Influence of Perimeter Recombination on High-Efficiency GaAs p/n Heteroface Solar Cells

PAUL D. DeMOULIN, MEMBER, IEEE, STEPHEN P. TOBIN, MEMBER, IEEE, MARK S. LUNDSTROM, MEMBER, IEEE, M. S. CARPENTER, AND MICHAEL R. MELLOCH, MEMBER, IEEE

Abstract—Perimeter recombination currents have been characterized for 0.5×0.5- and 2×2-cm^2 p/n GaAs solar cells. Measurements show that perimeter recombination dominates the $n = 2$ dark current component of these high-efficiency solar cells. The results also suggest that perimeter recombination will be substantial even in much larger area solar cells. Although little influence on open-circuit voltage is expected, perimeter recombination may adversely affect the cell's one-sun fill factor. Because of its importance to one-sun applications, recombination at the junction perimeter must be suppressed before GaAs solar cells approach their limiting conversion efficiencies.

I. INTRODUCTION

RECOMBINATION at surface space-charge regions typically controls the forward-biased current versus voltage characteristics of III–V diodes, but previous work has focused on relatively small (≤ 0.05 cm on a side) diodes [1], [2]. Gallium-arsenide solar cells, however, typically range in size from 0.5×0.5 cm^2 for cells intended for concentrator applications to 4×4 cm^2 for one-sun applications. The smaller size cells are also often used for diagnostics during process development. The record high conversion efficiencies now being reported for GaAs solar cells are due in part to the high material quality [3]. Because bulk recombination losses in such cells are so low, recombination along the mesa perimeter can control the dark current. In this letter we demonstrate that the $n = 2$ dark current component can degrade the one-sun performance of high-efficiency GaAs p/n heteroface solar cells. We also show that for 0.5×0.5- and 2×2-cm^2 solar cells the $n = 2$ current is typically dominated by perimeter recombination. Even for the larger, 4×4 cm^2 cells, perimeter recombination is expected to make a substantial contribution to the $n = 2$ current. These results are significant because they demonstrate the dominance of perimeter recombination in diodes more than 1000 times the area of those previously examined. The results show that perimeter recombination must be suppressed to increase the one-sun performance of GaAs cells. Perhaps as important is the demonstration

that the characteristics of the small-area cells typically used for diagnostics are dominated by perimeter recombination.

For high-quality GaAs solar cells with negligible series and infinite shunt resistance, the dark I–V characteristic is described by

$$I = I_{01}(e^{qV/kT} - 1) + I_{02}(e^{qV/2kT} - 1). \qquad (1)$$

Under high biases the $n = 1$ component dominates, whereas at low biases the $n = 2$ component is dominant. The $n = 2$ current is comprised of I_{02B}, the bulk space-charge component, and I_{02S}, the surface perimeter component. To assess the importance of the $n = 2$ current component, we consider a typical high-efficiency solar cell (cell number 1 in [4]). For that 0.5×0.5-cm^2 cell, the measured short-circuit current under an unconcentrated AM1.5 global solar spectrum was 26.39 mA/cm^2, the open-circuit voltage was 1.003 V, and the fill factor was 0.840 [4]. The conversion efficiency of the cell was 22.2 percent, and the saturation current densities were $J_{01} = 1.65 \times 10^{-19}$ and $J_{02} = 2.80 \times 10^{-11}$ A/cm^2. All measurements were performed at 25°C. At open-circuit voltage for one-sun illumination, the $n = 2$ current comprised 34 percent of the dark current; at the maximum power point ($V_{mp} = 0.894$ V) it accounted for 83 percent. The $n = 2$ current primarily affects cell performance by limiting the fill factor. The theoretical fill factor computed from the measured short-circuit current, series resistance (1.8 Ω), and using the $n = 1$ current component alone was 0.873, significantly higher than the measured value of 0.840. When the $n = 2$ current component is included, however, we compute a fill factor of 0.837, which is in good agreement with the measured value. The conclusion is that the cell's fill factor is lowered by the $n = 2$ current; if it could be suppressed, the one-sun efficiency of this cell would rise to 23.0 percent, which is a sizable increase.

This example serves to illustrate that the $n = 2$ current component can degrade the one-sun performance of high-efficiency cells. Having established the importance of the $n = 2$ current component, we now turn to the problem of identifying its source. In deep-level transient spectroscopy (DLTS) experiments on a variety of solar cells conducted during the course of one year, no correlation between the observed trap densities and the $n = 2$ current component could be found [5]. This observation led to the suspicion that the $n = 2$ current on small test diodes was dominated by

periphery current. The measured I–V characteristics of specially fabricated small-area test diodes with various perimeter-over-area ratios roughly confirmed this suspicion [5]. As a result, a set of experiments was designed to gauge the significance of perimeter recombination on much larger area solar cells.

II. EXPERIMENT

The dark current versus voltage characteristics of several diodes fabricated on films grown by metal-organic chemical vapor deposition (MOCVD) were examined. The layer thicknesses and doping densities of the diodes used in this study are shown in Fig. 1. The n-type dopant was silicon and the p-type zinc. For the first experiments reported below, the GaAs cap layer was present; solar cell fabrication is completed by etch-removing the GaAs cap layer between the metal grid lines and then depositing an anti-reflection coating. Details of film growth and cell processing are described in [4]. We note that the diodes were isolated by mesa etching in a solution of $HCl:H_2O_2: H_2O$ in a ratio of 1:1:2.

To characterize the $n = 2$ current, we compared the I–V characteristics of 0.5×0.5-cm^2 diodes with those of adjacent 0.5-cm $\times$ 310-μm test resistors. After measuring the I–V characteristic, I_{02} was extracted by curve fitting. The results for diodes on two different wafers at $25°C$, displayed in Table I, show that I_{02} of the solar cell was on average 2.1 times I_{02} of the resistor. The area of the solar cell is 16 times that of the resistor, and the perimeter of the solar cell is 1.9 times bigger. The data show therefore, that the measured I_{02} scales with perimeter and strongly suggest that perimeter recombination controls I_{02} in these devices.

The perimeter recombination saturation current can be written as [1]

$$I_{02S} = J_{02S}P = qn_i S_{SCR}L_s P \qquad (2)$$

where S_{SCR} is the surface-recombination velocity in the space-charge region at the perimeter, and L_S has been termed the surface diffusion length [1]. The saturation current density due to recombination in surface space-charge regions is J_{02S} in amperes per centimeter, and P is the perimeter length. By equating the measured I_{02} to (2), a value of $S_{SCR}L_S$ can be deduced; we find values of 3.2 and 3.8 cm^2/s for $S_{SCR}L_S$ on wafers 894 and 1048, respectively, which corresponds to J_{02S} = 0.95–1.1 pA/cm. These results are in general agreement with those reported by other workers [1], [2].

A second experiment to confirm the importance of perimeter recombination in these devices was also conducted. The application of $Na_2S \cdot 9H_2O$ on bare GaAs surfaces has been shown to substantially lower the surface recombination velocity [6]–[8]. When this solution was applied to the 0.5×0.5-cm^2 cells by spin-coating, the measured I_{02} was reduced to 60 percent of its original value, which confirms the importance of perimeter recombination. Before application of $Na_2S \cdot 9H_2O$, the measured I_{02} of this solar cell was 1.9 times that of the adjacent test resistor, which is exactly the ratio of the perimeter of the solar cell to that of the resistor. After treatment with $Na_2S \cdot 9H_2O$, however, the current ratio was 4. Since the area ratio was 16, these results indicate that
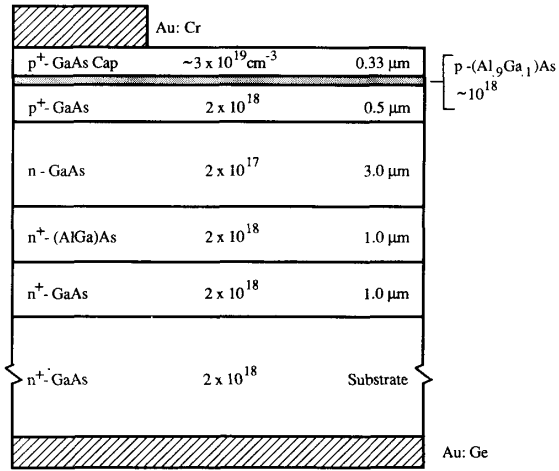

Fig. 1. Structure of the p/n heteroface solar cell and test resistor.

TABLE I
RESULTS OF THE I–V MEASUREMENTS (25°C) FOR CELLS AND RESISTORS ON TWO DIFFERENT WAFERS

ID	I_{02}(cell)	I_{02}(cell)/I_{02}(res)
1-894	0.21×10^{-11} A	2.0
3-894	0.19×10^{-11}	1.8
6-894	0.20×10^{-11}	2.1
8-894	0.19×10^{-11}	1.9
2-1048	0.31×10^{-11}	2.6
6-1048	0.24×10^{-11}	2.0
11-1048	0.24×10^{-11}	2.0
average	-	2.1

perimeter recombination was suppressed, but that the treatment did not completely eliminate it.

A third experiment to explore the perimeter recombination component in larger area solar cells was also performed. On two wafers with epitaxial layers grown by MOCVD at the same time, 0.5×0.5- and 2×2-cm^2 cells were fabricated. The average I_{01} of the large cells was 17.6 times that of the small cells, but the average I_{02} of the large cells was 4.7 times that of the small cells. Since the area of the large cells was 16 times that of the small cells and their perimeter was four times as large, these results show that the $n = 1$ current scales with cell area while the $n = 2$ current scales with cell perimeter. The results indicate that the $n = 2$ current of 2×2-cm^2 cells is also dominated by recombination in the perimeter space-charge region. By expressing the average $n = 2$ current as

$$I_{02} = J_{02B} \cdot A + J_{02S} \cdot P$$

values of $J_{02B} = 0.8$ pA/cm^2 and $J_{02S} = 1.2$ pA/cm for the 25°C bulk and perimeter saturation currents were deduced. This perimeter current agrees well with that obtained from the data in Table I for 0.5×0.5-cm^2 cells and adjacent test resistors.

III. DISCUSSION AND CONCLUSIONS

The measurements reported above demonstrate that for high-quality solar cells, perimeter recombination may control the $n = 2$ current in cells up to 2×2 cm^2. For the larger area 4 × 4-cm^2 cells being developed for space applications, the relative contributions of bulk and surface recombination can be estimated from the bulk and surface saturation current densities computed above. Using those numbers, we project that 75 percent of the $n = 2$ current in 4×4-cm^2 cells will be due to surface recombination. The surprisingly large influence of perimeter recombination in large-area GaAs solar cells underscores the need for careful treatment of the mesa edges. The quality of GaAs surfaces is highly variable; much higher edge currents have been observed in our laboratory and reported in the literature [2]. Even for very large-area solar cells, careful preparation of the mesa edges is essential to maintain cell performance.

In conclusion, we have demonstrated that the performance of high-efficiency GaAs, p/n heteroface solar cells is often degraded by the $n = 2$ current. The work described in this letter shows that the $n = 2$ current component is dominated by recombination along the mesa perimeter. Even for large area, 4×4-cm^2 cells, the perimeter recombination is dominant. Careful treatment of edges will be essential for maximizing the one-sun efficiency of GaAs solar cells. When cells are operated under concentrated sunlight, however, the $n = 2$ current component has little effect on cell performance. But it is important to realize that the small-area cells often used for diagnostics are controlled by perimeter recombination, so projections of cell performance based on such measurements may be misleading. Diagnostics should, whenever possible, be performed on large-area solar cells themselves, rather than on nearby test diodes. This observation was the motivation for a modified DLTS technique recently devised to analyze solar cells directly [5].

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