25%-Efficient GaAs Cassegrainian Concentrator Cell

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Very high-efficiency GaAs Cassegrainian solar cells have been fabricated in both the n-p and p-n configurations. The n-p configuration exhibits the highest efficiency at concentration, the best cells having an efficiency η of 24.5% (100X, AM0, temperature $T = 28\,^\circ$C). Although the cells are designed for operation at this concentration, peak efficiency is observed near 300 suns ($\eta = 25.1\%$). To our knowledge, this is the highest reported solar cell efficiency for space applications. The improvement in efficiency over that reported at the previous SPRAT conference is attributed primarily to lower series resistance and improved grid-line plating procedures. Using previously measured temperature coefficients, we estimate that the n-p GaAs cells should deliver approximately 22.5% efficiency at the operating conditions of 100 suns and $T = 80\,^\circ$C. This performance exceeds the NASA program goal of 22% for the Cassegrainian cell. One hundred Cassegrainian cells have been sent to NASA as deliverables, sixty-eight in the n-p configuration and thirty-two in the p-n configuration.

Introduction

Solar energy systems using GaAs cells in concentrator arrays 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]. The advantages of higher cell efficiency and reduced array costs in a concentrator system are balanced against optical losses of the reflecting mirrors and the need for greater accuracy in aiming the arrays at the sun. Since the cell comprises such a small fraction of the weight and area of the array, the most important of the cell parameters — cost, weight, *etc.* — is the conversion efficiency η. GaAs devices have a greater potential for this application than their Si counterparts due to their more optimal band gap, superior radiation resistance and lower temperature coefficient. The last factor enables the GaAs cells to operate efficiently at moderate to extreme solar concentrations, for which the operating temperatures T of the solar cells are higher than observed in flat-plate systems. In this paper, we report on improved performance of Varian's $Al_xGa_{1-x}As/GaAs$ heteroface solar concentrator cells grown by metalorganic chemical vapor deposition (MOCVD) for use in Cassegrainian arrays.

Cell Design and Fabrication

The structure of the concentrator cells described in this paper is very similar to that reported at the previous SPRAT conference[ref. 3]. The design conditions for the Cassegrainian cells were

defined to be 100 suns, AM0 at $T = 80\,^\circ C$, with a circularly illuminated area of 0.126 cm^2 (4-mm diameter) on a 5 × 5 mm^2 die. As before, the cells were designed with the aid of a computer model simulating the performance of $Al_xGa_{1-x}As$/GaAs heteroface solar cells [ref. 4]. The structure of a typical p-n cell 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 antireflection (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 p-n (or n-p) junction during processing. The cap layer is selectively etched away between the grid lines prior to the application of the AR coating. For n-p cells, the emitter thickness is approximately 0.2 μm.

The multilayer structure was grown in a horizontal rf-heated MOCVD reactor at $730\,^\circ C$, as described in Reference 5. Growth rates were 0.1 μm/min, and zinc and selenium were used as the p- and n-type dopants, respectively. Conventional photolithographic techniques were used to lay down the top grid pattern. Metallizations, which were deposited by evaporation, were Pd/Au and Au/Ge/Ni/Au for p- and n-type GaAs ohmic contacts, respectively. The SiO_xN_y AR coating was deposited by plasma deposition at $300\,^\circ C$.

To raise the cell conversion efficiency, improvements were sought in the grid-line quality and the series resistance R_s of the cell. To accomplish the first task, a superior technique for electroplating the front grid metallization was developed. This procedure, which uses thick photoresist as a plating mask, significantly reduced the mushrooming effects associated with plating. Since the Cassegrainian mask requires numerous narrow grid lines ($\sim$ 3 μm wide) for optimal efficiency, the reduction in the amount of mushrooming greatly lowered the obscuration and raised the spectral response.

The series resistance problem is a more difficult matter, however. The primary factors contributing to R_s are the contact resistance R_c, the sheet resistance $R_\square$, and the grid-line resistance R_g. With the good ohmic contact afforded by the highly doped GaAs cap layer, R_c does not significantly influence η, even for concentrations $\geq$ 1000 suns. Any improvement in R_s, therefore, must come from lowering either $R_\square$ or R_g. Recently, we have attempted to lower the value of $R_\square$ by reexamining the effects of the doping level in the emitter. Using the original material parameters included in the computer model, the calculated value for the optimal doping level in the emitter N_E was approximately 1×10^{18} cm^{-3} in both the p-n and n-p configurations. This value resulted from the conflicting objectives of maximizing the diffusion length L in the emitter for high quantum efficiency (low doping condition) and lowering $R_\square$ (high doping). Recent data [ref. 6] for L in GaAs indicate that the values originally used in the computer model [ref. 4] were unduly pessimistic. As a result, the optimum value for N_E is higher than the computer model predicted, since satisfactory quantum yield may be attained at higher doping levels. Consequently, in the cells presented here, we have empirically increased the value for N_E in both the p-n and n-p configurations until the optimal value was obtained.

Testing

One-sun efficiencies were determined using Spectrolab XT-10 simulators both at Varian and Sandia National Laboratories. For AM0 measurements, the simulator intensity was set using balloon-flight-calibrated GaAs solar cells which had similar spectral responses to the appropriate 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 sawing streets at the edges of the cell were masked off from any light to assure the accuracy of the measurements. Efficiency calculations were based on the total illuminated area, and no correction was made for obscuration.

Results and Discussion

Figure 2 plots the external quantum yield of an n-p spectral response sample, in which the grid obscuration has been eliminated. In this case, $N_E = 2 \times 10^{18}$ cm^{-3}, and at this doping level, the sheet resistance of the emitter is not a significant factor in limiting cell performance, $i.e.$, the power loss associated with $R_\square$ is much smaller than that associated with R_g. It is readily apparent that in spite of the increased doping level in the emitter, the cell still has excellent quantum efficiency. Nearly unity quantum yield is observed at the center of the spectrum, and most of the losses in the red and blue are due to a less-than-optimal AR coating on this particular sample. This demonstrates that the material quality is sufficiently high that low series resistance and high values for I_{sc} are not mutually exclusive. For p-n cells, 2×10^{18} cm^{-3} also appears to be the optimal value for N_E. Due to the lower mobility of the holes in this structure, $R_\square$ is not negligible. At the solar concentrations relevant to the Cassegrainian module, however, the series resistance problem is not serious, as will be shown below.

Figure 3 shows the current-voltage (I-V) characteristics of an n-p Cassegrainian cell at a solar concentration of 333 suns and $T = 28\,^{\circ}$C. Although the cell is intended for use at 100 suns, the efficiency remains very high ($\eta = 25.1\%$). The open-circuit voltage $V_{oc} = 1.18$ V, and the current density J_{sc} corresponds to 33.6 mA/cm^2/sun. The high value for the fill factor (FF $= 0.862$) indicates that series resistance is not a significant parameter limiting cell performance. Curve fitting of the I-V data yields an estimate of $R_s \sim 3$ mΩ. Figures 4–6 plot the dependence upon concentration of η, V_{oc} and FF, respectively. The efficiency peaks near 300 suns with a value of 25.1%; at 100 suns, $\eta = 24.5\%$. The drop in efficiency above ~ 400 suns results from the increasing importance of losses due to series resistance, as indicated by the decreasing fill factor. The p-n cells show slightly lower efficiencies, primarily due to lower values of I_{sc}. The advantages of the n-p configuration may be attributed to tenfold higher values of mobility for electrons vs holes in GaAs. By making electrons the majority carrier in the emitter, lower sheet resistance $R_\square$ may be obtained without the disadvantages of either overdoping or thickening the emitter. The lower value of $R_\square$ leads directly to the generally higher values for FF in the n-p case. The higher values for I_{sc} are the result of the thinner emitter coupled with the long diffusion length in the p-type base.

Comparing these results with those which were presented at the previous SPRAT conference [ref. 3], it is plain that the improvements in the plating procedures and sheet resistance have significantly improved cell performance. The more recent cells exhibit better values for I_{sc} (33.6 vs 32.4 mA/cm^2), presumably due to the reduced obscuration due to mushrooming. The series resistance is also less of a problem, as indicated by the increase in the concentration for which the efficiency peak is observed (300 vs 180 suns). Even higher efficiencies may be attained by lowering R_g, since this is the only remaining source of significant series resistance. This may be accomplished by widening and thickening the grid lines or lowering the resistivity of the grid-line metallization. Since increasing the grid-line width decreases I_{sc}, improvements must come from the latter two

factors. At this time, we are developing an improved metallization process to address this minor problem.

Although we have not yet measured the temperature behavior of the cell examined in Figs. 3–6, we can use the previously determined value for the temperature coefficient [ref. 3] ($-0.036\%/°C$ for a 23.4%-efficient cell at $T = 28°C$ and 90 suns) to estimate the performance of the cell under the intended operating conditions of 100 suns and $T = 80°C$. Such an estimate predicts that the most recent cell would be 22.5%-efficient under these conditions, which exceeds the NASA-program goal of 22%. The program also calls for the delivery of 100 Cassegrainian cells to NASA, so we have delivered sixty-eight n-p cells and thirty-two p-n cells.

Summary

Cassegrainian cells with a conversion efficiency near 25% have been fabricated in both the n-p and p-n configuration. To our knowledge, this is the highest reported cell efficiency for space applications. The improved performance is the result of new grid-line plating procedures and lower series resistance associated with higher doping in the emitter. Under the probable operating conditions of 100 suns and $T = 80°C$, the estimated efficiency is 22.5%. To meet program goals, we have delivered sixty-eight n-p cells and thirty-two p-n cells to NASA.

References

[1] R. E. Patterson, H. S. Rauschenbach and M. D. Cannady, *Conference Record of the 16th IEEE Photovoltaic Specialists Conference*, IEEE, New York, 1982, p. 39.

[2] T. G. Stern and E. W. Hayes, *Conference Record of the 17th IEEE Photovoltaic Specialists Conference*, IEEE, New York, 1984, p. 326.

[3] J. G. Werthen, G. F. Virshup, H. F. MacMillan, C. W. Ford and H. C. Hamaker, *Space Photovoltaic Research and Technology 1986*, NASA Conference Publication 2475, 1986, p. 25.

[4] H. C. Hamaker, J. Appl. Phys. **58**, 2344, 1985.

[5] C. R. Lewis, W. T. Dietze and M. J. Ludowise, J. Electron. Mater. **12**, 507, 1983.

[6] R. K. Ahrenkiel, D. J. Dunlavy, D. Greenberg, J. Schlupmann, H. C. Hamaker and H. F. MacMillan, Appl. Phys. Lett. **51**, 776, 1987.
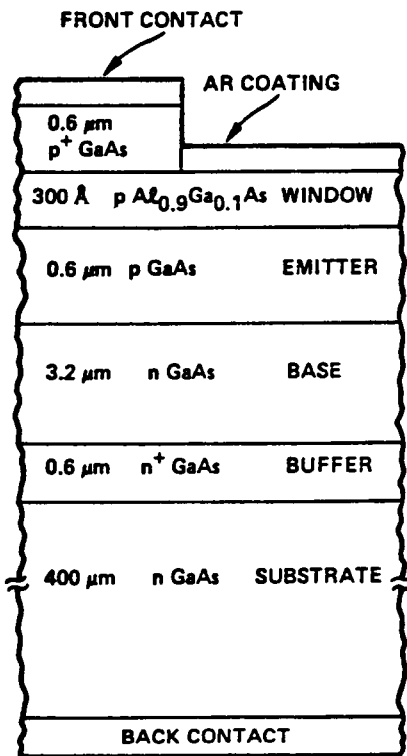
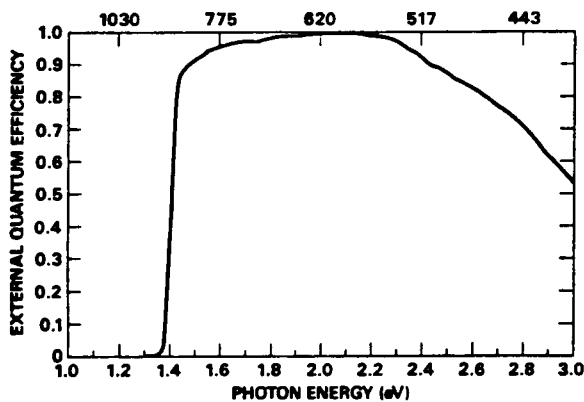Fig. 1. Schematic structure of a typical p-n GaAs concentrator cell.

Fig. 2. External quantum efficiency vs photon energy for an n-p GaAs spectral response sample. The scale on the top axis shows the wavelength in nm.
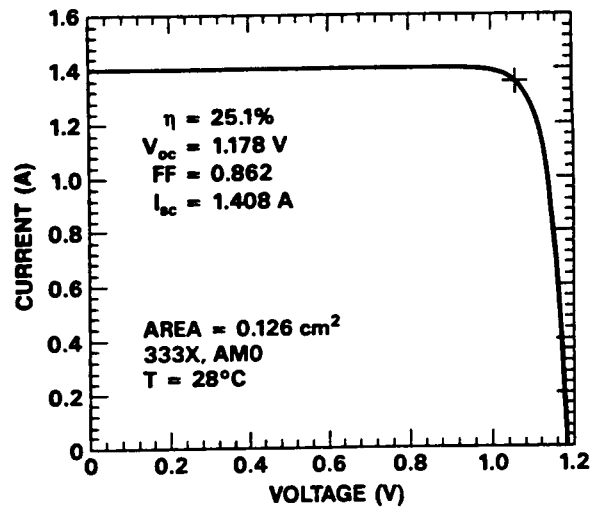

Fig. 3. Current vs voltage for an n-p GaAs Casse-grainian cell under a simulated 333×, AM0 spectrum. The cross indicates the maximum power point.
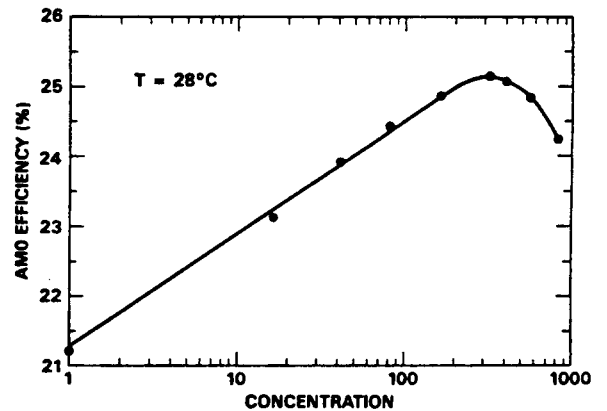

Fig. 4. AM0 efficiency vs solar concentration for the n-p GaAs cell shown in Fig. 3.
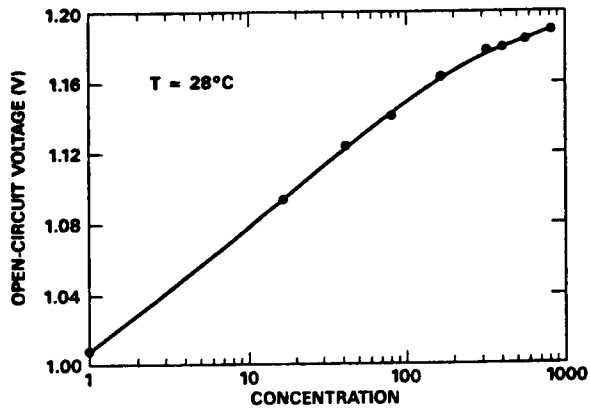
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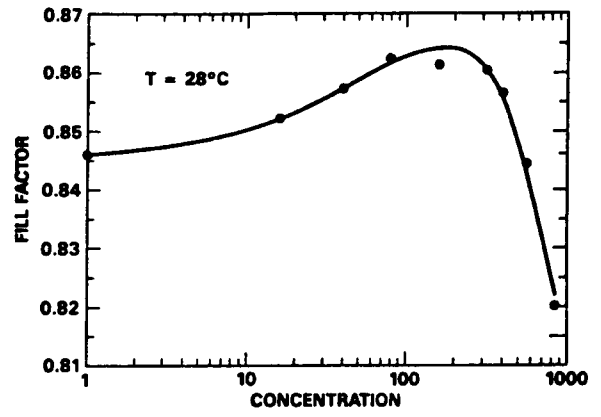Fig. 5. Open-circuit voltage *vs* solar concentration for the *n-p* GaAs cell shown in Fig. 3.

Fig. 6. Fill factor *vs* solar concentration for the *n-p* GaAs cell shown in Fig. 3.