"RADIATION HARDENED HIGH EFFICIENCY SILICON SPACE SOLAR CELL"

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ABSTRACT

A silicon solar cell with AM0 19% Beginning of Life (BOL) efficiency is reported. The cell has demonstrated equal or better radiation resistance when compared to conventional silicon space solar cells. Conventional silicon space solar cell performance is generally ≈ 14% at BOL. The Radiation Hardened High Efficiency Silicon (RHHES) cell is thinned for high specific power (watts/kilogram). The RHHES space cell provides compatibility with automatic surface mounting technology. The cells can be easily combined to provide desired power levels and voltages. The RHHES space cell is more resistant to mechanical damage due to micro-meteorites. Micro-meteorites which impinge upon conventional cells can crack the cell which, in turn, may cause string failure. The RHHES, operating in the same environment, can continue to function with a similar crack. The RHHES cell allows for very efficient thermal management which is essential for space cells generating higher specific power levels. The cell eliminates the need for electrical insulation layers which would otherwise increase the thermal resistance for conventional space panels. The RHHES cell can be applied to a space concentrator panel system without abandoning any of the attributes discussed. The power handling capability of the RHHES cell is approximately five times more than conventional space concentrator solar cells.

INTRODUCTION

Solar cells are presently the most important source of power for long-duration space mission satellites and space vehicles. Since the introduction of the silicon P-N junction solar cell by Chapin, Fuller, and Pearson in 1954 [1], silicon solar cells have provided space power for virtually the entire range of space missions. However, during the past decade, solar cells have been made using other semiconductor materials, utilizing various device configurations, and different material structures such as single crystal, poly-crystal and amorphous thin-film. Some solar cells of different semiconductor material have demonstrated higher conversion efficiencies and radiation resistance than silicon solar cells. Solar cells of different material structures have merit over single crystal solar cells for manufacturing cost effectiveness. However, single crystal silicon solar cells have proven to offer the best overall cost effectiveness and reliability as a space power generator.

The conventional silicon space solar cell has a typical BOL (Beginning of Life) conversion efficiency of 13 ~ 14%. Conventional silicon space solar cells typically have a N/P front junction structure which requires a top metal-grid/bus-bar and bottom metal-grid/contact. The bi-facial structure for metal contacts (top/bottom contact) mandated the use of connectors for serial/parallel connections of solar cells to achieve a proper power output at a desired voltage level. Interconnection of solar cells in a panel is a time consuming and laborious process subject to quality failures.

Conventional silicon space solar cells exhibit a typical radiation tolerance of 25 ~35% power reduction under 1 MeV electron fluence of 10^{14} ~ 10^{15} e/cm^2. A great deal of radiation experimental data was compiled and published by NASA and JPL for various types of conventional silicon space solar cells [2] and solar cells utilizing other semiconductors [3].

RHHES CELL

The RHHES (Radiation Hardened High Efficiency Silicon Space Solar Cell) is a back-contact solar cell of single crystalline silicon. An earlier version of a backside contact solar cell was reported for terrestrial concentrator applications by Lammert and Schwartz in 1977 [4], having an interdigitated backside metalization. Later, Swanson devised a point-contact back junction solar cell which demonstrated 19.7% under 88X concentrated sunlight of AM 1.5 at 25 °C in 1984 [5]. In 1986, Sinton et al [6] of Stanford University's Solar Cell Research Laboratory led by Swanson reported a 27.5% efficient cell at 100X (10w/m^2) concentration level at 25 °C for terrestrial concentrator applications. The RHHES cell possesses all the merits of the back-contact solar cell. First of all, there is no metal shadowing on the sunward front side of the RHHES cell

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allowing for maximum utilization of the available sunlight. A typical conventional silicon space solar cell has to suffer from obscuration of approximately 3 - 5% due to the metal grid for current collection and bus bars for cell interconnection. Secondly, back-contact cells operate optimally when the cell is 75 - 100 microns thick which automatically satisfies the requirement for light-weight space applications. Conventional silicon solar cells have thicknesses ranging from 100 ~200 microns. Thirdly, a back-contact cell has both electrodes on the back side of the cell allowing for surface mounting of individual cells on a mini-module as shown on Figure 1A. The concept of a mini-module is currently under application for letters patent. [7]. The introduction of a mini-module eliminated the need of connectors for interconnecting cells in series and parallel. The interconnecting metal patterns for serial and parallel cell interconnections are printed on the mini-module and cells are mounted automatically using an advanced surface mounting technique. A mini-module with a 2 x 4 arrangement of 2 cm x 4 cm cells covering 8 cm by 8 cm area would be a very useful building block for a large solar panel. Each mini-module can be configured for a specific voltage requirement. As shown in Figure 1B, the distance between any two cells can be controlled to be less than 100 microns in average resulting in a very high packing density. Figures 1B & 1C show SEM photographs of cell intersects. Conceptually, there is no limit on the size of the mini-module. Also, actual practice does not impose too much constraint on the size of the mini-module.

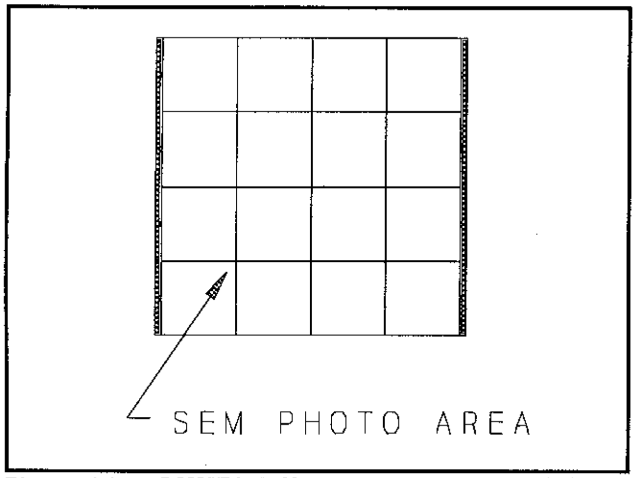

Figure 1A : RHHES Cells on a 4 X 4 Mini-Module Showing Area of SEM Photographs for Figures 1B & 1C

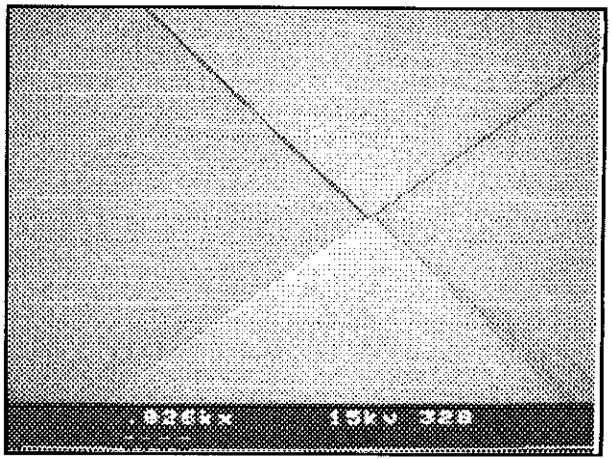

Figure 1B : SEM Photograph of RHHES on Mini-Module Showing High Packing Density

All three attributes described above contribute to the increase of power to weight ratio and power to area ratio for a solar panel using RHHES type cells. Some additional advantages of utilizing a back-contact cell and a mini-module in combination are; (1) minimized number of exposed inter-connectors and solder joints for higher reliability from oxidation and fatigues from temperature cycling and other causes, (2) redundant continuity on the cell backside metalization and mini-module printed metalization decrease the possibility of a string failure due to impinging micro-meteorites damaging the cell, (3) high current handling capability inherent to most back-contact cells due to high metal coverage on the back side increase the survivability from high current surge conditions.

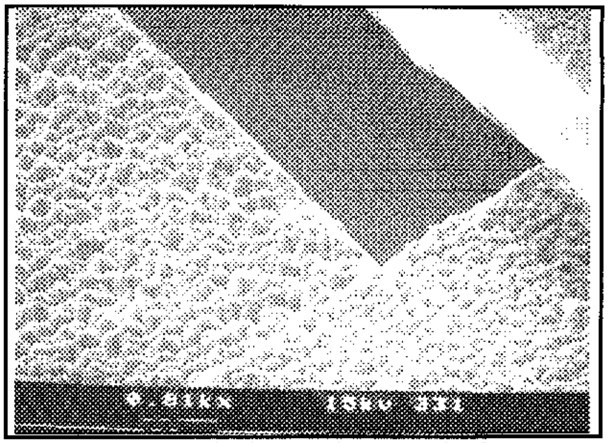

Figure 1C: Magnified SEM Photograph of RHHES on Mini-Module

RADIATION TOLERANCE

Back-contact cells have junctions on the backside (the far-side from the impinging photons). Therefore electron-hole pairs generated near the top sunnyside must diffuse down to the backside junctions to be collected by the appropriate diffused regions; electrons at the N-type diffusions and holes at the P-type diffusions as shown in Figure 2. The terminal current as collected by the respective terminals can be expressed as in Equation 1, including the losses due to recombination inside the cell,

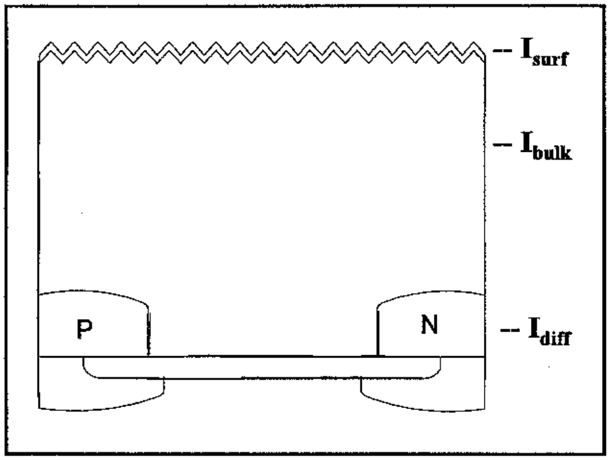

Figure 2: RHHES Cell Structure Showing Recombination Sites

$$I = I_{ph} - I_{rec} \qquad (1)$$

Equation 1 represents that the terminal current, I, is equal to the photo-generated current, I_{ph}, minus the recombination current, I_{rec} [8]. The recombination current losses are mainly from two mechanisms. The first mechanism is due to the imperfections contained in the crystal bulk and surface. The second mechanism for recombination loss is due to the direct collision of dissimilar charged particles. Therefore, the recombination current, I_{rec}, can be expressed:

$$I_{rec} = I_{rec,M1} + I_{rec,M2} \qquad (2)$$

However, it is more useful to account for the recombination current losses by the location within the cell where the recombination losses are occurring. The reason is twofold; (1) the second mechanism is important at high level injection and is not dominant or appreciable at AMO one sun conditions, and, (2) radiation of various particles induces defects within the crystalline bulk and at the surface of a solar cell as shown in Figure 2. If highly doped P and N diffused areas are separated from the bulk due to their high doping effect and junction effect, Equation 2 can be rewritten:

$$I_{rec} = I_{rec1,M1} = I_{surf} + I_{bulk} + I_{diff} \qquad (3)$$

where I_{surf} is the surface recombination, I_{bulk} is the bulk recombination and I_{diff} is the recombination occurring within the highly doped and space charge regions due to injected minority carriers into respective highly doped regions.

Irradiation of 1 MeV electron flux was selected for the radiation tolerance improvement study to simulate the space environment and utilize the vast amount of existing data for comparison. For the study, three basic assumptions were made. The first assumption was that electrons with 1 MeV energy would penetrate through the RHHES solar cell of 75 100 micron thickness, without appreciable attenuation, inducing fairly uniform radiation damage effects throughout the cell thickness. The second assumption was that the radiation effects within the crystalline bulk can be decoupled from surface and junction effects due to the relatively thin range of surface effect into the bulk and the shallow depth of the junction compared to the cell thickness. Thirdly, during radiation it is assumed that radiation induced effects on the surface and within the highly doped region do not affect the radiation effects onto bulk material and vice-versa due to the low dose rate and simple device structure of the solar cell.

It is noted hat the I_{diff} term in Equation 3 would be affected least by radiation damage among the three terms due to the fact that the region is highly doped with a high level of diffusion damage, and the total volume and area is comparatively small relative to the other terms.

Two experiments were performed to study the radiation tolerance of the RHHES type back-contact cell: (1) cell thickness variation maintaining all other structures and parameters (2) FSF (front surface field) variation while all other processes and parameters are maintained. In Figure 3 the result of radiation tolerance as a function of cell thickness variation is presented.

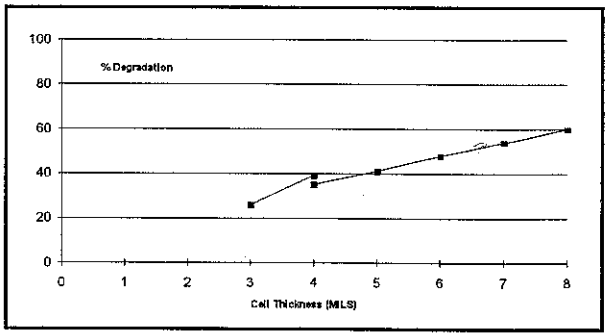

Figure 3: Effect of Cell Thickness on Radiation Hardness

The radiation tolerance was represented by percent degradation of the output power. The wafer processing was identical for all the wafers of different thickness except the final thickness. The final thickness was measured using ADE's non-contact microsense Model 6034 machine. Materials used were from two different crystal ingot runs. The material resistivity specification was 50 Ω-cm ±50%.

The effect of FSF (front surface field) variation on radiation tolerance is exemplified in Figure 4. The term FSF was used to emphasize the similarity of function a FSF has to the function of a BSF (back surface field) which is a very common structure built in a conventional front-junction solar cell to reflect minority carriers from the high recombination velocity back surface typical with a large area of metal contact. The FSF is not as deep as usual BSFs due to the fact that it is located in a high level generation region by high energy photons. For the experiment, FSF depth was controlled to be approximately the same for all concentrations by controlling the FSF diffusion. The data points were obtained using cells with a thickness range of 95 - 105 microns.

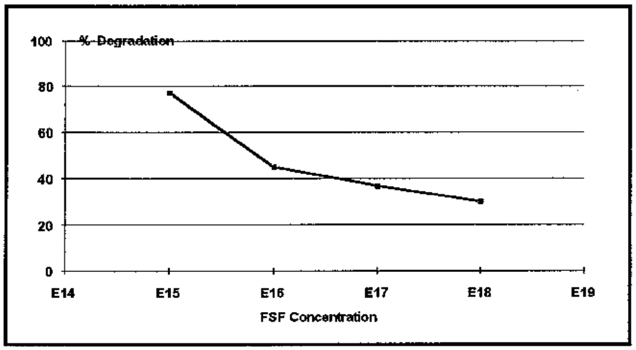

Figure 4: The Effect of FSF Concentration on Radiation Hardness

RADIATION TESTING

Radiation testing of the RHHES Cell was performed at two different locations, Jet Propulsion Laboratories in Pasadena California, and at Goddard Space Flight Center in Greenbelt, Maryland. In both instances, 1 Million Electron Volt (MeV) electrons were used for irradiation.

The Electron source at Goddard is a 1 MeV VanDeGraff generator and the source at JPL is a 3 MeV dynamatron.
Although the equipment and capacities to generate high energy electron differ, the radiation used at both sites was the same. The following differences do exist between the Goddard and JPL methods:

1. The Goddard system uses a deflection system, either magnetic or electrostatic, to spread the beam in a vertical, or Y-axis, direction over the target area. dispersion over the X-axis depends upon scattering through a .002" titanium window, located about five inches away from the specimen, which also serves as an interface between the atmosphere and the evacuated interior of the VanDeGraff generator beam switching system. Additional scattering is achieved as the beam passes through the atmosphere. Faraday cups are located at the center and at each end of the target plate.

2. In the JPL system the specimens are placed inside the vacuum. A .004" aluminum foil, located 30 inches ahead of the specimen, is used to disperse the beam over the target plate, located within the vacuum, to which the specimens are attached. Vacuum grease is used to hold the specimens to the target plate. A single Faraday cup is used slightly below the center of the target plate.

Prior to irradiating cells at Goddard, a trial run was made with a piece of radiation sensitive nylon film attached to an aluminum plate drilled to fit the target plate mounting screws. Visual examination of the film, which darkens upon exposure to the high energy electron beam, showed a fairly even coverage as observed by the unaided eye. A hole, which was located in the center of the aluminum plate, replicated on the film indicating that some backscattered radiation was being added to the primary dose. For the purpose of the experiment the information was noted but not taken into consideration. JPL had historical data on their system indicating a better than 90% uniformity over a 10 inch diameter circle, so no further uniformity testing was performed.

All in-process development testing was performed at JPL due to the proximity to the AMONIX facilities. Final evaluations were performed at Goddard by Naval Research Laboratories and AMONIX personnel using government supplied conventional solar cells, with coverglasses, as benchmark devices. Pre- and post- irradiation data were recorded at NRL using a Spectrolab X-25 solar simulator at AM0 conditions.

The results of the test are summarized in Figure 5 expressed in terms of efficiency.

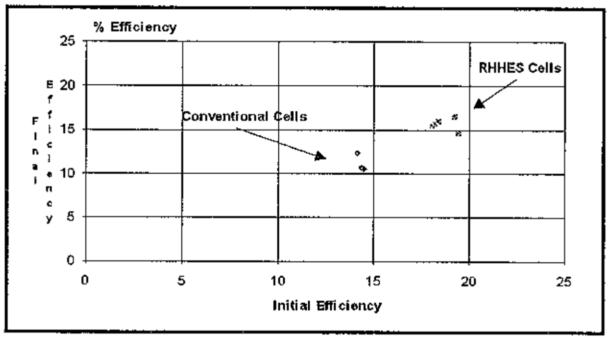

Figure 5: Pre vs. Post Irradiation Efficiency After Exposure to 1E14 1 MeV electrons/cm ^{2}

CONCLUSION

The RHHES solar cell has demonstrated a high efficiency of 19% at AMO. It has proved that the radiation tolerance can be improved further. The RHHES offers merits over conventional silicon space cells for the increase of power-to-area ratio, and power-to-weight ratio. It has a backside contact structure allowing the application of surface mounting technology. This also enables the use of a mini-module. The utilization of a pre-printed mini-module eliminates the need for cumbersome connectors for serial and parallel connections, and redundant connections to reduce the probability for string failure.

The RHHES cell and mini-module in combination also offers stronger survivability under micro-meteorite showers, or high current surge conditions due to a built-in metalization redundancy and high metal coverage with high current handling capability.

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