RADIATION TOLERANCE OF VERTICAL JUNCTION SOLAR CELLS*

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SUMMARY

Extensive radiation testing of vertical junction (VJ) solar cells has demonstrated a radiation tolerance better than both planar silicon cells and at least one type of (AlGa)As-GaAs cell. Due to trade-offs between short circuit current and open circuit voltage the end of life (10^{16} 1 MeV electrons/ cm^2) maximum power point is nearly independent of bulk resistivity between 2 and 10 ohm-cm, increases slightly with increasing wafer thickness between 3 and 11 mils, and increases slightly with increasing groove depth between 1 and 3 mils.

SILICON GEOMETRY

Vertical junction solar cells are made from wafers on which narrow grooves are formed using a preferential KOH etch. The echant is masked using a thermally grown oxide. The cells discussed in this report were made using a mask with 2.5 micron wide slots with 17.5 micron step and repeat. The geometry is shown in Figure 1. The bottom of a groove is as narrow as 2.5 microns while the top of a groove opens slightly so that a 75. micron deep groove has a groove width of about 5. microns and a wall width of about 12.5 microns at the top.

The grooved region is radiation tolerant because carriers generated in the narrow walls need diffuse only a short distance to the junction. While tapered walls would trap additional light, much of the additional light enters the silicon below the grooves thereby generating carriers relatively far from a junction. With straight walls, on the other hand, most of the light enters the flat tops of the walls. The cells described in this report use straight walls and a double layer antireflection coating to assure high absorption at the wall tops.

The wafers can be thinned prior to groove etching. We report herein vertical junction cells of 3, 5, 7 and 11 mils wafer thickness. The five mil thick cells have grooves as deep as three mils while the three mil thick cells have only one mil deep grooves.

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DESCRIPTION OF VJ CELLS

The VJ cells reported herein were made with p-type CZ grown silicon of 2 ohm-cm and 10 ohm-cm bulk resistivity. The junction was formed by gaseous phosphorus diffusion. A p^+ back surface field was made using aluminum paste alloy. The contacts are titanium/palladium/silver. A double layer AR coating is used, which for uncoverslided cells consists of TiO_2 and MgF_2.

Using the above parameters cells have been made with peak power as high as 82 mW for a 2 cm x 2 cm cell (15.1% efficiency). It is this kind of cell whose radiation tolerance is described in this report.

A new type of VJ cell has been developed recently that uses both a back surface field and a back surface reflector (BSF/BSR). The reflector is made from vacuum evaporated aluminum. Prior to the aluminum evaporation the paste alloyed back is thoroughly cleaned in HCl acid. The BSF/BSR cells have had a peak power as high as 84 mW (15.5% efficiency) and lot averages as high as 82 mW. The BSF/BSR cells have not yet undergone radiation testing.

RADIATION TOLERANCE

A matrix of cells underwent radiation testing. The cells consisted of 2 and 10 ohm-cm bulk resistivity; 3, 5, 7 and 11 mils wafer thickness; and 1, 2 and 3 mils groove depth. The irradiation was done at the Naval Research Laboratory in Washington, D.C. The cumulative dosages were 3. x 10^{13}, 1.2 x 10^{14}, 3. x 10^{14}, 1. x 10^{15}, 3. x 10^{15} and 1. x 10^{16} 1 MeV electrons/cm^2. The electrical measurements shown on the graphs were made using a Xenon light source calibrated to AMO. The cells were annealled for 16 hours and 60°C.

The maximum power point at the end of life (EOL: 10^{16} 1 MeV e^-/cm^2) was similar for various resistivities, wafer thicknesses and groove depths. This is due to trade-offs between current and voltage. In regards to groove depth the deeper grooves have better current collection but lower voltage for a given dosage. Also, lower resistivity cells have higher voltage but lower current for a given dosage. The short circuit current for the various VJ cell parameters are shown in Figures 2, 3, 4 and 5 as a function of radiation dosage. Each cell type is represented by two 2 cm x 2 cm VJ cells.

Individual cell differences can be eliminated by dividing by initial electrical measurements. Figure 6 shows the relative short circuit current for 11 mil thick VJ cells and for planar cells co-processed with the VJ cells.

The open circuit voltage for various cell parameters are shown in Figure 7. The measurements for 2 mil groove depth are not shown since in all cases the results are intermediate between to 1 mil and 3 mil groove depths. Notice that the trend at the end of life -- 2 ohm-cm, 1 mil groove depth is highest and 10 ohm-cm, 3 mil groove depth is lowest -- is essentially the reverse of the trend in regard to current.

It is interesting to look at the voltage as a function of groove depth. As the junction area increases the voltage decreases. At first thought, one might expect the open circuit voltage to decrease as a logarithmic function of junction area such that a ten fold increase in junction area results in a 60 mV decrease in voltage. The actual decrease is about 20 mV. The relative insensitivity to junction area can be explained qualitatively by realizing that the diode saturation current is a function of the distribution and density of recombination sinks rather than the junction area. Viewed in another way, minority carriers injected from one wall junction may show up at the opposing wall indistinguishable from photogenerated carriers.

The open circuit voltage divided by the initial open circuit voltage is plotted versus radiation dosage in Figure 8.

The maximum power as a function of radiation dosage is shown in milliwatts in Figure 9 and relative to initial values in Figure 10. Only 7 mil thick wafers are shown since 11 and 5 mil wafers had very similar results. The differences in maximum power at the end of life can be seen more clearly on a magnified scale as used in Figure 11. The results for 2 ohm-cm and 10 ohm-cm silicon are averaged in Figure 11.

COMPUTER MODELLING

The damage coefficient of the silicon can be estimated by comparing the measured short circuit current with a computer program that models the VJ cells. The computer model solves the diffusion equation in two dimensions. The computer program takes into account the back surface recombination velocity, which in this case we assume to be 1000. cm/sec. The program also models the distribution of photogeneration inside the grooved silicon.

The computer model results depend on the diffusion length rather than the radiation dosage. The two are related by equation 1,

$$\left(\frac{1}{L}\right)^2 - \left(\frac{1}{L_{initial}}\right)^2 = K\Phi \qquad (1)$$

where Φ is the fluence, K is the damage coefficient, and L is the diffusion length. By fitting the computer model to the actual data we deduced a damage coefficient of roughly $1. \times 10^{-10}$ for 2 ohm-cm silicon and $4. \times 10^{-11}$ for 10 ohm-cm silicon.

The computer model was also used to study deeper groove depths. Four and five mil grooves were found to have power that is nearly identical to three mil grooves. This is consistent with the measured results which shows diminishing returns between two and three mil groove depth.

TILT ANGLE

An interesting phenomenon is that the VJ cell current increases for small tilt angles. This is particularly evident at the end of life, as shown in Figure 12. The explanation is that when the cell is tilted light that enters the groove must reflect from the groove walls several times before reaching the bottom, which enhances light absorption in the radiation tolerant walls. The percentage increase in power between 0° and 12.5° tilt is 2.3%, 4.5% and 9.1% for 1, 2 and 3 mil groove depths, respectively. The ratio of initial power under direct normal illumination to EOL power (10^{16} 1 MeV e^-/cm^2) at 12.5° tilt is 59.6%, 64.9% and 67.2% for 1, 2, and 3 mil deep grooves, respectively. Therefore the VJ cell has the capability of providing even more end of life power by proper orientation.

CONCLUSION

Figure 13 compares a VJ cell with a planar cell and with a (AlGa)As-GaAs cell. The VJ cell has 2 mil grooves, 11 mils wafer thickness and 10 ohm-cm resistivity. The planar cell is silicon with 2 ohm-cm resistivity. The (AlGa) As-GaAs cell was reported in "High Efficiency Solar Panel, Phase II, Gallium Arsenide", Interim Report, September 77 - January 79, Hughes Aircraft Company.

Since vertical junction solar cells have shown excellent radiation tolerance as well as good beginning of life power they should receive serious consideration for use in future missions.

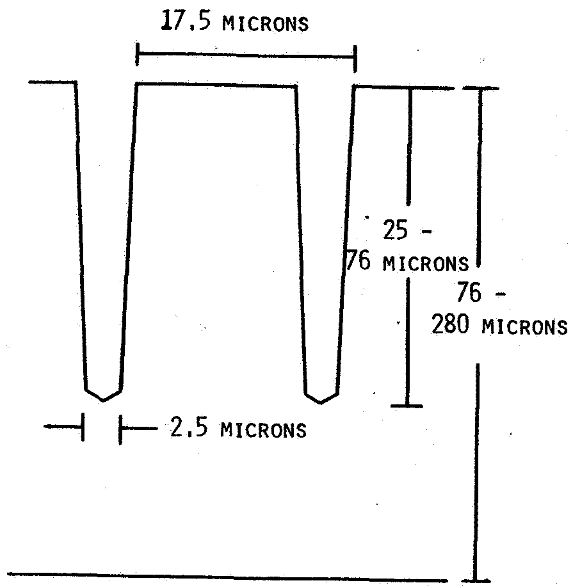

FIGURE 1. VERTICAL JUNCTION GEOMETRY

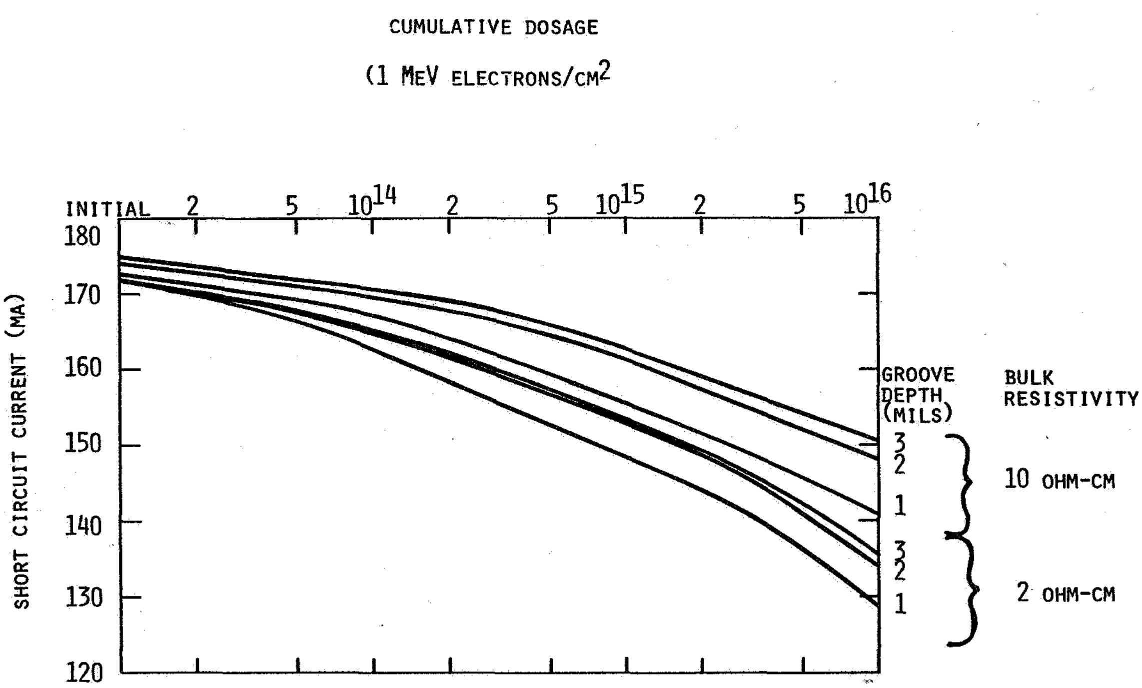

FIGURE 2. SHORT CIRCUIT CURRENT VS. FLUENCE, 2 CM X 2 CM VJ CELL, 11 MILS WAFER THICKNESS.

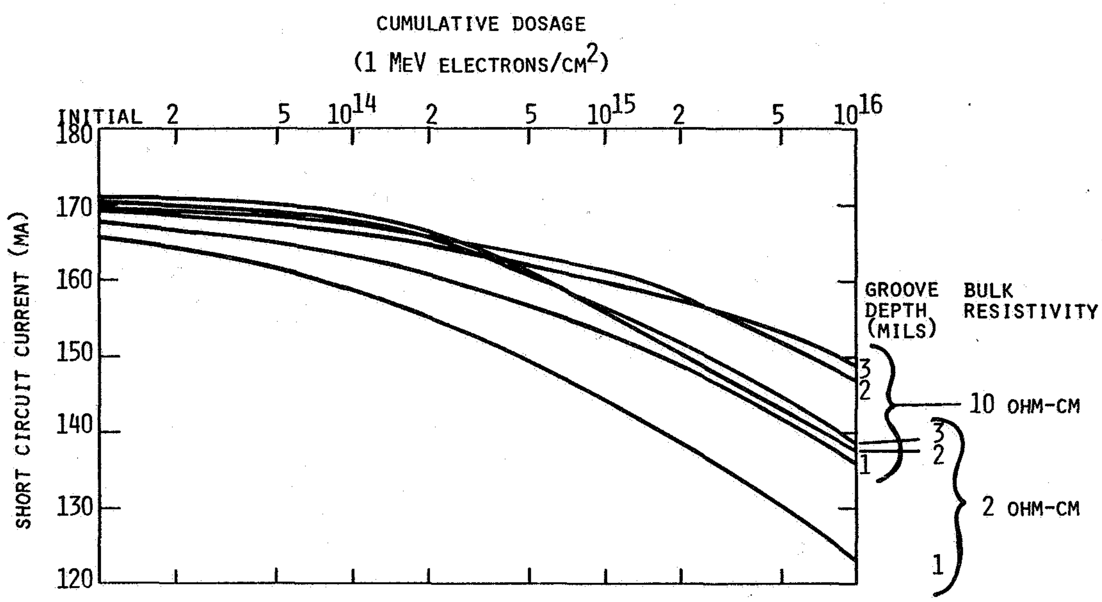

FIGURE 3. SHORT CIRCUIT CURRENT VS. FLUENCE, 2 CM X 2 CM VJ CELL, 7 MILS WAFER THICKNESS

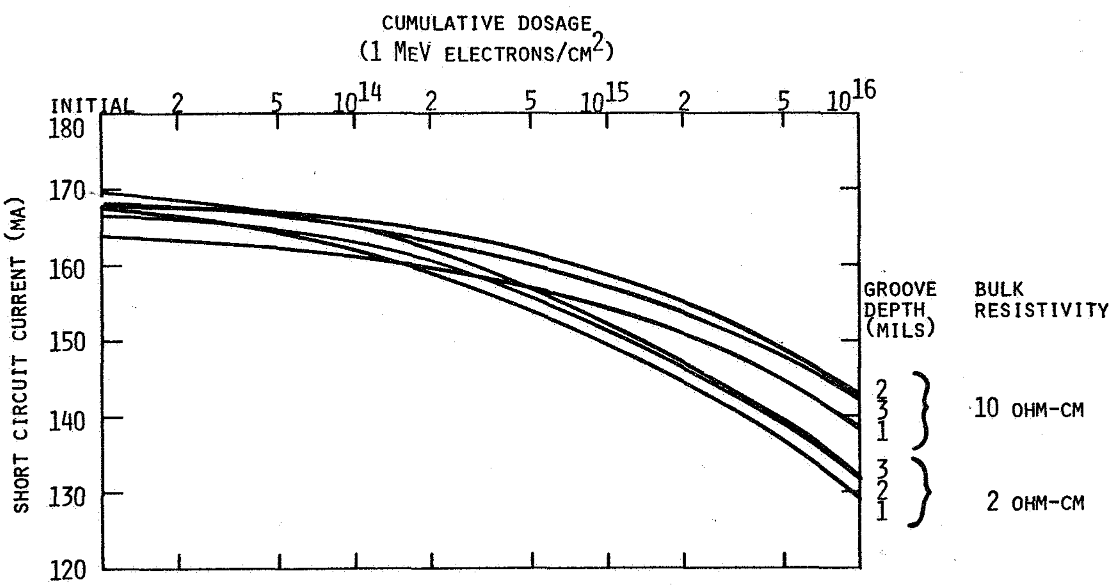

FIGURE 4. SHORT CIRCUIT CURRENT VS. FLUENCE, 2 CM X 2 CM VJ CELL, 5 MILS WAFER THICKNESS

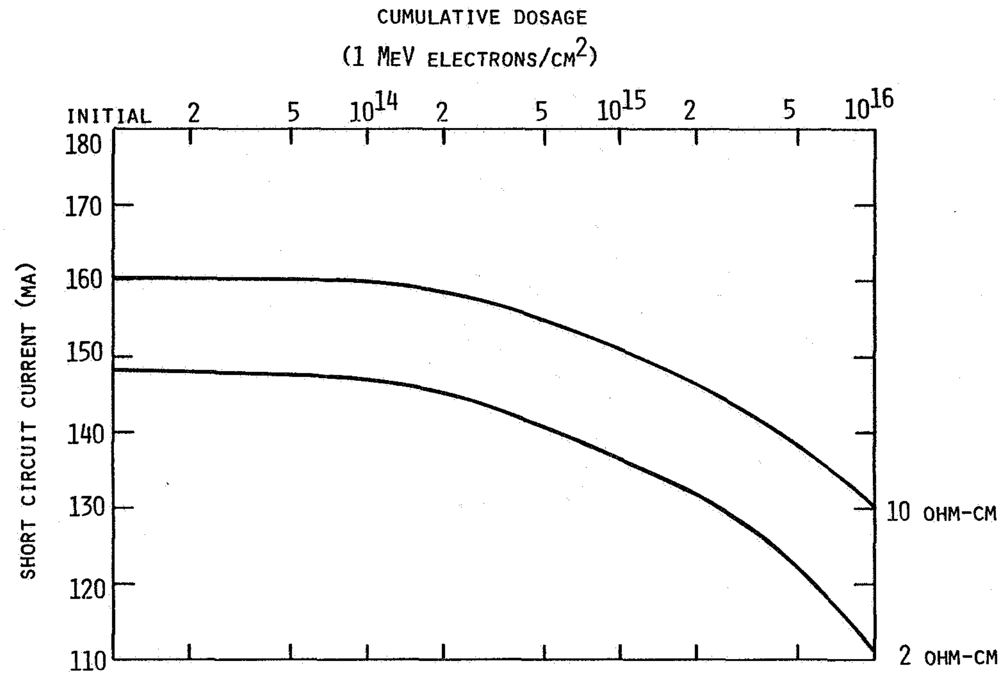

FIGURE 5. SHORT CIRCUIT CURRENT VS. FLUENCE, 2 CM X 2 CM VJ CELL, 3 MILS WAFER THICKNESS, 1 MIL GROOVE DEPTH.

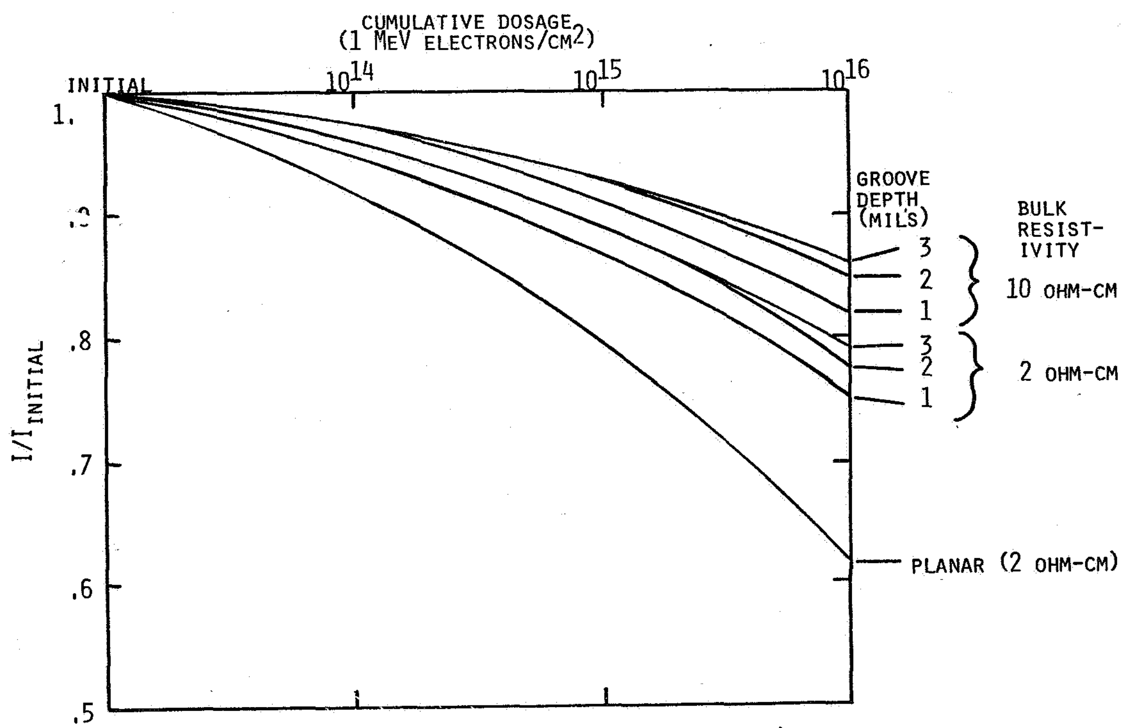

FIGURE 6. RELATIVE SHORT CIRCUIT CURRENT ($I/I_{INITIAL}$) FOR VJ CELLS AND PLANAR CELL.

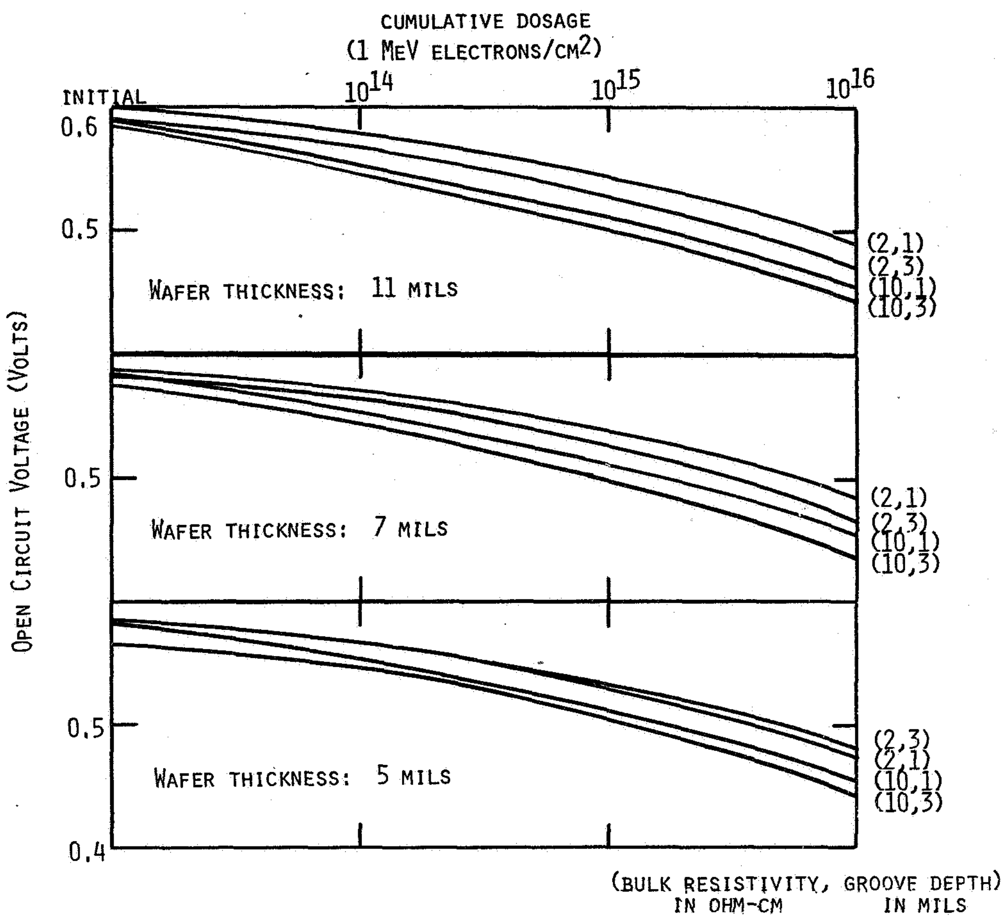

FIGURE 7. OPEN CIRCUIT VOLTAGE VERSUS RADIATION FLUENCE

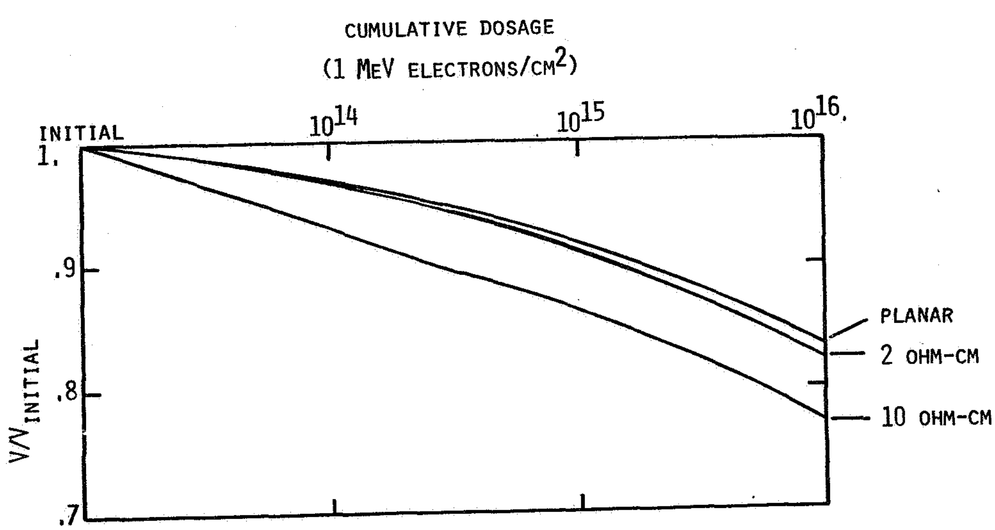

FIGURE 8. RELATIVE OPEN CIRCUIT VOLTAGE ($V/V_{INITIAL}$)
FOR VJ CELLS AND PLANAR CELL.

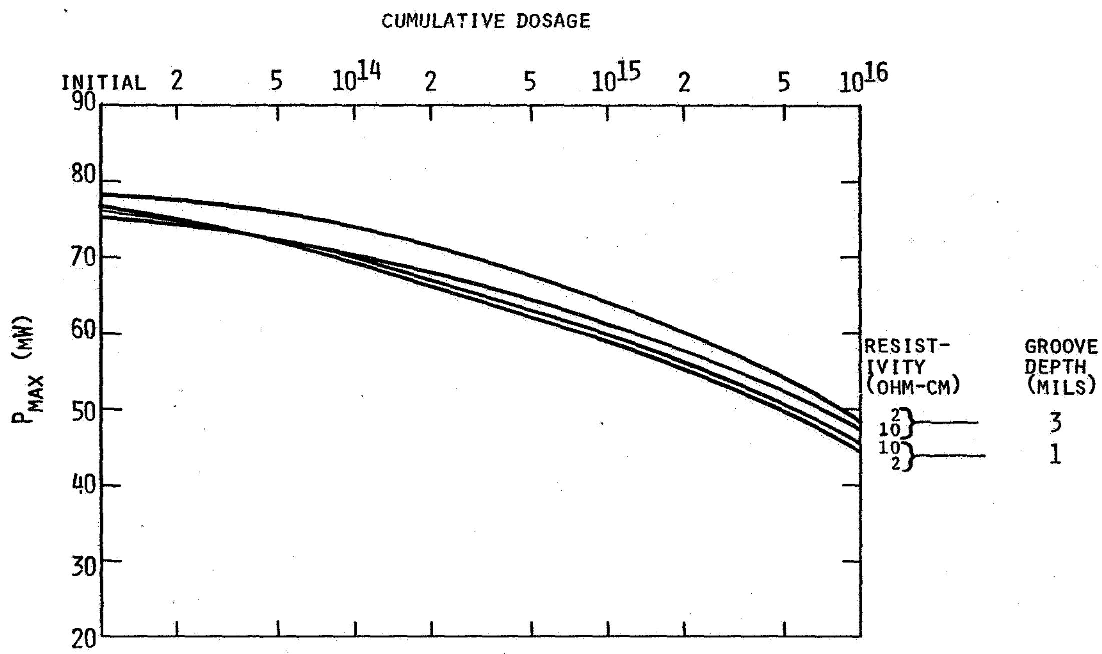

FIGURE 9. MAXIMUM POWER POINT VS. FLUENCE, 2 CM X 2 CM VJ CELL, 7 MILS WAFER THICKNESS

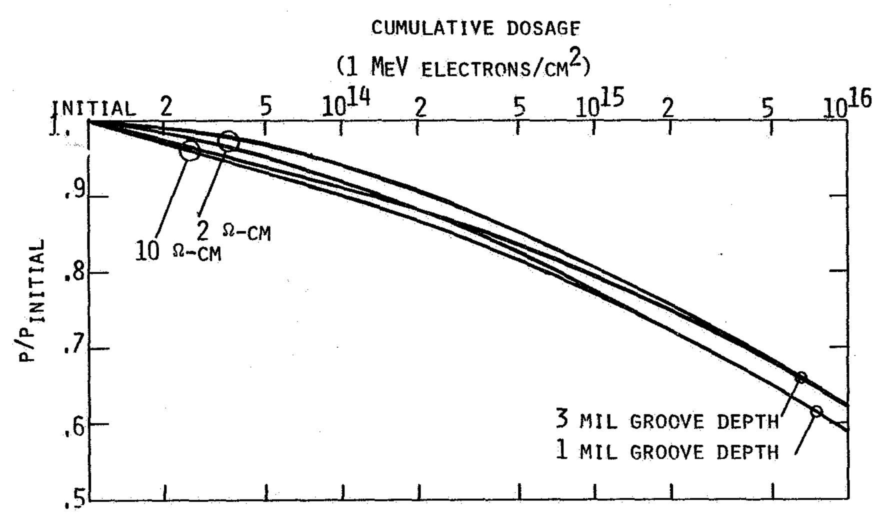

FIGURE 10. RELATIVE MAXIMUM POWER POINT ($P/P_{INITIAL}$) VS. FLUENCE FOR 2 CM X 2 CM VJ CELLS, 7 MILS WAFER THICKNESS.

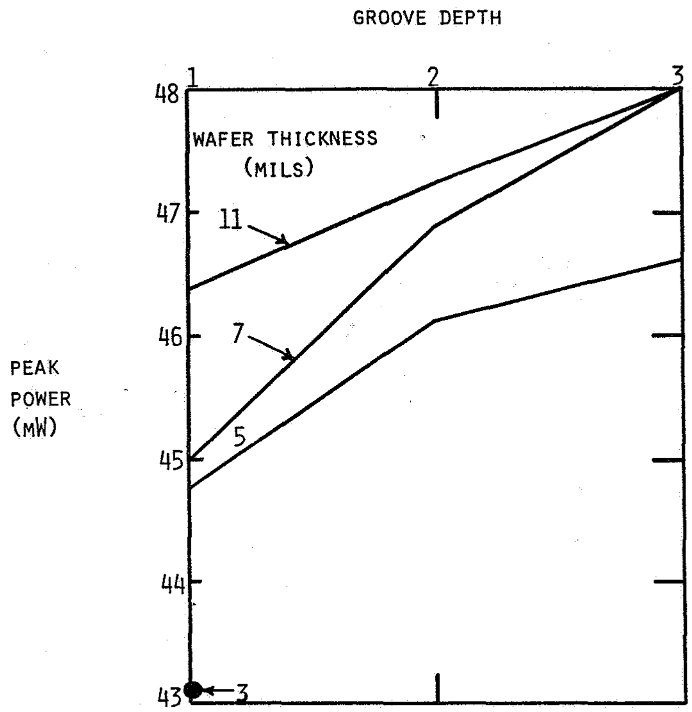

FIGURE 11. END OF LIFE (10^{16} 1 MEV e^-/cm^2 PEAK POWER AS A FUNCTION OF WAFER THICKNESS AND GROOVE DEPTH (AVERAGE OF 2 & 10 OHM-CM BULK RESISTIVITIES)

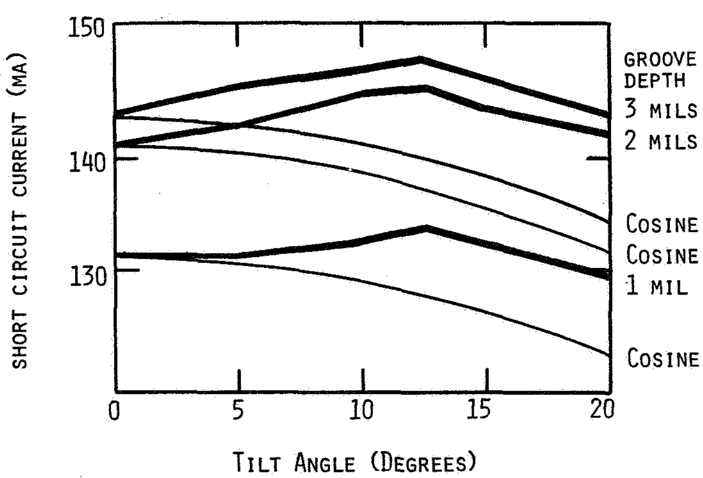

FIGURE 12. SHORT CIRCUIT CURRENT VS. TILT ANGLE. CELL SPECIFICATIONS: 10 OHM-CM, 11 MILS THICKNESS, 10^{16} 1 MEV ELECTRONS/CM^2 IRRADIATION.

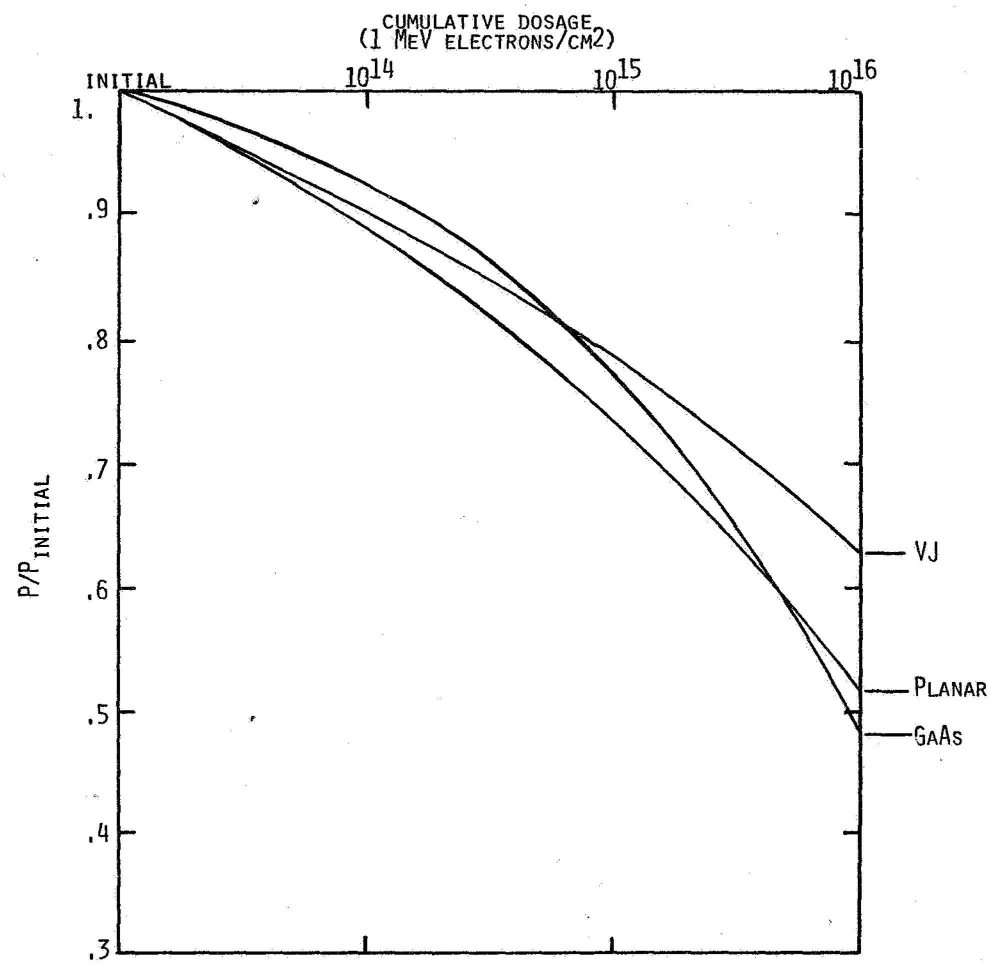

FIGURE 13. RELATIVE MAXIMUM POWER POINT ($P/P_{INITIAL}$) FOR VJ CELL, SILICON PLANAR CELL, AND GAAS CELL