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GALLIUM ARSENIDE SOLAR CELL RADIATION DAMAGE EXPERIMENT

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ABSTRACT

Gallium arsenide (GaAs) solar cells for space applications from three different manufacturers were irradiated with 10-MeV protons or 1-MeV electrons. The electrical performance of the cells was measured at several fluence levels and compared. Silicon cells were also included for reference and comparison. All of the GaAs cell types performed similarly throughout the testing and showed a 36–56% power areal density advantage over the silicon cells. Thinner (8-mil versus 12-mil) GaAs cells provide a significant weight reduction and the use of germanium (Ge) substrates to improve mechanical integrity can be implemented with little impact on end-of-life performance in a radiation environment.

INTRODUCTION

Interest in gallium arsenide (GaAs) solar cells for space applications is increasing to the point where a significant percentage of near-future space missions will employ these cells as the primary power source. With these applications in mind, The Johns Hopkins University Applied Physics Laboratory (APL) was funded by the joint NASA-CNES MFE–Magnolia study program to carry out the radiation testing described in this paper. This electron and proton radiation experiment was a follow-on to some previous work performed by APL (ref. 1). The fundamental goals of this experiment were to do the following:

1. Verify the suitability of all of these GaAs cell types, primarily of production line quality (and availability), for use in a low-earth radiation environment.

2. Provide data on the bare and covered Mitsubishi cells for the Magnolia program (CNES-France). CNES is responsible for the solar cell array design and delivery for this program.

3. Compare the performance, both before and after charged particle irradiation, of present-day GaAs cells from different manufacturers, including a check against silicon cells.

4. Increase the precision of the measurements by using larger sample sizes and fewer variables than previous experiments.

A total of 48 cells were tested from three manufacturers: Mitsubishi Corporation, Applied Solar Energy Corporation (ASEC), and Spectrolab, Inc.

APL purchased bare cells from ASEC and Spectrolab, made electrical connections, bonded the cells to a small plate, and mounted the cover slides. The Mitsubishi cells were provided by Mitsubishi (through CNES) with tabs and covers already attached. Electrical data were taken at APL; proton irradiation was accomplished using the Brookhaven National Laboratory (BNL) tandem Van de Graaff, and electron irradiation was supplied by the Van de Graaff at Goddard Space Flight Center (GSFC). Compatibility with existing radiation data was achieved by using 10-MeV protons and 1-MeV electrons in addition to providing a damage equivalence factor measurement. Described below are the solar cells tested, the test and measurement techniques used, and significant results and conclusions.

TEST ARTICLES

Five different cell types were included in the testing and are defined in Table 1. It was assumed that the cell types were "production line quality," meaning that the manufacturing specifications were reasonably well established and large quantities of the cells could be purchased at the present time.

TEST AND MEASUREMENT TECHNIQUES

CELL USAGE AND MOUNTING

Two separate wheels were rotated through the radiation beam: one for electron irradiation and one for proton irradiation. Each wheel could hold a total of 24 cells. Two of the silicon cells, two of the Spectrolab GaAs/Ge cells, and five each of the remaining four types were mounted on the wheel. The cover slides were 6-mil ceria-doped Microsheet; these were used on all cells except for two Mitsubishi cells on the proton wheel and three on the electron wheel, which remained bare. In addition to the 48 irradiated cells, 12 were used as control cells (two of each type).

PROTON IRRADIATION

The proton doses were obtained using the BNL tandem Van de Graaff. Particle energy was 10 MeV, and beam currents ranged from 5 to 200 nA. The beam was rastered up and down at a frequency of four cycles per second as the wheel was rotated at 33 rpm. The shortest run time was 129 s, which corresponded to 71 rotations of the wheel. Dosimetry was performed by taking several readings with a Faraday cup before exposing the wheel and repeating this procedure once during and following the exposure. By averaging several readings and adjusting the run time to compensate for slight drifts in the beam current, the actual total doses are within a few percent of what was desired.

Data (solar cell I-V curves) were taken at fluence levels of 0 (beginning-of-life—BOL), 10^{10}, 5×10^{10}, 10^{11}, 10^{12}, and 10^{13} (end-of-life—EOL) protons/cm^2.

ELECTRON IRRADIATION

As in reference 1, the GSFC Van de Graaff was used to achieve the electron fluences. By breaking the beam pipe, a flux level of 10^{13} 1-MeV electrons/cm^2 per second was achieved, resulting in the final run time of approximately 6 hours. The electron energy was 1 MeV. The fluence was calculated by using measurements from a Faraday cup before and after the exposures and monitoring the beam current during the run. The beam current chosen (0.5 μA) remained quite stable over time.

Data were taken at fluence levels of 0, 5×10^{13}, 10^{14}, 5×10^{14}, 10^{15}, and 10^{16} electrons/cm^2.

CELL ELECTRICAL CHARACTERISTICS MEASUREMENT

Care was taken throughout this testing to maintain consistency and accuracy of the measurement of the cell electrical characteristics.

Solar Simulation

A xenon flash lamp, formally termed a medium area pulsed solar simulator (or MAPSS), located at APL was used to measure the current-voltage (I-V) curves of the cells. The light pulse covers an area of 60 ft^2 for a duration of 2 ms, during which time the I-V curve is swept. The test articles were always placed in the same spot in the test plane, very close to the standard cells, and were tested at room temperature (23°C).

The spectral quality of this source is not ideal for testing damaged solar cells but provides accurate BOL data (±0.5%) on all cells and EOL (10^{16} 1-MeV electrons/cm^2) data that is conservative by 2-5% in current and power. Reference 3 discusses the cross calibration work that was done between this simulator and a modified X-25 solar simulator in use at COMSAT Laboratories. The modifications of the COMSAT X-25 include additional filtering to provide a nearly ideal spectral match to the sun. However, the data presented in the figures below are not corrected for spectral match.

The inaccuracies of the MAPSS are due to the excess red (infrared) and blue energy of the xenon lamp as compared to 1 sun in space (AM0). The intensity in the mid-region of the spectrum is actually less than 1 sun AM0 to compensate for these excesses. For undamaged cells, this is easily overcome by using calibrated standards of the same type as the test article. As the cells are damaged, their spectral response changes such that they are not receiving a full 1 sun AM0 (in the mid-spectrum region), but the undamaged standard cell still does receive the proper illumination, resulting in a low reading on the test article. As the damage gets worse, so does the accuracy. This problem could also be overcome by using cells that are damaged to the same level as the test articles and then calibrated as standards, but this would be difficult and expensive. The voltage measurements are primarily dependent on the cell temperature and are typically within 2 mV (~1°C).

The MAPSS does have the advantage of not heating the cell during the measurement, producing consistent results and performing many measurements in a short time period. A wheel of 24 cells could be tested in about an hour.

Standard Cells

Two secondary standards were used throughout this testing: a 2 × 4 cm K6 silicon cell from Spectrolab and a 2 × 4 cm GaAs cell made by ASEC. The silicon cell was provided by Spectrolab as a standard to be used with a recent flight program and was of the same type as the K6 cells used in the test. The GaAs cell was calibrated using a primary standard at COMSAT Laboratories with the X-25 solar simulator mentioned above.

Both of these standards, along with a 2 × 2 cm K4 type silicon, were mounted on blocks with 28°C water circulating through them. All data are referenced to 28°C. The small silicon cell was used as a standard when the other standards were put through the test input as a system check. This was done following each set of measurements on each wheel.

Measurement Temperature Corrections

Typically, a 5°C temperature correction was made by the MAPSS computer to adjust between the 23°C test cell temperatures and the 28°C standard cell temperatures. The correction factors used were 2.2 mV/°C and 0.025 mA/°C/cm^2 for the silicon cells and 2.0 mV/°C and 0.020 mA/°C/cm^2 for the GaAs cells (ref. 4). Any errors in these correction values would result in quite small errors in the final electrical data, well within the overall uncertainty of the measurements.

EXPERIMENTAL RESULTS

The mean values of the parametric results on five samples each of the ASEC GaAs, Mitsubishi GaAs, Spectrolab GaAs, and ASEC GaAs/Ge solar cells, as well as two samples of the K6 silicon cells were analyzed. These 22 solar cells were subjected to each type of radiation, 1-MeV electrons or 10-MeV protons. Analysis of these two data sets consisted of graphical displays and a statistical analysis of variance (ANOVA). The ANOVA on the initial maximum power density (P_{max}) values gave an experimental error of 3.13 mW for cells with mean values from 185 to 210 mW.

GALLIUM ARSENIDE SOLAR CELL DISPLACEMENT DAMAGE

Figures 1-6 show the electrical responses of cell open-circuit voltage (V_{oc}), short-circuit current density (I_{sc}), and P_{max} versus both electron (Figures 1, 3, and 5) and proton (Figures 2, 4, and 6) fluences in particles/cm^2. The Spectrolab GaAs/Ge cells are excluded from this part of the discussion because of their classification as prototype cells instead of production line cells.

Initially, the GaAs cells from all three manufacturers have efficiencies in the 18-19% range and power densities in the 24-26 mW/cm^2 range (see Table 2). The five ASEC GaAs cells selected for electron exposure were statistically better (at a 95% confidence level), with a mean efficiency exceeding 19% and a mean power density exceeding 26 mW/cm^2, by small margins in each case. Otherwise, there were no significant differences among the six cell groups (three for electron exposure and three for proton exposure). The less mature ASEC GaAs/Ge cells have a lower efficiency and power density (16.5-17.5% and 22.5-23.5 mW/cm^2). We note that prototype GaAs cells studied around 1978 had power densities of 22 mW/cm^2 (ref. 5).

Figures 1-6 show that the GaAs cell electrical parameters from the various manufacturers degrade in a similar manner, with their degradation curves having similar shapes. After 10^{16} 1-MeV electrons/cm^2, the Mitsubishi cells are the superior performers with efficiencies 9.4% and power densities of 12.7 mW/cm^2. After 10^{13} 10-MeV protons/cm^2, the Mitsubishi GaAs cells are also superior (at a 95% confidence level), with a mean efficiency of 9.7% and a mean maximum power density of 13.2 mW/cm^2. However, in less severe radiation environments ($<10^{15}$ e/cm^2 or $<10^{12}$ p/cm^2), the lower starting efficiences of the Mitsubishi and GaAs/Ge cells may be a handicap. The lower BOL efficiences for the ASEC GaAs/Ge cells are due to their being early cells coming off the production line. Efficiences equal to the pure GaAs cells have been subsequently reported by the manufacturer for these cells.

GALLIUM ARSENIDE VERSUS SILICON SOLAR CELLS

Figures 1-6 include the degradation curves for the K6 series silicon solar cells, a space industry standard. The most interesting of these are Figures 5 and 6, which compare the maximum power densities of the silicon and GaAs cells.

The degradation curves for P_{max} of the silicon cells versus particle fluence are quasi-linear on these semi-log plots, whereas the like curves for the GaAs cells exhibit a sharp increase in slope above 10^{15} electrons/cm^2 and 10^{12} protons/cm^2. This increase in rate of degradation for the GaAs cells is such that their absolute maximum power densities will eventually be less than those of the silicon cells at very high fluence levels ($>10^{16}$ electrons/cm^2 and $>10^{13}$ protons/cm^2). This phenomenon has been observed before (refs. 4,5). For space missions of moderate duration in nominal natural environments, GaAs cells are obviously superior; however, in extremely severe environments, silicon cells would have better EOL values.

Figures 7 and 8 show the absolute spectral responses of typical individual silicon and GaAs cells before and after 1-MeV electron irradiation to 2×10^{16} electrons/cm^2. Figure 7 shows that the bulk of the electron displacement damage affects the red part of the spectrum. Figure 8 shows that GaAs cells suffer electron displacement degradation to both red and blue wavelength response.

As a final comment we note that our previous experiment showed that the maximum power of thin silicon cells (2.5-3 mils) was not significantly different from that of K6 series cells (8 mils thick) after very high fluences (2×10^{16} 1-MeV electrons/cm^2) (ref. 1). However, in the denser GaAs cells a 4-mil thickness differential (from 12 to 8 mils) removes about twice the amount of material as contrasted to the 5-mil differential in the 8-mil and 3-mil silicon cells.

DAMAGE EQUIVALENCE FACTORS

By using the data on relative P_{max} versus electron fluence or by examining the fits to the data, we can determine damage equivalence factors between 10-MeV protons and 1-MeV electrons for the GaAs solar cells. These factors are calculated by taking the ratio of 1-MeV electron fluence to 10-MeV proton fluence at the same damage level, e.g., 80% relative or normalized P_{max}. For a baseline comparison we compute a damage equivalence factor for the K6 silicon cells. Table 3 shows these data. These data are in good agreement with those of Anspaugh and Downing (ref. 6), except for the silicon cells at relative P_{max} values of 0.5 and 0.6, where 10-MeV protons become more damaging for the K6 cells with back surface reflectors (BSR) (ref. 6). (The Anspaugh and Downing data were for cells with no BSR.)

The damage equivalence factors for the GaAs cells remain fairly constant over two orders of magnitude in proton (10^{11}-10^{13} protons/cm^2) and electron (10^{14}-10^{16} electrons/cm^2) fluence. The low end of the ranges for GaAs is for the Mitsubishi 8-mil GaAs and ASEC GaAs/Ge cells, the two sets of cells with lower starting efficiencies.

The bare Mitsubishi cells suffered less damage (~2% in power) than those with 6-mil cover slides, as expected for protons but not, a priori, for electrons. (Cover slide reduction of beam intensity and average energy may be less important than its reduction in net backscattering from the GaAs.) This means that cells to be tested should be covered and with the same cover slide thickness.

Of course, any predictions for space missions must take into account the variation of damage equivalence factors with proton energy (lower-energy protons are relatively more damaging, particularly in GaAs) and the omnidirectional incidence of the particles as contrasted to the normally incident particles used to generate these data.

The similarity of the shapes of the degradation curves for both proton and electron irradiated cells and associated damage analysis are discussed in detail elsewhere (ref. 7). The differences between silicon and GaAs cells in Figures 1-6 are attributed to the monatomic and diatomic crystal structures. Under heavy irradiation by electrons (producing only point defects), the monatomic structure provides annealing by recombination of silicon vacancies and interstitials. The diatomic structure provides additional permanent defects by recombination of Ga interstitials with As vacancies (and vise versa). The difference between silicon and GaAs cells in Table 3 results from the competition of the proton-generated cluster defects with the annealing and increased degradation effects above. Cluster defects reduce annealing in silicon, thereby increasing the damage equivalence factors at high fluences. They reduce point-defect formation, by trapping primary mobile defects, thereby decreasing the damage equivalence factors at high fluences for GaAs.

EFFECTS OF JUNCTION DEPTH AND MATERIAL PROPERTIES IN GALLIUM ARSENIDE CELLS

Figure 9 shows a plot of mean relative P_{max} versus electron fluence for three types of ASEC GaAs solar cells. In the previous experiment we had a 12-mil thick GaAs cell with a 0.7-μm junction depth (ref. 1). In this experiment we had both 12-mil GaAs cells with a 0.45-μm junction depth and 8-mil GaAs/Ge cells with a 0.45-μm junction depth.

It is readily seen from Figure 9 that junction depth is more important with respect to electron displacement damage than substrate material. After exposure to 10^{16} electrons/cm^2, the GaAs/Ge cell has a relative P_{max} of 0.51 as compared to 0.47 for the GaAs cell of the same junction depth. In contrast, the GaAs cell with the 0.7-μm junction depth had a relative P_{max} of 0.23. The effects of substrate material (Ge versus GaAs), ~8.5%, is probably negligible (since this difference is close to the difference in BOL maximum power values) whereas shallower junctions give improvement of a factor of 2. The importance of having junctions in GaAs cells less than 0.5 μm deep has been known for some time (ref. 4). The selection of doping levels to maximize EOL performance, common for silicon cells in a radiation environment, might be seen for GaAs in the differences between the BOL V_{oc} and EOL I_{sc} values for the Spectrolab and Mitsubishi cells (Table 2 and Figure 4). The crossover in P_{max} (Figures 5 and 6) may be accidental or the result from a deliberate attempt to optimize performance at BOL.

DISCUSSION AND CONCLUSIONS

Gallium arsenide solar cells and the manufacturing processes have matured to a level that makes them quite attractive for use in many space applications. Sample sizes of five give a high level of confidence in the results since standard deviations were relatively small. Coefficients of variation for the initial values of P_{max} are in the range of 1-2.5%. All of the goals stated in the introduction were met satisfactorily by this experiment.

A typical low-earth orbit (LEO) mission may have a total radiation fluence in the range of 1-5 $\times$ 10^{14} equivalent 1-MeV electrons/cm^2. Our data show (Figure 3) that the EOL power per unit area will be 36-56% greater for a typical GaAs cell than for a K6-type silicon cell for such a mission. For very severe environments ($>10^{16}$ electrons/cm^2), we have corroborated previous results for the greater EOL power density of silicon cells. However, this may be overcome by in-orbit annealing techniques since defects in GaAs are repaired at much lower temperatures than those in silicon. We found the damage equivalence factor for 10-MeV protons (to 1-MeV electrons) to be approximately 1000 and slowly varying over 2 orders of magnitude in proton and electron fluence.

The doping densities of the Mitsubishi GaAs cells give them a slight edge over the U.S. GaAs cells. The data on these thinner cells and the data on the 12-mil ASEC cells with two significantly different junction depths (Figure 9) provided a quantitative comparison of the effects of junction depth and material properties. Assuming BOL efficiencies equal to pure GaAs cells, GaAs/Ge cells should show a significant advantage for any use because of the structural integrity of Ge, the ability to make these cells thinner (as thin as the thinnest silicon cells, ~3 mil), and the equivalent EOL performance.

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Table 1. - SOLAR CELL SPECIFICATIONS

Manufacturer	Cell Type	Area Dimensions (cm)	Thickness (mil)	Junction Depth (μm)	Manufacturing Process
1. Mitsubishi	GaAs P/N	2 × 4	8	<0.6	MOCVD
2. ASEC	GaAs P/N	2 × 4	12	0.45	MOCVD
3. Spectrolab	GaAs P/N	2 × 4	12	0.5	LPE
4. ASEC	GaAs/Ge P/N Inactive Ge Substrate	2 × 4	8	0.45	MOCVD
5. Spectrolab BSR, BSF N/P	K6 Si	2 × 4	8	0.12	Diffusion

Table 2.—INITIAL MEAN ELECTRICAL PARAMETER DATA

Cell	Maximum Power Density (mW/cm^2)	Efficiency (%)	Short Circuit Current (mA/cm^2)	Open Circuit Voltage (mV)	No. of Samples
Mitsubishi GaAs					
(e group)	24.8	18.3	31.6	971	5
(p group)	24.6	18.2	31.5	970	5
ASEC GaAs					
(e group)	26.0	19.2	31.9	1000	5
(p group)	25.3	18.7	31.6	996	5
Spectrolab GaAs					
(e group)	25.0	18.6	29.8	1011	5
(p group)	25.3	18.7	30.0	1011	5
ASEC GaAs/Ge					
(e group)	23.4	17.3	31.2	956	5
(p group)	22.5	16.6	31.5	940	5
Spectrolab K6 silicon					
(e group)	19.7	14.6	43.0	606	2
(p group)	19.7	14.6	42.8	608	2

Table 3.—DAMAGE EQUIVALENCE FACTORS, $f = Q_e/Q_p$, FOR 1-Mev ELECTRONS AND 10-MeV PROTONS.

Relative P_{max}	GaAs	Silicon
0.9	1130–1460	3880
0.8	1020–1470	3220
0.7	1000–1160	3600
0.6	960–1030	5220
0.5	890	6820

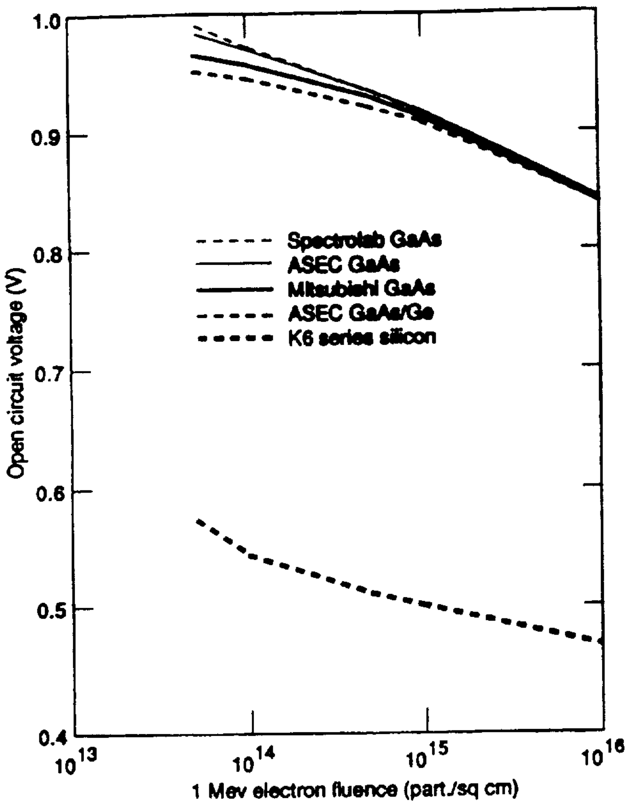

Fig. 1 Solar cell open circuit voltage versus electron fluence

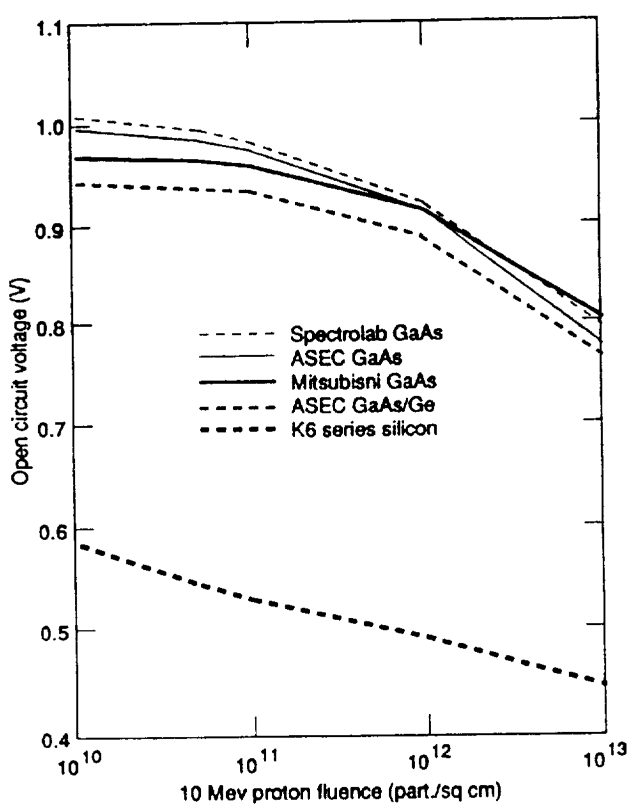

Fig. 2 Solar cell open circuit voltage versus proton fluence

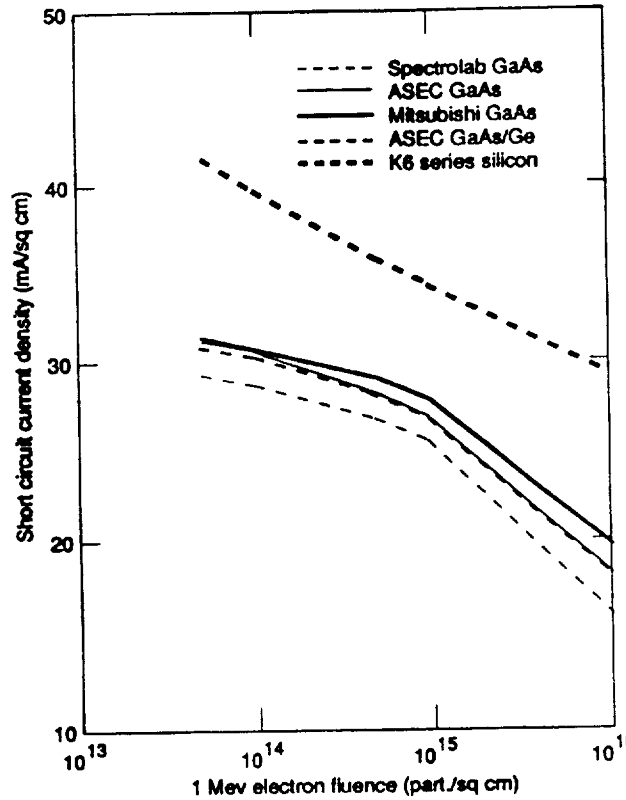

Fig. 3 Solar cell short circuit current density versus electron fluence

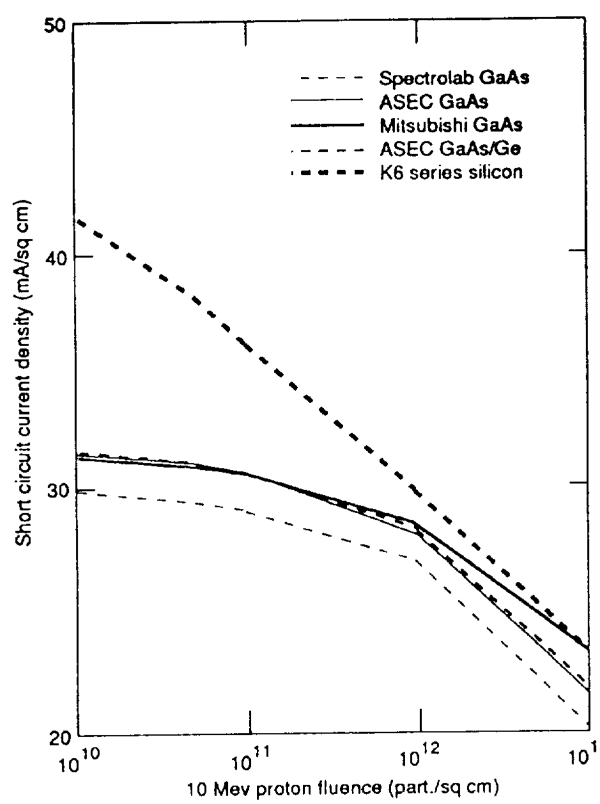

Fig. 4 Solar cell short circuit current density versus proton fluence

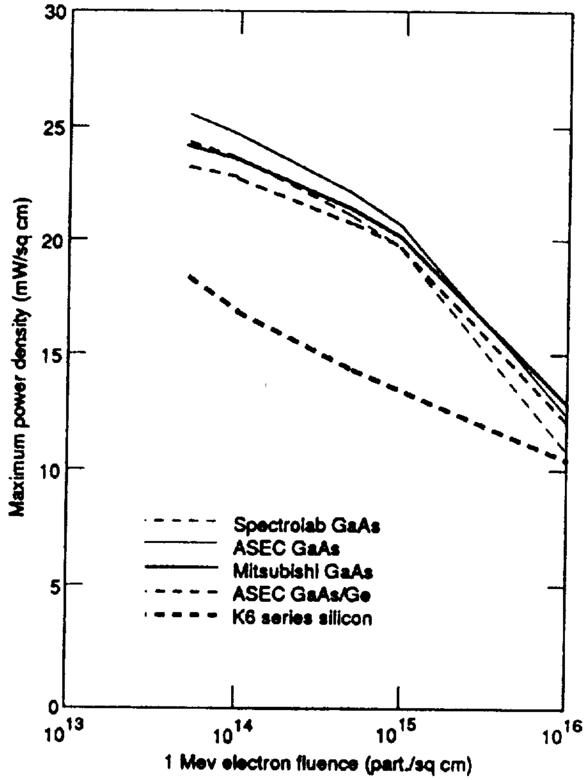

Fig. 5 Solar cell maximum power density versus electron fluence

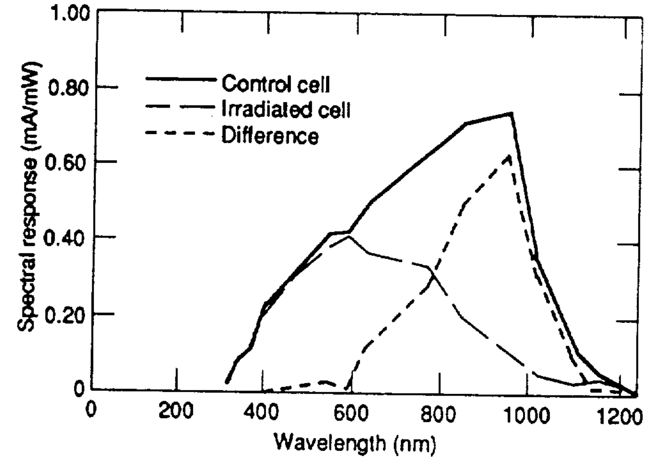

Fig. 7 Control cell versus electron irradiated cell spectral response-Spectrolab K6.

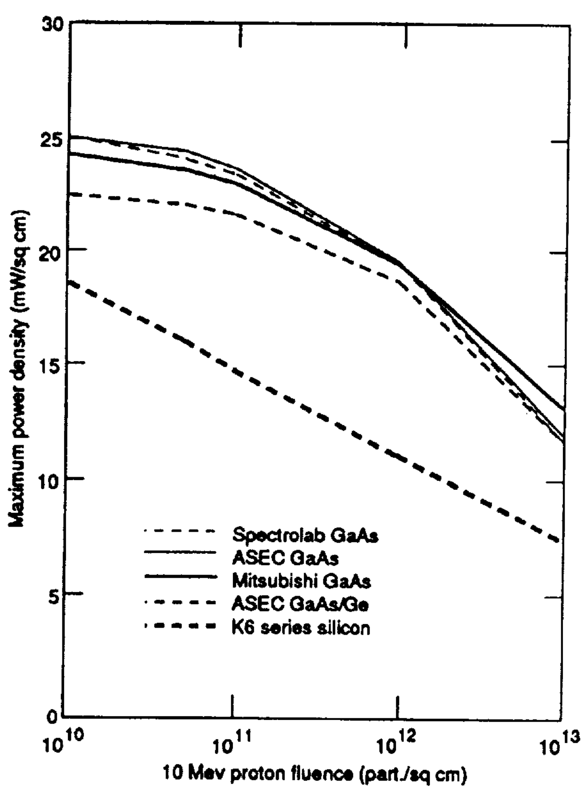

Fig. 6 Solar cell maximum power density versus proton fluence

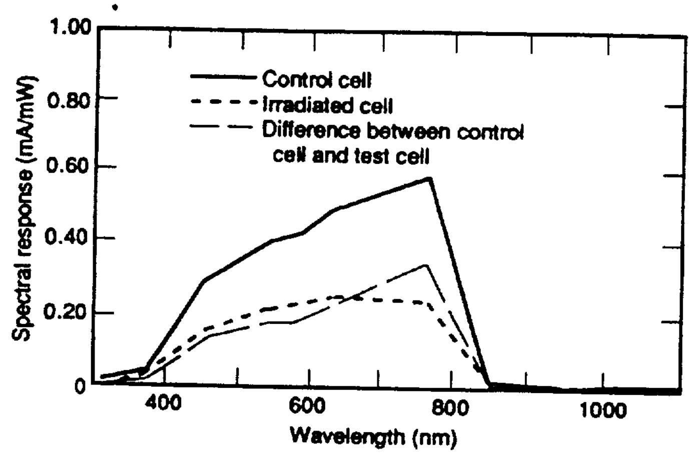

Fig. 8 Spectrolab GaAs - electron irradiated

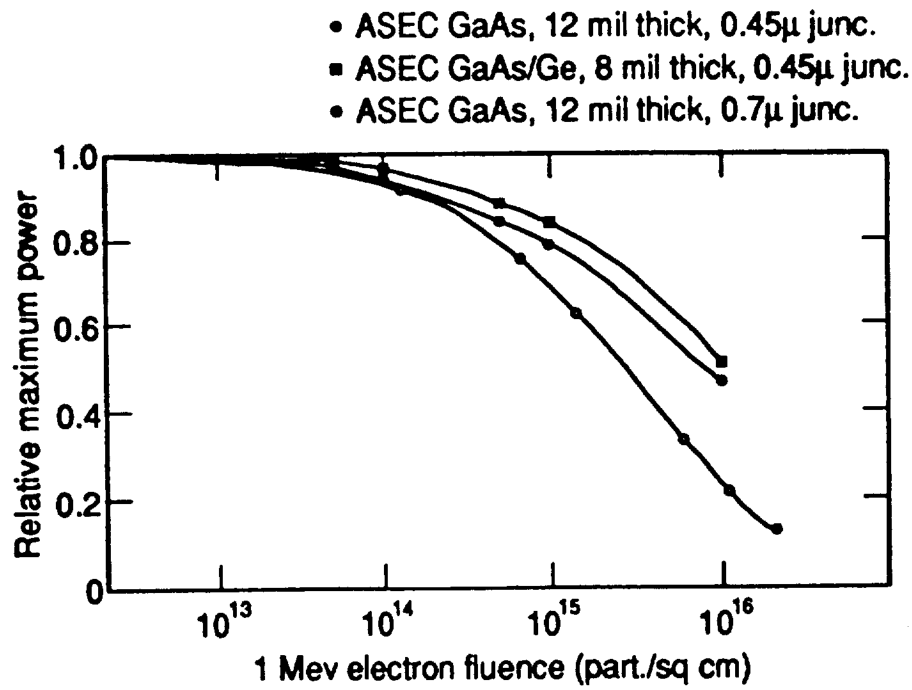

Fig. 9 Relative maximum power versus electron fluence for GaAs solar cells of different thickness and junction depth.