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PROCESSING AND CHARACTERIZATION OF HIGH-EFFICIENCY SILICON SOLAR CELLS FOR SPACE

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Silicon solar cells with AMO efficiencies ranging from 17 to 17.7% are described. These cells were processed on low-resistivity FZ substrates using techniques recently developed for high-efficiency terrestrial silicon solar cells. Not surprisingly, preliminary results indicate that the JPL high efficiency cell is more susceptible to radiation damage in that it retains a smaller proportion of its original power output when compared to conventional space cells after exposure to 5×10^{14} 1 MeV electrons. However, the JPL cell does maintain a greater overall power output than the conventional cells to which it was compared. Furthermore, this cell does not demonstrate post-electron irradiation photon decay as has been described for cells processed on 1-10 ohm-cm float zone silicon.

INTRODUCTION

To meet NASA goals for high performance, arrays of 300 W/kg will require thin solar cells with BOL efficiencies >20%, or thin film devices with equivalent power-to-weight ratios (ref. 1). A number of technologies such as GaAs, thin film multijunction cells, indium phosphide and a-Si:H show promise of meeting or exceeding these goals and are currently in various stages of development.

Until these technologies mature, however, silicon will continue to be the workhorse of the space photovoltaics industry. This is most likely to be the case for some time and silicon should be expected to maintain a place in spacecraft power systems even as other technologies begin to prove themselves as viable alternatives.

The theoretical maximum efficiency for a silicon solar cell at AMO is between 21 to 24%. Actual achievable efficiency will be considerably lower, but it is probably not unrealistic to strive for 18 to 19%. Recently, considerable progress in increasing terrestrial silicon solar cell efficiency has been made. JPL's DOE-supported efforts have resulted in silicon solar cells with AM1.5, global efficiencies as high as 20%. At AMO, these same cells measure 17.7%.

These cells, although initially designed primarily for terrestrial use, may conceivably find application in space. This paper will describe the design and processing of the JPL high-efficiency cell. Also discussed, will be preliminary tests of these cells to moderate 1 MeV electron radiation and comparison to conventional space cells. Post-electron irradiation photon degradation will also be discussed.

DESIGN AND PROCESSING

The JPL high-efficiency silicon solar cell incorporates many of the recent developments in solar cell processing technology designed to reduce minority carrier recombination in the bulk, at the front surfaces and under the contacts. Figure 1 is a diagrammatic view of the JPL high-efficiency cell. The structure of this cell is similar to the microgrooved PESC cell reported by Green, et al. (ref. 2), in that the contacts rest on mesas above a textured surface. The mesas offer two advantages. One is that since the surface is not textured, it reduces the total surface area contacted by the metal. The other advantage is that they aid in the alignment of the masks during various photolithography steps.

Following texturing, the N-type emitter is formed using a phosphine source at 825°C. Total diffusion time is 15 minutes. After removing the diffusion glass, the wafers are oxidized at 900°C in an atmosphere composed of 94.5% N_2, 4.5% O_2, and 1% HCl. This step results in an oxide that has been measured on planar <100> surfaces to be 100-120 Å thick. Following oxidation, the wafers are annealed at 600°C for one hour. The furnace is then cooled to 450°C. After cooling, the wafers are kept at 450°C for one hour, and then pulled from the furnace. This annealing step was chosen because it has been found to recover the minority carrier lifetimes in float zone ingots after high temperature treatments (ref. 3).

Ohmic back contacts are formed by electron beam evaporation of Al, Ti, Pd and Ag followed by a 20 minute sinter at 490°C in hydrogen. Front contact to the cells is made by opening 4-μm-square contact windows in the oxide and then evaporating the Ti, Pd and Ag grid lines and bus bar over the windows. These windows were spaced at 50, 100, 200 and 400 μm centers for each of the four cells processed on an individual wafer. This spacing results in actual contact areas of 0.575 to 0.075% of the total cell surface. Table I lists the spacing percent contact area for each cell measured. Shadowing from the front contact grid amounts to approximately 3.3% of the total cell surface.

The primary purpose for varying the contact area was to determine the effect of contact area on V_{oc} and series resistance. From Table I, V_{oc} does not show the expected increase with decreasing contact area. This may be because recombination in the base and emitter, along with band bending effects have begun to dominate so that recombination under the contacts is no longer relevant. As can be seen from the fill factors in Table I, series resistance does not increase with decreasing area.

RADIATION TESTS

To gain some understanding of the extent to which these cells might degrade in the space environment, cell 2B from Table 1 was irradiated with 5×10^{14} 1 MeV electrons. Light I-V data for this cell is summarized in Table II.

The power degradation of the JPL cell was compared to that of two types of cells routinely used in space photovoltaic arrays (ref. 4). K6-3/4 is a 2-mil cell with a dual layer AR coating. K7 is similar in design to the JPL cell in that it is textured, has a dual layer AR coating and is 8 mils thick. Both K6-3/4 and K7 were fabricated on 10 ohm-cm base material and have back surface fields and reflectors.

Figure 2 exhibits the power loss of cells K6-3/4 and K7 through a range of 1 MeV electron fluences along with the JPL cell before and after 5 x 10^{14} 1 MeV electrons. Cells K-6/34 and K7 retained 75 to 85% of their original power. The JPL cell exhibits considerably more deterioration in that it maintains only 67% of its original power output. Nevertheless, the power output of this cell is still 2.3% greater than for cell K6-3/4 and 4.3% greater than cell K7.

Float zone silicon has not typically been used on space arrays in part because of the additional photon degradation observed for devices made on 1-10 ohm-cm FZ material (ref. 5). Even though devices processed on float zone material may initially demonstrate higher performance than devices made on Cz material, after electron irradiation, the performance of the float zone devices deteriorates to where they are comparable to Cz devices after photon irradiation. Therefore, Cz is the material of choice since it is less costly and easier to obtain.

Photon degradation was also expected for the JPL cell. Table II summarizes the light I-V data for cell 2B following a 24-hour photon irradiation period carried out after 5 x 10^{14} 1 MeV electron irradiation. Surprisingly, no further degradation is observed for this cell processed on low-resistivity float zone material.

These radiation studies to date are encouraging, even though the results are very preliminary. If the trend toward higher post-irradiation power output continues, it is possible that this material and device structure may find future mission applications.

CONCLUSION

The significant increase in efficiency exhibited by the JPL high-efficiency cell is derived primarily from optimization of relatively conventional design approaches. These include very high-quality starting material, textured surfaces, front surface passivation, reduced contact area and reduced contact shadowing.

The behavior of these cells in radiation is encouraging in that they maintain a higher power output after 5 x 10^{14} 1 MeV electrons than for conventional space cells and do not suffer from photon degradation.

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Table I - AM0 I-V Data for 7 of the JPL High-Efficiency Silicon Solar Cells

Cell ID	S* (μm)	Contact Area (%)	V_{oc} (mV)	I_{sc} (mA)	Fill Factor	Effic. (%)
1A	400	0.575	647.0	179.4	0.799	17.14
1D	50	0.075	649.2	179.2	0.804	17.27
2B	200	0.29	650.4	176.8	0.810	17.20
3B	200	0.29	652.8	178.1	0.802	17.23
3C	100	0.15	660.1	178.4	0.815	17.74
4A	400	0.575	649.2	178.9	0.801	17.20
4D	50	0.075	649.7	178.9	0.805	17.30

*S = contact spacing

Table II - I-V Data for Cell #2B

V_{oc} (mV)	I_{sc} (mA)	Fill Factor	Effic. (%)	Remarks
650.4	176.8	0.810	17.2	Prior to 5×10^{14} 1 MeV electron irradiation
587.2	126.3	0.795	11.50	After irradiation
588.7	127.7	0.794	11.51	After 24-hr photon irradiation

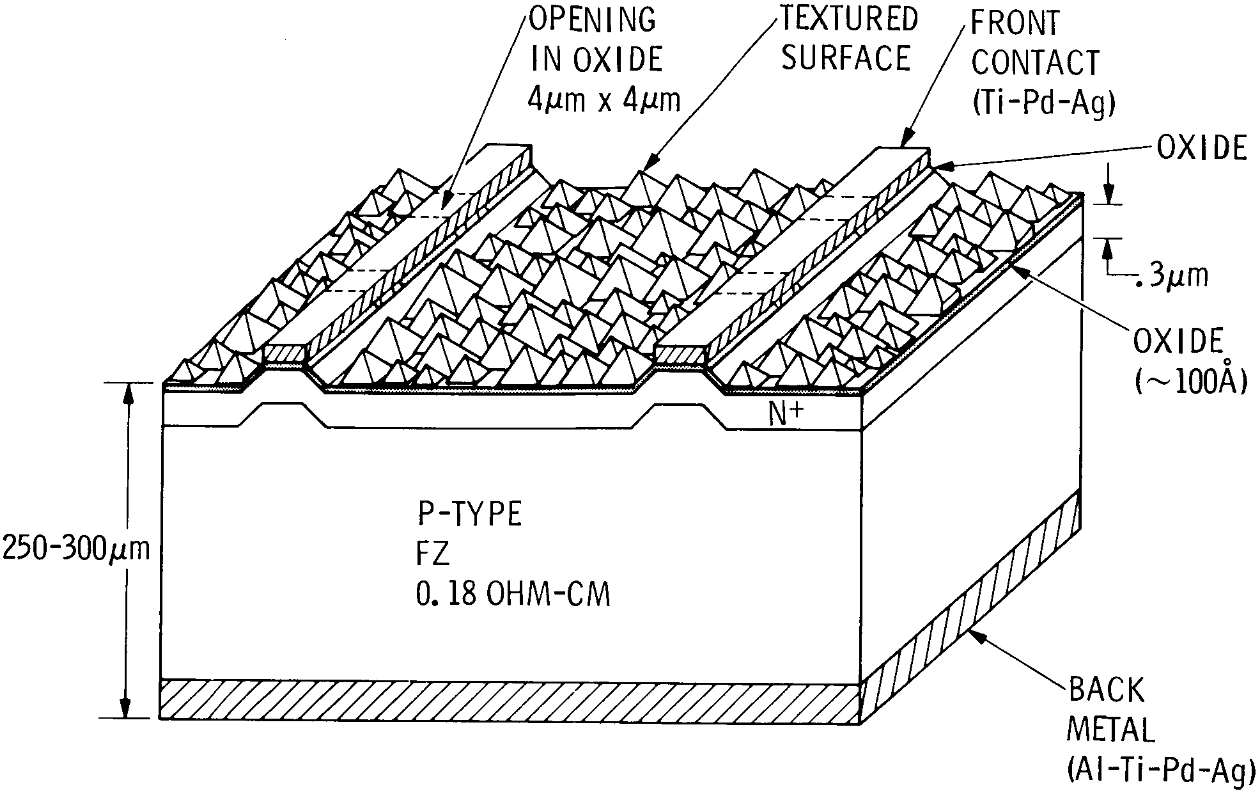

Figure 1. Schematic diagram of the JPL high-efficiency silicon solar cell

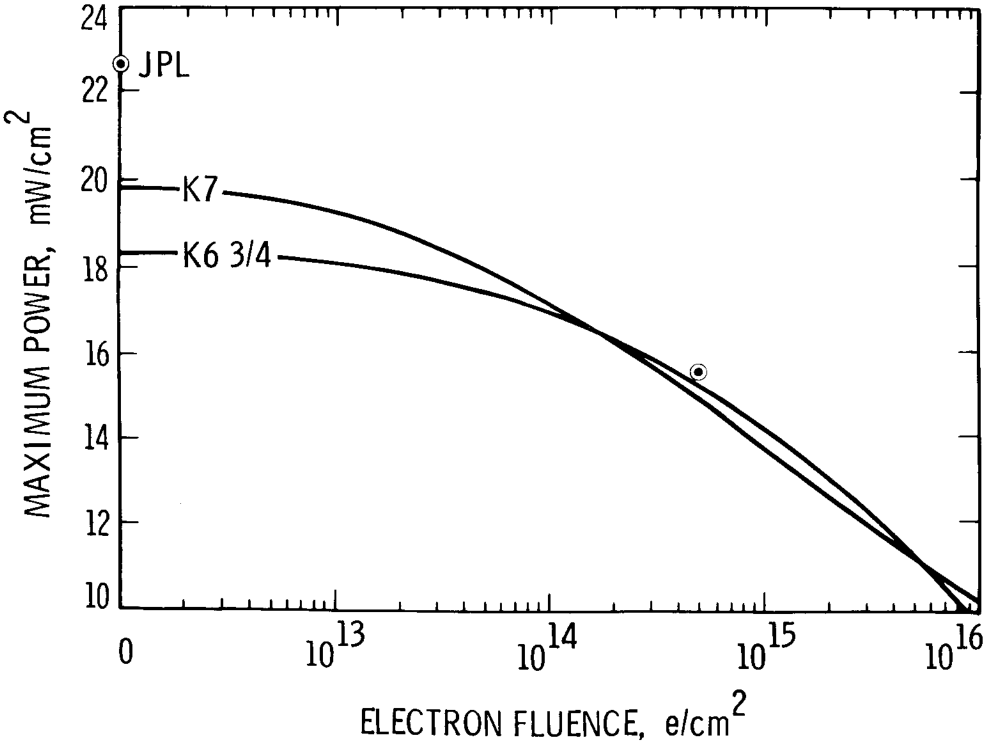

Figure 2. Maximum power vs. 1 MeV electron fluence for JPL high-efficiency cell and 2 conventional space cells. Maximum power after 5 x 10^{14} e/cm^2 is 15.6 mW/cm^2 for the JPL cell, 15.2 mW/cm^2 for K6-3/4 and 14.9 mW/cm^2 for K 7.