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RADIATION DAMAGE IN HIGH-RESISTIVITY SILICON SOLAR CELLS

I. Weinberg, C.K. Swartz, and C. Goradia*
NASA Lewis Research Center
Cleveland, Ohio

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High-resistivity silicon solar cells exhibit reduced radiation damage when light is incident on the gridded back surface. Under back illumination, radiation damage decreases as cell resistivity increases; under front illumination, radiation damage increases as cell resistivity increases. Thin (50 μm) back-illuminated cells outperform conventional 10-Ω-cm 50 and 200 μm cells at low 1-MeV electron fluences. However, at higher fluences, the conventional cells exhibit superior radiation resistance. This is attributed to the low BOL diffusion lengths observed in the thin, back-illuminated cell. These results are discussed in terms of injected charge distributions, electric fields in the cell base, and the effects of a dominant boron-oxygen defect.

INTRODUCTION

The motivation for investigating radiation-damage effects in high-resistivity silicon cells stems from the fact that, at low resistivities ($\rho < 20$ Ω-cm), radiation damage decreases as cell resistivity increases. Thus, it was our initial expectation that the effects of radiation could be decreased by increasing the p-base resistivity of n^+pp^+ silicon solar cells. Unfortunately, when, after electron irradiation, the cells were illuminated in the conventional way (light incident on the n^+ side, or front illuminated), the opposite effect occurred (fig. 1). Since the cells were provided with gridded metallic contacts on both the n^+ and p^+ faces, light could be incident on either the front or back. In this respect, for high enough cell resistivities, radiation damage decreased when the cell was back illuminated (ref. 1). This effect was demonstrated previously for a 1250-Ω-cm cell (ref. 1). In the present study, these results are extended to 800- and 8000-Ω-cm, 250-μm thick cells, and performance data are presented for a back-illuminated, 8000-Ω-cm, 50-μm-thick cell. The mechanisms responsible for the observed effects are discussed.

EXPERIMENTAL RESULTS

All cells were n^+pp^+ with gridded front and back contacts and p-base resistivities of 84, 800, 1250, and 8000 Ω-cm, respectively. Details of cell fabrication are contained in reference 1. The behavior of P_{max} after irradiation by 1-MeV electrons is seen in figure 2 for the 84- and 8000-Ω-cm cells. When the difference between front and back illumination is considered, the 84-Ω-cm cell is less degraded when it is front illuminated. However, for the 8000-Ω-cm cell, the degradation is less under back illumination. The data for all cell resistivities, including a 10-Ω-cm conventional cell, are summarized in figure 3. In general, for front-illuminated cells in the resistivity range shown, the radiation-induced degradation increases with cell resistivity. However, for cells with resistivities

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*Department of Electrical Engineering, Cleveland State University above several hundred Ω-cm, the degradation decreases with increasing resistivity when the cells are back illuminated.

DISCUSSION

In order to understand these effects, we first examined the injected minority carrier charge distribution in the cell base. Figure 4 shows the calculated injected charge distribution for a 1250-Ω-cm cell. The charge distributions show that the total injected minority carrier charge is greater when the cell is back illuminated. For the present cells, the increase in carrier concentration varies as much as an order of magnitude. This implies that the cell base resistivity and therefore the ohmic voltage drops are less when the cell is back illuminated, a fact which is confirmed by detailed calculations (ref. 1). The increased charge concentration results essentially from an increase in charge at the pp^+ junction. Schwartz (ref. 2) has shown that an electric field in the cell base tends to draw minority carriers away from the pp^+ junction. We have calculated the electric field using the expression

$$E = \left[q(n\mu_n + p\mu_p)\right]^{-1} \left[J - kT(\mu_n - \mu_p)\left(\frac{d\Delta n}{dx}\right)\right] \qquad (1)$$

where J is total cell current, μ_n and μ_p the electron and hole mobilities, n and p the carrier concentrations in the cells p-base, and Δn the injected minority carrier concentration in the p region. Since $d\Delta n/dx$ changes sign, it is obvious that the second term in brackets will have opposite signs under front and back illumination. Figure 5 shows the results of a calculation of E using the data of figure 4 in equation (1). The field is considerably decreased in the back-illuminated condition. This results in a decreased tendency for the field to draw charge away from the pp^+ junction. The net result is an increased injected charge in the p region and, consequently, a decreased ohmic drop in the cell base under back illumination.

As shown in figure 3, the ohmic drop is the dominant loss mechanism for all but the 10- and 84-Ω-cm cells. Although ohmic effects are nontrivial in the 84-Ω-cm cell, loss in collection efficiency is the dominant cell-degradation mechanism. Hence, this cell performs better under front illumination. For the higher-resistivity cells, the ohmic voltage drop in the p-base, which is the dominant loss mechanism, decreases under back illumination, and less degradation occurs than when the cell is front illuminated. On the other hand, under front illumination, the decrease in cell output with increased resistivity is due to the increased ohmic drop.

The decreased degradation, with increased resistivity, observed under back illumination is due to the decreasing boron concentration in the cell as resistivity increases. Previous results have shown that a radiation-induced boron-oxygen defect is the principal cause of cell degradation (ref. 3) and that the concentration of this defect decreases with decreasing boron concentration (ref. 4). Since ohmic drops are less significant under back illumination, the effects of decreasing boron concentration result in decreased degradation as resistivity increases. Figure 3 shows that this effect begins to saturate at the highest resistivities. Thus, it appears unlikely that the degradation will decrease significantly above 8000 Ω-cm. Obviously, however, for the present cells, as resistivity increases, radiation resistance increases under back illumination.

To optimize this latter effect, we have utilized thin, high-resistivity, back-illuminated cells. The results for an 8000-Ω-cm, 50-μm-thick, back-illuminated cell are presented in figure 6. This figure also shows, for comparison, performanc data for conventional, front-illuminated, thin and relatively thick 10-Ω-cm cells (ref. 5). At the lower fluences, the thin, back-illuminated cell shows improved performance over the conventional cells. At the higher fluences, however, the base diffusion length becomes comparable to cell thickness and degradation occurs. It is noted here that the BOL diffusion length in the thin, 8000-Ω-cm, back-illuminated cell was 120 μm. This length is much lower than the diffusion length (450 μm) we observed at BOL for the thicker high-resistivity cells. Hence, increases in diffusion length for the thin high-resistivity cell should result in superior performance over a greater portion of the fluence range than that shown in figure 6.

CONCLUSIONS

By considering the effects of electric fields in the cell base, and their effect on the ohmic voltage drop, we have contributed to an understanding of the decreased degradation encountered by back-illuminated, high-resistivity cells. Thi effect occurs for cell resistivities above several hundred Ω-cm. Below this resistivity range, loss in collection efficiency begins to dominate and the back illuminated cells show more degradation. The increased degradation for front illumination, with increasing cell resistivity, is attributable to the ohmic voltage drop in the cell base. For the back-illuminated, high-resistivity cells, the decreased degradation with increasing resistivity is attributed to the decreasing importance of the ohmic drop and the decreasing boron content.

From these results, it appears unlikely that one can increase indefinitely the radiation resistance of thick silicon solar cells by increasing the base resistivit above 8000 Ω-cm. However, the present results for the thin, 8000-Ω-cm, back-illuminated cell indicate that, with improved processing, this cell should outperform the conventional cells at higher fluences.

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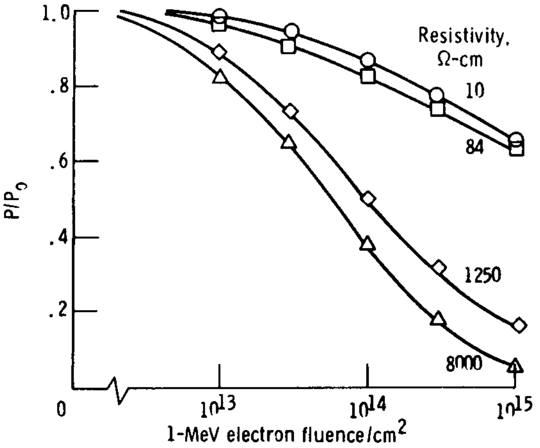

Figure 1. - Normalized maximum power for front-illuminated cells. Thickness, 250 μm.

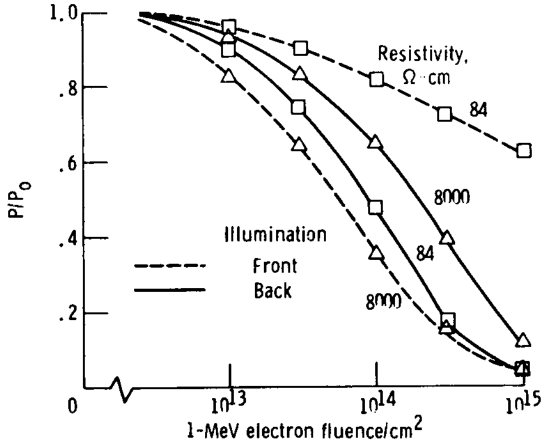

Figure 2. - Normalized maximum power for front- and back-illuminated high-resistivity cells.

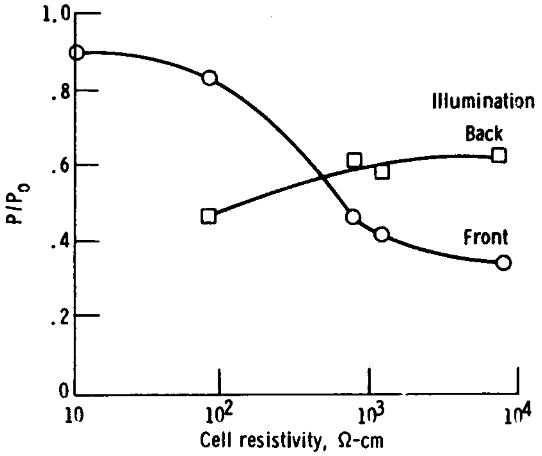

Figure 3. - Normalized maximum power for n^+pp^+ back- and front-illuminated cells after 1-MeV electron irradiation. Fluence, 10^{14}/cm^2; thickness, 250 μm.

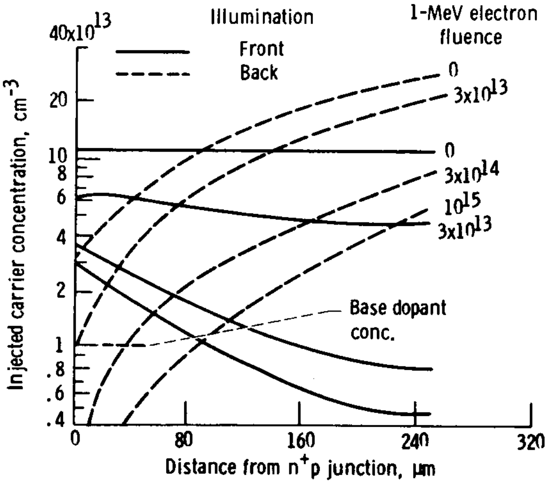

Figure 4. - Injected minority carrier concentration in p region of 1250 Ω-cm cell.

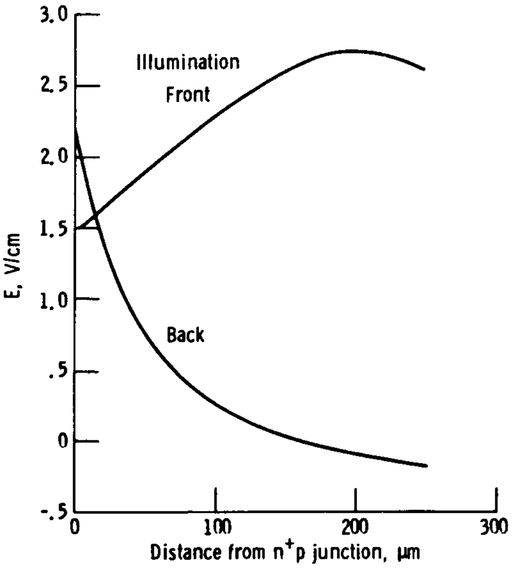

Figure 5. - Calculated electric fields in cells p region Resistivity, 1250 Ω-cm; thickness; 250 μm.

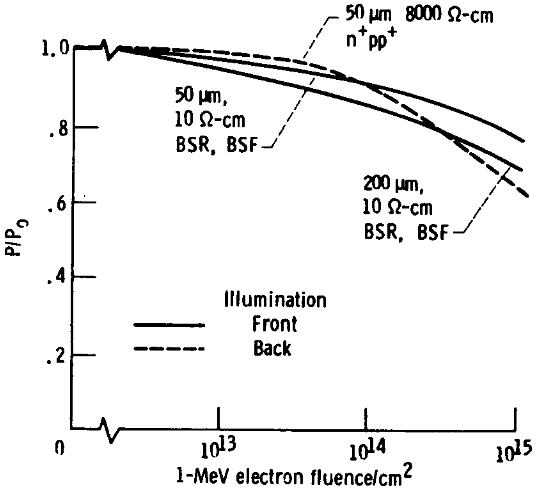

Figure 6. - Comparison of thin, back-illuminated, high-resistivity silicon cell with conventional cells.