

## RADIATION DAMAGE OF GALLIUM ARSENIDE PRODUCTION CELLS

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In 1985 a process for manufacturing gallium arsenide solar cells by Liquid Phase Epitaxy (LPE) was transferred from Hughes Research Laboratories, Malibu to Spectrolab, Inc. The process, involving the growth of GaAs and AlGaAs from a super cooled liquid gallium semi-infinite melt has been described elsewhere (Reference 1) and will not be repeated here. Existing facilities allow the fabrication of up to 15,000, 2 cm x 4 cm (or equivalent area) GaAs cells of 17% nominal efficiency with the provision for rapid scale-up when required.

In a joint study with Jet Propulsion Laboratory (JPL) we have irradiated high efficiency LPE GaAs cells made on our manufacturing line with 1 MeV electrons up to fluences of  $1 \times 10^{16}$  cm<sup>-2</sup>. Measurements of spectral response and dark and illuminated I-V data were made at each fluence and then, using computer codes developed here for our HP3000 "in-house" computer, we have fitted experimental data to our GaAs cell models. In this way it has been possible to determine the extent of the damage, and hence damage coefficients in both the emitter and base of the cell.

## CELL DESCRIPTION

Cells manufactured for this test were produced on Spectrolab's GaAs LPE production line. The cross-sectional view of the device is illustrated in Figure 1, where a nominal 300  $\mu$ m substrate was used to produce a 7  $\mu$ m buffer, 0.45  $\mu$ m emitter and 0.40  $\mu$ m window. The typical dopant concentrations in the substrate, buffer and emitter were  $2 \times 10^{18}$  Si/cc,  $2 \times 10^{17}$  Sn/cc and  $2 \times 10^{18}$  Be/cc respectively. The ohmic contacts were made directly to the P- GaAs and N+ GaAs (substrate) for the front and back respectively.

Typical production cells of 16.7% (AMO) average efficiency, (22.6 mW/cm<sup>2</sup>), were used in the radiation evaluation.  $I_{sc}$  and  $V_{oc}$  were nominally 28.7 mA/cm and 985 mV respectively.

With the limited number of pilot runs which have been produced, the typical electrical yield of devices above 16.0% (average above 16.5%) was 75%. Figure 2 is a composite graph of 5 lots manufactured over the period from July through September.

## THEORETICAL BASIS FOR ANALYSIS

Computer models have been developed by Spectrolab for windowed gallium arsenide cells (Reference 2). These can provide from basic cell parameters (see Table 1) such as diffusion lengths for carriers in the various cell layers, a prediction of cell performance. These outputs give overall parameters such as  $I_{sc}$ ,  $V_{oc}$ ,  $P_{max}$ , CFF, etc., as well as spectral response for cells, as functions of radiation damage. The models

give the component spectral response due to window, emitter, junction and buffer as well as the overall spectral response. A typical output is shown in Figure 3 for BOL and for EOL ( $\phi = 1.16 \text{ e/cm}^2$ ). An important feature of the spectral analysis is that at a wavelength of  $.5 \mu\text{m}$  the response is almost entirely due to the emitter. This makes it possible to deduce the emitter damage coefficient separately from that in the buffer. Then since the analysis gives the component ratios for the long wavelength response ( $.88 \mu\text{m}$ ) the  $.5 \mu\text{m}$  data can be used to find the emitter component at  $.88 \mu\text{m}$  and hence to determine the buffer damage coefficient.

The modeling (as discussed in Reference 2) examines the effect of first diode (diffusion limited behavior) and of the second diode (depletion layer recombination limited behavior). The latter is important in high band gap cells such as gallium arsenide. In addition to the obvious parameters  $I_{sc}$ ,  $V_{oc}$ , etc., the model analysis also gives the saturation currents for the first and second diodes ( $I_{01}$  and  $I_{02}$  respectively) as functions of the radiation damage.

#### TEST EQUIPMENT AND SET-UP

The current-voltage (I-V) characteristic, as recorded for cells before and after irradiation, was accomplished with the aid of a computerized data acquisition system. The system acquires 300 data points, which are stored into memory and then manipulated to produce the I-V curve, short circuit current ( $I_{sc}$ ), open circuit voltage ( $V_{oc}$ ), and maximum power operating point ( $P_{max}$ ).

The simulator used in this test is designated Spectrolab X-25. It's AMO intensity was set using a GaAs encapsulated secondary standard 83-156 traceable to balloon flown standard 80-132. However, unirradiated sister cells to the ones tested were measured before and after irradiation to verify simulator intensity. Irradiated balloon flown standard 85-132 was also used to verify correct blue-red color ratio. The sample temperature on the test block was held to  $28 \pm 1^\circ\text{C}$  by water cooling the block.

The instrumentation used to measure the spectral irradiance of the simulator was an Optronics Spectroradiometer with a Hewlett Packard 85 computer used for converting detector current to irradiance values, and for system control. The lower and upper limits of the range was 280 nm and 1050 nm, respectively. The slit width on the monochromator and the wavelength interval was 5 nm during both the calibration and the actual scan.

Spectrolab has developed a computerized data acquisition system for dark I-V measurement. The system based on a 10 bit D/A and A/D interface is driven by an Apple IIe computer and enables rapid I-V measurement to be made over six orders of magnitude of current. Algorithms within the computer code allow the determination  $I_{01}$ ,  $I_{02}$  and shunt resistance to be made and also a hard copy may be made on an HP X-Y recorder. The system is bipolar, enabling forward and reverse measurements to be made with ease.

Spectral response measurements were made by use of a computer controlled multi-filter system. Twenty optical filters cover the expected cell response range with "crowding" filters at crucial parts of the spectrum for gallium arsenide cells ( $.4 - .5$  and  $.8$  to  $.9 \mu\text{m}$  respectively). At each filter position many readings are taken and averaged to increase accuracy and the system is calibrated by a sub-standard silicon cell with a spectral range much greater than that of gallium arsenide. This cell was calibrated against a silicon diode calibrated at Optoelectronics Laboratories

and also had formed one of a group of cells circulated among various establishments by Spectrolab in an attempt to standardize interlaboratory results. The system output gives cell response in mA/mW and also the quantum efficiency at each wavelength. An integration procedure gives an estimate of  $I_{SC}$  at AMO from the spectral data and this can be compared with  $I_{SC}$  data from the AMO simulator.

## RESULTS

The cells used for irradiation were divided into four groups. The first group were held as standards and were not irradiated. The second group were irradiated to  $10^{14}$ ,  $9 \times 10^{14}$ ,  $2.0 \times 10^{15}$  and  $7 \times 10^{15}$   $e^-/cm^2$ . The cells were tested at every level and a few cells were held as controls at each level. The third group were irradiated to  $9 \times 10^{14}$ ,  $2.0 \times 10^{15}$  and  $7 \times 10^{15}$   $e^-/cm^2$  for a total dosage of  $9.9 \times 10^{15}/cm^2$ . Cells at each dosage level were also held as controls. The fourth and final group were irradiated to  $7 \times 10^{15}$   $e^-/cm^2$ . The average  $P/P_0$ ,  $J_{SC}/J_{SC0}$  or  $V_{OC}/V_{OC0}$  of the total starting group were within  $\pm 0.3\%$  of the final diminished group receiving the total dosage.

Table 2 and Figure 4 represent the degradation of the average cell and typical I-V curve for cells in group 2. This data is plotted in Figure 5 as a function of fluence. Representative spectral response curves for the range of fluence are plotted in Figure 6. Table 2 includes predicted values (in brackets) from the cell model using the parameters of Table 1.

From the response spectra of cells under the various fluences the variation at certain chosen wavelengths was determined. The results are plotted in Figure 7 for the wavelengths of  $.5 \mu m$  and  $.88 \mu m$  together with the overall  $I_{SC}$  calculated from the full spectral response. Also included is the plot for  $I_{SC}$  taken from the X-25 simulator measurements. These curves now have to be compared with those deduced from the modeling. The main cell specifications are as in Table 1 but parameters such as damage coefficients are varied to test fits with data. The broken curves in Figure 7 give the modeling curves for emitter and buffer damage coefficients of  $3.5 \cdot 10^{-8}$  and  $2 \cdot 10^{-7}/e$  respectively. A discussion of the comparative behavior is given below.

## DISCUSSION

As shown by Table 2 the results of the 1 MeV electron irradiation tests can be predicted by the model using appropriate damage coefficients for emitter and buffer. We have chosen first to match these to prediction of  $I_{SC}$  values which depend on the total surface interface velocity between emitter and window. The model  $V_{OC}$  values at BOL are then too large but this is likely to be due to the fact that under the front grid contacts which penetrate into the emitter much higher velocities occur. Computation then shows that under  $V_{OC}$  conditions the experimental BOL value of  $V_{OC}$  would be obtained if the velocity averages  $2 \cdot 10^6$  cm/s indicating much higher values under the contacts.

From dark state current-voltage curves we have computed the second diode (depletion layer recombination) saturation currents ( $I_{02}$ ) as functions of damage. Initially, for the model parameters of Table 1 the value of  $I_{02}$  is about  $5-6 \cdot 10^{-11}$  A/cm<sup>2</sup> and at EOL ( $10^{16}$   $e^-/cm^2$ ) it is about  $8-9 \cdot 10^{-10}$  A/cm<sup>2</sup> i.e. a factor of 7 higher. The model gives a BOL value of  $5 \cdot 10^{-11}$  A/cm<sup>2</sup>, close to the experimental value; at  $10^{16}$   $e^-/cm^2$  fluence it is also about 7 times higher.

The extensive spectral response measurements in this work afford an opportunity to test the model. The data in Figure 7 at  $.5 \mu m$  give the ability to see damage in

the emitter almost exclusively while the data at  $.88\mu\text{m}$  give the combined buffer, junction and emitter effects. In this region the discrepancies between model and experiment are evident. To match the  $.88\mu\text{m}$  values the damage coefficient for emitter would have to be increased so much that the  $.5\mu\text{m}$  data would not correlate with the model. There is clearly a situation here which needs to be followed up by model review and by further, more detailed analysis of the spectral data.

In conclusion we have carried out extensive studies of the effects of 1 MeV electron damage in gallium arsenide windowed cells. Overall the results are very similar to those published earlier by Mitsubishi (Reference 3) and by Hughes Research Laboratories (Reference 4). This is very significant since these devices were manufactured by us and these companies at different times; only the LPE layer growth is similar. We have extended diagnostics to include dark current-voltage curves and to detailed spectral analysis. What has been revealed is that overall modeling is satisfactory but that there are significant and interesting discrepancies which demand further attention.

Reference 1 - Mardesich, N. IEEE Proc. 18th PVSC, P.105 (1985)

Reference 2 - Garlick, G.F.J. IEEE Proc. 18th PVSC, P.854 (1985)

Reference 3 - Kato, M. IEEE Proc. 18th PVSC, P.652 (1985)

Reference 4 - Anspaugh, B. et al. Solar Cell Radiation Handbook 3rd Ed.  
JPL Publication 82-69 1982

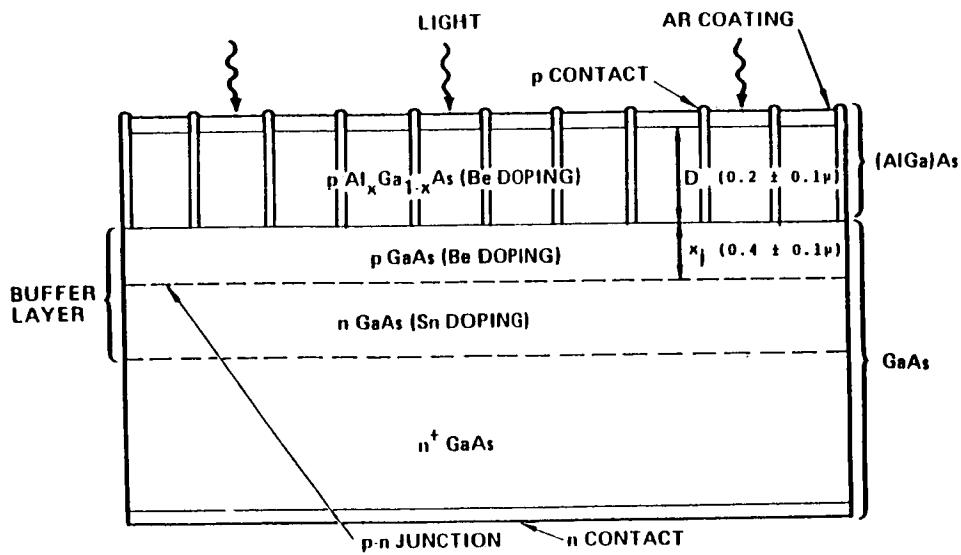


FIGURE 1. CROSS-SECTIONAL VIEW OF GaAs SOLAR CELL

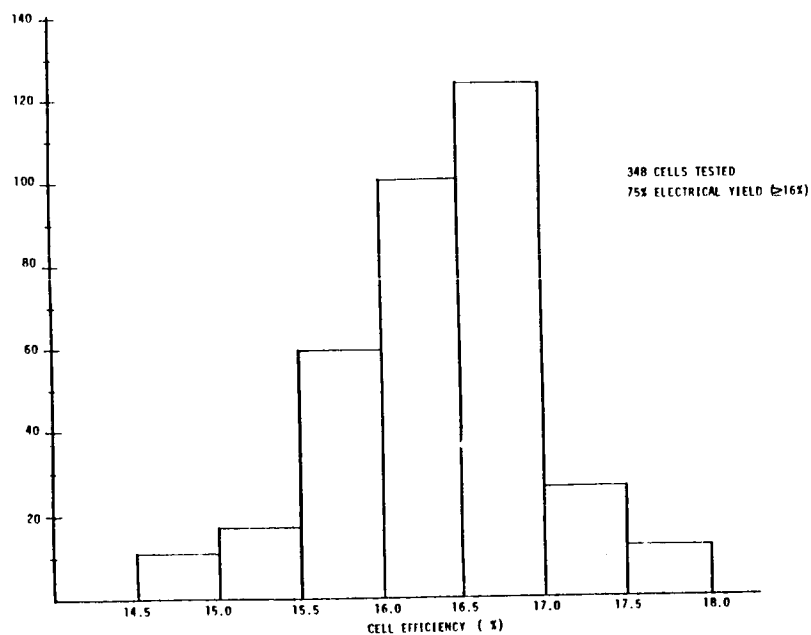
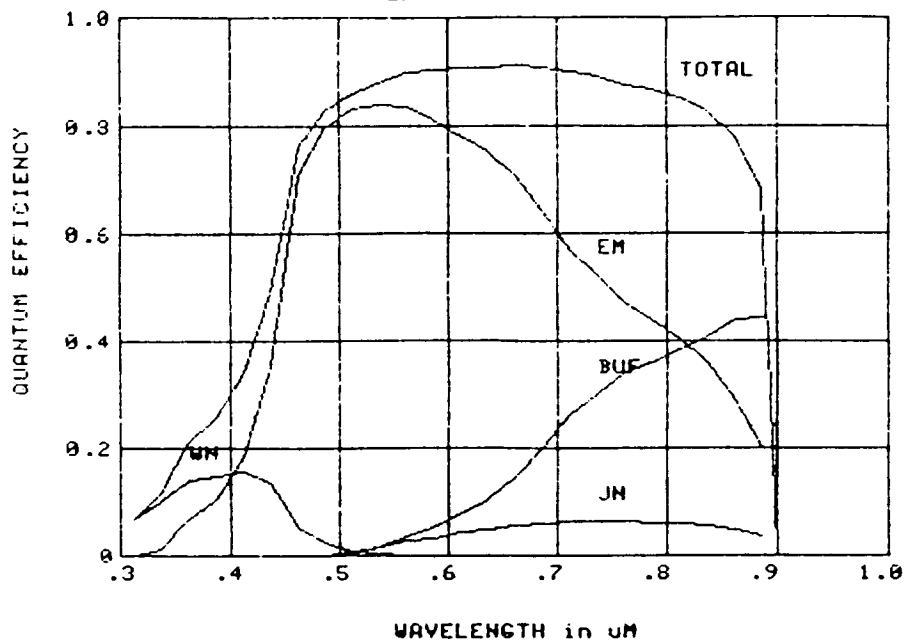


FIGURE 2. EFFICIENCY DISTRIBUTION OF GaAs CELL (4.30 CM<sup>2</sup>)

SPECTRAL RESPONSE OF AlGaAs SOLAR CELL

1 MeV ELECTRON FLUENCE =  $0e/cm^2$



1 MeV ELECTRON FLUENCE =  $1E16e/cm^2$

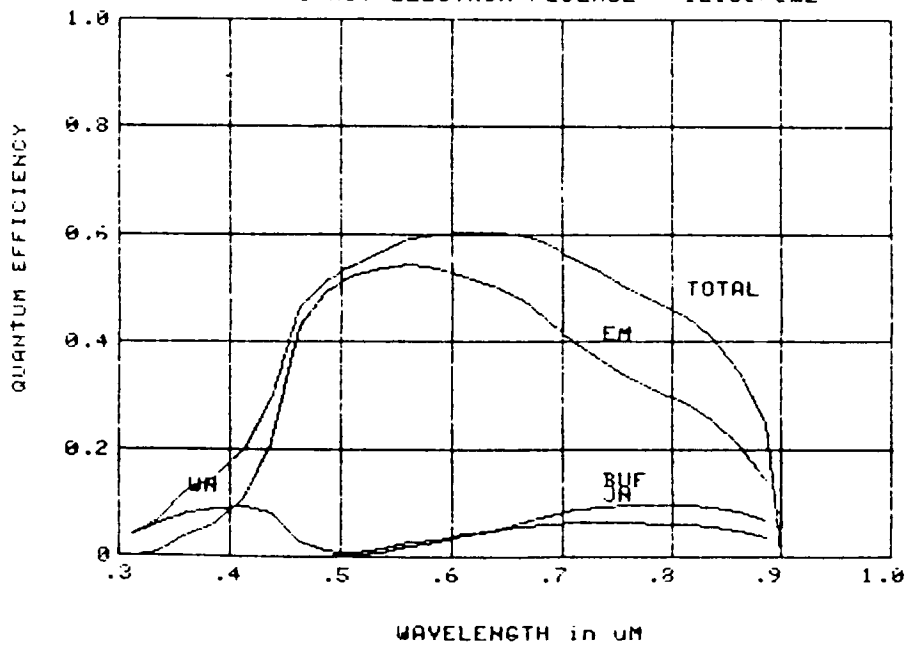


FIGURE 3. CALCULATED SPECTRAL RESPONSE OF GaAs CELL AT ZERO AND  $10^{16} e-/cm^2$  FLUENCE

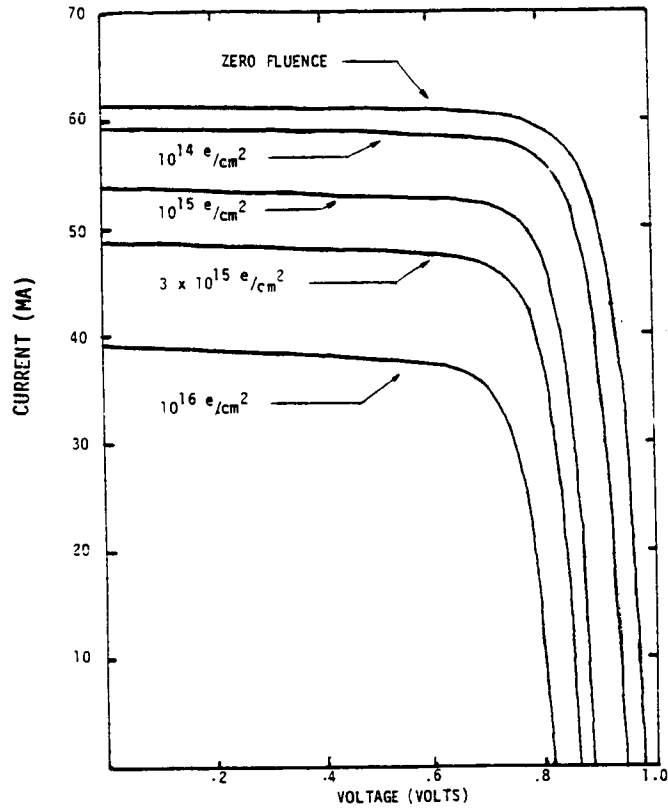


FIGURE 4. I-V CURVE OF A TYPICAL GaAs CELL AT VARYING 1 MeV FLUENCE

○	□	△
$P_{max}$	$J_{sc}$	$V_{oc}$
$\frac{mW}{cm^2}$	$\frac{mA}{cm^2}$	(mV)

RADIATION DAMAGE

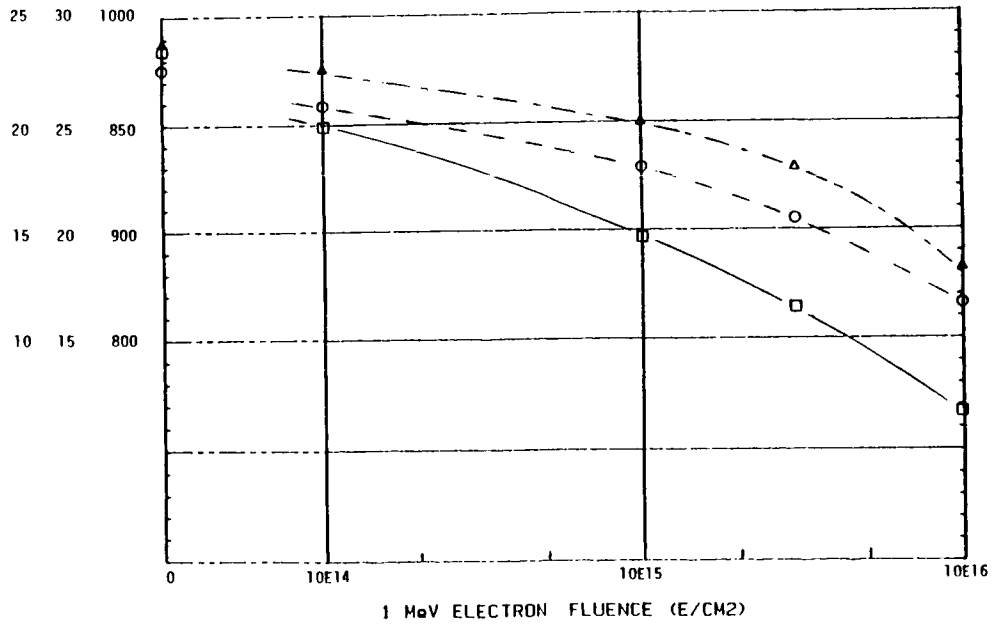


FIGURE 5.  $P_{max}$ ,  $J_{sc}$ , AND  $V_{oc}$  vs. 1 MeV ELECTRON FLUENCE FOR TYPICAL GaAs CELL

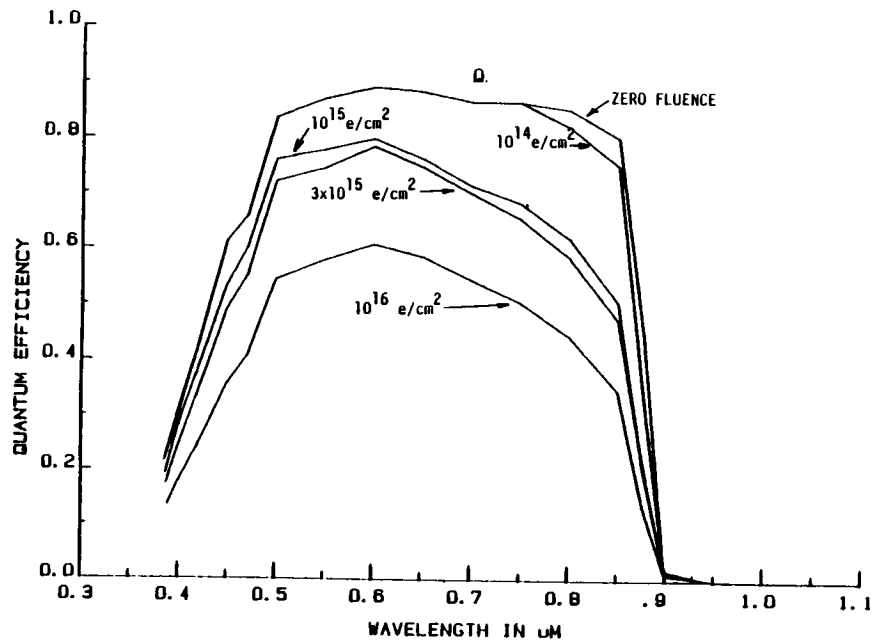


FIGURE 6: QUANTUM EFFICIENCY DEGRADATION AS A FUNCTION OF 1 MeV ELECTRONS

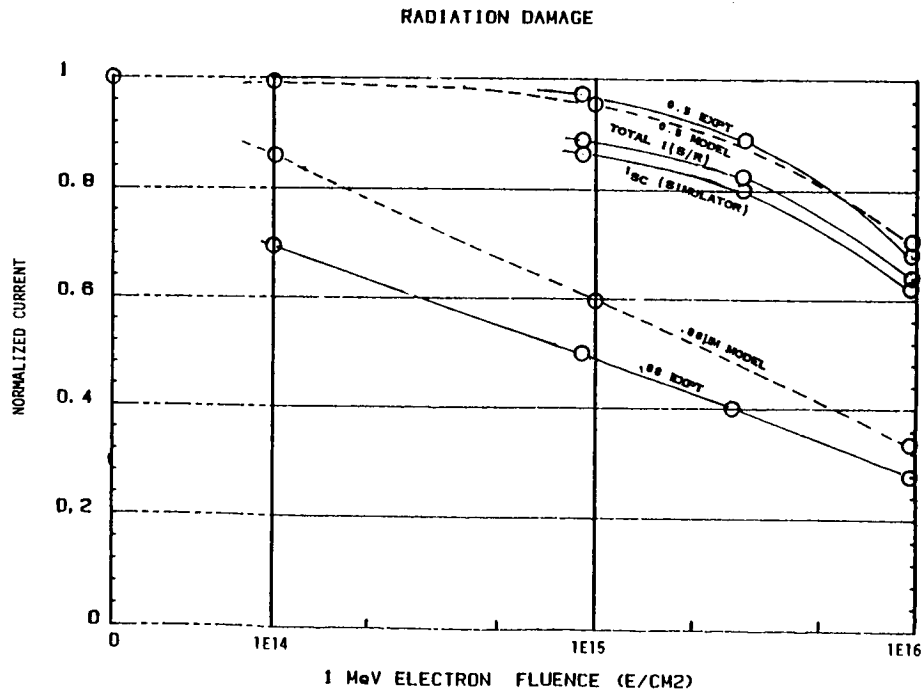
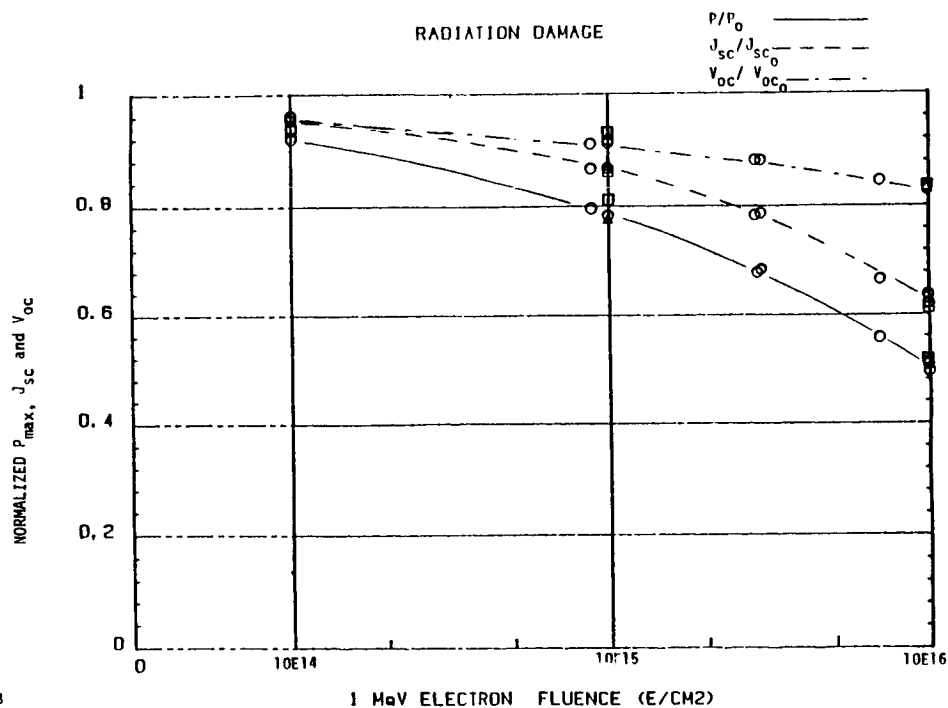


FIGURE 7:  $I_{SC}$  (AHO)  $I_{SC}$  (SPECTRAL RESPONSE),  $I_{SC}$  (.5 $\mu$ m) AND  $I_{SC}$  (.88 $\mu$ m) AS A FUNCTION OF 1 MeV ELECTRONS COMPARED TO THEORETICAL MODEL





- SPECTROLAB
- HRL - REF. 4
- ▲ MITSUBISHI REF. 3

FIGURE 8. NORMALIZED  $P_{max}$ ,  $J_{sc}$ , AND  $V_{oc}$  AS A FUNCTION OF 1 MeV ELECTRONS FOR RECENT TEST AND PUBLISHED DATA

TABLE 1

TYPICAL CELL PARAMETERS FOR MODELING OF CHARACTERISTICS  
TO MATCH EXPERIMENTAL DATA

WINDOW LAYER

Thickness	.5 $\mu\text{m}$
Diffusion length	.2 $\mu\text{m}$
Diffusion coefficient	.27 $\text{cm}^2/\text{s}$
Surface recombination velocity	$10^6$ cm/s
Doping concentration	$2.10^{18}/\text{cm}^3$

EMITTER LAYER

Thickness	.5 $\mu\text{m}$
Diffusion length	5 $\mu\text{m}$
Diffusion coefficient	90 $\text{cm}^2/\text{s}$
Interface recombination velocity	$3.10^5$ cm/s
Doping concentration	$2.10^{18}/\text{cm}^3$

BUFFER LAYER

Thickness	7 $\mu\text{m}$
Diffusion length	2 $\mu\text{m}$
Diffusion coefficient	5 $\text{cm}^2/\text{s}$
Doping concentration	$2.10^{17}/\text{cm}^3$

DAMAGE COEFFICIENTS

Emitter	$3.5.10^{-8}/e$
Buffer	$1.8.10^{-7}/e$

TABLE 2

FLUENCE ( $e/cm^2$ )	$V_{oc}$ (mV)	$I^{sc}$ (mA/cm <sup>2</sup> )	$P_{max}$ (mW/cm <sup>2</sup> )	FF
0	984 (1006)	28.7 (28.0)	22.6 (22.8)	.800
$10^{14}$	948 ( 992)	27.5 (27.63)	20.9 (21.86)	.802
$10^{15}$	896 ( 933)	25.0 (25.77)	17.9 (18.5)	.800
$3 \times 10^{15}$	863	22.7	15.4	.788
$10^{16}$	817 ( 812)	18.3 (18.14)	11.5 (11.09)	.769

\*Bracketed values are model predictions

AVERAGE  $V_{oc}$ ,  $J_{sc}$ ,  $P_{max}$ , FF OF GROUP 2 GaAs SOLAR CELLS AFTER 1 MeV FLUENCE