

FABRICATION OF HIGH EFFICIENCY AND RADIATION

RESISTANT GaAs SOLAR CELLS*

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SUMMARY

In our development of the technology for making GaAs solar cells suitable for space applications, we are concerned with AMO efficiency, radiation hardness and reproducible fabrication. Systematic improvements in fabrication yield were obtained by appropriate control of the liquid phase epitaxial growth process, contact fabrication and surface preparation. To improve radiation hardness, we decreased the junction depth while overcoming the penalty in decreased solar cell efficiency which tends to go hand-in-hand with the reduction of junction depth in (AlGa) As-GaAs solar cells. We have succeeded in making cells with an AMO efficiency of 18% and a junction depth of 0.5 μm , as compared to junction depths on the order of 1.0 μm which had previously been reported. With respect to the damage caused by proton irradiation, we have been able to correlate the nature of the observed damage to the energy and penetration depth of the damaging protons.

FABRICATION TECHNOLOGY

In developing the technology for GaAs solar cells for space applications, we emphasized the reproducible fabrication of large area (2 cm x 2 cm) solar cells. The infinite solution liquid epitaxial growth developed at HRL is ideally suited for the growth of large area layers of GaAs and AlGaAs required for these cells. The growth system illustrated in Figure 1 has been described in past papers. The figure also shows a new modification of the graphite substrate holder that enables us to grow on multiple substrates and proceed with batch processing, leading to reduced cost per cell. Irradiation of the solar cells produced early in the program with junction depths of about 1 μm led us to conclude that shallower junctions would lead to considerable improvement in radiation hardness. The main objection to a shallow junction in the GaAs cell is that it causes the electrical junction to approach the (AlGa)As-GaAs heterophase boundary which is a region of heavy strain and dislocations; this generally leads to a lower fill factor for the cell. In our case, lowering the junction depth from 1 μm to less than 0.5 μm led to a decrease in efficiency

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from > 17% AMO to < 15% AMO. A detailed study of epitaxial growth parameters led us to decrease the growth temperature for (AlGa)As layers to 750°C and increase the growth time to over 5 minutes per micron to achieve improved shallow junctions of <0.5 μm . The progress achieved can be judged by the statistics in Figure 2. The performance of our best 4 cm^2 cell to date with 0.5 μm junction depth is shown in Figure 3.

Since the LPE growth tends to be the slowest step in the fabrication of cells, ultimate cost reduction for large scale production would require the adaptation of the technique to batch production. We have succeeded in demonstrating the adaptability of the HRL technique for this purpose by growing layers on 4 substrates in a single growth run, using a multiple slide bar assembly of the type illustrated in Figure 1. We are presently extending this capability to even larger numbers.

RESISTANCE TO RADIATION DAMAGE

For space applications, the ability of GaAs solar cells to withstand radiation by high energy particles is of great importance in addition to superior beginning of life efficiency vis-a-vis silicon. Our first step to determining the radiation resistance of the GaAs cells was to study the damage produced by 1 MeV electrons at normal incidence. This study led us to formulate a model which showed the critical importance of decreasing junction depth to increase radiation resistance. The results on cells produced during the past year with 0.5 μm junction depth fully confirm our model. Our theoretical calculations indicate, however, that minimum radiation damage is likely to occur at about 0.2 μm . Recently we have fabricated and tested cells with a junction depth of 0.3 μm and AMO efficiency of 16%. The results are shown in Figure 4 and again confirm our model. We are continuing our systematic studies towards lowering the junction depth to 0.2 μm without adversely affecting the efficiency of the cell.

In practical space missions, we have to be concerned with irradiation by protons as well as electrons. We have investigated the behavior of GaAs cells under proton irradiation. Data in Figure 5 represent the effect of both protons and electrons on a number of our cells on a semilogarithmic plot. The cells are all similar with a junction depth of 0.5 μm . The electrons were 1 MeV and the protons were 100 and 290 KeV. Within measurement accuracy, 100 KeV and 290 KeV protons had the same effect on the solar cell power output. It is interesting to observe that in the semilog plot, the curves representing electron and proton damage are parallel. It lends credence to the concept of equivalent fluence over extended ranges of fluence for these cells.

The radiation damage caused by high energy particles is obviously a function of their energy. As far as protons are concerned, they produce most damage at the end of their track, after penetration in the solar cell. The nature of the damage which they produce is therefore largely determined by their depth of penetration into the solar cell. This led us to examine the damage caused in our cells as a function of proton penetration depth. The

results are shown in Fig. 6. While we still lack measurements in the intermediate proton energy range, the observation of the damage caused by low energy protons is especially instructive. As we start with very low energy protons (< 50 KeV), they are arrested within the surface p-layer of the GaAs, before even reaching the junction. Their major effect is therefore, to increase bulk recombination in this layer, thus decreasing the short-circuit current without affecting the junction quality. Consistently with this, we observe in Fig. 6 that the short-circuit current decreases with increasing proton energy before the open-circuit voltage is much affected. As the proton energy is increased up to about 100 KeV, most protons are arrested in the junction region. The resulting deterioration of the junction quality leads to increasing leakage current and correspondingly lower open-circuit voltage. As the proton energy is further increased above 100 KeV, most protons penetrate beyond the junction and do their damage in the n-doped base region. This leads to additional bulk recombination and further reduction of the short circuit current. As the proton energy is further increased above 300 KeV, the protons are arrested at depths past the active part of the cell. As the energy of all protons traversing the active part of the solar cell keeps increasing, the damage which they cause in this part of the cell decreases and the effect on both short-circuit current and open-circuit voltage decreases with further increases in proton energy. In summary, the measurements of Fig. 6 show that the protons arrested in the vicinity of the junction have a most deleterious effect on the open-circuit voltage, while the protons arrested within the active part of the cell, but further away from the junction affect mostly the short-circuit current. An interesting practical result is the fact that the shallow active depth of the GaAs solar cells ($< 2 \mu\text{m}$, because GaAs is a direct bandgap material) limits to a very low and narrow energy range (< 0.5 MeV) the protons which cause most damage. This leads to most effective coverglass shielding of GaAs solar cells for protection against proton damage in a real space environment. In particular, this compares favorably with Si solar cells where most damage is caused by protons with an energy on the order of 2 MeV, as compared to 200 KeV for GaAs solar cells.

To compare the radiation damage caused by protons on GaAs and on Si solar cells respectively, we have summarized in Fig. 7 the results of a number of our measurements. We show the damage caused by a given fluence to both types of cells, as a function of proton energy. While very low energy protons cause more damage to GaAs than to Si solar cells, at higher energies the reverse is true. Insofar as these solar cells are readily protected against low energy protons, but remain susceptible to the higher energy protons, Fig. 7 shows that GaAs solar cells compare favorably with Si solar cells in their ability to resist proton radiation damage in a real space environment.

EFFICIENCY

The initial motivation for developing GaAs solar cells was their potential for better AMO efficiency than Si solar cells. Our present state-of-the-art for a 4 cm^2 shallow junction GaAs solar cell has the characteristics shown in Fig. 3. The fill factor of the cell is still relatively poor, even though

its AMO efficiency is 18%. The theoretical upper limit for the fill factor of such a cell is 0.88. Some of our deeper junction cells, have a fill factor as high as 0.86. On this basis, we consider realistic an extrapolation to a fill factor of 0.85, as a result of further progress in controlling the crystal quality at the interface and in the junction region. Such an extrapolation leads to an AM- efficiency of 20.3%. Under ideal conditions, Fig. 8 shows that an AMO efficiency of 24% can be achieved with a GaAs solar cell. This idealized calculation makes however, no allowance for any losses associated with contact shadowing, reflection, or for junction imperfections leading to a lower fill factor. The ideal calculation also assumes the p-doping level to be at the limit of degeneracy ($p = 7.10^{18}$ holes/cm³). For these reasons, we consider our estimate of an AMO efficiency of 20%, based on our experimental results, to be more realistic.

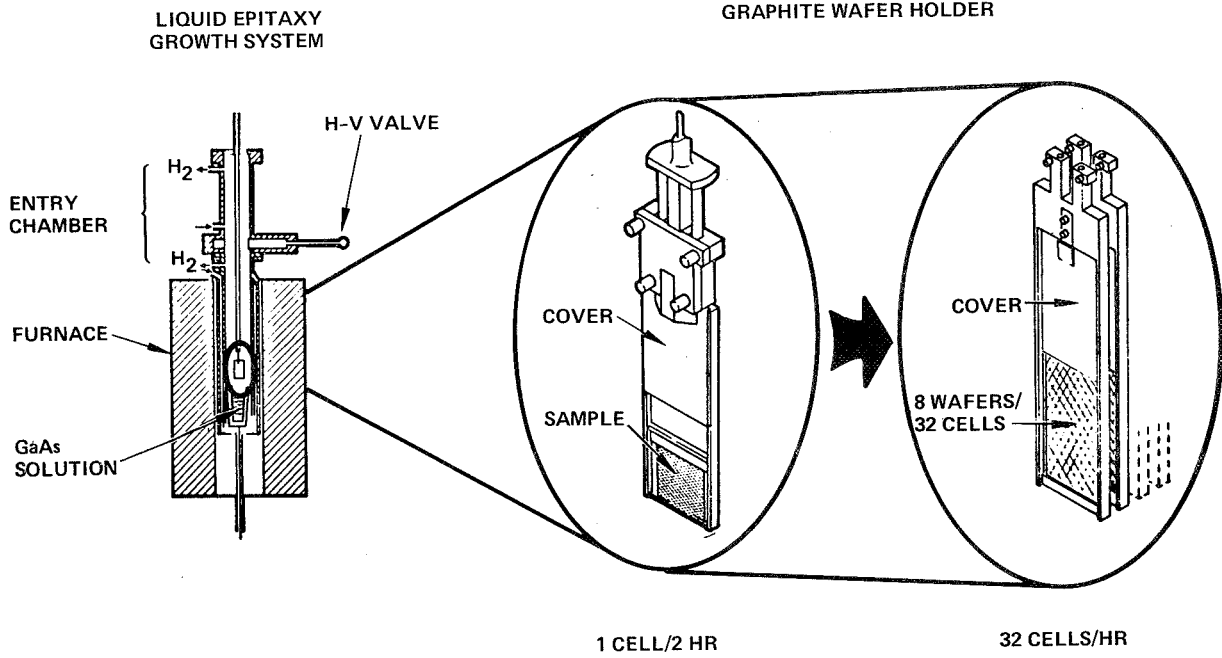


Figure 1. - Batch fabrication of GaAs solar cells.

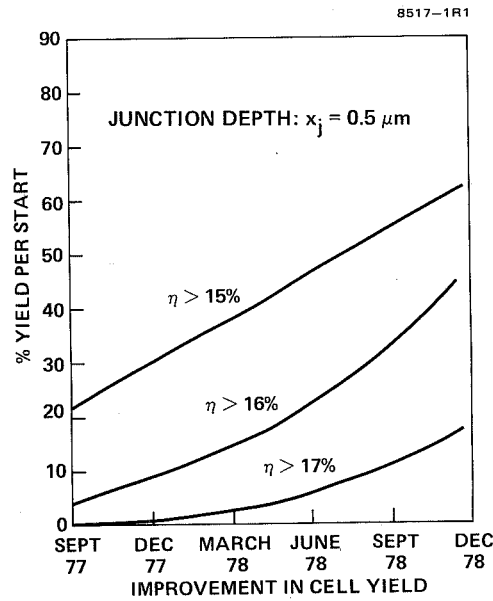


Figure 2. - Improvement of GaAs solar cell yield with time.

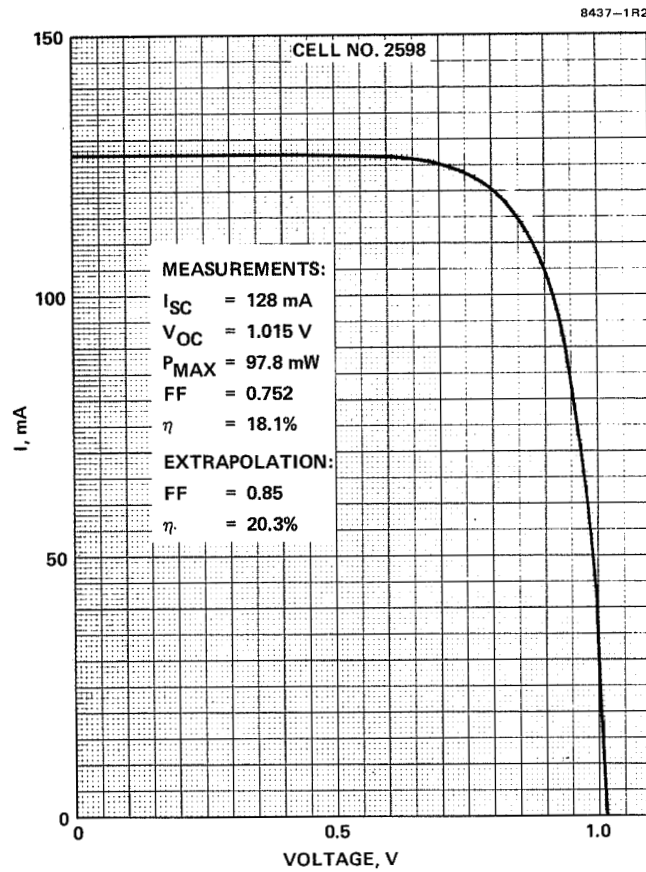


Figure 3. - High efficiency GaAs solar cell.

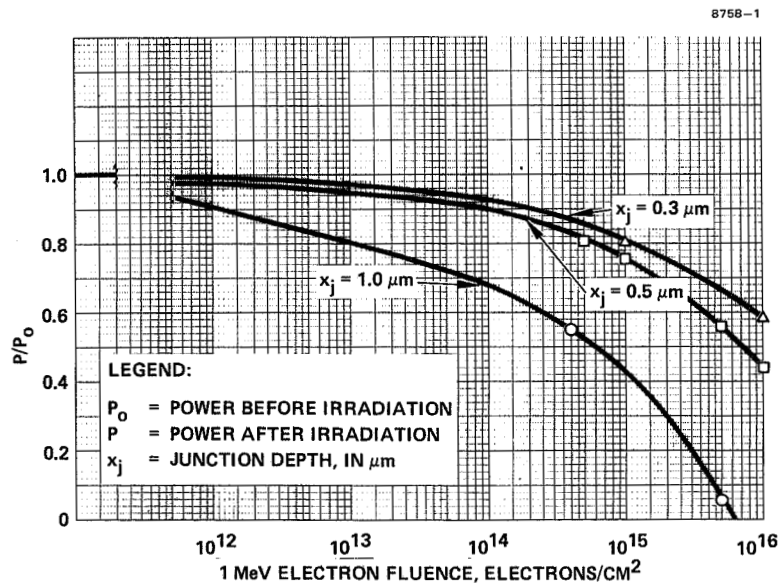


Figure 4. - Effect of junction depth on radiation damage.

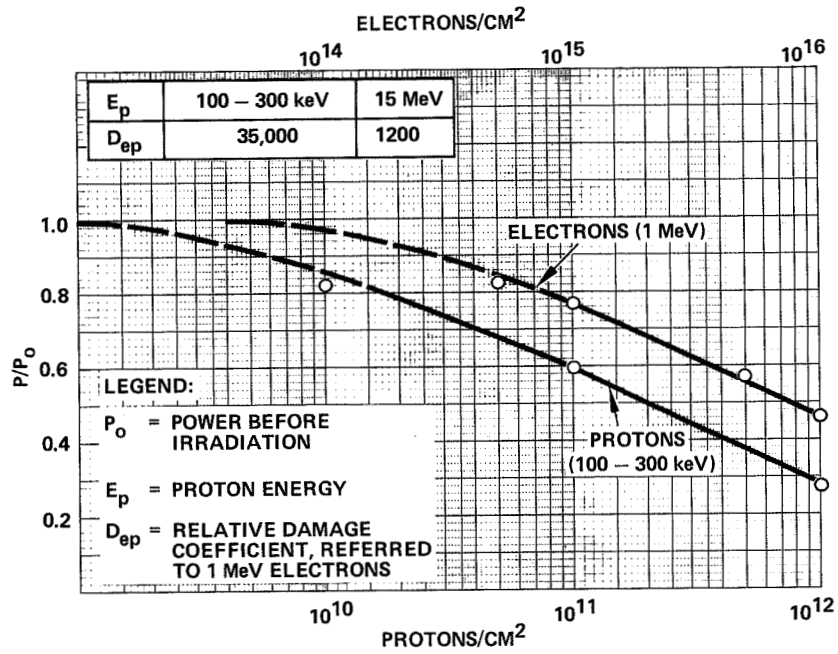


Figure 5. - Proton versus electron radiation damage.

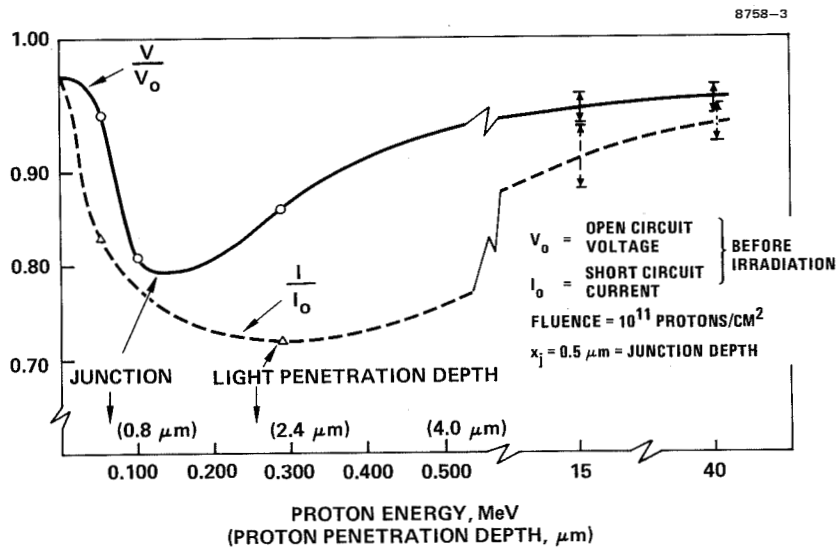


Figure 6. - Effect of proton energy on radiation damage.

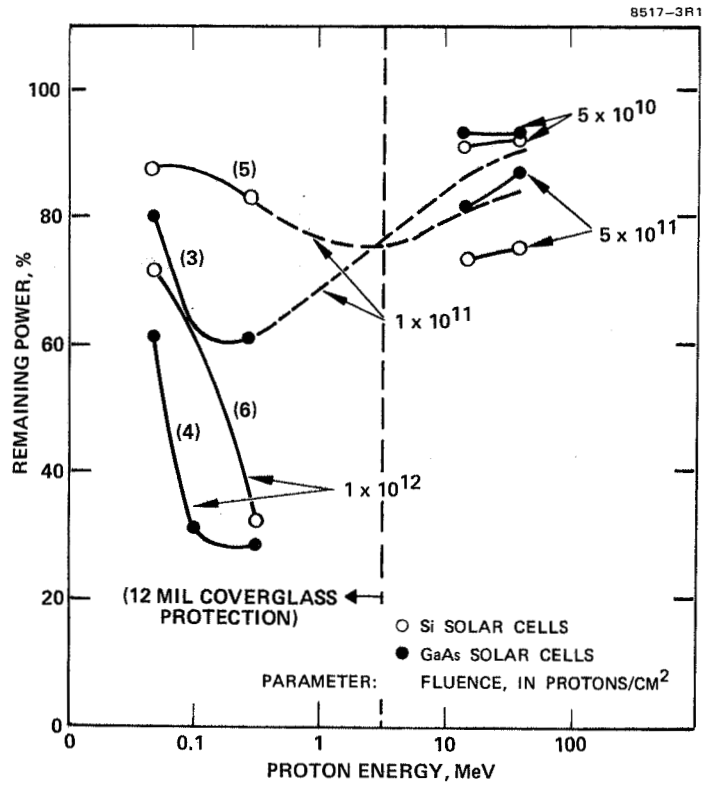


Figure 7. - Proton radiation damage on GaAs versus Si solar cells.

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PARAMETER	BEST ESTIMATE	THEORETICAL MAXIMUM
SHORT-CIRCUIT CURRENT	32 mA/CM ²	35 mA/CM ²
OPEN CIRCUIT VOLTAGE	1.01 V	1.05 V
FILL FACTOR	0.85	0.88
EFFICIENCY	20.3%	23.9%

EXPECTED EFFICIENCY \approx 20%
MAXIMUM EFFICIENCY \approx 24%

Figure 8. - Theoretical limit for GaAs solar cell efficiency.