Silicon Point Contact Concentrator Solar Cells

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Abstract—**Experimental results are presented for thin high resistivity concentrator silicon solar cells which use a back-side point-contact geometry. Cells of 130 and 233 μm thickness were fabricated and characterized. The thin cells were found to have efficiencies greater than 22 percent for incident solar intensities of 3 to 30 W/cm^2 (30-300 "suns"). Efficiency peaked at 23 percent at 11 W/cm^2 measured at 22-25°C. Strategies for obtaining higher efficiencies with this solar cell design are discussed.**

I. INTRODUCTION

THIS LETTER presents new results from back-side point contact Si solar cells of the type first reported by Swanson *et al.* [1]. These cells differ from conventional solar cells in that both n- and p-type diffusions and contacts are alternated on gridpoints on the back face of the cell. The areas of these diffusions and the contacts to the diffusions are minimized towards the limit of point contacts. This design benefits from the advantages shown for backside cells such as the elimination of shading loss from a front grid, decreased metal series resistance, and additional freedom in the choice of emitter profile since the diffusions are far from the regions of maximum photogeneration [1], [3].

The surface, bulk, and contact recombination must be minimized in order to operate these cells at high carrier densities while maintaining the quantum efficiency. The high carrier densities minimize the base resistive voltage drop and result in a high output voltage. The point contact design with a high resistivity base has been shown to approach these goals in silicon thermophotovoltaic cells [4]. The design was optimized for use in back-side contact concentrator solar cells using a quasi-three-dimensional model [2], which resulted in a 20-percent efficient cell at 8.8 W/cm^2 [1].

A version of this cell with a simplified metallization has been developed and used to optimize and study this design. Experimental results for cells 130 and 233 μm thick are reported here.

II. FABRICATION

The cells were built on ⟨100⟩ float zone n-type 100–200-Ω·cm wafers. The p and n diffusions were formed by diffusion from boron and phosphorus doped SiO_2 at 1120°C for 2 h. This resulted in sheet resistivities of 5 and 6 Ω/□ for the n and p diffusions, respectively. The finished cell has a low surface recombination velocity oxide on both the front and back which was grown in dry oxygen with 2-percent TCA for 130 min at 1000°C followed by an argon anneal [5]. This provided an 1120-Å antireflection layer on the front of the cell. The contacts were Al contacts annealed in forming gas for 10 min at 380°C. The resulting specific contact resistivities were 1-2 × 10^{-6} Ω·cm^2 for both the n- and p-type contacts.

A single-level Al metallization was used which consists of two meshed combs extending from opposite sides of the cell. To minimize the series resistance which results from long Al lines, a small cell size, 3 by 5 mm, was used. The contact and diffused region sizes and spacing were chosen by utilizing a quasi-three-dimensional model and were unchanged from [1]. A cross section of the device indicates these dimensions (Fig. 1.).

III. RESULTS

The illuminated current versus voltage characteristics were obtained using a four-point electrical measurement in sunlight concentrated by front surface mirrors. The cells were cooled during testing by spraying water directly onto the cell back side. Additional testing used incident light chopped to minimize cell heating and eliminate the necessity of water cooling. The absolute power for the incident sunlight was found by comparing the power of the incident beam measured with a black-body calorimeter to an equivalent heat flow produced by resistive heating in the calorimeter.

The plots of efficiency versus incident power for both cells are shown in Fig. 2. Notice the faster dropoff in efficiency at high incident intensities for the thick cell as compared to the thin one. This effect is a predicted result of the bulk Auger recombination due to the higher front-side carrier densities associated with thicker cells [1], [2]. Two curves of current versus voltage for each cell are shown in Fig. 3 with some key features collected in Table I. The series resistance was found to be 26 mΩ by fitting the dark current versus voltage characteristics. It can be attributed entirely to the resistance of the 1-μm-thick metal lines.

The average Shockley–Read–Hall carrier lifetimes in the wafers were measured before the metallization step using a photoconductivity method similar to that of Curtis and Verkuil [6]. This procedure provides a nondestructive process monitoring of the actual device wafers at several points during the fabrication. The lifetime measured by this technique can be related to the bulk base recombination lifetime τ, and the surface recombination velocity S. When two or more wafers of identical τ and S but different thicknesses W are measured, then

$$\frac{1}{\tau_{\text{measured}}} = \frac{1}{\tau_{\text{base,SRH}}} + \frac{2S}{W}$$

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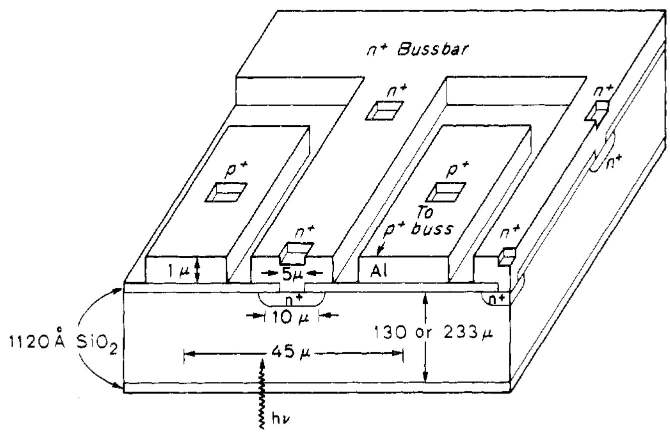

Fig. 1. A cross section of a portion of the solar cell near the Al bussbar that collects current from the n^+ diffusions. The dimensions for the p^+ and the n^--diffusions are the same.

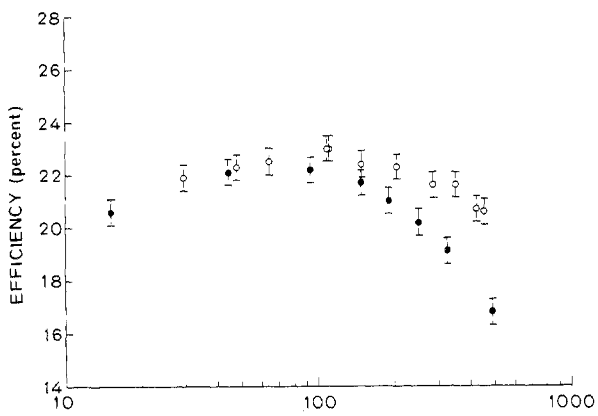

Fig. 2. The efficiency versus incident intensity for a 130- (upper curve with open circles) and a 233-μm cell (filled dots).

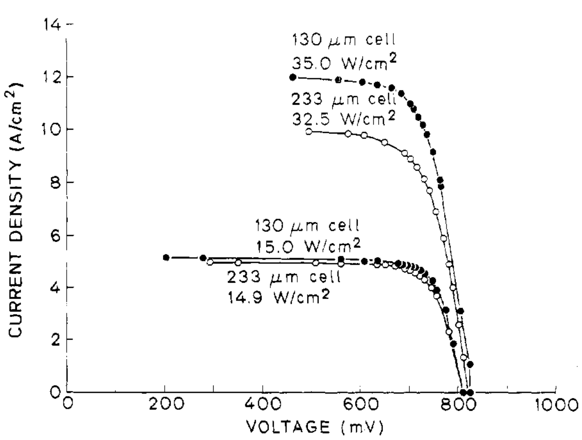

Fig. 3. Current density versus voltage curves for a 130-μm cell (filled dots) and a 233-μm cell (open dots). Intensities near 15 and 35 W/cm² are shown to illustrate the performance at high intensities.

TABLE I
CELL CHARACTERISTICS FOR THE CURRENT DENSITY VERSUS VOLTAGE CURVES SHOWN IN FIG. 3

Cell Characteristics, cell area = .15 cm²				
Cell Thickness (microns)	130	233	130	233
Incident Power (suns ±1%) (1 sun = .1 watt/cm²)	150	149	350	325
V_{oc} (±5 mV)	810	810	825	820
I_{sc} (±0.5% A/cm²)	5.17	4.98	12.0	9.97
V_{mp}(±8 mV)	704	701	701	690
I_{mp} (±1% A/cm²)	4.83	4.67	11.0	9.15
Fill Factor (±1.0%)	.81	.81	.78	.77
Cell Mount Temp. (±1.0°C)	24	22	23	23
Efficiency (±0.5) (Calibrated Calorimetrically)	22.4%	21.7%	21.6%	19.1%

for low carrier densities where τ is independent of carrier concentration [7], [8]. The bulk lifetime obtained in this way was 1.5 ms with a surface recombination velocity of 14 cm/s. These results are consistent with expected values [7].

The contact recombination was determined from the dark characteristics. The reverse saturation current was 9×10^{-14} A/cm². This includes an average of the effect of the n- and p-type diffused regions. This J_0 is lower than the values normally seen for sheet diffusions because of the reduction resulting from the low back surface coverage fraction of the diffusions in the point contact geometry. Most of the back surface area is covered by a low surface recombination velocity passivating oxide over an undiffused region.

IV. DISCUSSION

The efficiencies reported here are the highest reported for a silicon solar cell. Modeling of this cell indicates that efficiencies near 28 percent at 60°C should be possible with this existing technology and efficiencies in the low 30-percent range may be possible in an ideal cell [2]. The dropoff in efficiency of the thin cell at high intensity corresponds to the measured value of the series resistance, 26 mΩ, attributed to the metal lines. The more fundamental mechanisms expected to contribute to this rolloff are contact recombination and Auger recombination. Cells with reduced metallization series resistance are currently being fabricated to further investigate the thickness dependence by approaching the predicted optimum cell thickness of 60–75 μm [2].

A significant improvement in efficiency will result from an improved antireflection scheme. An implementation of a texturized cell with an optimized antireflection coating could improve the optical absorption by 20 percent over a cell with a 1/4 wavelength antireflection layer of SiO_2 as reported here. This could boost a 23-percent efficient cell above 27 percent.

V. CONCLUSION

Unconventional Si concentrator solar cells have been fabricated and characterized. These cells have back-side point contacts and are designed to operate at high carrier densities. This requires that recombination mechanisms in the cell be minimized using careful processing. The contact recombination was minimized by the reduced contact coverage fraction inherent in the point contact design as well as the deep diffusion profiles. The efficiencies of these cells were found to exceed 22 percent for 3–30 W/cm^2 of incident sunlight near 22°C and exhibit higher efficiencies at high concentrations than previously reported in silicon cells. A 130-μm cell shows efficiencies in excess of 20 percent at 500 suns (50 W/cm^2). The efficiencies of the best cells are limited at high concentrations primarily by the series resistance of the metal lines which was not optimized in this experiment. These results are for cells with a simple antireflection coating which can be substantially improved.

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