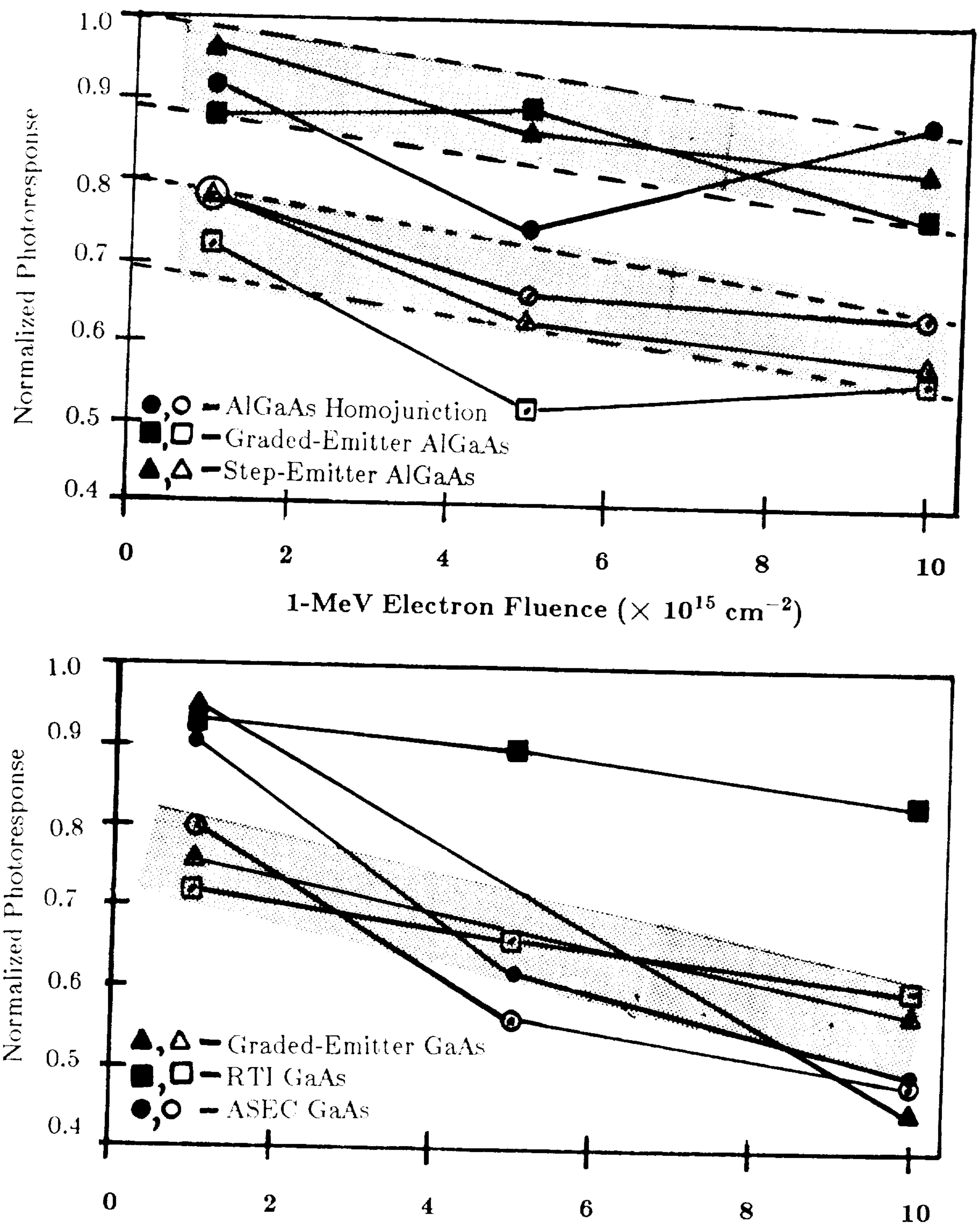

Figure 3. Normalized photocurrents versus fluence from a two-source solar simulator using the xenon and tungsten sources separately to illuminate the cells. This technique produces qualitative "blue" (closed symbols) and "red" (open symbols) responses.

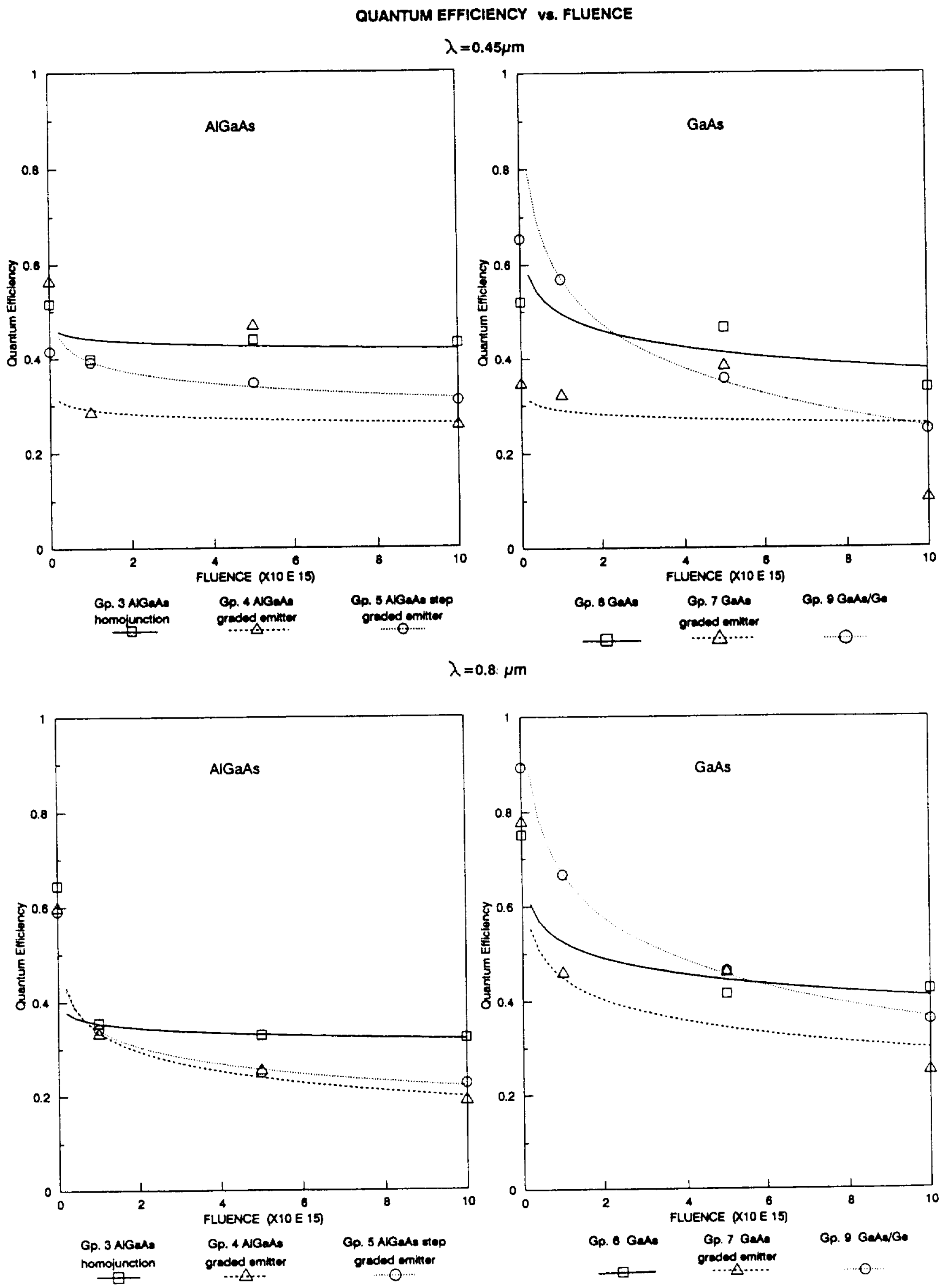

Figure 4. Quantum efficiency measurements as a function of fluence made at wavelengths of 450 and 800 nm for GaAs and AlGaAs solar cells.

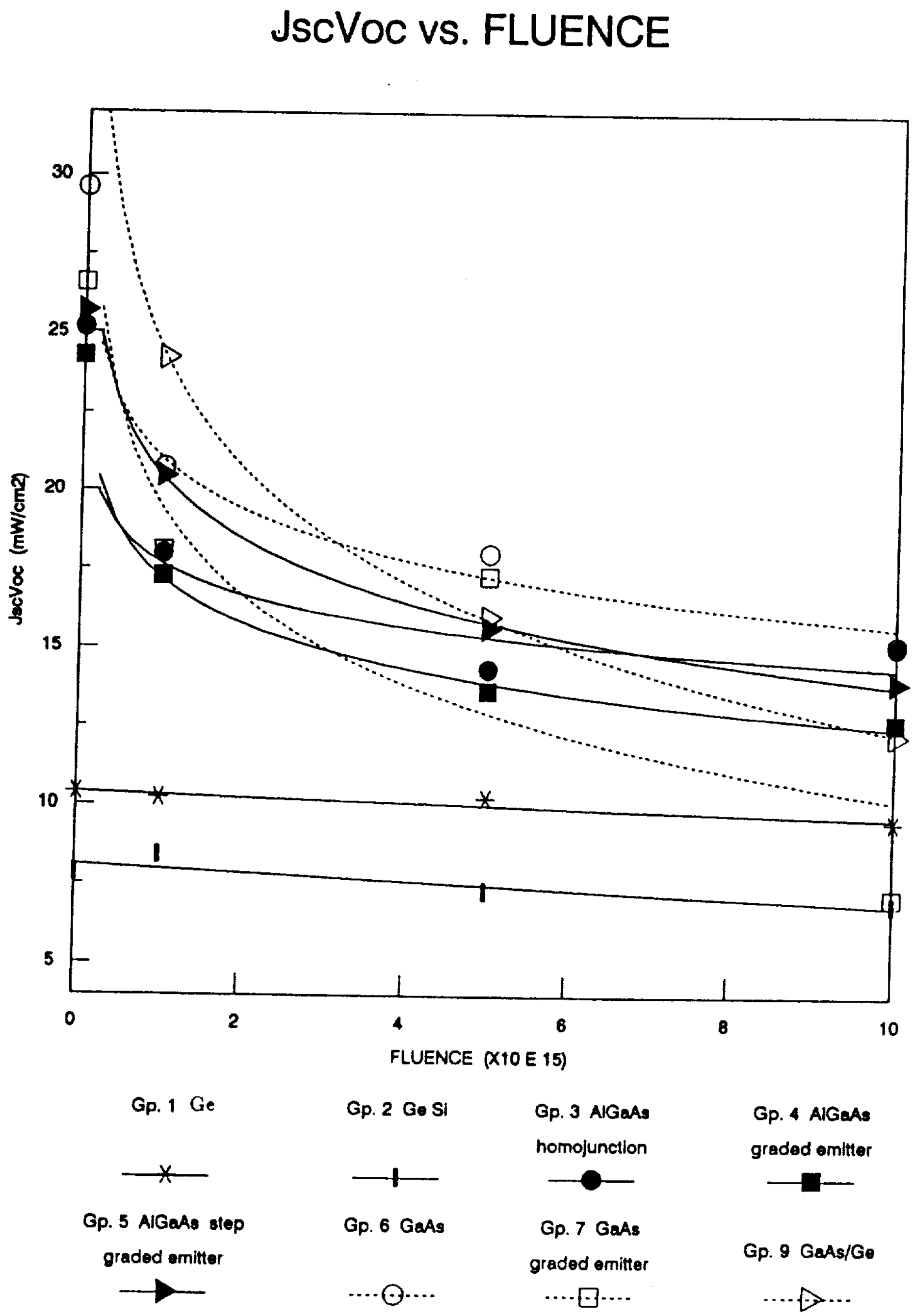

Figure 5. The product of J_{sc} and V_{oc} as a function of fluence for GaAs and AlGaAs solar cells. The a fluence of 10^{16} cm^{-2}, the performance of the GaAs and AlGaAs cells are equal.