NEW DEVELOPMENTS IN VERTICAL JUNCTION SILICON SOLAR CELLS*

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ABSTRACT

Recent efforts in the development of vertical junction silicon solar cells have resulted in improvements in cell efficiency, high yield manufacture of large numbers of 2 cm x 2 cm, 2 cm x 4 cm, and 2 cm x 6 cm cells, the use of new geometries to improve the efficiency and radiation resistance, improved optical coupling using newly developed texturing techniques and double layer anti-reflective coatings and modelling efforts to predict cell performance.

Vertical junction cells have now been produced with greater than 15% AMO efficiency. The use of new cell geometries has resulted in the fabrication of cell assemblies that can withstand thermal cycling. Thinning techniques have been employed to produce vertical junction cells with as little as 75 microns of silicon below the bottom of the grooves. Radiation testing has shown the inherent radiation resistance of the vertical junction structure and has provided information on the performance of various cell structures.

INTRODUCTION

The vertical junction solar cell is made from a silicon slice with grooves etched into one surface. Narrow grooves on the order of 5 microns wide are etched in the surface in a regular pattern spaced 15 to 20 microns apart. Figure 1 shows such a VJ structure with 25 micron deep grooves. The diode junction follows the surface of the silicon up and down the walls. Since the walls are very narrow, carriers generated in the walls by incident light are always close to the collecting junction. Even if the carrier diffusion length is reduced, say by exposure to particulate irradiation, the carriers created in the walls will still be able to traverse the short distance to the junction and be collected. Therefore, the vertical junction cell has the inherent capability of providing superior radiation resistance. The technique for fabrication of the vertical junction cell is well documented in the literature (1-5).

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CELL PERFORMANCE

Vertical junction solar cells have been fabricated with AMO efficiencies greater than 15%. Table 1 summarizes the materials and structural parameters, while Table 2 summarizes the performance parameters of these cells. The high current density indicates the excellent light coupling properties of the VJ cells. The open circuit voltages are somewhat reduced from planar cell values (610 to 620 mV) due to the larger junction area. The fill factors are comparable with other high efficiency silicon cells.

TABLE 1

Parameters of 15% Efficient VJ Cells

Base Silicon:	P Type - Boron Doped 110 Orientation CZ Growth 10 to 12 Mils Thick 2 Ω-CM Resistivity
Processing:	Gaseous Phosphorous Diffusion Al Paste BSF Ti-Pd-Ag Front and Back TiO_2 - MgF_2 AR Coating
Geometry:	17.5 Microns Step and Repeat 2.5 Microns Groove Openings ≈5.0 Micron Wide Grooves 25 and 75 Micron Deep Grooves Cells 2 CM x 2 CM

A VJ pilot line fabrication effort has been completed. A total of 500 VJ cells were produced (100 2 cm x 2 cm, 300 2 cm x 4 cm and 100 2 cm x 6 cm) with grooves 75 microns deep. The yield of cells greater than 12% AMO efficiency was 68%, while the yield of cells with greater than 13% AMO efficiency was 42%.

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TABLE 2

Performance of 15% Efficient VJ Cells at AMO and 25°C

25 Micron Deep Grooves		
I_{sc}	=	175 mA
V_{oc}	=	597 mV
MAX P	=	82 mW (15.1%)
I_{sc} Blue	=	48 mA Corning #9788
I_{sc} Red	=	91 mA Corning #2408
FF	=	78.5%
75 Micron Deep Grooves		
I_{sc}	=	177 mA
V_{oc}	=	583 mV
MAX P	=	82 mW (15.1%)
I_{sc} Blue	=	49 mA Corning #9788
I_{sc} Red	=	92 mA Corning #2408
FF	=	79.5%

Thinning techniques have been developed for use with VJ cells. Cells have been made with various substrate thicknesses down to a thickness of 75 microns of silicon below the bottom of the grooves. Table 3 summarizes the results of the best cells to date made for each substrate thickness. These results indicate that with improvements in optical coupling and back surface field, thinner VJ cells with nearly the same power levels as the standard 10 to 12 mil thickness can be made.

TABLE 3

Thin Substrate VJ Cells

Present Best Performance for 2 CM x 2 CM Cells

Thickness of Silicon Below Bottom of Grooves (Mils)	P_{MAX} (mW) at AMO
10-12	82
7	80
5	74
3	73

With the original vertical junction geometry, covered solar cell assemblies suffered severe degradation under thermal cycling (2). However, the new geometry, narrower grooves and wider walls, has alleviated this problem without sacrificing cell performance. Covered cells have now been subjected to numerous thermal cycles (-120°C to +100°C) without measurable degradation or perceptible cracking of the walls.

RADIATION RESISTANCE

Various VJ cells have been irradiated at NRL using 1 Mev electrons. Figure 2 shows the effect of substrate thickness on radiation resistance for 10 Ω-cm bulk silicon with 1 mil deep grooves. While the standard thickness VJ cells are more radiation resistant than planar cells, the thinner substrate cells are more radiation resistant with the effect saturating below a 5 mil thickness. Both 2 Ω-cm and 10 Ω-cm bulk resistivity VJ cells have been irradiated as seen in Figure 3. Figure 3 indicates that 10 Ω-cm cells are more radiation resistant than 2 Ω-cm cells. This data was taken after a 40 hour post-irradiation anneal at 60°C. The cells were also measured before this anneal. The 2 Ω-cm cells were almost identical to the 10 Ω-cm cells before the anneal, but the 2 Ω-cm cells did not recover after the anneal while the 10 Ω-cm did recover significant power.

The effect of groove depth on radiation resistance is shown in Figure 4. The deep groove cells have appreciably better radiation resistance than the shallow groove cells, although even 25 micron deep grooves result in a significant improvement in radiation resistance. Figure 5 shows that a thin shallow groove VJ cell using 10 Ω-cm silicon is nearly as radiation resistant as a thicker deep groove VJ cell using 2 Ω-cm silicon. The relationship between initial power and radiation resistance could be used to tailor design a VJ cell to a particular mission to provide the optimum end-of-life power.

COMPUTER MODELLING

Typical first order theoretical modelling of solar cells assumes a one dimensional current flow. The VJ structure requires a two dimensional current flow model. Theoretical I-V curves can be generated by solving the diffusion equation, including carrier generation due to light, given by:

$$\nabla^2 n + G/D - n/L^2 = 0 \qquad (1)$$

where n = free electron density in p-type silicon
G = carrier generation rate due to illumination
D = diffusion constant
L = diffusion length of minority carrier

The following boundary conditions have been used:

- at the n^+/p front junction

$$n = n_o \exp(Vq/kT) \qquad (2)$$

- at the p-p+ back junction there is a given surface recombination velocity such that

$$\nabla n = nV_s/D \qquad (3)$$

This set of equations has been solved using the relaxation method to determine values of the minority carrier concentration at all points within the bulk. Then the cell current density can be determined by solving equation (4) at the n^+/p junction boundary.

$$\vec{J} = qD\vec{\nabla}n \qquad (4)$$

This technique is applicable to VJ cells at AM0, but may not be applicable at higher concentrations when the current in the bulk generates an electric field that significantly modifies the diffusive flow.

This model has now been employed to generate idealized (no series or shunt resistance included) I-V curves for a variety of VJ structures using various materials characteristics. Figure 6 shows the effect of diffusion length on the I-V curves for one particular cell structure. Such a set of curves can be generated for each geometry to estimate the expected radiation resistance of the cell.

Figure 7 is a plot of the I-V curves for one particular geometry for a range of diffusion lengths and three different groove depths. As expected, the deeper grooves result in more current generation while the shallower grooves result in a higher open circuit voltage. The maximum power points, however, are nearly equal for the three groove depths at any diffusion length. The radiation degradation data, however, indicates that the shallower groove cells lose power more rapidly than the deeper groove cells. It is the open circuit voltage of the shallow groove cells that decays faster than expected from the sample model. This may be because the back surface field is not unaffected by the radiation and so cannot be modelled by a constant recombination velocity. Before this model can be utilized to accurately predict cell performance it must be expanded to model performance of the back surface field. Better understanding of light coupling at the VJ surface, including diffraction effects, must also be added to the complete model.

CONCLUSIONS

Vertical junction solar cells have now been fabricated with efficiencies nearly as high as any other silicon solar cell. Their enhanced radiation resistance means that VJ cells are now the silicon cell with the best end-of-life efficiencies available. The fabrication of VJ cells with thin substrates show that lightweight radiation resistant arrays can be made using these cells. The development of two dimensional computer modelling is aiding in the understanding and development of new VJ structures of higher efficiency and increased radiation resistance.

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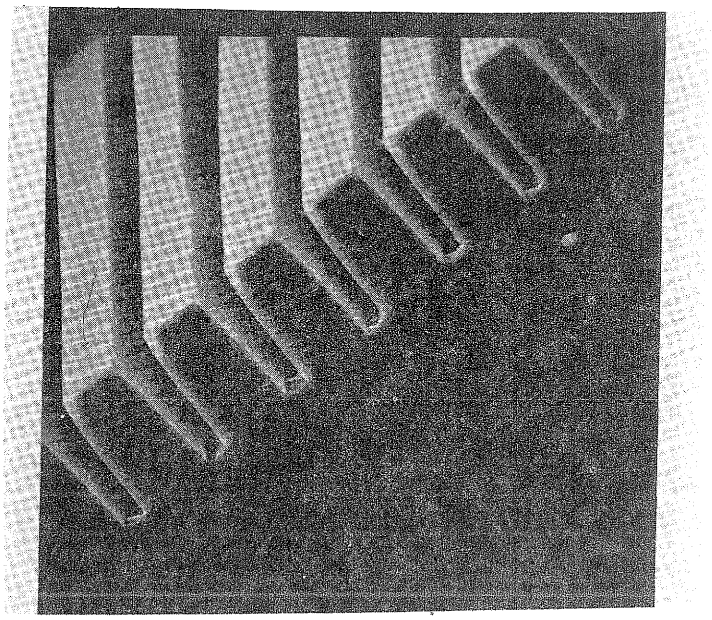


Figure 1. SEM Picutre of Vertical Junction Structure Taken at a Magnification of 720

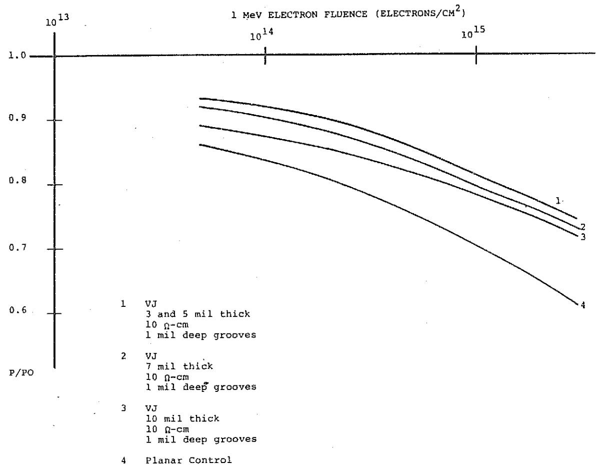


Figure 2. P/P_o Fluence for Various Substrate Thicknesses

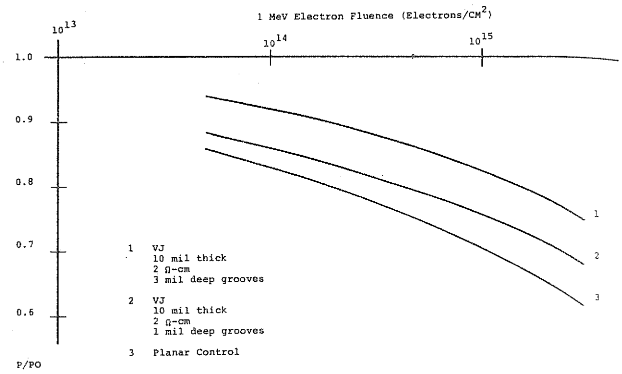


Figure 4. P/P_o Fluence as a Function of Groove Fi Depth

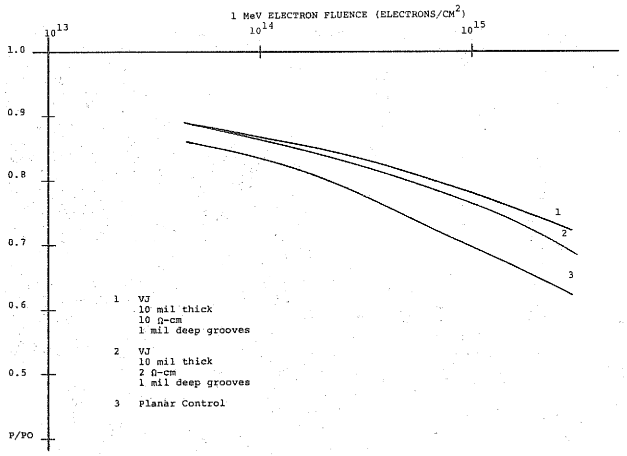


Figure 3. P/P_o Fluence as a Function of Bulk Resistivity

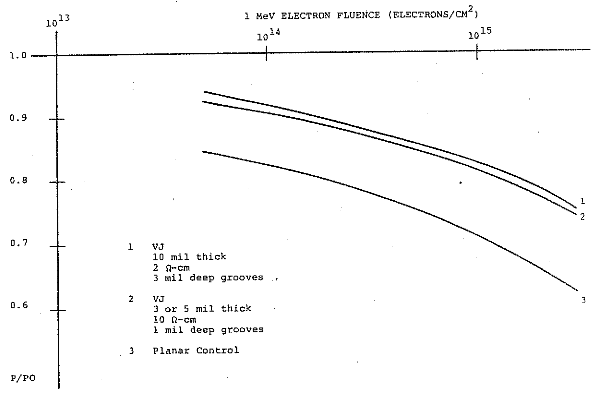
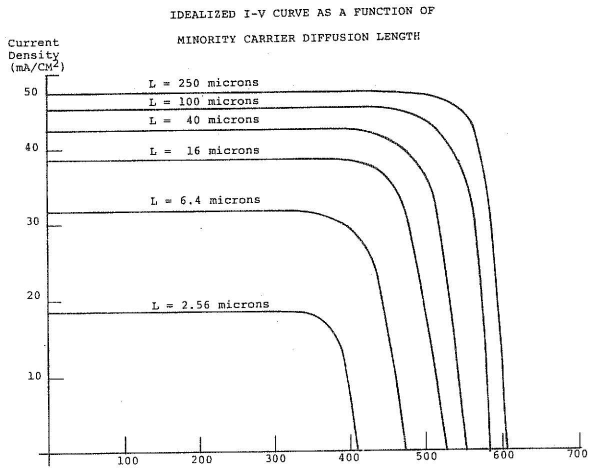


Figure 5. P/P_o Fluence for a Thin Shallow Groove 10 Ω-cm VJ Cell and a Thick Deep Groove 2 Ω-cm VJ Cell



Cell Geometry:

- 7.5 micron wide grooves
- 7.5 micron wide walls
- 50 micron deep grooves
- 300 micron thick Si
- 50% of light entering grooves is absorbed in bottom of grooves.
- 50% of light entering grooves is absorbed in the side walls.
- back surface recombination velocity of 100 cm/sec.

Figure 6. Idealized I-V Curve as a Function of Minority Carrier Diffusion Length

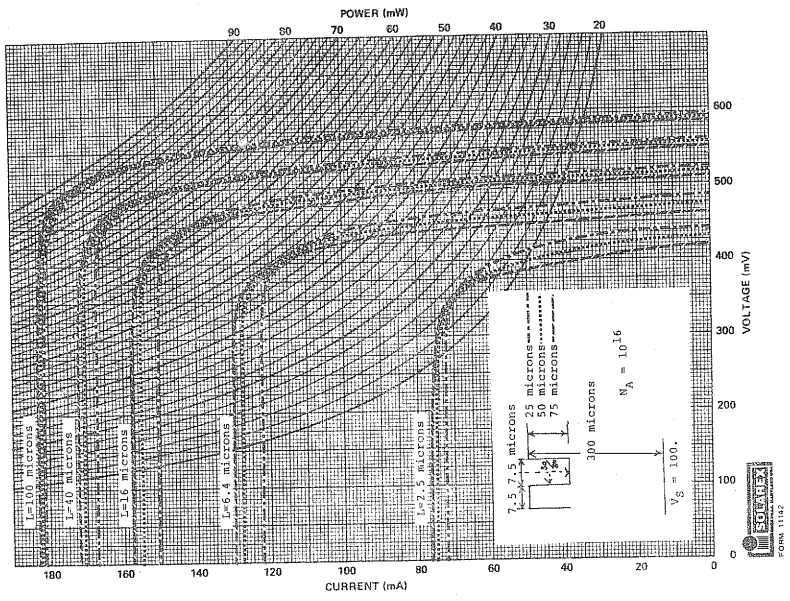


Figure 7. Idealized I-V Curve as a Function of Minority Carrier Diffusion Length for 3 Different Groove Depths