SHALLOW-HOMOJUNCTION GaAs SOLAR CELLS*

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SUMMARY

We have developed single-crystal GaAs shallow-homojunction solar cells on GaAs or Ge substrates, without $Ga_{1-x}Al_xAs$ window layers, that have conversion efficiencies exceeding 20% at AM1 (17% at AM0). Using a simple theoretical model, we have obtained good fits between computer calculations and experimental data for external quantum efficiency and conversion efficiency of cells with different values of n^+ layer thickness. The calculations not only yield values for material properties of the GaAs layers composing the cells but will also permit the optimization of cell designs for space and terrestrial applications. Preliminary measurements indicate that the shallow-homojunction cells are resistant to electron irradiation. In the best test so far, bombardment with a 1×10^{16} cm^{-2} fluence of 1 MeV electrons reduced the short-circuit current by only about 6%.

We have recently developed (ref. 1,2) single-crystal GaAs shallow-homojunction solar cells without $Ga_{1-x}Al_xAs$ window layers, that have conversion efficiencies of about 20% at AM1 (17% at AM0). The cells employ an $n^+/p/p^+$ structure, prepared by chemical vapor deposition (CVD) on either GaAs or Ge substrates, in which surface recombination losses are reduced because the n^+ layer is so thin that most of the carriers are generated in the p layer below the junction. Figure 1 shows schematic diagrams of GaAs solar cells grown on a Ge substrate (on the left side) and on a GaAs substrate (on the right side). An oxide film formed by anodization of the n^+ layer is used as an antireflection coating. Two different metallization schemes have been developed -- electroplated Sn or electroplated Au. Figure 2 shows a schematic diagram of our CVD system showing the H_2-$AsCl_3$ and doping gas flow control, and also a cross sectional view of the reactor tube. Figure 3 shows the photocurrent as a function of applied voltage for a GaAs shallow-homojunction solar cell grown on a GaAs single-crystal substrate with 20% conversion efficiency at AM1, as measured at 20°C. Solar cells grown on single-crystal Ge have characteristics very similar to those of cells grown on GaAs, as long as the n^+ layer thickness is the same.

By using a simple analytical model (ref. 3), we have obtained good fits between computer calculations and experimental data for the external quantum efficiency and AM1 conversion efficiency of cells with different values of n^+ layer thickness. Figure 4 shows external quantum efficiency as a function of wavelength for GaAs cells with n^+ layer thickness of 450, 750, 1000, and 1550 Å. The solid curves were calculated using only three adjustable parameters, while the points were measured. From the best values of the adjustable parameters, we obtained values of L_p (hole diffusion length in n^+ layer) ~ 0.05 μm, L_n (electron diffusion length in p layer) ~ 20 μm, and effective S_p (recombination velocity on n^+ surface) $\sim 10^7$ cm/sec. Using these values, we calculated the conversion efficiency at AM1 as a function of n^+ layer thickness.

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The calculated efficiency values compare well with the measured values as shown in (fig. 5). Having demonstrated the applicability of this simple analytical model, we can now use it in optimizing cell designs for space and terrestrial applications.

To investigate the potential of our cells for space applications, we have performed some initial experiments that show these cells to be resistant to electron irradiation. Cells with the n^+/p structure should be considerably more radiation resistant than those with p^+/n structure because the minority carrier diffusion length is much larger for electrons than for holes. The thin n^+ layer not only minimizes the effect of surface recombination velocity but also allows almost all the electron damage effects to occur in the p layer, where the electron diffusion lengths are long. The back-surface-field p/p^+ structure also restricts the effects of electron damage to the narrow active p region (~ 2 μm). We have confirmed this superior space resistance in a series of experiments using 1 MeV electrons with fluence up to 10^{16} e/cm^2.

Figure 6 shows the maximum power per unit area P_{max} in mW/cm^2 for one of our 1/2 cm x 1 cm GaAs shallow-homojunction cells grown on Ge substrates as a function of cumulative electron fluence. The cell initially had P_{max} of over 22 mW/cm^2 (cell efficiency η at AM0 was 16.7%), which slowly decreased with increasing fluence to about 13 mW/cm^2 at 10^{16} e/cm^2. Our results compare very favorably with reported results on three other types of space cells (ref. 4, 5), as shown in (fig. 6). Both the initial and final values of P_{max} are higher for our cell than for any of the others.

The reduction in P_{max} for our cell occurs because the open-circuit voltage V_{oc} and short-circuit current I_{sc} both decrease by about 20% after 10^{16} e/cm^2 electron dosage. The decrease in V_{oc} corresponds to an increase in leakage current, as indicated by an increase in saturation current density J_o for the injected current component from 6 x 10^{-18} A/cm^2 to 1 x 10^{-14} A/cm^2. The diode factor remained the same, however, at 1.1. The decrease in I_{sc} may be attributed to the degradation of electron diffusion length in the p layer of the cell, as well as to an observed change in the anodic antireflection (AR) coating.

The decrease in I_{sc} should be greatly reduced if the doping level in the p layer of the cell is lowered from 1 x 10^{17} /cm^3, so that the electron diffusion length is increased, and if the anodic AR coating is not used. This prediction has been confirmed by our experiments on another cell, which has a lower p doping level (~ 10^{16}/cm^3) and no AR coating. Figure 7 shows the characteristics of this cell after successive electron irradiations. After 10^{16} e/cm^2 dosage, I_{sc} decreases only slightly to about 94% of the original value. This small decrease is confirmed by the quantum efficiency measurements on the cell at various electron dosages (also shown in the figure). The cell, however, still exhibits a significant decrease in V_{oc}. As in the previous cell, the diode factor changed only slightly, from 1.1 before irradiation to 1.3 after 10^{16} e/cm^2 dosage. The value J_o, however, increased greatly from 2 x 10^{-18} A/cm^2 to 1 x 10^{-11} A/cm^2, thus reducing the V_{oc}.

Our initial experimental results indicate that the $n^+/p/p^+$ shallow-homojunction GaAs solar cells are resistant to electron irradiation. A very small change in I_{sc} was observed for a cell with low doping level in the p layer and no AR coating. The changes in V_{oc} are tentatively attributed to an increase in leakage current, partially from the exposed edges of the etched mesas in our cells. This increase in leakage current is expected to be reduced when our cell area is increased from 0.5 cm^2 to 4 cm^2, and when the exposed mesa edges are protected with an encapsulant. A different AR coating using Si_3N_4 is also being developed. Therefore, by optimizing the design and fabrication of shallow-homojunction GaAs cells, even better cells can be obtained which would provide high power density and very long life in space.

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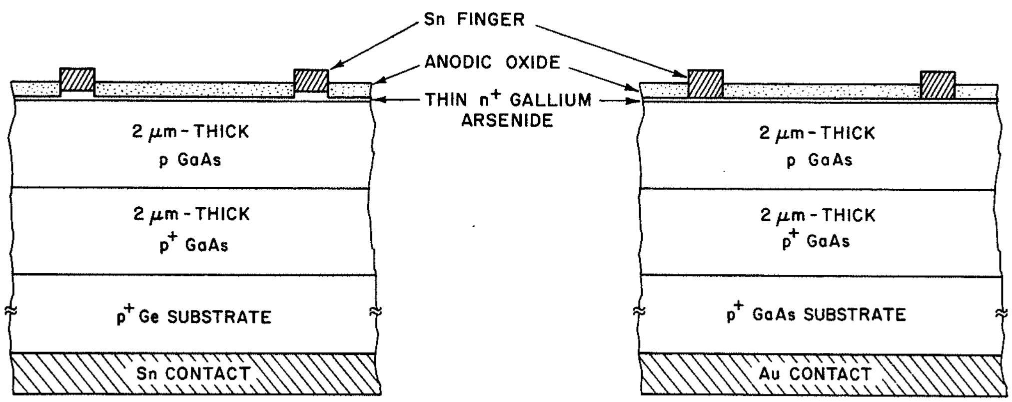

Fig. 1 Schematic diagram of GaAs solar cells grown on GaAs and Ge substrates.

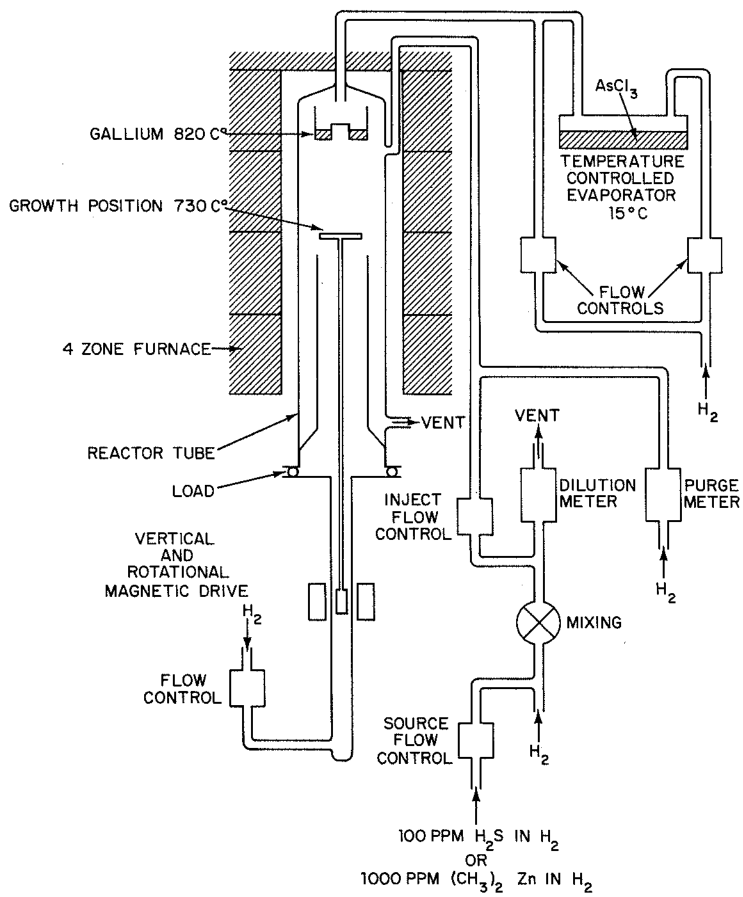

Fig. 2 Schematic diagram of GaAs vapor deposition system showing the $AsCl_3$-Ga-H_2 and doping gas flow control, and also a cross sectional view of the reactor tube.

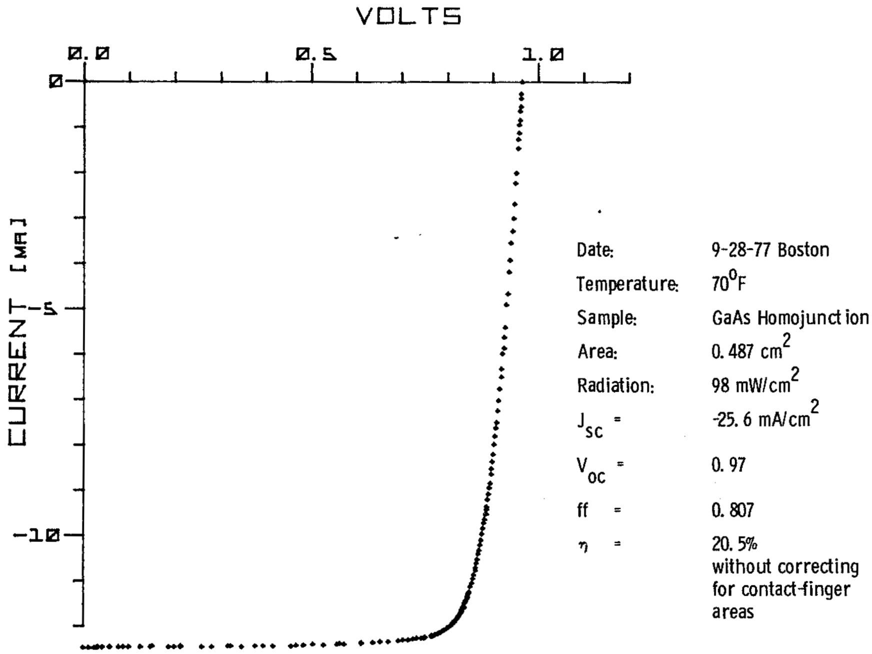

Fig. 3 Photocurrent as a function of applied voltage for a GaAs shallow-homojunction solar cell with 20% conversion efficiency at AM1, as measured at 20^{o}C.

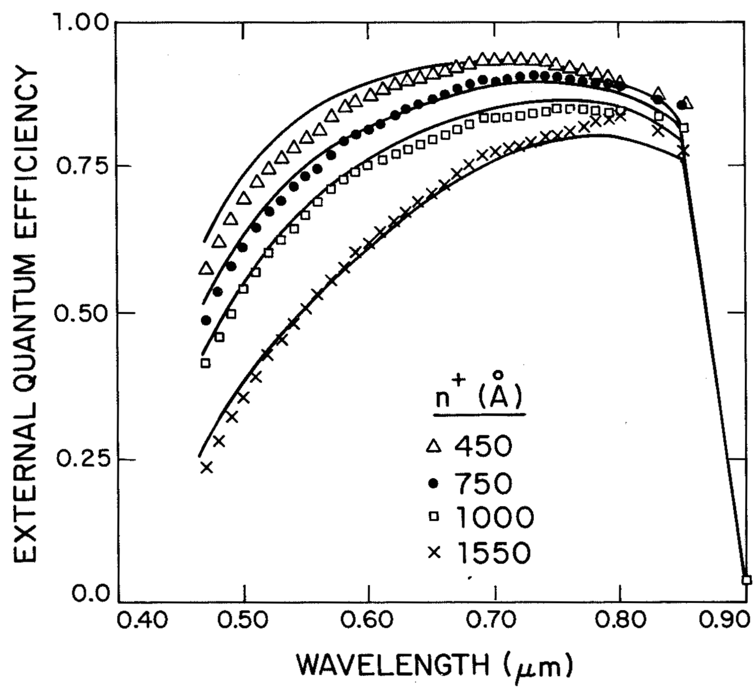

Fig. 4 External quantum efficiency as a function of wavelength for GaAs shallow-homojunction solar cells with n^+ layer thickness of 450, 750, 1000, and 1500 Å.

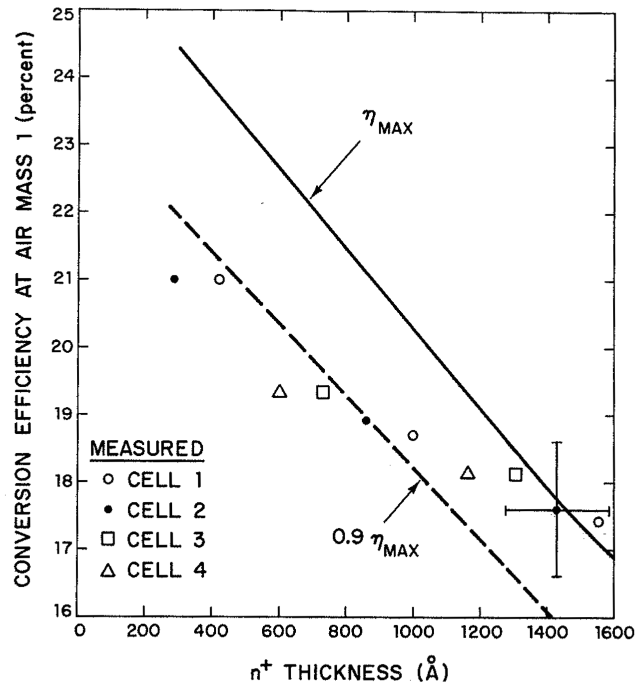

Fig. 5 Efficiency at AM1 as a function of n^+ layer thickness. Measured values are represented by points, calculated values of maximum conversion efficiency η_{max} and of 0.9 η_{max} by solid and dashed lines, respectively.

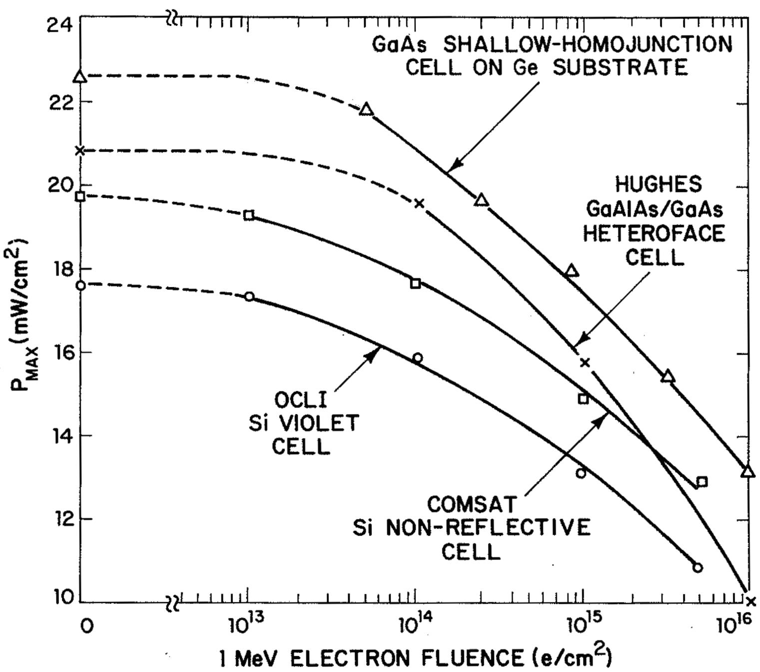

Fig. 6 The maximum output power density at AM0, P_{max}, for Cell 1 as a function of cumulative electron fluence. The results for three other types of cells were included for comparison.

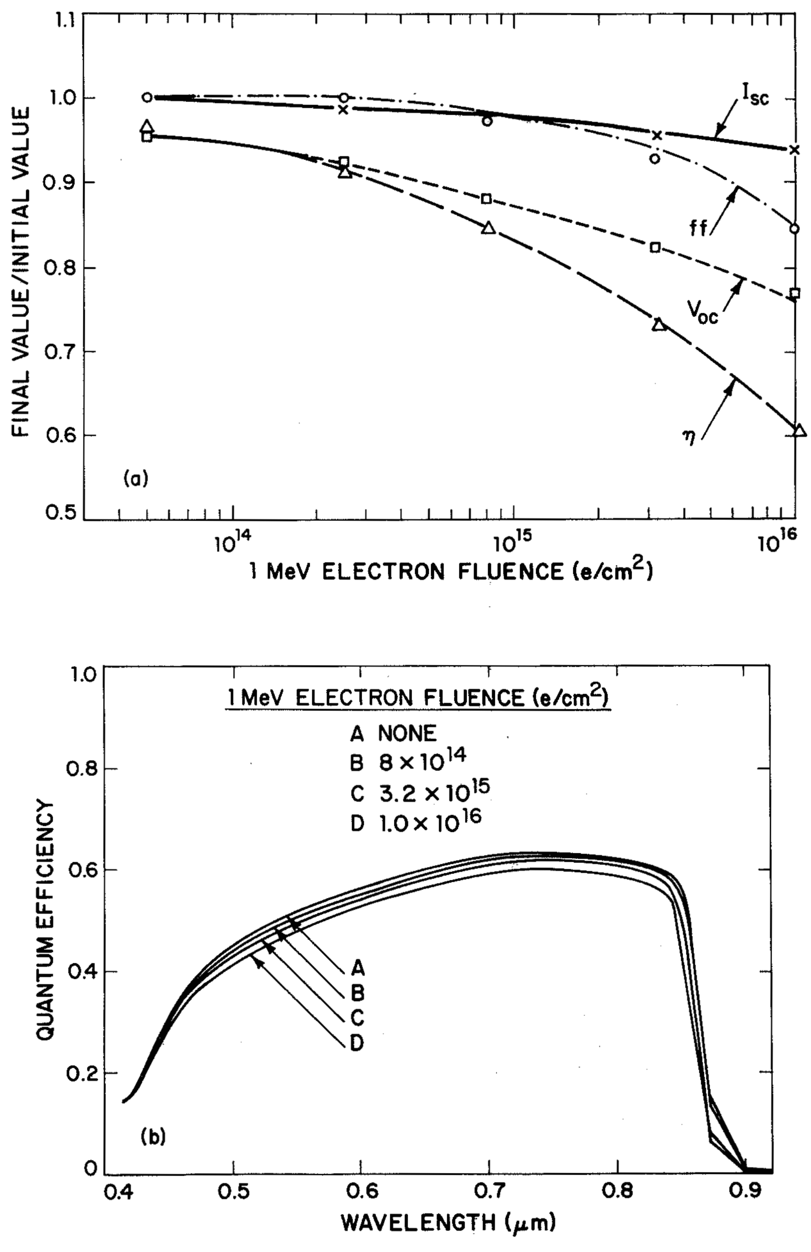

Fig. 7 a) The characteristics of Cell 2 as a function of cumulative electron fluence.
b) The quantum efficiency measurements on Cell 2 at various electron fluences.