High-efficiency AlGaAs/GaAs concentrator solar cells

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Efficiencies of 25% have been obtained with 1-cm-diam AlGaAs/GaAs heteroface concentrator solar cells utilizing an ultrathin AlGaAs window layer design. A low specific resistance ($<0.005\ \Omega\,cm^2$) Ohmic contact is achieved by direct contact to the *p*-GaAs active layer. Liquid phase epitaxy has been developed to grow <500-Å thick window layers on large-area (3.3×3.3 cm) GaAs substrates. Four 1-cm-diam cells are produced from each wafer and demonstrate the potential for larger-scale production.

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System studies[1,2] on concentrator photovoltaic systems clearly demonstrate the importance of high cell efficiency in reducing the overall cost of solar-electric generation. GaAs is near the optimum band gap for optimum photovoltaic conversion and has demonstrated high conversion efficiency.[3] The high cost of high-quality single-crystal concentrator cells requires that the cells operate under highly concentrated sunlight. One major obstacle facing the fabrication of concentrator solar cells has been the relatively high sheet resistance for the parallel combination of the top Ohmic contact and semiconductor layer. Prior work on AlGaAs/GaAs concentrator solar cells utilized a relatively thick heavily doped AlGaAs window layer to minimize the sheet resistance.[4,5] This thick window layer, however, reduces the cell quantum efficiency for wavelengths <5000 Å because of optical absorption in the window layer. In this paper, we report the design and successful demonstration of high-efficiency AlGaAs/GaAs concentrator cells based upon a thin AlGaAs window design which achieves near-theoretical performance. Terrestrial measurements on these cells have shown conversion efficiencies as high as 24.7% at 178 suns (AM1) and 21.7% at 900 suns.

The thin-window AlGaAs/GaAs solar cell design incorporates the following major design elements:

(1) An ultrathin (<500 Å) *p*-AlGaAs surface which reduces surface recombination losses with negligible optical absorption.

(2) A relatively thick *p*-GaAs active epitaxial layer with good electron diffusion length ($>5\ \mu m$) which reduces top layer sheet resistance yet still achieves high current collection efficiency.

(3) An efficient front contact grid design which directly contacts the active *p*-GaAs layer and reduces the cell series resistance.

(4) A broad-band two-layer antireflection coating which minimizes reflection losses.

The major advantage of using an ultrathin AlGaAs window layer is illustrated by the data of Fig. 1. Figure 1 shows the calculated internal collection efficiency versus wavelength for various AlGaAs layer thicknesses. Thick window layers result in loss of photoresponse at wavelengths $<0.5\ \mu m$ due to photogeneration in the AlGaAs layer and poor collection due to high surface recombination losses. By using an AlGaAs layer only 500 Å thick, there is negligible absorption in the AlGaAs and the near-perfect AlGaAs-/GaAs heterojunction interface eliminates the high surface recombination loss for all carriers generated in the *p*-GaAs layer. This results in efficient collection of photogenerated carriers down to ultraviolet wavelengths. The measured response on a liquid phase epitaxially grown cell structure is also shown in Fig. 1 and demonstrates that indeed an ultrathin AlGaAs epitaxial layer with a low-loss hetrojunction interface has been achieved.

Si_3N_4 is a good single-layer antireflection (AR) dielectric for GaAs; however, this results in $\sim12\%$ reflection loss for a thin-window AlGaAs/GaAs cell. In order to take full advantage of the broadband internal photoresponse described above, a two-layer AR-coating is required to reduce this external reflection loss. A two-layer coating consisting of 530 Å of Ta_2O_5 followed by 760 Å of SiO_2 is utilized,[3] which reduces reflection losses to $\sim4\%$.

The value of the cell series resistance becomes critical under high sunlight concentration. Figure 2 shows the effect of series resistance on cell performance as a function of con-

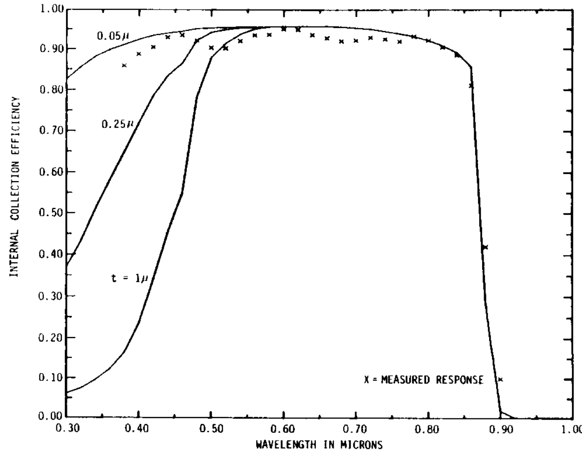

FIG. 1. Calculated internal collection efficiency curves for different GaAlAs layer thickness. Also shown are the measured response points after correction for reflection loss.

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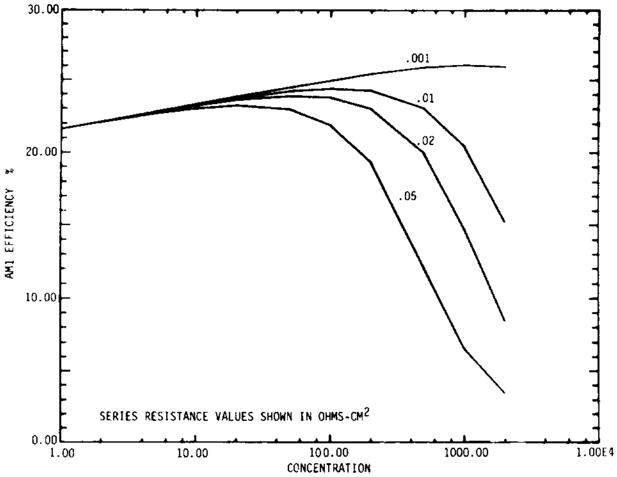

FIG. 2. Calculated GaAs concentrator cell efficiency as a function of concentration for a number of series resistance values.

centration level. For high-concentration high-efficiency operation (~1000 suns), the $R_s \times A$ product for the cell must be $< 10\ \mathrm{m}\Omega\ \mathrm{cm}^2$. Our approach to lower the series resistance is to use an efficient front contact grid design with a relatively thick *p*-GaAs active layer to which a direct Ohmic contact can be made. We have developed efficient grid designs for both the circular and rectangular concentrator cells.[6] Figure 3(a) shows the radial contact pattern for 1-cm-diam concentrator cells with 256 tapered grid lines leading to the outer contact ring. The average finger width is 6 μm with an average spacing of 92 μm. Figure 3(b) shows the details of the direct Ohmic contact to the *p*-GaAs active region. This contact requires photolithographic definition of the grid pattern and selective etching of the thin AlGaAs layer before the Ag-Zn contact metallization is evaporated. After contact alloying, the pattern is electroplated with Ag to a total thickness of 5 μm. This technique results in low specific contact resistance to the active cell region.

We have fabricated and tested a large number of concentrator cells with a 1-cm-diam illuminated area. The initial cell design had a contact pattern similar to that shown in Fig. 3(a) with 128 radial grid lines, while the most recent cells have 256 lines. Both front contact grid designs cover ~10% of the illuminated cell area. Several of these cells were calibrated for AM0 by NASA Lewis Research Center[7] on a high-altitude F-106 test flight. The best of these calibrated cells has short-circuit current of 23.49 mA, open-circuit voltage of 0.996 V, and a fill factor of 0.857, leading to an AM0 efficiency of 18.8% for a 1-cm-diam cell. These calibrated cells are used as standards for all of our test measurements.

High-concentration measurements on similar 1-cm-diam cells were made in natural sunlight at the Jet Propulsion Laboratory's test facility on Table Mountain, California. A portable cassagrain concentrator mounted on an equatorial mount in the tracking mode was used to obtain concentration levels up to 440 suns. The concentrator and measurement techniques are described in Ref. 6. Figure 4

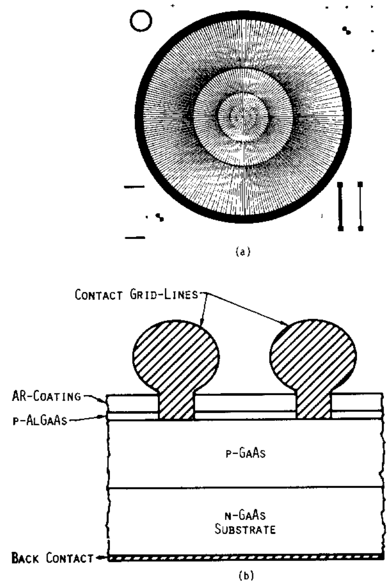

FIG. 3. (a) The front grid pattern for 1-cm-diam concentrator cell. (b) A section of the solar cell showing the Ohmic contact technique for the front grid.

shows the measured current-voltage (*IV*) characteristics for one of the best 128 grid line cells (No. 976). The cell temperature, as indicated by a thermocouple just under the center of the cell, was maintained at 50 °C with the cell operating at the maximum power point. Although the cell could have been operated at lower temperatures at the lower concentrations, a constant temperature was maintained so that cell performance as a function of concentration could be measured and the cell series resistance estimated from the set of *I-V* curves. The concentration ratio, the power conversion efficiency, and fill factor are indicated for each curve in Fig.

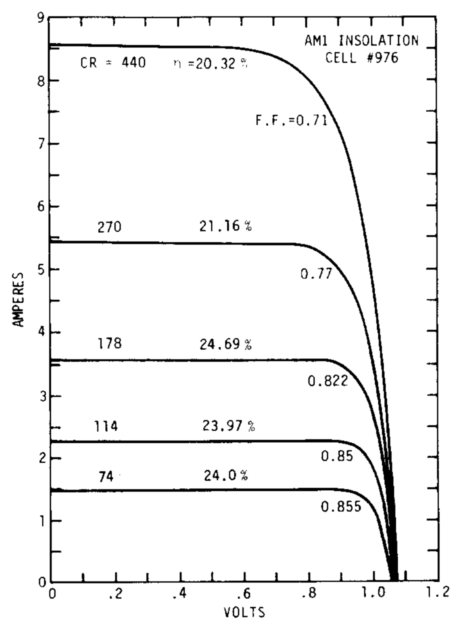

FIG. 4. *I-V* curves for concentrator cell No. 976 measured at Table Mountain, Calif. The cell temperature at the maximum power point was maintained at 50 °C for each curve.

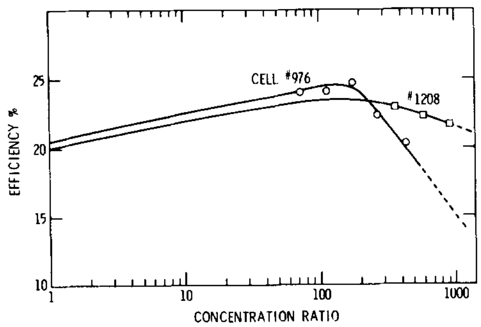

FIG. 5. Measured efficiency-vs-concentration data for cell No. 1208 with the 256-line grid pattern of Fig. 3(a) and cell No. 976 with an earlier 128-line grid pattern.

4. The highest measured cell efficiency was 24.7% at 178 suns (AM1). To our knowledge, this is the highest efficiency ever measured for any solar cell. At higher concentrations, the efficiency decreases because of fill-factor degradation due to a relatively high series resistance. The series resistance R_s value estimated[8] from this set of I-V curves is between 20 and 30 mΩ, giving a series resistance and cell area product ($R_s \times A$) of ~20 mΩ cm^2. In order to achieve high performance at higher concentration levels, the new 256-line pattern shown in Fig. 3(a) was generated and cells fabricated. Cells with this pattern were tested in our new solar-cell test facility[9] capable of reaching up to 2000 suns on 1-cm-diam cells. Figure 5 shows the efficiency-vs-concentration data obtained on one of these new cells (No. 1208) tested up to ~900 suns and compares it with the performance of the earlier cell shown in Fig. 4. Table I lists the measured values of the conversion efficiency and the fill factor at various concentrations for these two cells. The R_s value estimated from the I-V curves for cell No. 1208 with the new contact pattern is ~6 mΩ, giving a $R_s \times A$ value of ~4.7 mΩ cm^2. The relatively high efficiency (~22%) and fill factor for this cell do not show a significant fall off at the higher concentrations and demonstrate the improvement in series resistance realized with the new contact pattern. The efficiency-vs-concentration behavior of Fig. 5 compares well with the predicted behavior shown in Fig. 2.

TABLE I. Concentration dependence of the cell efficiency and fill factor.

Cell No.	Concentration	Efficiency (%)	Fill factor
	74	24	0.855
	114	24	0.85
976	178	24.7	0.822
(AM1, 50 °C)	270	21.2	0.77
	440	20.3	0.71
	365	22.5	0.856
1208	596	22.3	0.835
(AM2, 65 °C)	899	21.7	0.803

In summary, we have demonstrated that the thin-window AlGaAs/GaAs solar-cell design leads to high conversion efficiencies (~25%) and that an efficient grid design with direct Ohmic contact to the p-GaAs active layer leads to low series resistance ($R_s \times A < 5$ mΩ cm^2) yielding efficient cell operation at very high concentration levels.

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