GaAs SOLAR CELLS FOR CONCENTRATOR SYSTEMS IN SPACE*

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ABSTRACT

A number of solar cell systems operating with concentrated sunlight are being considered for space applications. GaAs solar cells are specially attractive for such systems. Even modest solar concentration ratios lead to substantial increases in the efficiency of the GaAs cells. This compounds the superior efficiency which these cells already exhibit in the absence of solar concentration.

We have made cells for operation in space up to more than 100 suns and have obtained an AMO efficiency of 21% at 100 suns with these cells. The increased efficiency resulted not only from the higher open circuit voltage associated with the higher light intensity (higher short circuit current); it also benefitted from the increase in fill factor caused by the lower relative contribution of the generation recombination current to the forward bias current when the cell's operating current density is increased.

Another attractive feature of these GaAs concentrator solar cells is their ability to retain a good efficiency up to high temperatures. The experimental cells mentioned above exhibited an AMO efficiency close to 16% at 200°C. The prospect of exploiting this capability for the continuous annealing of radiation damage or for high temperature missions (e.g., near sun missions) remains therefore open.

Space systems with concentration ratios on the order of 100 suns are presently under development. We will show that the tradeoff between increased concentration ratio and increased loss due to the cell's series resistance remains attractive even for space applications at a solar concentrator ratio of 100 suns. In the design of contact configuration with low enough series resistance for such solar concentration ratios, the shallow junction depth (<0.5 μm) needed for good radiation hardness and the thin AlGaAs layer thickness needed to avoid excessive optical absorption losses have to be retained. This leads to some constraints which are more severe for space cells than for terrestrial applications. However, even with these constraints, high AMO efficiencies remain attainable at 100 suns for space cells, as shown above.

INTRODUCTION

Concentrator solar cell systems are of interest for space applications because of the prospects of providing lower cost systems with longer life in the radiation environment representative of practical space missions. The GaAs solar cells are especially attractive for this purpose because of their superior efficiency and resistance to radiation damage, together with their ability to operate efficiently at higher temperatures than silicon solar cells. One important observation is that the GaAs solar cells' efficiency, which is already high in the absence of solar concentration, increases even further with increasing solar concentration. Another important property of the GaAs solar cells is their ability to substantially recover from

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radiation damage by annealing at temperatures as low as 200°C. One consequence of these features is the possibility of combining both the high solar concentration and high temperature properties of GaAs solar cells so that they can be operated continuously in space for long periods of time. An alternate option is to provide capabilities for periodic annealing of the cells.

While several groups have had an active interest in the development of GaAs solar cells for concentrator applications[1,2], most of this work had been directed to terrestrial applications. Our own work is specifically directed to space applications. This means that we are interested in AM0 efficiency rather than AM1 or AM2 performance. Furthermore, the need to minimize radiation damage limits us to consider only cells with relatively shallow junction depth ($\leq$ 0.5 μm). Finally, because of the difficulty of cooling in space, we have an additional incentive to operate at relatively high temperatures.

In this report we consider specifically two cell designs: a large square 2 cm x 2 cm cell for space systems operated at relatively low solar concentration ratios (on the order of 10 suns), and a small concentrator cell with 4 mm diameter circular active area for high solar concentration systems operated at $\geq$100 suns.

CELL DESIGN

Figure 1 shows the baseline design for our space concentrator cell. This design follows the same guidelines as the space qualified GaAs cells reported in our earlier work.[3] As indicated above, the special features of our concentrator cells are the thin (AlGa)As window layer ($\leq$ 0.5 μm) and shallow junction depth (0.5 μm). Figure 2 shows the calculated efficiency of our GaAs cells as a function of solar concentration ratio with normalized series resistance R_{s1} as a parameter. This provides the guidelines needed for the design of our cells' contacts. More specifically, figure 2 shows that we have to keep R_{s1} $\leq$0.1 Ω cm^2 for our large 2 cm x 2 cm cells to avoid excessive penalty in efficiency for concentration ratios up to X = 10 suns. Alternately, for our small 0.4 cm diameter cell designed for operation at X = 100 suns, we wish to keep R_{s1} $\leq$0.01 Ω cm^2.

The gridline designs adopted to satisfy these requirements are shown on figure 3. The large cell (2 cm x 2 cm) has 80 guidelines running in parallel to each other. Each finger linewidth is 20 μm wide. There are two bus bars connecting the fingers at each end of the cell. The small circular cell has 90 radial gridlines extending from a radius of 2 mm down to 0.75 mm, 36 radial fingers from a radius of 0.75 to 0.50 mm and 12 radial fingers from a radius of 0.50 mm to 0.25 mm. The width of all fingers is tapered from 10 μm at the outer radius to 5 μm at the inner radius. The finger height is nominally 3 μm in all cells (Ag overlay). The corresponding contact finger metal resistivity is 2 x 10^{-6} Ω cm. The average resistivity of the semiconductor p-layer is 2 x 10^{-2} Ω cm^2. The metal-semiconductor interface resistance (normalized to the actual contact finger area, not to the total solar cell areas) is taken to be equal to 1 x 10^{-3} Ω cm^2. This latter value falls within the range of values measured on our experimental cells. With these values and the contact configuration described above, the calculated normalized series resistances are 0.04 Ω cm^2 for the 2 cm x 2 cm cell and 0.01 Ω cm^2 for the 0.4 cm diameter cell. These calculated values fall within the range specified above by inspection of figure 2.

CELL FABRICATION

Our GaAs concentrator solar cells were fabricated with the same infinite melt liquid phase epitaxial growth (LPE) technique now routinely used for the batch fabrication of our conventional 2 cm x 2 cm space qualified cells. We used photolithography for the fabrication of the front contact. We have selected to make direct contact to the (AlGa)As layer even though this is more difficult to do with conventional techniques than making contact to the GaAs. We have overcome the difficulty of contacting to (AlGa)As by using sputter-deposition of the initial layers of AuZn on the (AlGa)As. For the back contact, we use conventional vapor deposition of Au Ge Ni. A 3 μm thick Ag overlay is plated to both front and back sides of the metallization in order to reduce the finger gridline resistance. Finally, the cells are coated with 650Å of Ta_2O_5 for antireflection coating.

TEST RESULTS

Figure 4 shows a set of measurements performed on the large 2 cm x 2 cm cells designed for operation at a concentration of X = 10 suns; figure 5 shows the measurements of the small cells (0.4 cm diameter active area) designed for operation at X = 100 suns. The efficiencies shown on figure 4c and figure 4d at concentration ratio up to X = 10 suns for our 2 cm x 2 cm concentrator cells are relatively low and compare unfavorably in the absence of concentration with our conventional 2 cm x 2 cm GaAs solar cells. While the cause for this deficiency has been identified (inadequate AR coating), no additional cells of this type were made to correct this deficiency prior to this meeting. Higher priority was given to the development of the smaller cells for operation at 100 suns. This led to the rewarding results (high AMO efficiencies) shown on figure 5c and 5d for operation at 100 suns with those cells.

The effect of temperature on the short-circuit current of our cells is shown on figure 4a and 5a. The increase of short-circuit current with temperature exhibited by these measurements is explained in part by the narrowing of the bandgap of GaAs with increasing temperature ($dE_g/dT \simeq -5 \times 10^{-4}$ eV/°K). This feature is helpful insofar as it partly compensates the loss of open-circuit voltage caused by increasing temperature. The loss of open-circuit voltage with increasing temperature is shown on figure 4b and 5b. It is found to be $dV_{oc}/dT = -2$ mV/°K and closely matches the theoretically calculated value. The loss of efficiency with increasing temperature results from the combination of the changes in open-circuit voltage, short-circuit current and fill factor with increasing temperature. The measured values of efficiency versus temperature are shown on figure 4c and 5c. We observe that in the absence of solar concentration, the efficiency obtained at an elevated temperature of 200°C is still 11% for both types of cells. Furthermore, this efficiency becomes even higher when the solar concentration ratio is increased above unity.

The increase in efficiency with increasing solar concentration results not only from the increased open-circuit voltage, it also benefits from the increased fill factor. The latter results from the decreasing relative contribution of the generation current in the depletion region at the junction when the GaAs solar cell operates at higher current densities. These beneficial effects are off-set at increasing solar concentrations by the growing power loss due to the series resistance. As shown below, our measurements confirm that this contribution becomes important at concentration ratios in excess of 100 suns for our small cells. The measured data is shown on figure 4d and 5d, where the AMO efficiency is shown as a function of concentration ratio for the 3 temperatures of 25°C, 100°C, and 200°C. Alternately, the AMO efficiency of our cells has already been shown as a function of temperature with the concentration ratio as a parameter in figure 4c and 5c. It is especially rewarding to observe (figure 5c) that an AMO efficiency close to 16% is obtained at a temperature as high as 200°C with a cell suitable for operation in space.

A final task is to compare the experimental results obtained to date with the theoretical calculations. More specifically, the curve of efficiency versus concentration ratio measured at 25°C and shown as one of the curves of figure 5d can be compared with the theoretical curves shown on figure 2. Two observations are to be made in this context:

1) At high concentration ratios (X = 100), the measured and calculated efficiencies (21%) are in close agreement, provided the series resistance of the

experimental cell is R_s <10^{-2} Ωcm^2. This falls within the range of measured series resistances for our small cells.

2) At low concentration ratios (X = 1), the calculated efficiency is substantially higher than the measured value (19% versus 16%). We have been able to trace this back to the poor fill factor exhibited at low concentration ratio on the measured set of small cells. This was caused by excessive edge-leakage current, a defect which has been overcome since those measurements were performed. This defect becomes inconsequential at the higher concentration ratios, which explains the improved agreement between theory and measurements observed at the high concentration ratios.

CONCLUSIONS

We have established that GaAs solar cells designed for operation in space under concentrated sunlight are attractive for concentration ratios up to more than 100 suns. AMO efficiencies in excess of 20% were obtained at 100 suns. Operation at elevated temperatures was found to be possible at AMO efficiencies in excess of 16% with a temperature as high as 200°C. The cells providing this performance had the shallow junction depth and thin AlGaAs window layer thickness required for good radiation hardness and favorable spectral response under AMO illumination in space.

REFERENCES

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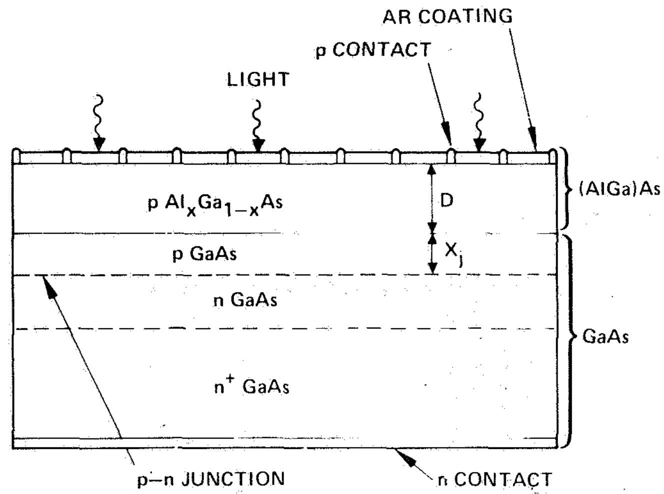
3. R.C. Knechtli, et al., "Development of Space - Qualified GaAs Solar Cells," Proc. 2nd European Symposium on Photovoltaic Generators in Space, ESA SP-147, p. 121 (1980).



p CONTACT: Au–Zn–Ag

n CONTACT: Au–Ge–Ni–Ag

AR COATING: Ta_2O_x

p $Al_xGa_{1-x}As$: $x > 0.85$

$D + X_j \leq 1.0\,\mu m$

Figure 1. The (AlGa) As-GaAs solar cell: baseline structure.

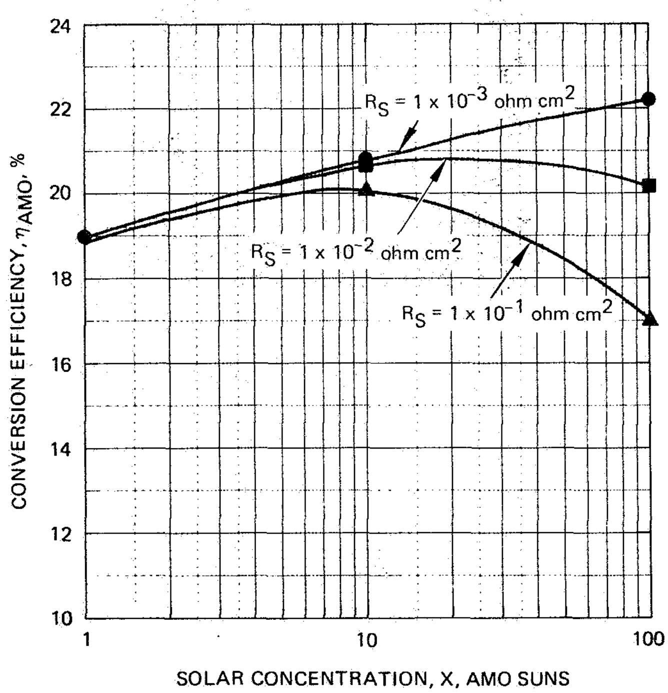
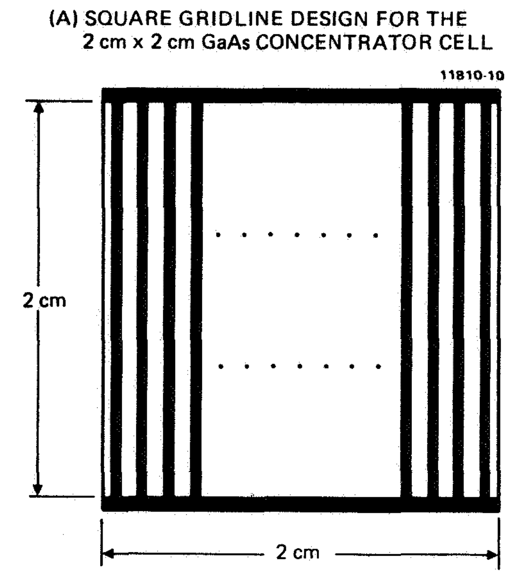
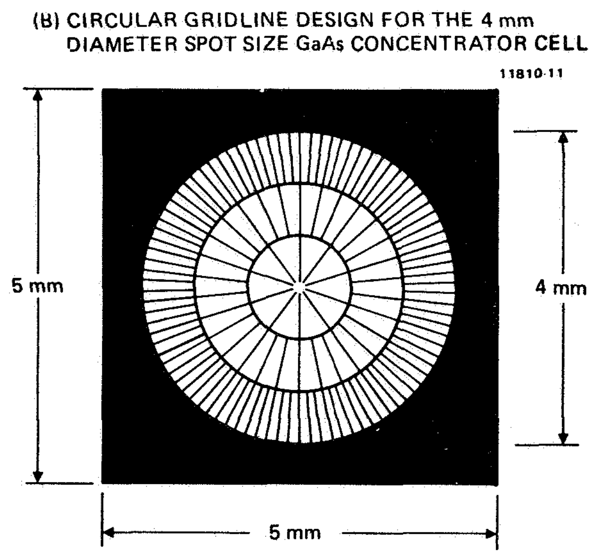


Figure 2. GaAs solar cells: calculated AMO efficiency vs solar concentration





NOTE: SEE TEXT FOR FINGER NUMBERS AND DIMENSIONS FOR BOTH DESIGNS

Figure 3. Grid line designs.

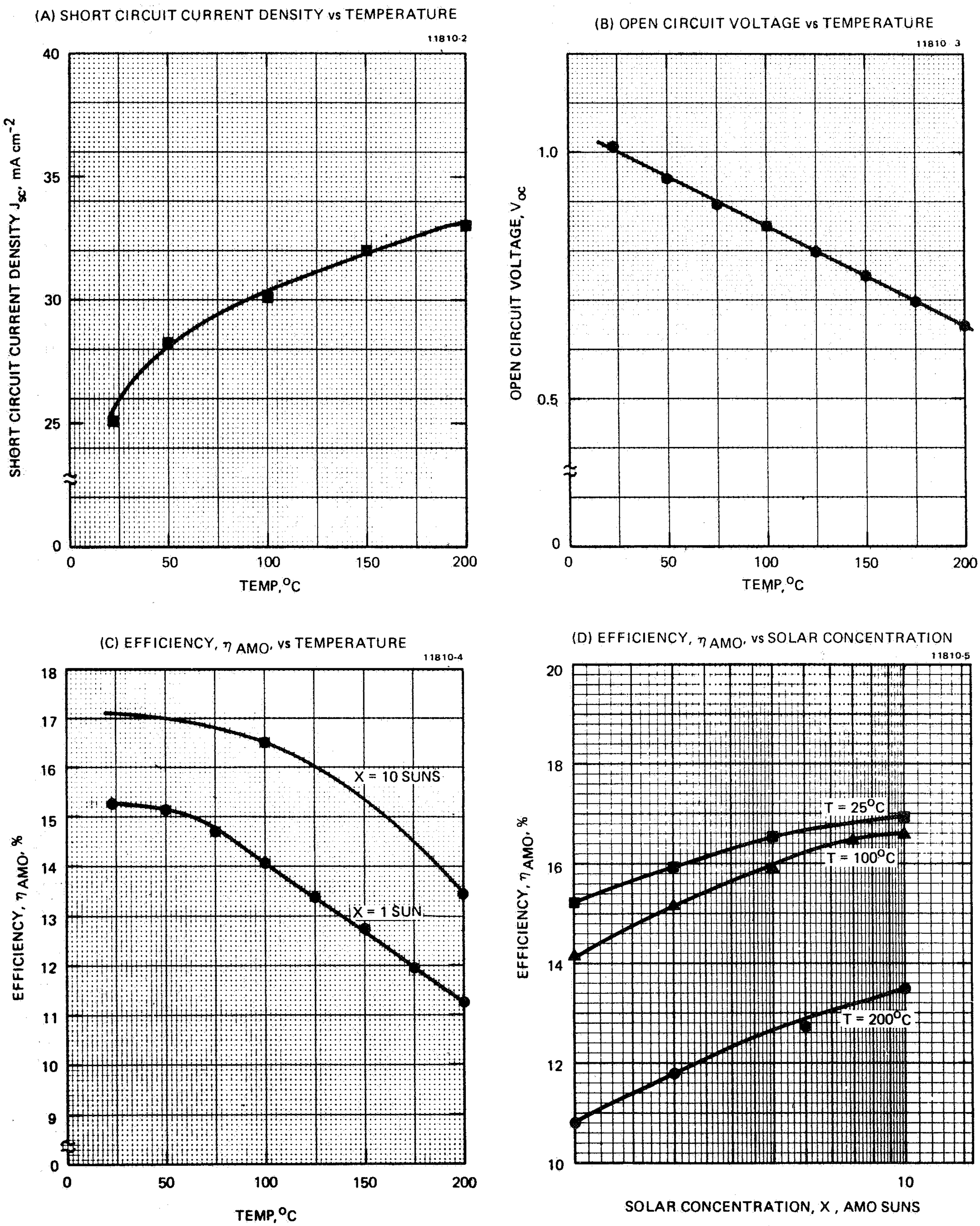


Figure 4. Large area 2 cm x 2 cm GaAs space concentrator cell characteristics.

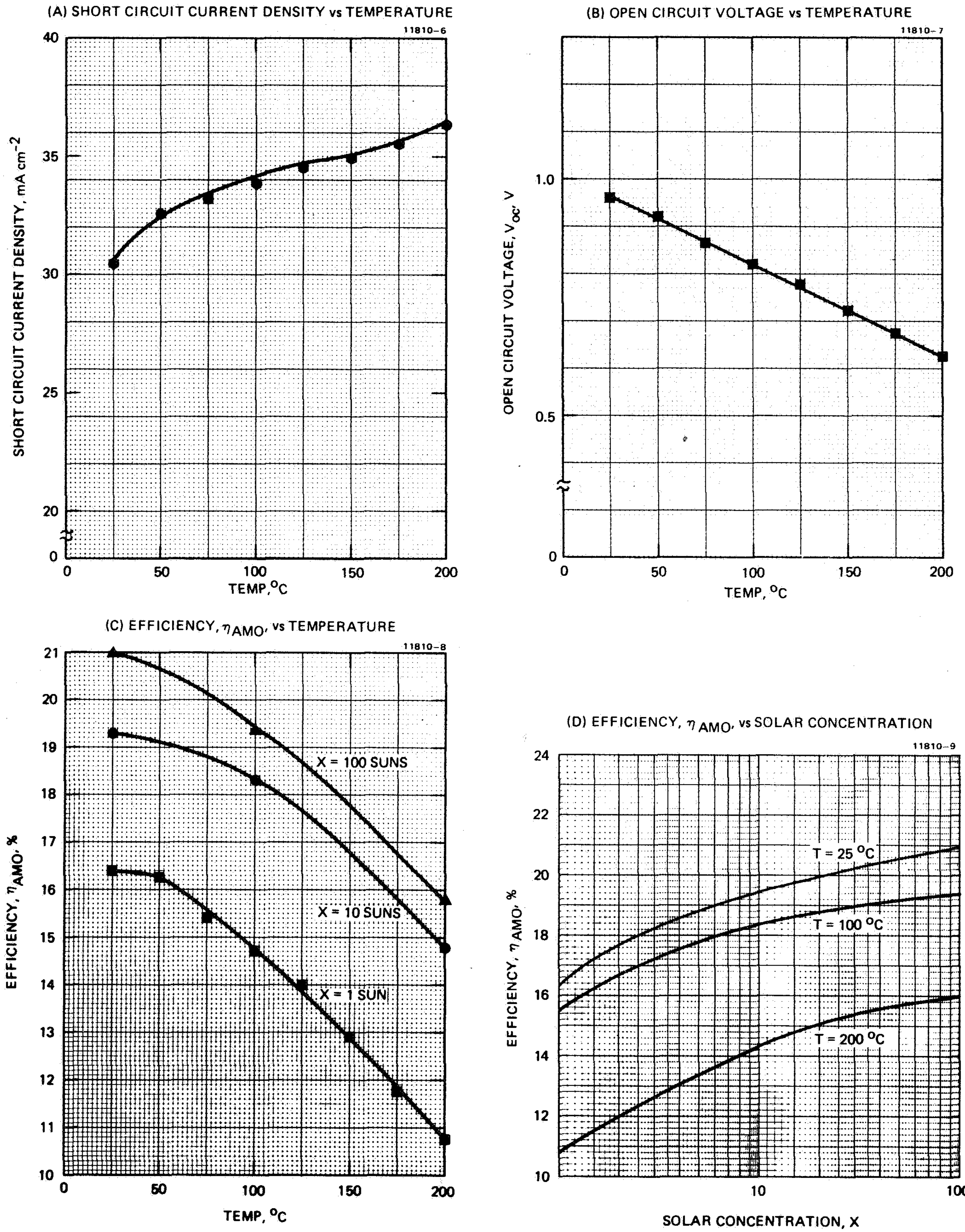


Figure 5. Small circular GaAs space concentrator cell characteristics.