DEVELOPMENT OF BACK JUNCTION POINT CONTACT PHOTOVOLTAIC CELLS AND ARRAYS FOR SPACE

V. Garboushian, G. Turner, S. Yoon
AMONIX, Inc., 3425 Fujita Street, Torrance, CA 90505

G.J. Vendura Jr.
TRW Space and Technology Division
One Space Park, Redondo Beach, CA 90278

ABSTRACT

This paper presents the results of a project to develop back-junction, point-contact silicon solar cells and modules for space. Such cells are already fabricated commercially for terrestrial applications using standardized equipment and processes originally developed for high manufacturing throughput, low-cost semiconductor chip technologies. Individual 2cm X 2cm cell outputs of 18%, AM0 are routinely obtained. In addition, since all contacting takes place at the back surface, very high packing densities are possible resulting in comparatively higher output for arrays. The present study is divided into three phases (1) development of individual cells into a space product, (2) development of rigid and flexible modules (3) module fabrication for flight experimentation upon the Small Satellite Technology Initiative (SSTI). The first phase focused upon silicon surface and bulk features to increase photon absorption and reduce recombination. The compatibility of the finished cells with space worthy components such as interconnects and coverglasses was confirmed. In the next phase, cells were assembled into small modules. Substrate material included both rigid, 8 mil, silicon wafers as well as flexible, 1 mil Kapton. A unique interconnection system was developed which consisted of redundant thin-film metal patterns deposited directly on the substrate surfaces. This was followed by a solder reflow bonding process compatable with high volume robotic fabrication equipment. This effort resulted in the fabrication and testing of two SSTI flight modules consisting of a series arrangement of nine 2cm X 2 CM cells each.

Development of RHHES

In 1993 Amonix Inc. developed a Radiation Hardened High Efficiency Silicon Space Solar Cell (RHHES)[1] This cell was a back contact, laboratory sized cell. The cell has been expanded and optimized, emerging as a 2cm. X 2cm. lightweight, high efficiency space solar cell. The development, and transition from laboratory cell to production is reported elsewhere.[2] The new RHHES was selected to fly on NASA's, TRW built, Small Spacecraft Technology Initiative. Prior to committing the RHHES to the satellite, extensive vacuum temperature cycle testing was performed by TRW.

Development of Rigid Modules

The RHHES is not a physical replacement for conventional solar cells, having both contacts on the backside of the cell. The rigid module, or carrier, not only solves the problem of a unconventional configuration, but affords an opportunity to create a "high(er) voltage" solar cell which can be assembled into space solar panels using existing technology and facilities. Furthermore, the carrier technology, combined with the back contact RHHES, permits tighter spacing of the individual cells in the array, due to the fact that spatial allowance for interconnects between the front and back sides of the cells is eliminated. In addition, the carrier technology permits integration of bypass diodes into the individual modules which eliminates the need to allow further unproductive area on the panel for the purpose of mounting discrete components. These modules can be pre-fabricated or pre-assembled on a production line resulting in sub units that can be mixed and matched on various satellite wings. In effect the result would be the equivalent of larger solar cells, with battery like voltages, reducing time and complexity in populating the final array.

The carrier consists of an 8 mil thick silicon substrate metalized by means of standard semiconductor processing techniques to provide a surface mount array of individual RHHES interconnected in series, or series parallel, to form a module which can be used in exactly the same manner as a conventional solar cell with a higher output voltage. One advantage of the surface mount technique is that the thermal conductivity of the solder used for electrical connection also removes heat, the result of unconverted solar radiation, from the cell to the silicon substrate. The metal contacts on the back of the RHHES are large, covering almost 90% of the cell area. In order to assure uniform attachment of the cells during assembly of the module, the metalization on the substrate was broken into sixteen individual pads for each mating cell termination (32 per cell). The interconnection between cells is accomplished by four separate traces connecting adjacent pads at the cell interfaces. Each trace is fully capable of supporting the full current of the series

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connected cells, providing a 4X redundancy factor. Each of these pads received a measured quantity of solder paste prior to the reflow soldering of cells to the substrate. The spacing of the pads is such that the heat cones from each of the solder attach points on the carrier either touch or overlap at the back of the carrier. Not only do these individual applications of solder paste assure a uniform solder interface, but the channels formed by the advancing front of molten solder allow the excess flux to flow out to the edge of the individual cells rather than becoming entrapped in a large area solder joint.

The terminations for the module appear at the edge of the silicon carrier, occupying about the same width as the front contact on a conventional solar cell. In the case of the SSTI flight module, a 4 X 4 array of RHHES, the area required for terminations is one fourth that required for the equivalent conventional solar cells. This is the maximum amount of non energy producing area that would be required for any module. If the aspect ratio of the module were changed, that fraction of total area devoted to terminations would be reduced accordingly, assuming the terminations are located on the shorter edge of the rectangular substrate.

For the SSTI flight module, the RHHES were glassed individually before soldering to the carrier. This decision was based upon the availability of cover glasses and the established single cell glassing procedure of the TRW solar panel fabrication facility, at which the glassing operation was performed. An alternative method would be to treat the entire module as a single cell and cover with a single large area cover glass

Development of a Flexible Module

A standardized flexible module exhibits all of the advantages of the rigid modules plus the following:

1) The module is lighter in weight.
2) A flexible module is more robust (less fragile).
3) Being flexible the module has the ability to conform to curved surfaces.
4) The flexible module has the ability to integrate with foldable, rollable Kapton array wings.
5) A flexible array has smaller volume, and requires less storage volume.

Silicon is not the only candidate material for module substrates. It is an ideal material due to the fact that no thermal mismatch exists between the substrate and the RHHES. It is also a very high thermally conductive material. If we are willing to engineer out the problems of thermal mismatch, a very nice tradeoff exists between thermal conductivity and physical utility.

Polyimide film, often known by one of the more popular trade names, Kapton, is used extensively in the electronics industry for flexible circuitry. In this process the film is supplied bonded to a layer of copper. The circuitry is defined by photolithographic processes, and all unwanted copper is etched away leaving only the current carrying traces. This technology was borrowed intact for the production of flexible substrates.

Early attempts at populating these flexible carriers was disappointing. The higher coefficient of expansion (COE) of the polyimide resulted in distortion of the cells upon cooling from the reflow soldering operation. The polyimide expands at a greater rate than the silicon during the soldering operation, and after soldering, the cell and polyimide are mechanically locked together at the freezing temperature of the molten solder. As the assembly continues to cool down, the polyimide is now contracting at a greater rate than the silicon. This would present no problem if the substrate were rigid, since crystalline silicon is very strong in compression mode and the stress strain relationship of polyimide is much more compliant than that of silicon. In the case of the flexible circuit, the difference in COE resulted in a warping of the composite structure much like the movement of a bimetallic strip in a thermostat.

Several approaches were considered to overcome the problem of the differential COE. The method which offered the most practical solution to the problem was to design a fixture which would pre stress the polyimide film during the reflow soldering operation. The polyimide film appears to yield slightly at reflow temperature, setting the strain caused by the fixture permanently into the film. The tension on the film is maintained until the assembly has returned to room temperature, after which the assembly is removed from the fixture. After removal, almost all of the distortion observed in earlier experiments is eliminated. The relationship between stress, strain, and temperature of the polyimide film has not been fully investigated at this time, however additional matrix experiments should result in a process capable of producing distortion free flexible modules.

The reduced thermal conductivity of the polyimide film is offset by the ability to use a much thinner substrate, typically 1 mil thick as opposed to the 8 mil silicon substrate. The polyimide film is also available in an alumina filled version which has a higher thermal conductivity than the standard flex circuit material. The dielectric strength of polyimide is in the order of 5,000 volts per mil, making additional layers of insulation unnecessary.

Developmental testing

Each of the RHHES are tested both in wafer form and after separation by the Amonix solar cell test station. Data is automatically stored by the test station computer in numeric form. IV curves are displayed by the station during testing and can be printed by the operator if desired. For the module development effort all RHHES were documented at final test with a hard copy IV curve. This procedure was repeated after glassing and, for loose cells, after soldering interconnects to the individual RHESS to facilitate measurement by TRW. The Amonix solar cell test station was designed for single cell testing, and would have required some software and hardware modification to accommodate the higher voltage output of the completed module. A Tektronix model 370 curve tracer was used for testing assembled modules, in conjunction with the solar simulator section of the solar cell test station.. This curve tracer is capable of digitally storing the CRT display and replaying the information to a pen plotter. The assembled modules were tested, and curves plotted, with the curve tracer after reflow soldering and after each endpoint in the temp cycle sequence. The RHHES and assembled modules were returned to Amonix for retest and endpoint verification after each endpoint measurement at TRW.

Radiation hardness testing of the RHHES has been performed at two different facilities; Jet Propulsion Laboratories in Pasadena California. and Goddard Space Flight Center in Greenbelt, Maryland. The results of this testing was reported earlier[3].

Vacuum temperature cycle testing was performed on three modules and nine individual cells. Two of the modules were assembled as a 3 X 3 array of RHHES on silicon carriers and glassed with 6 mil and 2 mil cover glasses respectively. The third module was assembled on a flex substrate with 16 cells (4 X 4 array), and had no cover glasses. The individual cells consisted of three groups; 5 with no cover glass, 3 with 6 mil cover glass, and 3 with 2 mil covers. In addition to the temp cycle specimens 11 loose cells and the two flight modules were included as controls. These control devices were not temperature cycled, but were tested alongside the cycled items at 0, 50, and 1000 cycles. All loose cells had 1 mil thick tabs of kovar attached to each termination to facilitate endpoint testing at TRW. The test equipment at TRW is configured to make contact to conventional solar cells. The kovar tabs, actually interconnects used for the assembly of conventional solar panels, simplify the test equipment interface. The COE of kovar matches that of the silicon, so very little stress is induced by the temperature cycling. Table I summarizes the individual groups and purpose.

The temperature cycling was performed at Aerospace Corporation in El Segundo, California. The cells and modules were mounted inside cavities machined, to fit the individual components, into a fixture which is then inserted into a vacuum chamber. shims are placed on top of the components in their cavities before a solid metal cover plate is bolted over the components. The result is that the cells and modules are embedded in a solid metal plate with good thermal conduction, via the shims, from the plate to the cells. Figure 1 shows the loaded fixture before the addition of shims or cover plate. The thermocouples, which can be seen in Figure 1 are mounted on dummy RHHES, and are used to determine the temperature of the devices under test.

Table I

No. Cells	Configuration.	Cover Glass	Purpose
9	Rigid Si	6 mil	Temp Cycle
9	Rigid Si	2 mil	Temp Cycle
16	Flex	none	Temp Cycle
5	Loose	none	Temp Cycle
3	Loose	6 mil	Temp Cycle
3	Loose	2 mil	Temp Cycle
9	Rigid Si	6 mil	Flight/Control
9	Rigid Si	2 mil	Flight/Control
3	Loose	6 mil	Control
3	Loose	2 mil	Control
5	Loose	none	Control

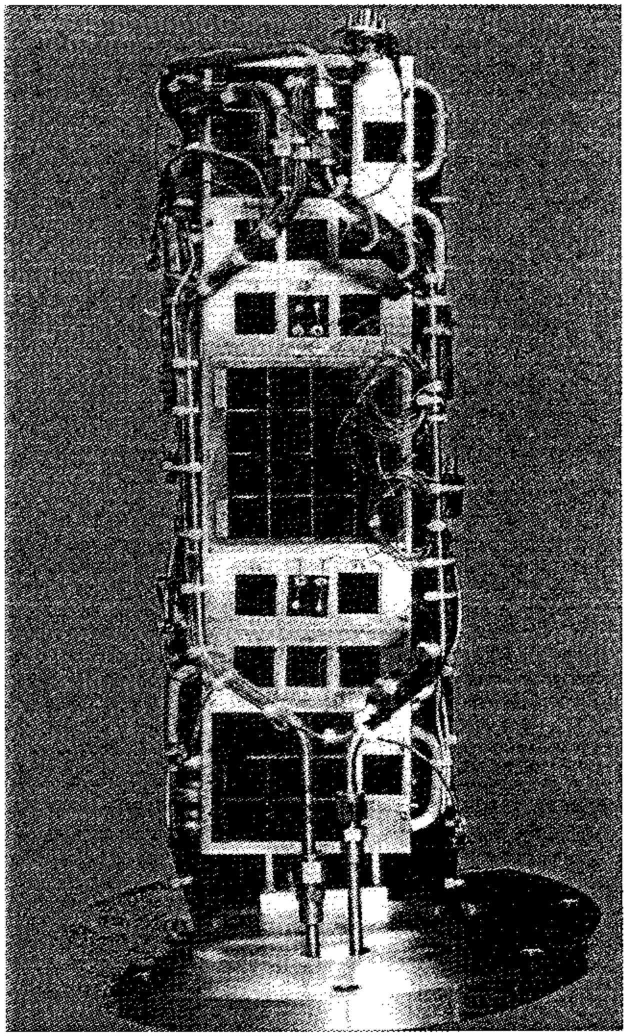

Figure 1: SSTI Temperature Cycle Fixture

The primary purpose of the temperature cycle testing was to determine the survivability of the SSTI flight modules. The loose cells, with and without cover glass, were included to isolate any mechanisms which may be related to the assembly of RHHES to the rigid silicon substrate. The flex module was included as an "information only" development test on a best effort basis. The scheduled number of cycles is 3,000, however at this writing only 1,000 cycle data is available. The test plan is summarized in Table II.

Table II

Temperature Extremes:	+80°C(-0 °C/+10 °C) -100 °C(-10 °C/+0 °C)
Dwell at Extremes:	5 minutes
Rate:	Open
Number of Cycles:	3,000
Test Points:	0, 50, 1000, 3000 cyc.
Tests:	Electrical (Full IV curves) Visual (Full Maps)

At the 1,000 hour endpoint, the flex module exhibited an open circuit failure. No analysis was performed. All other specimens showed no degradation within the bounds of experimental repeatability through the 1,000 cycle end point measurements. The following general conclusions can be drawn from the temperature cycling test results:

1) The cover glasses stay intact when bonded to the textured surface of the RHHES
2) The solder bond from RHHES to substrate remains intact without degradation.
3) The substrate metalization (interconnects) show no degradation or delamination.
4) With the exception of the flex module, there was no degradation or loss of power in the modules' electrical performance.

From the forgoing, we may conclude that the flight test modules can be expected to survive the SSTI environment.

SSTI Flight Experiment

NASA's Small Spacecraft Technology Initiative consists of a pair of small satellites, Lewis and Clark, designed to act as a test bed to develop, demonstrate, and test new technologies aimed at light weight, low cost, next generation spacecraft. An experiment involving back junction, point contact solar cells has been included on the Lewis satellite, shown in Figure 2. The design life of this spacecraft is three years with a five year goal in a 525 Km (282.7 nm) non synchronous orbit.

The silicon back junction point contact array experiment consists of two rigid modules, each with nine 2 X 2 cm. cells in series mounted upon 8 mil silicon as described previously. The cells of one module were individually covered with 6 mil of CMZ cerium oxide doped borosilicate cover glass while those of the second module were covered with 2 mils of the same material. Thermistors were positioned in contact with the backs of each module by vias in the underlying honeycomb for the purpose of monitoring module temperature in space. Dosimeters located in the body of the satellite will measure radiation.

The objective of the SSTI experiment is to validate ground measurements, beginning of life (BOL) and end of life (EOL) electrical measurements, determine the shape and/or slope of the degradation curve for comparison with JPL values and predictions[4], and to demonstrate the performance and survivability of RHHES in space.

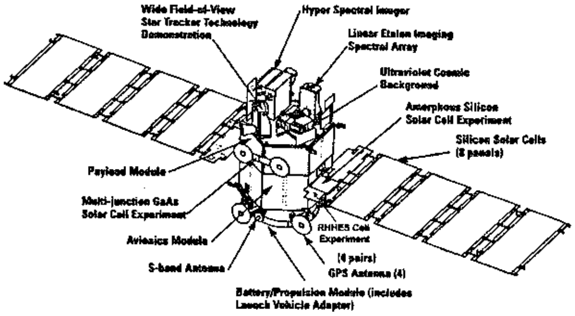

Figure 2: The Small Spacecraft Technology Initiative

The SSTI data acquisition will record, full IV curves, at 32 points ranging in current from 0 to 223.5 mA, temperature, and radiation dosage. For the first month of the mission, IV measurements will be made every 10 minutes while the satellite is "in sun". Temperature measurements will be made every ten minutes during both sun and eclipse periods. After the first month, the data acquisition will be reduced to one measurement of IV and temperature at peak sun, and one temperature measurement at the trough of the eclipse period. The satellite will make 15 revolutions per day with a 58 minute sun exposure plus a 37 minute eclipse for a total of 95 minutes per cycle.

Prior to installation on the satellite, the panels upon which the flight modules are mounted will be subjected to a series of pre-flight tests comprised of: 1) Induced Acoustic Levels, 2) Thermal Cycle Test, 3) Random Vibration, and 4) Induced Shock. Some of these tests have been completed at this time and the remainder are pending. The expected launch date is November 15, 1996.

ACKNOWLEDGEMENTS

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