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# Large Area Low-Cost Space Solar Cell Development

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# LARGE AREA LOW-COST SPACE SOLAR CELL DEVELOPMENT

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## ABSTRACT

A development program to produce large-area (5.9 x 5.9 cm) space quality silicon solar cells with a cost goal of 30 $/watt is described. Five cell types under investigation include wraparound dielectric, mechanical wraparound and conventional contact configurations with combinations of 2 or 10 ohm-cm resistivity, back surface reflectors and/or fields, and diffused or ion implanted junctions. A single step process to cut cell and cover-glass simultaneously is being developed. A description of cell developments by Applied Solar Energy Corp., Spectrolab and Spire is included. Results are given for cell and array tests, performed by Lockheed, TRW and NASA. Future large solar arrays that might use cells of this type are discussed.

## INTRODUCTION

Future large space systems such as the Space Operations Center or the Space Platform (refs. 1 and 2) will require solar array power levels in the multikilowatt range. The cost of these solar arrays may be a significant proportion of the total spacecraft acquisition cost. The solar cell cost in turn may be as much as 40% of the array cost. Present space cells are 8 $cm^2$ in area, 12-13% efficient and cost about $100 per watt. Therefore, solar cell cost reductions could have a significant impact on future programs.

In early 1980, NASA initiated a program to develop low cost solar cells. The goals of this effort are to develop a space quality silicon solar cell with an area greater than 25 $cm^2$, an efficiency of 15% AMO, (air mass zero) that can have a cell cost of less than $30 per watt in volume production.

## APPROACH

Studies have shown that cell costs can be reduced by increasing cell size, simplifying cell fabrication processes, streamlining cell specifications and documentation and minimizing redundant in-process destructive testing.

The use of large cells can be beneficial in several ways: 1) more of the silicon in the round starting wafer is used, 2) fewer cells need to be fabricated to achieve the required power level and 3) fewer cells need to be

handled (interconnected, etc.) in array production. One technique for simplifying cell fabrication is to use a single step to saw-cut both the cell and its attached coverglass (i.e. autoregistration-sizing). Autoregistration-sizing eliminates the need for expensive, close dimensional tolerances on the coverglass and reduces labor cost and assembly time usually needed for cell-cover glass alignment.

Another means to reduce costs is to increase cell efficiency. Solar cell costs are expressed in terms of dollars per watt so that the greater the power output per cell (i.e. the higher the AMO efficiency) the less the cost per watt. Using the same fabrication process, if cell efficiency could be increased from 13 to 15% AMO, then costs could be reduced, for example, from $100/watt to $86/watt.

## CELL DEVELOPMENT

In early 1980, NASA initiated a low cost solar cell development program. The program to produce low cost solar cells attacks the problem in three phases. In Phase I, the questions to be addressed were 1) can a large area cell be fabricated which will perform as well as a 2 x 2 cm or a 2 x 4 cm size cell? 2) are large area 5.9 x 5.9 cm cells usable in flexible substrate solar arrays? 3) is a cost goal of $30 per watt a reasonable target? and 4) are ion implantation and the autoregistration-sizing technique viable strategies for cost reduction?

In Phase II a large quantity of cells will be produced to determine cell yields, cost and performance, and to demonstrate a production rate of 12,000 cells per month. These cells will be available for qualification tests. Phase III is the production of large area cells for future large space arrays such as SEP, PEP, or space stations.

The program organization includes NASA, the solar cell vendors (ASEC, Spire and Spectrolab) and two array vendors (TRW and Lockheed Missiles & Space Company). This arrangement is used to assure that the cells and the specifications to which they are manufactured are compatible with array requirements. Under this arrangement, NASA acts as an overseer with Lewis Research Center (LeRC) being responsible for cell technology issues and Johnson Space Center (JSC) being responsible for cell array systems and programmatic issues.

The cost goal for Phase I is to produce cells for $30 per watt. This cost is about one third of present space cell costs. Two primary types of baseline cells are under development: 1) a cell with a base resistivity of two ohm-cm incorporating a back surface reflector (BSR) with a thermal absorptivity (alpha) of 0.70 and 2) a ten ohm-cm cell with a back surface field (BSF) and a BSR with an alpha of 0.75. A third cell type (two ohm-cm BSR, BSF) was also evaluated for PEP mission suitability.

The electrical contact metallization system to be applied to the generic cell type (i.e. base resistivity and back surface treatment) selected will be either a wraparound or a conventional top-bottom contact. Air mass zero (AMO) efficiency goals for each contact type are 12.8% for the wraparound and 14% for the conventional cell. Multilayer antireflection (AR) coatings may be used.

The system designer will select the solar cell technologies that yield the best combination of beginning-of-life (BOL) and/or end-of-life (EOL) performance, lowest overall system cost and acceptable technical and schedular reliability and risk. The low cost cell development activity will provide the information needed for that selection.

Some of the advantages and disadvantages of the various cell technologies are as follows: The base resistivity affects power output (performance), radiation degradation rate and temperature coefficient of performance. As resistivity increases, power decreases during irradiation. Use of a BSF increases BOL performance. However, this increase is lost after moderate radiation fluences. Conversely, a BSF increases thermal absorptivity which raises cell operating temperature in orbit thus reducing performance. On the other hand, a BSR reduces thermal absorptivity and operating temperature and thus increases performance. Both BSR and BSF add to the complexity and cost of the cell. AR coating type affects power output, temperature coefficient and cell cost. Thus there is a multitude of effects which mandates side by side comparative development and testing.

The cell development efforts at Spectrolab (ref. 3), at ASEC (ref. 4) and at Spire (ref. 5) have addressed a wide range of similar, though not identical issues. Some of the development efforts are as follows: 1) investigation of alternate cell technologies and processing techniques, 2) optimization of cell design and manufacturing process, 3) equipment and tooling design and construction, 4) acceptance and approval type testing, 5) generation of software such as manufacturing control documents, solar cell specifications and test plans, and plans for implementing full production, 6) cell fabrication, and 7) analysis of cell costs.

The cell development contractors at ASEC and Spectrolab have shown that large area (5.9 x 5.9 cm) cells can be made and that the 12.8 and 14% performance goals can be met. Preliminary analysis indicates that the $30/watt cost goal can be achieved with optimistic but realistic assumptions of process yield.

Figure 1 enumerates solar cell cost reduction expected by cell area increases and shows that a single three inch diameter silicon wafer can be used to make either three 2 x 4 cm cells, one 5 x 5 cm, or one 5.9 x 5.9 cm cell. Three 8 $cm^2$ area cells require more handling during manufacture, use only 53% of the wafer area and have the highest normalized cost. Increasing cell area to 25 $cm^2$ uses about the same wafer area (55%) but decreases normalized cost per watt (.66) by reducing the number of wafers handled during manufacture. If the cell is made with slightly rounded corners, a 5.9 cm "square" cell can be made that uses 75% of the wafer area (i.e. wastes only 25%) and reduces the cost to about half that of three 2 x 4 cm cells. The figure also shows that for a 25 kilowatt array the number of cells that must be assembled can be reduced from about 179,000 to about 36,000 if cell area and efficiency were increased from 8 $cm^2$ at 13% AMO to 34 $cm^2$ at 15% AMO.

Spire is working on a 5.9 x 5.9 cm cell with two ohm-cm base resistivity, ion implanted boron back surface field and an evaporated aluminum back surface reflector. Experiments are in progress to determine if a sintered

or non-sintered back contact with full or gridded metallization will be optimum. Emitter formation experiments have shown that arsenic implantation, either directly or thru an oxide, may be the best technique. Lamination of six mil 0211 coverglass has been achieved with three adhesives: Teflon FEP, ethylene vinyl acetate (EVA), and Dow Corning 93-500. Both FEP and 93-500 are space proven adhesives. EVA is a low cost material that has only been used in terrestrial modules to date. Sawing of assemblies to final size has been achieved.

Figure 2 illustrates the autoregistration-sizing technique. A processed round wafer containing a 5.9 cm "square" solar cell with interconnect tabs attached at the rounded corners has an over sized coverglass bonded to the cell surface. The bonded cell-cover assembly is sawed to size in one cutting operation (4 cuts). The extra step of separately cutting the fused silica cover glass to exact size is eliminated.

## CELL TESTING

Extensive measurements and tests of large area cells were performed at all the contractor facilities. These include current-voltage characteristics, contact reliability evaluation, optical properties, temperature coefficients, thermal cycling, environmental tests, module fabrication and process and handling tests.

Future large area space arrays will operate in low earth orbit for up to 10 years and will be subjected to some performance degradation by space radiation. Laboratory tests to determine the amount of cell degradation due to radiation were performed at NASA-Lewis Research Center in a damage test with side-by-side comparison of candidate cell types and pre- and post-irradiation airplace calibration of outer space short-circuit current. These results have been published (ref. 6).

Six different cell types with the best potential for meeting the system requirements were supplied by ASEC and Spectrolab for evaulation. The cells had combinations of resistivity, BSR, BSF, and AR coating. The code used to describe the cells and the test conditions shown in Table I.

The average maximum power versus fluence for the 10 and 2 ohm-cm cells is shown in figures 3 and 4 respectively. For each point, the data spread was less than 3%. These data show that the A10FRM, (i.e. the ten ohm-cm cell with a BSF, a BSR and a multilayer AR coating) had the highest beginning of life (BOL) power (76.8 mW) under laboratory conditions. At $3 \times 10^{14}$ e/cm$^2$ fluence, the A10FRM and the A2RM cells both had the highest average power (56.4 mW). The S2FRT, a unique 2 ohm-cm BSF cell, has about 10% higher BOL power (72.4 mW) than the S2RT, (65.6 mW) due to the BSF. however, the S2FRT degrades more quickly than the S2RT and at $3 \times 10^{14}$ e/cm$^2$, the power increase due to the BSF effect is almost completely eliminated (53.2 vs. 52.8 mw) and S2FRT (72.4 mW) shows about a 3.7% boost in power due to the multilayer AR coating. In terms of normalized power (i.e. maximum power at zero fluence divided by maximum power after $3 \times 10^{14}$ e/cm$^2$) the 2 ohm-cm BSR cells degraded to 0.80 of original; the 10 ohm-cm BSR/BSF cells degraded to 0.73 of their original power.

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These radiation damage results are necessary, but not sufficient, information needed by the array designer. These tests show that the cell type with the highest power output at room temperature was the 10FRM at BOL. The 10FRM and 2RM groups had equal power at EOL. The lower thermal absorptivity (measured elsewhere) of non-BSF cells results in lower orbit operating temperature and higher power output. Thus, the 2 ohm-cm BSR cell will have the best EOL performance in orbit. The 2RM cells also had the least change in power over mission life which aids power supply design.

## RECOMMENDATIONS

A variety of large area, silicon solar cell types have been developed which demonstrate a reduction in the cost per watt of space photovoltaic devices. Manufacturing processes have been refined and engineering data have been derived. Technology issues to further improve cell performance and reduce cost have been identified. Examples of these issues which are specific to each manufacturer are as follows:

- Heat treatment of the evaporated aluminum back surface reflector and other cell processing steps should be studied to further increase reflectivity and lower thermal absorptivity.

- Photomask for front contact patterns should be redesigned to increase short circuit current and collection efficiency and to provide fiduciary marks.

- Degradation mechanisms of wraparound cells must be identified and eliminated. Refinements in etch and thermal cureing steps may further increase bond strength in mechanical wraparounds. Redesign of back contacts to minimize n contact area and p contact giveaway may improve dielectric wraparound cells.

- Cell cost reductions and production capacity increases are possible with improved equipment and augmented facilities (e.g. large capacity contact metal evaporation systems).

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TABLE I. - CELL AND TEST DESCRIPTION

Cell Code

| | |
|---|---|
| A | Cell manufacturer |
| S | Cell manufacturer |
| 10 | Base resistivity in ohm-cm |
| 2 | Base resistivity in ohm-cm |
| F | Back surface field |
| R | Back surface reflector |
| T | $Ta_2O_5$ AR coating |
| M | Multilayer AR coating |

Test Conditions

- 1 MeV electron flux $10^{12}$ e/cm$^2$/sec in air.
- Cell temperature 40° C during irradiation, 60° C for 17 hours in air post irradiation annealing.
- Measurements: AMO I-V at 28° C, spectral response and aircraft calibration of AMO $I_{sc}$.
- All cells 2x2x0.02 cm, no coverglass, conventional contact.

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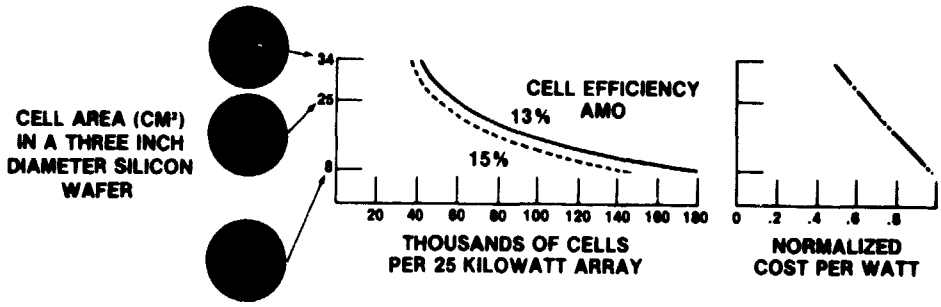


Figure 1. - Reduction of solar cell costs by increasing area in a 3-inch (76-mm) diameter silicon wafer.

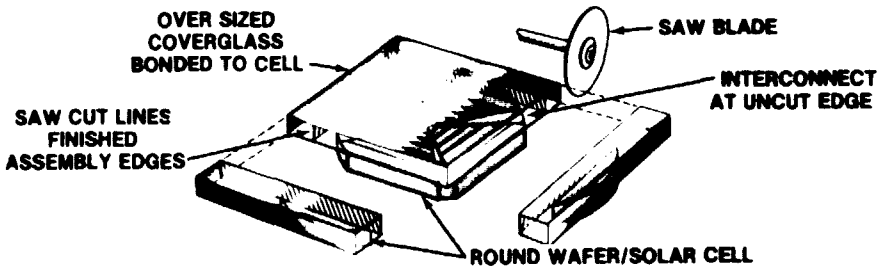


Figure 2. - Reduction of solar cell costs by autoregistration sizing (single step sawing of cell with bonded cover glass).

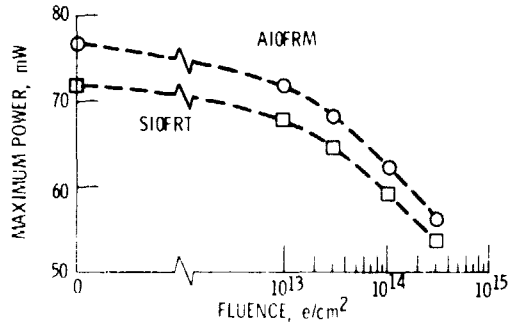


Figure 3. - Variation of maximum power with fluence for 10 ohm-cm low cost solar cells.

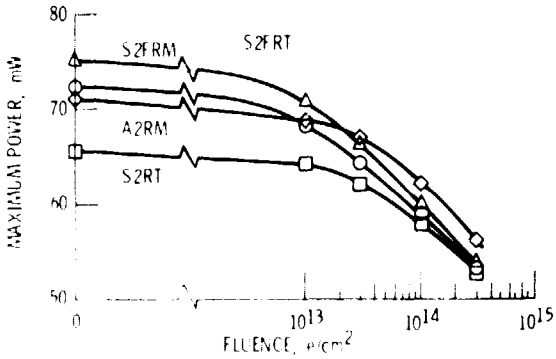


Figure 4. - Variation of maximum power with fluence for 2 ohm-cm low cost solar cells.