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by B. L. Sater, H.W. Brandhorst, Jr., T.J. Riley,
and R.E. Hart, Jr.
Lewis Research Center
Cleveland, Ohio

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B.L.Sater, H.W.Brandhorst, Jr., T.J.Riley
and R.E.Hart, Jr.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

E-7795

Summary

The Multiple Junction Edge Illuminated Solar Cell (M-J Cell) was devised for high voltage low current applications. Devices to be flight tested in early 1974 with 96 series connected PNN+ junctions in a 2 cm X 2.3 cm size deliver 36 volts at 1 Milliampere. Test data of M-J Cells fabricated with resistivities of 10, 50, 100, 200, 450, and 1000 ohm cm silicon are presented and problem areas are discussed.

An additional potential application of the M-J Cell lies in ultilization of its high intensity performance that has been demonstrated at levels in excess of 100 AMO suns.

Introduction

The multiple junction edge illuminated solar cell (M-J Cell) was devised to fulfill a need for a high voltage low current application (Ref.1). The M-J Cells developed for a flight test in early 1974 on the MINX experiment (Ref.2) on the SPHINX spacecraft have 96 series connected PNN+ junctions in a 2 cm X 2.3 cm size where each individual junction consists of an area of approximately .048 cm^2. A typical M-J Cell for MINX develops 36 volts at 1 mA. The purpose of this paper is to present the status of the M-J Cell technology.

The M-J Cell is fabricated using processes developed to manufacture high voltage diodes. This paper describes the basic fabrication processes and presents a model of one of its PNN+ junctions. It should be emphasized that the M-J Cell has not been optimized from a theoretical viewpoint and future improvements may be probable.

The basis of the M-J Cell technology was a "cut and try" approach. For evaluation purposes, 16-junction devices (1/6 of 96 junction MINX M-J Cell) were utilized to determine characteristics and performance. Samples were fabricated for base resistivities of 10, 50, 100, 200, 450 and 1000 ohm-cm. These samples were evaluated to determine the electrical characteristics, efficiency, spectral response, temperature effects and radiation damage characteristics. Results are presented in this paper.

The major problems encountered appear to be related to the surface states and the exposed junction on the upper surface. For example, a) applying standard anti-reflection (AR) coatings to the upper surface degraded the M-J Cell's performance rather than enhancing it, and b) applying standard solar cell covers with RTV adhesives increased the radiation damage rate rather than decreasing it. These problem areas are discussed in the paper.

Perhaps the major potential application for the M-J Cell lies in its high intensity capabilities. The M-J Cell has been tested in concentrated sunlight to levels in excess of 100 AMO levels with good performance as will be shown in the paper.

M-J Cell Fabrication Processes

The M-J Cell is fabricated using processes developed by Semicon, Inc., Burlington, Massachusetts to manufacture high voltage diodes. Fig. 1 shows the significant processes involved in manufacturing of the 96 junction cells for the MINX flight test. Except for starting base resistivities all process steps up to the soldering step are those employed in the high voltage diode manufacturing. High voltage diodes rated at 12.5 kV PIV are manufactured by dicing the 16 junction 40 mil slabs resulting from the cutting step, attaching leads, etching, coating, and encapsulating.

The 16 junction M-J Cells used to determine the characteristics and performance were obtained similarly after the cutting step. Attempts to alloy 96 junctions in one step were successful but the yield after the cutting step was low due to a tendency for the saw blades to wander. However the use of thicker blades should improve this yield. Six 16 junction devices are soldered together to form the 96 junction M-J Cell for MINX. There were no problems in cutting the 16 junction alloyed stack.

The process results in an integrally bonded stack of PNN+ junctions that gives the M-J Cell a rugged mechanical and thermally stable characteristic.

Single Junction Model

A model of a single PNN+ junction of the M-J Cell is shown in fig. 2. Each cell is approximately 0.024 cm (9.5 mils) wide, (thickness of original wafers), 2 cm long and .089 cm (35 mil)thick. The 12 hoursdiffusion at 1275°C results in a rather deep P-N junction of 25-50 mm (1-2 mils), see fig. 2. The N+ diffusion, necessary for providing an ohmic contact for the aluminum alloying, provides a drift field in the bulk material.

The alloying process under heat and pressure squeezes some of the 17.8 μm (0.7mil) aluminum melt from between the slices. Also some changes in cell dimension were observed. From microscope observations, the width of the silicon region decreased to 207.8 μm (8.18 mils) and the alloyed region increased to 36μm(1.4 mils)typically. The composition of the alloyed region has not yet been determined. The active region is that area falling within the minority carrier diffusion length of the junction. The junction being vertical is edge illuminated hence its descriptive name.

The vertical multi-junction configuration (VMJ) has been treated theoretically in several recent papers (References 3,4 and 5). However, the M-J Cell differs considerably from the VMJ device described in these papers in several ways: (a) the use of a single PNN+ junction instead of the dual NPN junctions: (b) use of high resistivity base material greater than 100 ohm cm and (c) a low number of junctions per unit length (less than 50 junctions per cm instead of about 1000 junctions per cm).

The junction is exposed on the upper surface and there is a large junction length to area relation of approximately 40 cm/cm^2 for the M-J Cell compared with a conventional 2 cm x 2 cm solar cell of 2 cm/cm^2. Therefore, passivation of this surface is quite important. The referenced reports (Ref. 3 and 5) discuss the importance and the sensitivity of the VM J performance upper surface recombination velocities. Presently a silicone varnish is used to protect this surface in the M-J Cell since no better technique has been identified.

The M-J Cell is cut to 0.102 cm (40 mils) and then etched which reduces its thickness to approximately 0.089 cm (35 mils). This is considerably thicker than conventional solar cells and is one area where improvement is just a matter of investing in a new set of saw blades.

The M-J Cell has unique properties for a high intensity solar cell. The vertical aluminum interconnects provide excellent thermal stability under high heat flux. Aluminum has a thermal conductivity more than 200 times higher than silicon. In addition the reduction of the sheet resistance with the deep P region diffusion and metal contacting to the entire diffused region provides a low series resistance solar cell.

Last but not least the M-J Cell can be illuminated from either or both sides because of its symmetry.

Characteristics of the M-J Cell

For evaluation purposes, samples of 16-junction M-J Cells were fabricated from N type silicon base material with resistivities of 10, 50, 100, 200, 450 and 1000 ohm-cm. These devices had an overall geometry of approximately .385 cm x 2 cm x .089 cm or a total projected area of .770 cm^2. These cells were utilized to determine the M-J Cell performance under various conditions. The results of these tests will be discussed in the following sections.

Typical I-V Characteristics

A typical I-V characteristic for a 450 ohm-cm 16-junction M-J Cell is shown in fig.3. This curve was taken under Xenon light using a Spectro-lab. X25L solar simulator in a Martin-Marietta, Denver Division facility. At this facility data were taken on a sample M-J Cell of each resistivity to determine their characteristics under Xenon light over the temperature range of -160°C to +80°C and at intensities of 0.5, 1.0 and 2.0 suns.

Efficiency vs Resistivity

In fig. 4 the average efficiency of a number of M-J Cell samples is presented as a function of base doping level or resistivity. This curve is for tunsten illumination. The M-J Cell efficiency peaks in the 200 ohm cm to 450 ohm cm range. For comparison of tungsten and Xenon efficiency, one 200 ohm cm M-J Cell measuring 7.6% under tungsten illumination was determined to be 7.1% under Xenon.

Temperature Effects

A summary of typical performance measurements over the temperature range of -160°C to 80°C, and AMO Xenon light conditions is shown in fig. 5. This curve is for a 450 ohm cm device and is a compilation of data taken during testing at Martin Marietta.

For testing, the M-J Cells were mounted with silicone rubber (RTV 560) to a Kapton film-insulated aluminum substrate. The substrate was installed in a temperature chamber consisting of a styrofoam box with an aluminum block mounted on the bottom. The substrate was attached to an electrical heater on this block. A layer of LN_2 a few centimeters deep suround the lower portion of the block and served as an infinite heat sink. The substrate received heat from the light source and also from the electric heater mounted between it and the block. By controlling the power dissipation in the heater, the temperature of the substrate and solar cells was controlled. A quartz window on the box prevented moisture condensation and preserved a dry nitrogen gas environment around the solar cells in the test chamber. The test set up is described in an internal Martin Marietta report (Ref. 6).

High Intensity Effects

Various tests of the M-J Cell have demonstrated its feasibility for high intensity applications. In the Martin Marietta tests under Xenon illumination, it was noted that efficiency of the M-J Cell increased slightly with increased intensity. For the conditions of 0.5, 1.0 and 2.0 sun intensities, the normalized efficiency was 0.94, 1.0 and 1.023 respectively. Further testing under tungsten illumination verified the efficiency gain for intensity levels up to 20 "suns" intensities (Ref.7).

Fig. 6 shows the I-V characteristics of a M-J Cell tested under concentrated sunlight conditions obtained with an optical reflector. The M-J Cell was bonded to a water cooled copper heat sink mounted near the focal point of an optical reflector. On the particular test day a calibrated solar cell indicated the 1.0 "sun" intensity to be a 0.588 AMO sun level. The I-V characteristic of the M-J Cell under 1 "sun" shows 0.67 mA, Isc and 7.5 Volts, Voc. In the concentrated sunlight, two sets of data points were taken. The first was taken with the illumination defocused to cover the entire surface of the M-J Cell. In this test, the Isc current increased to 99 mA. Using the ratio of short circuit current as a measure of "sun" concentration we get an concentration of 148 "suns". The 148 "suns" I-V curve shown still has an excellent curve shape with a fill factor of approximately .725 and an efficiency of 6.4%. Focusing the illumination on to only a portion of the M-J Cell to increase the short circuit current, resulted in the 210 "suns" I-V curve. Under these conditions the open circuit voltage and max. power voltage dropped indicating heating in the M-J Cell.

Converting the M-J Cell outputs in watts per unit area at various intensities normalized to equivalent AMO sun intensities, we obtain the relationships shown in fig. 7. For comparison purposes conventional solar cell data from Lewis and Kirkpatrick's paper (ref.8) is shown on the same basis. This shows that the M-J Cell's efficiency is less than that for conventional solar cell's at nominal intensities near one sun but at about 2.5 AMO suns its efficiency becomes higher. At 20 suns (the limits of data available on the conventional solar cell) the M-J Cell has an efficiency of approximately 2.5 times that of the conventional solar cell. The data points beyond 80 suns were taken from the previous figure while other points were obtained with tungsten illumination.

The M-J Cell's application with low cost plastic lenses and reflectors may offer potential cost reduction for terrestrial solar electric power generation.

Spectral Response

Spectral response measurements were made using eighteen narrow band mass interference filters in conjunction with the illumination from a 1000 watt tungsten iodine lamp that was filtered through two inches of water. The M-J Cells were mounted on a temperature controlled plate with a vacuum hold down to maintain a 25°C cell temperature. The equipment utilized is described in an earlier report (Ref. 9). The M-J Cells were loaded to near short circuit current with a ten ohm resistor and the output current response to each spectral filter condition was recorded.

In order to present the spectral response on a normalized area basis, the illuminated area for a single junction unit must be determined, since the current is controlled by a single junction is the series string. From the measurements made earlier, the thickness of the silicon region was .0208 cm (8.18 mils) for a single junction. The width of the aluminum alloyed region was excluded in the area. Therefore, an area of 0.041 cm^2 was obtained for a single junction unit.

The normalized spectral response is shown in fig. 8 for two M-J Cell resistivities of 10 and 450 ohm cm. The 450 ohm-cm device exhibited an AMO short circuit current of 1.22 mA, whereas the 10 ohm-cm device had a lower output of .63 mA. This difference is reflected in their spectral response. For comparison an uncovered bare conventional 10 ohm - cm,N on P silicon solar cell's spectral response is shown.

There are several differences that can be noted. The M-J Cell's spectral response peaks at 1.0 micrometer compared to the conventional solar cell's peak at .85 to .9 micrometer. This enhanced "red" response would be expected since carriers generated deep in the M-J Cell have a better chance of reaching the vertical junction and contributing to output current than carriers generated deep in the conventional cell (Ref. 3). The "blue" response however appears to suffer in the M-J Cell and is attributed to the problem of high upper surface recombination velocities.

Anti-Reflection Coatings

The application of anti-reflection (AR) coatings is an area requiring further investigation. In our preliminary efforts involving a small sample of M-J Cells, unexpected and conflicting results were noted. Standard AR coatings were applied to 96 junction devices from the MINX program that had been reworked for problems that existed, i.e., loss of interconnects. Unfortunately, they did not have typical performance of good representative M-J Cells after the rework and this may have had lead to some of the idiosyncrasy. Applying standard AR coatings of SiO_x TiO_x and SiN_x to these M-J Cells with exposed surfaces and junctions, gave unexpected and conflicting results. The output of coated cells was no greater than that of normal, good uncoated cells. These coatings also did not appear to passivate the surfaces and junctions, since unstable electrical performance was noted usually with output increasing as a function of time under illumination. Also an AR coating applied to a side of a cell could degrade its performance. However, when the opposite (back) uncoated side was illuminated, cell performance increased. This performance was greater than when the same back side was illuminated with no AR coating being present.

Several materials tested, Parylene[R] and General Electric's SR-155 Silicone Varnish, appeared to passivate the surfaces but were applied too thick to serve as AR coatings.

Parylene[R] registered trade name - Union Carbide Corp.

Radiation Damage

Samples of M-J Cells were irradiated with 1 MEV electrons to determine their damage rates. In the test, two conventional 10 ohm cm cells were used for control and comparison purposes. The M-J Cells irradiated consisted of 16-junction devices manufactured from each resistivity from the 10 to 1000 ohm cm range and 96-junction MINX devices with and without 20 mil (.0508 cm) fused silica covers. They were bonded to the M-J Cell with Dow Corning's RC-3489 Adhesive with companion catalyst.

The 1 MEV electron accelerator used in this test was described in an earlier report (Ref. 9). The cells were removed ten different times for I-V measurements before accumulating a total dose of $1.1X10^{16}$ electrons/cm^2. Fig. 9 shows the normalized short circuit current, Isc as a function of the fluence of 1 MEV electrons for the conventional solar cell and 96-junction MINX cells with and without covers.

It appears that the uncovered M-J Cell radiation degradation rate is comparable to the conventional solar cell for dose levels up to $2X10^{15}$ 1 MEV electrons/cm^2. However, the covered M-J Cell degraded drastically for dose levels above $1X10^{14}$ electrons/cm^2, which was unexpected. A plausible explanation may be that under the influence of radiation the adhesive in contact with the silicone varnish degraded and affected the upper surface states of the M-J Cells.

Acknowledgement

The authors wish to acknowledge the cooperation received during the development of the M-J Cell by Semicon Inc. and their component specialist, Mr. Daniel Kane.

Conclusion

The M-J Cell demonstrated electrical performance and characteristics that makes it a viable high voltage low current solar cell. Technology efforts are required to optimize its performance and to find an AR coating that will provide surface and junction passivation.

Perhaps the major potential application of the M-J Cell will be in utilization of its high intensity capabilities. Its demonstrated performance at levels in excess of 100 solar constants is far superior than that possible with conventional solar cells. Its use with mirror or lens concentrators may offer a lower cost approach for solar electric terrestrial systems.

References

1. Sater, B.L: The Advantages of the High Voltage Solar Array for Electric Propulsion, AIAA 10th Electric Propulsion Conference, October 31 - November 2, 1973, Lake Tahoe, Nevada

2. Riley, T.J, Triner, J.E, and Sater, B.L: A Miniature High Voltage Plasma Interaction Flight Experiment - Project MINX, IEEE 10th Photovoltaic Specialist Conf., November 13-15, 1973, Palo Alto, Calif.

3. Rahilly, W.P: Vertical Multi-Junction Solar Cells, IEEE 9th Photovoltaic Specialist Conference, May 2-4, 1972, Silver Spring, Maryland.

4. Stella, P., and Grover A: Vertical Multi-Junction Solar Cell, IEEE 9th Photovoltaic Specialist Conference, May 2-4, 1972, Silver Spring, Maryland.

5. Chadda, T.B.S., and Wolf, M: The Effect on Surface Recombination Velocity on the Performance of Vertical Multi-Junction Solar Cell, IEEE 9th Photovoltaic Specialist Conference, May 2-4, 1972, Silver Spring, Maryland.

6. Thomas, R.E. and Bruno, J: Evaluation of Silicon Solar Cell Output Characteristics 1/2 to 3 Suns Intensity, -190°C to +120°C Temperature. Report #D-72-48704-003, June 1972, Martin Marietta, Aerospace Group, Denver, Colorado.

7. Sater, B.L. and Riley, T.J: A New Solar Cell for High Intensity Applications, Presentation at International Solar Energy Conference, October 3-4, 1973, NASA-Lewis Research Center, Cleveland, O.

8. Lewis, C.A. and Kirkpatrick, J.P: Solar Cell Characteristics at High Intensities and Temperatures. IEEE 8th Photovoltaic Specialist Conference, August 4-6, 1970, Seattle, Washington.

9. Brandhorst, H.W.,Jr., and Hart, R.E.,Jr: Radiation Damage to Cadmium Sulfide Solar Cells, NASA TN D-2932, 1965.

5

Figure 1

MJ CELL FABRICATION PROCESSES

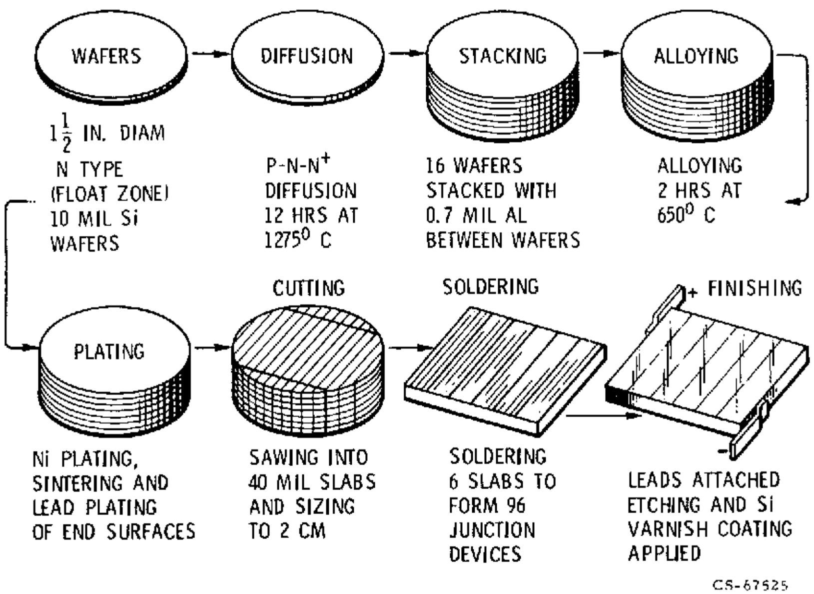

Figure 2

JUNCTION OF MJ CELL

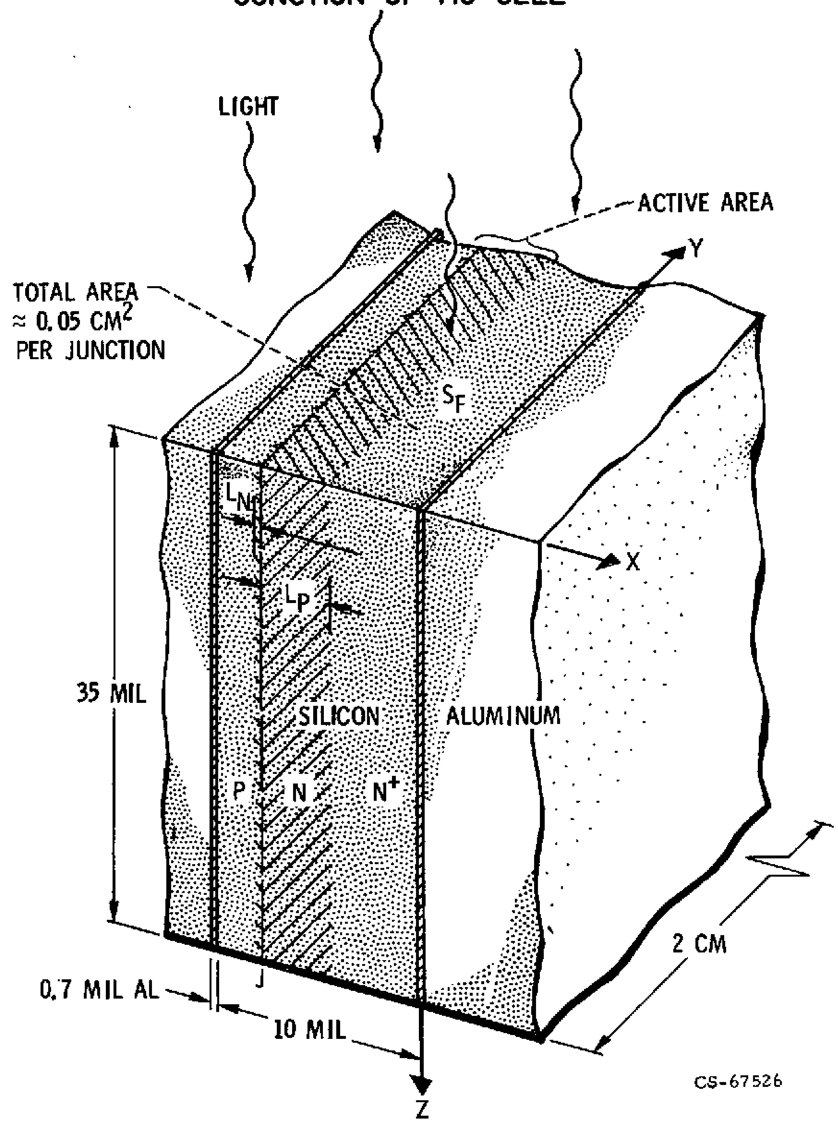

Figure 3

I–V CHARACTERISTICS

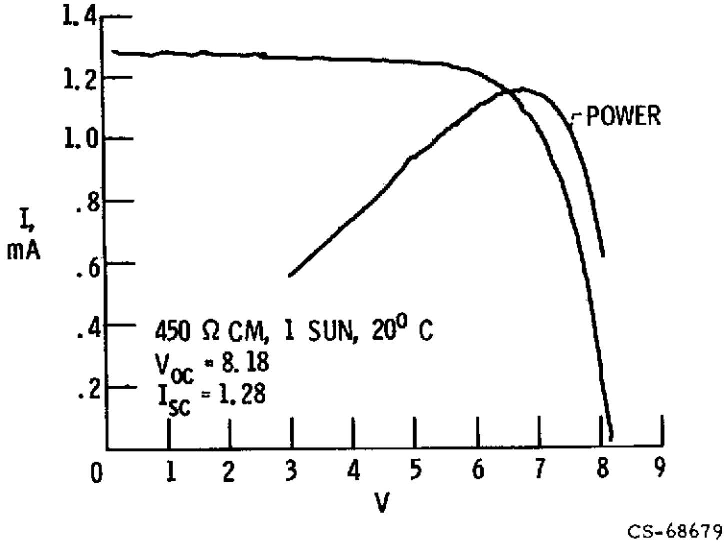

Figure 4

MJ CELL EFFICIENCY VS BASE DOPING LEVEL

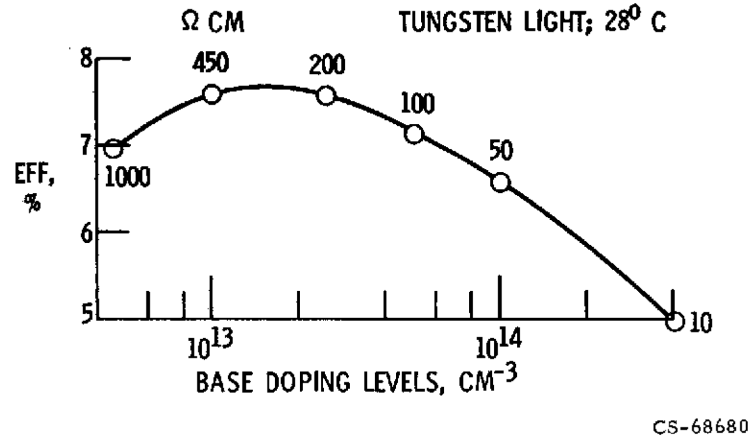

Figure 5

MJ CELL TEMPERATURE CHARACTERISTICS

450 Ω CM, 16 JUNCTION MJ CELL

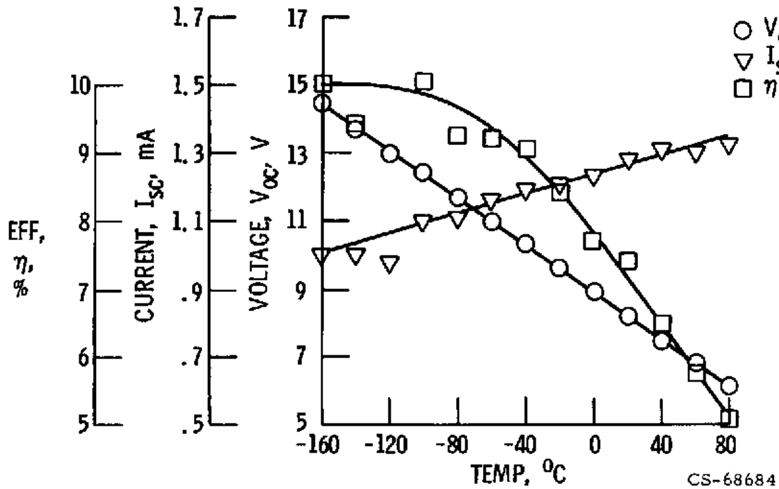

Figure 6

I-V CHARACTERISTICS WITH SUN INTENSITY

OPTICAL SOLAR REFLECTOR CONCENTRATOR

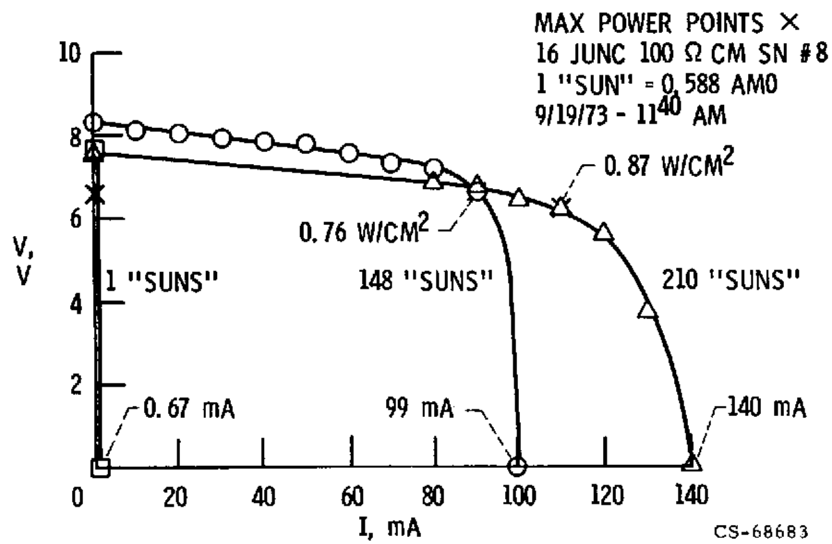

Figure 7

MJ CELL POWER OUTPUT PER UNIT AREA AT VARIOUS INTENSITY

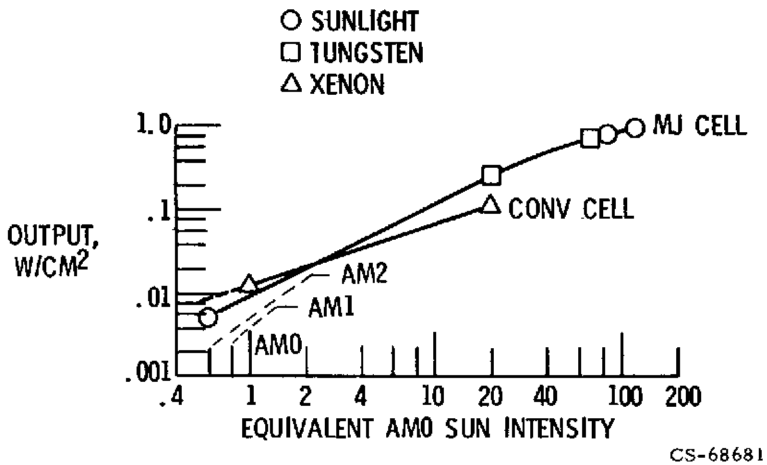

Figure 8

SPECTRAL RESPONSE OF CONVENTIONAL AND MULTIJUNCTION CELLS

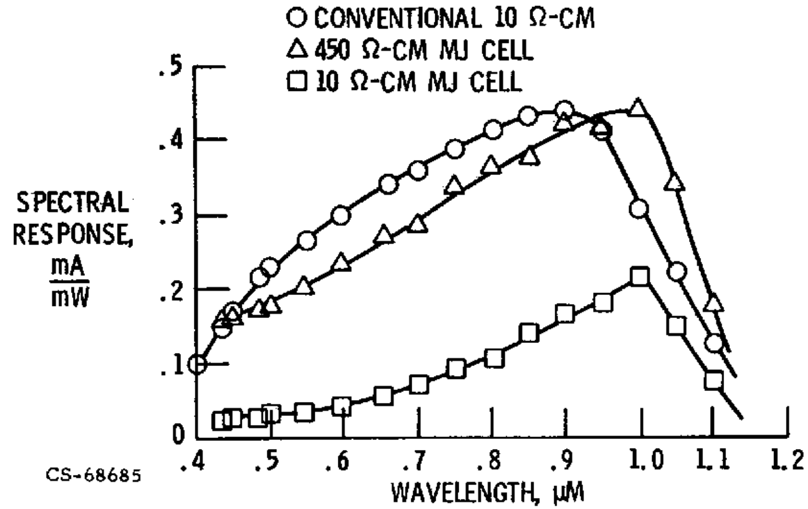

Figure 9

I_{sc} RADIATION DAMAGE CHARACTERISTICS