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HIGH-EFFICIENCY GaAs CONCENTRATOR SPACE CELLS

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High-efficiency $Al_xGa_{1-x}As/GaAs$ heteroface solar concentrator cells have been developed for space applications. The cells, which were grown using metalorganic chemical vapor deposition (MOCVD), have been fabricated in both the p-n and n-p configurations. Magnesium and zinc are used as p-type dopants, and Se is used as the n-type dopant. The space cells, which are designed for use in a Cassegrainian concentrator operating at 100 suns, AMO, have a circular illuminated area 4 mm in diameter on a 5 mm x 5 mm cell. These cells have exhibited flash-tested efficiencies as high as 23.6% at 28°C and 21.6% at 80°C.

INTRODUCTION

Solar energy systems using GaAs cells in a concentrator array offer the potential for very high conversion efficiency along with low array costs. Several concepts for light-weight, radiation-resistant space concentrators have been proposed such as the point-focus miniature Cassegrainian array (Ref. 1) and the parabolic trough design (Ref. 2). GaAs devices have greater potential than Si cells in such applications due to their more optimal bandgap and more favorable temperature behavior. The latter factor enables the GaAs cells to operate efficiently at extreme concentrations ~1000 suns or at the higher operating temperatures which are inherent to concentrator systems. In this paper, we report $Al_xGa_{1-x}As/GaAs$ heteroface solar concentrator cells grown by metalorganic chemical vapor deposition (MOCVD) for use in Cassegrainian arrays.

CELL DESIGN AND FABRICATION

The concentrator cells were designed with the aid of a detailed computer model. The model simulates the performance of GaAs solar cells and can be used to optimize the relevant cell parameters, e.g., layer thicknesses, doping levels of the emitter and base, grid pattern, and antireflection (AR) coating. Details of the model may be found elsewhere (Ref. 4). The design conditions for the Cassegrainian cell were defined to be 100 suns, AMO at an operating temperature T = 80°C, with a circular illuminated area of 0.126 cm^2 (4-mm diameter) on a 5 mm x 5 mm die. Under such conditions, it is crucial that the emitter and the grid pattern each have very low series resistance. At the same time, the spectral response should remain high and the obscuration must be minimized. The structures of the cells that resulted from these computer optimizations are very similar; this structure is shown in Fig. 1. In addition to the emitter and base, the devices include a highly doped buffer layer to minimize surface recombination effects at the back of the base and to provide a smooth surface upon which the overlying structure is grown. The $Al_{0.9}Ga_{0.1}As$ window layer passivates the front surface of the emitter and, in combination with the single-layer AR coating, minimizes the reflectance. Finally, the GaAs cap layer enables excellent ohmic contact by the top grid pattern while simultaneously minimizing the possibility of the grid metallization diffusing into the semiconducting materials during processing. The cap layer is selectively etched away between the grid lines prior to the application of the AR coating. Doping levels for the cells are approximately 2×10^{18} and $7 \times 10^{17} cm^{-3}$ in the emitter and base, respectively. For the n-p cells, the emitter thickness was reduced to about 0.15 μm.

The multilayer structure was grown in a horizontal rf-heated MOCVD reactor at 730°C, as described in Ref. 5. Growth rates were 0.06 μm/min. In the p-n cells, Mg and Se were used as the dopants, whereas Se and Zn were used as the dopants in the n-p cells. Conventional photolithographic techniques were used to lay down the top grid pattern. Metallizations, which were deposited by evaporation, were Au/Ge/Ni/Au and Pd/Au for n- and p-type GaAs ohmic contacts, respectively. The front grid pattern was subsequently plated with Ag and/or Au to a total thickness of 2 μm. The AR coating was deposited by plasma deposition at 350°C.

TESTING

One-sun efficiencies were determined using Spectrolab XT-10 simulators both at Varian and at Sandia National Laboratories. For AMO measurements, the simulator intensity was set using a balloon-flight-calibrated GaAs p-n solar cell which had a similar spectral response to the concentrator cells. A xenon-lamp flash tester was used to determine device performance under concentration. The incident power upon the cell in the flash tester was determined by assuming that the short-circuit current I_{sc} was linearly dependent upon the solar concentration. The exposed scribing streets at the edges of the cells were masked off from any light to assure the accuracy of the measurements. Efficiencies were based on the total illuminated area, and no correction was made for obscuration.

RESULTS OF CASSEGRAINIAN CELLS

Figure 2 shows the current-voltage (I-V) characteristics of one of the best p-n Cassegrainian cells at one-sun, AMO, and T = 28°C. The efficiency η = 20.8% is quite high, with a particularly high value of the fill factor FF = 0.86. Such a value for FF is attainable due to the low series resistance which results from the optimization of the grid pattern for high concentration. The open-circuit voltage V_{oc} is 1.02 V, and $J_{sc} = 32.2$ mA/cm^2. As shown in Fig. 3, the same cell at a concentration of 91 suns has η = 23.3%, while maintaining the good fill factor. Curve fitting of these data yield an estimate of ~5 mΩ for the series resistance in this cell. The conversion efficiency versus concentration is plotted in Fig. 4. The data show that η has its maximum value near 100 suns, which is very near the intended operating concentration. However, comparable performance is attainable over a comparatively wide range between 80 and 200 suns, and even at 400 suns, η exceeds 22%.

The temperature dependence of the cell at 94 suns, AMO is shown in Fig. 5. As expected, η drops linearly with increasing temperature, and a least-squares fit to the data yields a temperature coefficient of -0.036%/°C. At the intended operating conditions of ~100 suns and T = 80°C, η = 21.6%. Radiation damage experiments have been performed on similar Varian Cassegrainian p-n cells at NASA-Lewis (Ref. 6). After a fluence of $1 \times 10^{15} cm^{-2}$ 1-MeV electrons on the bare cells, the 100-sun efficiency was reduced to 79% of its initial value. Using this result and those presented above, end-of-life (EOL) efficiencies could potentially exceed 17% under operating conditions. Since in the Cassegrainian module the cells are shielded from much of the radiation, as shown in Ref. 1, the actual EOL efficiency could be significantly higher.

Although the data presented in Figs. 2-5 indicate the performance of one of the best cells, the results are reproducible. Figure 6 shows the distribution of one-sun efficiencies for all cells, including the one discussed above, fabricated from the same wafer. Of the forty-eight devices which were obtained, twenty-seven exhibit $\eta > 20\%$, and eighty-five percent have $\eta > 17\%$. Lower cell efficiencies are almost invariably due to lower values of FF and, to a lesser extent, V_{oc}. The observed values of I_{sc} are relatively unchanged from cell to cell. When the values of η under concentration are used, the yield is even more impressive, as shown in Fig. 7. Over half of the tested devices have $\eta > 23\%$, and ninety-three percent exceed $\eta = 22\%$. Several other wafers have shown similar efficiency distributions, thus indicating the feasibility of producing these high-efficiciency cells in large quantities using MOCVD.

Although most of the Cassegrainian cells which have been fabricated to date have had the p-n configuration, several n-p cells have also been made. Figure 8 shows the one-sun I-V characteristics of one of these cells. Comparison with the data in Fig. 2 shows that the performance of this cell is very similar to the best p-n cells. The η versus concentration data for another n-p device, which is plotted in Fig. 9, shows an even higher peak efficiency of 23.6%. Furthermore, the decrease in η at greater concentrations is less pronounced, presumably due to the superior majority-carrier mobility in the n-type emitter. The computer modeling results indicate that the n-p structures may potentially have higher efficiencies than p-n, primarily due to better quantum efficiencies.

CONCLUSIONS

High-efficiency GaAs concentrator cells have been developed for both space and terrestrial applications. Their optimal structures were determined with the aid of a computer model which realistically simulates the performance of $Al_xGa_{1-x}As/GaAs$ heteroface cells. Cassegrainian cells have shown 100-sun, AMO efficiencies as high as 23.6% at T = 28°C and 21.6% at T = 80°C. The space cells have shown excellent radiation resistance to 1-MeV electrons, so in combination with the protective design of the magnifying element, the Cassegrainian arrays should offer excellent end-of-life performance. Although most of the development efforts have focused on the p-n configuration, several high-efficiency n-p cells were also fabricated. The computer modeling indicates that even higher efficiencies may be obtained in the latter case.

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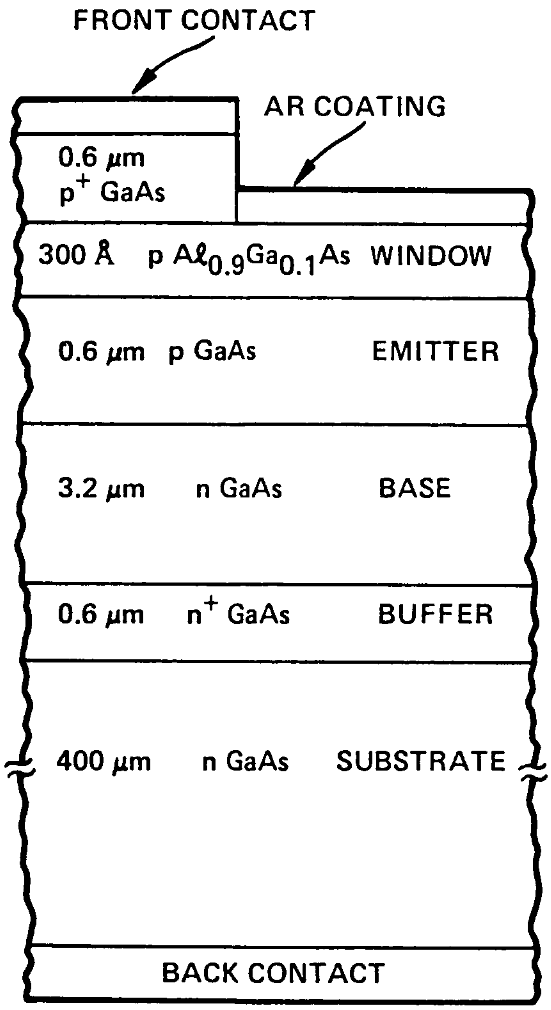

Figure 1: Optimized p-n solar cell structure obtained from the computer model.

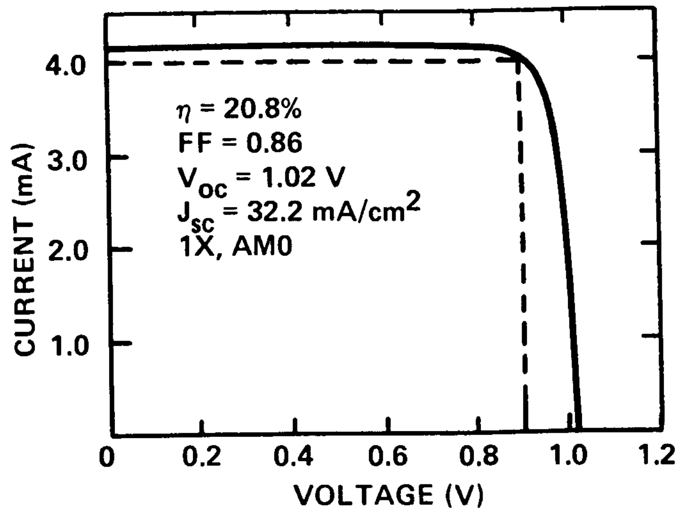

Figure 2: Current vs voltage for a p-n Cassegrainian solar cell at T = 28°C and 1-sun, AMO. The dashed lines indicate voltage and current at maximum power point.

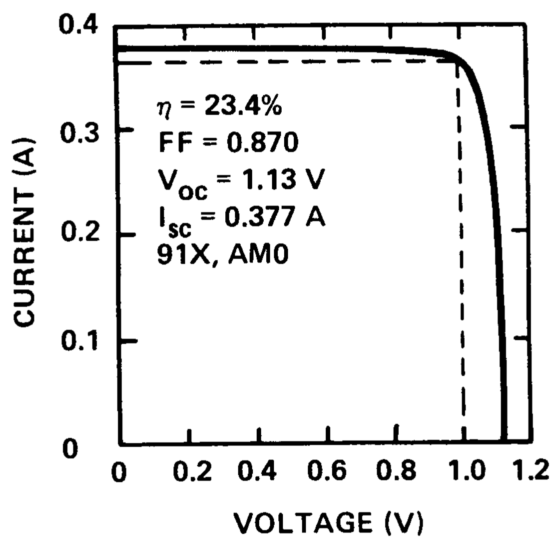

Figure 3: Current vs voltage for cell discussed in Fig. 2 at 91 suns. Dashed lines indicate voltage and current at maximum power point.

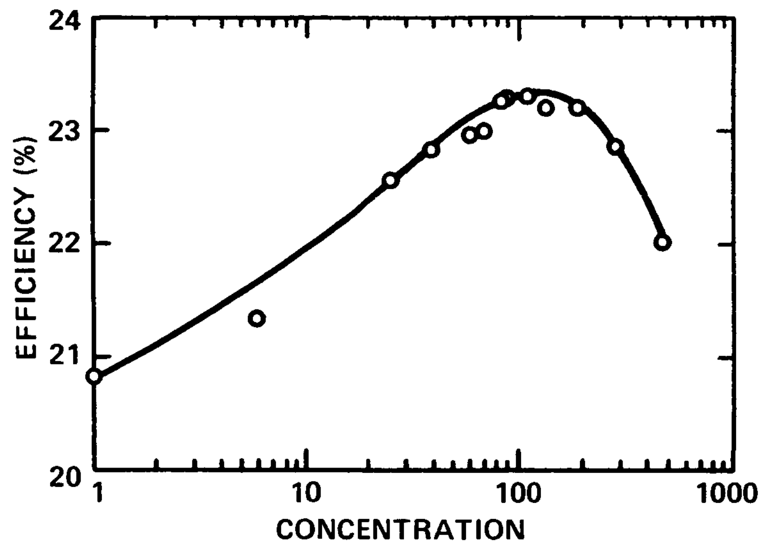

Figure 4: AMO efficiency versus solar concentration for cell discussed in Fig. 2 at T = 28°C.

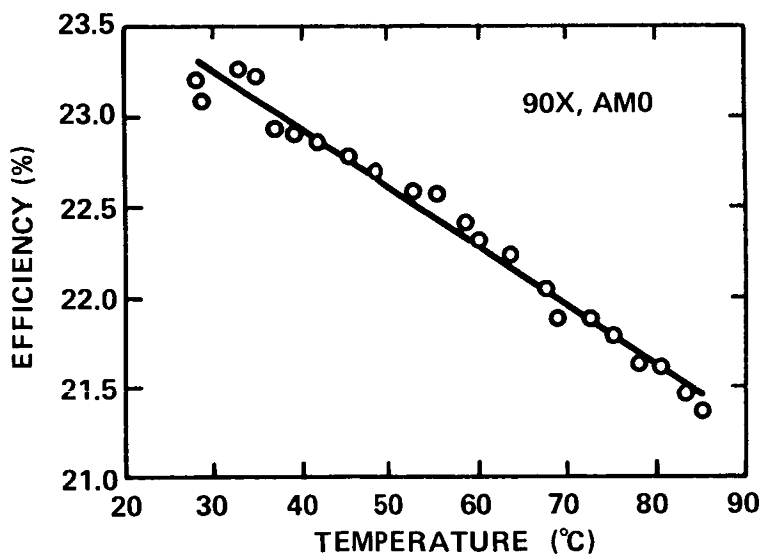

Figure 5: AMO efficiency versus temperature at 94 suns for cell discussed in Fig. 2. The line represents a least-squares fit to the data and has a slope of -0.036%/°C.

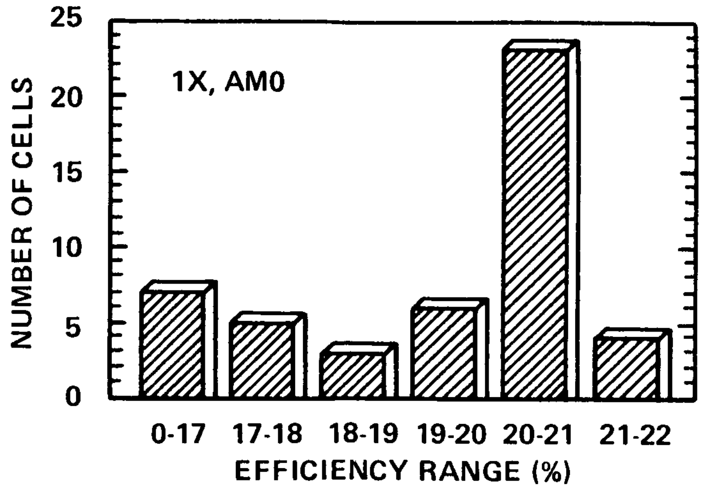

Figure 6: One-sun, AMO efficiency distribution of all Cassegrainian cells processed from a single wafer, including cell discussed in Fig. 2.

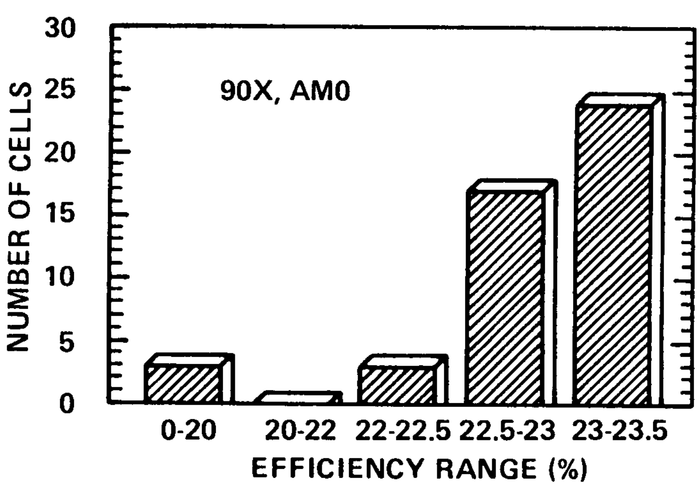

Figure 7: Efficiency distribution of all Cassegrainian cells processed from wafer of Fig. 6 at 90 suns, AMO and T = 28°C.

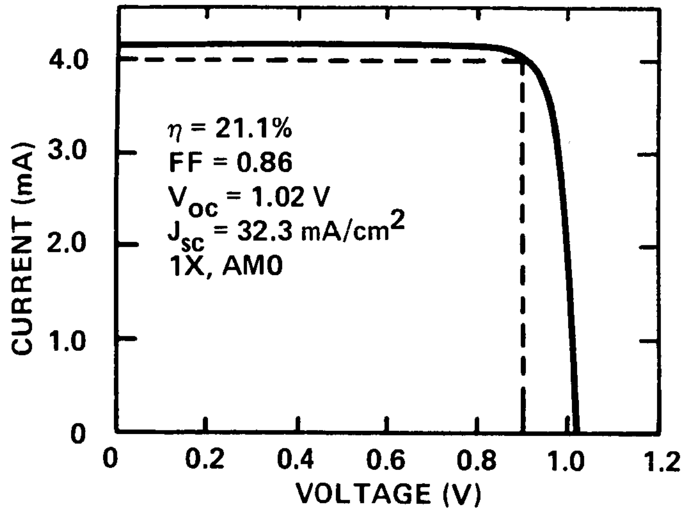

Figure 8: Current versus voltage for n-p Cassegrainian solar cell at T = 28°C and 1-sun, AMO. The dashed lines indicate voltage and current at the maximum power point.

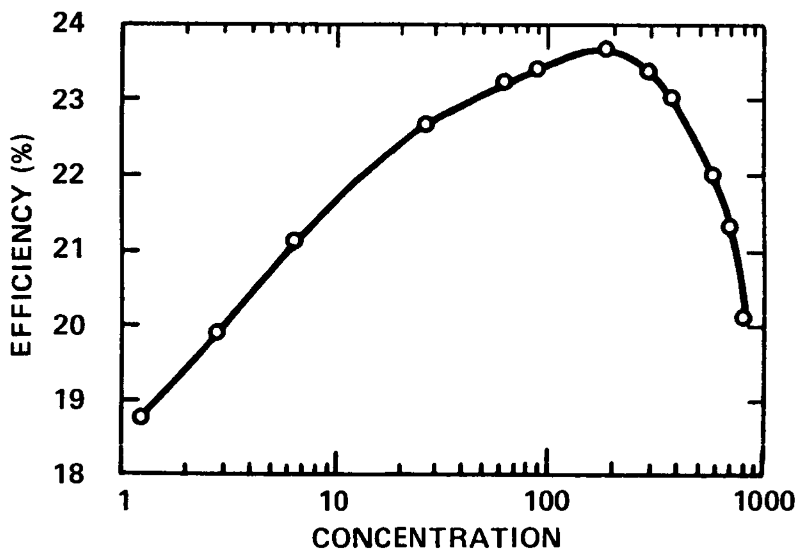

Figure 9: AMO efficiency versus solar concentration for a n-p Cassegrainian solar cell at T = 28°C.