A BRIEF SURVEY OF THE SOLAR CELL STATE-OF-THE-ART

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INTRODUCTION

This is a brief survey of the space solar cell state-of-the-art at the present time. Modern high performance cells made for space are discussed and the major recent developments that are expected to influence what solar cells will be available in five years or so are described.

MODERN SILICON SOLAR CELLS

The modern solar cell era started in 1972 when the COMSAT Corporation announced the violet cell with an efficiency exceeding 13% AMO (reference 1). For nearly a decade prior to that the efficiency level for silicon solar cells had reached a plateau of 10 to 11%. A number of further innovations have been made since 1972. Modern cells in commercial production and in use or selected for flight use incorporate various combinations of these improvements.

Figure 1 illustrates the major features available. The cells are generally 0.2 to 0.3 mm (8 to 12 mils) in thickness and have a nominal base resistivity of 2 or 10 ohm-cm. Most have a smooth front surface, as depicted in the right-hand portion of figure 1, and have a shallow junction in the range of 0.10 to 0.15 µm in depth. The shallow junction increases the short-circuit current about 10% and improves radiation resistance. The top contact grid fingers are more closely spaced to compensate for the higher sheet resistance of the top N layer due to the shallow junction. So as not to increase the shadowing, grid fingers are now much narrower. Photoresist masks or bimetallic shadow masks are used to make fingers less than 0.025 mm wide and the shadowed area is reduced by 3 to 5%.

Tantalum pentoxide has now replaced silicon monoxide as the antireflection coating because its index of refraction provides a better optical coupling with the cover cement. The improvement in current is about 7%. Multiple layer antireflection (MLAR) coatings are now also becoming available on cells. They can lower the reflectivity and increase current another 3% or more. The shallow junction, tantalum oxide and thin photoresist fingers are the main features of the violet cell.

Another means employed to reduce surface reflections is the textured surface. The front surface is etched chemically to yield a random arrangement of small ($\sim$ 5 μm) pyramids which trap the light and also refract the light entering the cell so that it has a longer path length within the cell. The textured front surface, also with a tantalum oxide antireflection coating, increases the current about 7%. However, because the rough surface also has a low reflectivity for infrared light, the textured surface increases the operating temperature of the cell. An increase in cell temperature reduces voltage and hence power output. The advantage of the increased current is reduced or nullified by the reduced voltage.

At this time it appears the textured surface is most important for thin cells, especially when used in conjunction with a back surface reflector. The back surface reflector is a layer of reflecting metal, usually aluminum, that provides for internal reflection of light that would otherwise be absorbed at the rear contact. The back surface reflector reduces cell operating temperature by reflecting the unuseable red light from the back surface and out the front.

The back surface field is a heavily doped P^+ region at the back surface. Aluminum is usually employed as the dopant for the P^+ region. The back surface field increases the open-circuit voltage to 0.6 V or higher, independent of thickness and base resistivity. It also increases the current about 2%. The advantage of the back surface field is lost after sufficient electron irradiation. For example a back surface field cell 0.2 mm in thickness loses its advantage over a non-field cell of the same thickness after a fluence of about 5×10^{14} 1-MeV electrons/cm^2 (reference 2).

Modern cells are available in quite a variety of combinations of these features with efficiencies ranging from 11.8 to 14.8% AMO. They can be classed into two categories as shown in table I, hybrid and violet-type cells and back surface field cells. The back surface field cells generally have higher initial performance but there is overlap in the performance of these groups because of the different combinations of features available.

The cost of the cells are dependent on the specific details of a particular purchase (specifications, schedule, etc.) as well as cell type. A rough generalization (to within $\pm$ 10%) can be made, however--namely that the cell cost is about $100 per watt at beginning of life. For some missions the power requirements are heaviest early in the mission and back surface field cells may be cost effective. For other missions end-of-life power requirements dictate the array size and the non-field cells would be the economical choice.

RECENT SOLAR CELL R&D ADVANCEMENTS

Research is continuing on raising the efficiency of silicon solar cells. The open-circuit voltage is the parameter limiting the efficiency. Theory indicates that an open-circuit voltage approaching 0.70 V and an efficiency in the range of 18 to 19% AMO are possible if the N^+ region of the cell can be improved (references 3 and 4). Figure 2 shows as a function of base doping level the predicted open-circuit voltage and the voltage actually achieved with conventional N-P junctions. The data points are for base resistivities of 0.01, 0.1, 1, and 10 ohm-cm. Until recently the voltage has been limited to about 0.6 V. Also shown in figure 2 is a recent, yet unpublished, result by Lindholm at the University of Florida. By employing an N^+-N-P-P^+ structure Lindholm achieved a voltage of 0.64 V. More importantly his measurements indicate that in his device the voltage was not limited by the N or N^+ region but by the P region, which is amenable to improvement.

A recent spectacular achievement in silicon cell technology is the ultra thin cell. The key step in achieving a practical cell 0.05 mm (2 mils) in thickness is the use of an alkaline etch that very uniformly reduces the cell thickness (reference 5). The status of the thin cell activity at Solarex is summarized in table II. Pilot production of 2x2 cm cells is underway with efficiencies as high as 14% AMO; large cells, 5x5 cm, are in development with efficiency as high as 11% AMO.

Thin cell development is being supported at Spectrolab also, and the status is summarized in table III. This effort is in the laboratory development phase and cells with efficiencies to 15% AMO have been made. Some of these cells, which have back surface fields, were irradiated at JPL and exhibited radiation damage comparable to non-BSF cells for a 1-MeV electron fluence of 10^{15}. This result conforms to expectations that thin BSF cells should maintain their advantage out to high fluences (reference 6).

Wraparound contact cells have both contacts on the rear of the cell and thereby offer important advantages in cell interconnection and array assembly. Two general types are illustrated in figure 3. In one type the junction and N region are wrapped around the edge of the cell to the rear. With the wraparound junction approach it has been found that shallow junctions could not be used because of shorting through the junction at the cell edge. The efficiency is limited thereby to about 11.5% AMO (reference 7). The other approach shown in figure 3 employs an insulator around the edge and avoids the junction shorting problem. A shallow junction can be used. However, insulating layers applied by vacuum evaporation have pinholes that allow shorting of the N contact metallization to the P base region.

A method for applying a wraparound glass insulator layer by screen printing and firing was developed during a program to develop techniques for low cost fabrication of space-quality solar cells. In this program the main interest was on methods that would be easily mechanized or automated, especially methods that do not require use of vacuum chambers. This work was extended to include wraparound contacts. Table IV lists the main processes. The metallization steps utilized screen printing and the antireflection coating was applied by spinning-on and firing a commercially available preparation to yield a silicon oxide-titanium oxide coating. Junction diffusion was by heating of a spin-on source of dopant commonly used in the semiconductor device industry. Fifteen hundred cells were made in the contractor's terrestrial cell production facilities with an average efficiency of 10.9%.

High efficiency wraparound contact cells are now under development and the processes selected for their fabrication are listed in table V. Screen printing was found superior to vacuum evaporation for the application of the aluminum for the back surface field and the glass wraparound insulator. Efficiencies for a few cells have been over 15% AMO (reference 7). Pilot production with a goal of 14.5% average efficiency is planned.

The nonreflecting vertical-junction silicon solar cell which was conceived to increase radiation resistance is fulfilling its promise. The cell is made with a profusion of thin deep grooves in the top surface of the cell (figure 4). The junction follows the surface of the grooves and a greater portion of the electrons and holes are generated near the junction than in a planar cell, resulting in less sensitivity to carrier lifetime reduction by radiation damage. In the present program at Solarex the grooves are chemically etched into the surface of the aligned 110 silicon wafer through an oxide mask. Cells have been made in the laboratory with efficiencies as high as 14%. The vertical-junction cell has been found to degrade at about one half the rate of planar cells under 1-MeV electron irradiation (references 8 and 9).

It has long been recognized that gallium arsenide solar cells have the potential for higher efficiency, higher temperature operation, and better radiation resistance than silicon cells. However, results with gallium arsenide were not good until Hovel and Woodall (reference 10) introduced the gallium arsenide cell with a gallium aluminum arsenide window, which is illustrated in figure 5. The clear window is epitaxially grown on the gallium arsenide and eliminates carrier recombination at the gallium arsenide surface that had caused poor performance in early non-window cells. The performance achieved in space-program-supported gallium arsenide R&D activities is summarized in table VI (references 11 and 12). The best cells from terrestrial programs, whose efficiencies are reported for a terrestrial sunlight spectrum and sometimes with concentration, are estimated to have AMO efficiencies comparable to the space cells. Efficiencies above 18% AMO have been achieved, but it has been found that higher radiation resistance and higher end-of-life efficiency is achieved by using a smaller junction depth and window thickness. The beginning-of-life efficiency for the more resistant cells is in the 16-17% AMO range. The radiation damage resistance for the thin window and junction cells is significantly better than for silicon cells.

Individual glass covers are customarily bonded to solar cells to protect them from the electrons and protons in space. Fused silica microsheet, and cerium-doped microsheet are commonly used. They are stable and well proven but are expensive (very roughly 1/3 the cost of a cell). The covers are bonded to the cells with a silicone adhesive, the best of which are darkened slightly by UV light. Coatings are sometimes applied to the covers to filter out the UV and protect the adhesive.

FEP-Teflon sheet which has high resistance to UV darkening has been adopted as the cover glass adhesive on the Solar Maximum Mission to save costs. The material cost is low, a UV filter on the cover is not required, and the application and cleanup labor is reduced. The glass cover is applied by heat and pressure bonding of the sandwich of FEP sheet between the cell and cover. FEP cemented covers have been successfully tested in flight experiments on the ATS-6 and NTS-2 satellites.

Borosilicate glass has a thermal expansion coefficient closely matching that of silicon. Such glass can be bonded directly to the silicon cell by electrostatic bonding. The bond is made under pressure at elevated temperature with an electrostatic field between the cell and cover (reference 13). The SPIRE Corporation under Air Force support is investigating how to adapt the process to the modern, high performance cells.

Plastic materials have been investigated as cover materials that are less expensive and/or easier to apply than glass. Heat-bonded FEP Teflon covers were found to embrittle and crack, allowing proton damage to the cells in the ATS-6 flight experiment. Preliminary investigations at Lewis indicate adhesive bonding of FEP covers may eliminate cracking but the process requires further development.

Other polymeric materials that can be applied by spraying, dipping or spinning are also being investigated. Such coatings would be especially suitable for thin cells. The materials include FEP, silicones and polyimides. The coatings investigated so far have been darkened by UV, some severely. These coatings require further development before they would be acceptable for use on space cells.

The Air Force and NASA are continuing to support improvements in space solar cells. The general goals include improved efficiency, radiation resistance, lower weight and lower cost. The major ongoing solar cell R&D programs and their targets are listed in table VII for the Air Force and table VIII for NASA.

CONCLUSIONS

The following conclusions were reached from this brief survey of the solar cell state-of-the-art:

1. High performance silicon solar cells with a wide variety of features and efficiency to nearly 15% AMO are commercially available and are being utilized in flight programs.

2. Silicon cells as thin as 0.05 mm (2 mils) with high efficiency (14% AMO) and radiation resistance are nearing readiness.

3. Wraparound contacts can be applied to silicon cells 0.2 mm (8 mil) thick without compromising performance.

4. R&D programs are continuing to yield more efficient and radiation resistant silicon solar cells.

5. Gallium arsenide cells with high efficiency and radiation resistance have been made in laboratory facilities.

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TABLE I. - MODERN SILICON SOLAR CELLS

BEGINNING OF LIFE OUTPUT, AMO 28^{o} C

	POWER FOR 2 x 4 CM	EFFICIENCY
HYBRID AND VIOLET-TYPE CELLS	128-148 mW	11.8-13.7%
BACK SURFACE FIELD CELLS	136-160 mW	12.6-14.8%

COST

$90-$110 PER WATT, BOL

TABLE II. - ULTRA THIN SILICON SOLAR CELLS

SOLAREX/JPL

DESCRIPTION

ETCHED TO FINAL THICKNESS
0.05 MM THICK
SHALLOW JUNCTION
UNTEXTURED
PARTIALLY REFLECTING BACK SURFACE FIELD

STATUS

2 x 2 CM CELLS

IN PILOT PRODUCTION, 2000 CELLS DELIVERED TO JPL.
CURRENT PRODUCTION CELLS GIVE 65-74 MW (12 - 14% AMO).

5 x 5 CM CELLS

IN LAB DEVELOPMENT.
150 CELLS DELIVERED.
BEST EFFICIENCY ABOUT 11%.

TABLE III. - ULTRA THIN SILICON SOLAR CELLS

SPECTROLAB/JPL

DESCRIPTION

- 2 x 2 CM ETCHED TO FINAL THICKNESS
- 0.05 MM THICK
- SHALLOW JUNCTION
- TEXTURED
- PRINTED AL PASTE BSF
- AL BACK SURFACE REFLECTOR

STATUS

- IN LAB DEVELOPMENT
- BEST CELLS GIVE > 80 mW (14 - 15% AMO)
- EXHIBIT LOW RADIATION DAMAGE -- ONLY 17% LOSS AFTER 10^{15} 1 MeV ELECTRON FLUENCE, COMPARABLE TO NON-BSF

TABLE IV. - NON VACUUM PROCESSES FOR POTENTIALLY LOW COST SOLAR CELLS

SPECTROLAB/LeRC

DESCRIPTION

SURFACE TREATMENT	NaOH TEXTURING ETCH
JUNCTION DIFFUSION SOURCE	SPIN-ON DOPANT
CONTACTS	SCREEN-PRINTED Ag
ANTIREFLECTION COATING	SPIN-ON SiO_2-TiO_2
BACK SURFACE FIELD	SCREEN-PRINTED AL
INSULATOR FOR WRAPAROUND CONTACTS	SCREEN-PRINTED GLASS

STATUS

1500 CELLS MADE IN TERRESTRIAL CELL PRODUCTION FACILITIES

AVERAGE EFFICIENCY, AMO	10.9%

TABLE V. - HIGH EFFICIENCY WRAPAROUND CONTACT SOLAR CELL PROCESSES AND STATUS

DESCRIPTION	SPECTROLAB/LeRC
SURFACE TREATMENT	NaOH TEXTURING ETCH
JUNCTION DIFFUSION SOURCE	GASEOUS DOPANT
CONTACTS	EVAPORATED CrPdAg
ANTIREFLECTION COATING	EVAPORATED Ta_2O_5
BACK SURFACE FIELD	SCREEN-PRINTED Al
INSULATOR FOR WRAPAROUND CONTACTS	SCREEN-PRINTED GLASS
STATUS	
LAB R&D NEARING COMPLETION	
MAXIMUM EFFICIENCY ACHIEVED	15.2%
EFFICIENCY GOAL FOR PILOT PRODUCTION	14.5% AVG.

TABLE VI. - GaAlAs-GaAs SOLAR CELL PERFORMANCE

EFFICIENCY

- HUGHES/AFAPL
  - CELL SIZE: 2 x 2 CM
  - EFFICIENCY: 16 - 17% AMO
- IBM/LaRC
  - CELL SIZE: 0.1 CM^2
  - EFFICIENCY: 18.5% AMO

RADIATION DAMAGE RESISTANCE

- EOL AND BOL EFFICIENCIES CAN BE TRADED OFF BY VARYING THICKNESS OF WINDOW AND JUNCTION DEPTH.
- DAMAGE RESISTANCE WITH OPTIMUM WINDOW AND JUNCTION IS SIGNIFICANTLY BETTER THAN FOR SILICON

TABLE VII. - MAJOR ONGOING SOLAR CELL R&D PROGRAMS –

AIR FORCE

ACTIVITY	TARGET	
NON-REFLECTING VERTICAL JUNCTION SILICON CELL	15% BOL, 12% @ 5 x 10^{15}	1978
HIGH EFFICIENCY SOLAR PANEL PROGRAM-PHASE II-Si	16% BOL, RAD. RES.	1979
SILICON CELL OPTIMIZATION	18% BOL, RAD. RES.	1981
EXTENSION OF ELECTROSTATIC BONDING TECHNOLOGY		
PULSED LASER HARDENING		
HIGH EFFICIENCY SOLAR PANEL PROGRAM-PHASE II GaAs	18% BOL, RAD. RES.	1980
MULTIBANDGAP SOLAR CELLS	25% BOL	1982

TABLE VIII. - MAJOR ONGOING SOLAR CELL R&D PROGRAMS –

NASA

ACTIVITY	TARGET		CENTER
HIGH EFFICIENCY SILICON CELL	18% BOL	1980	LeRC
INCREASED RADIATION RESISTANCE FOR HIGH EFFICIENCY SILICON CELLS	< 15% DEGRAD. AFTER 10 Y IN GEO	1982	LeRC
ULTRA THIN SILICON CELLS AND COVERS			
FRONT AND BACK CONTACT CELLS	13% BOL, 2 x 2 PILOT	1979	JPL
BACK SURFACE CONTACT CELLS	14% BOL	1980	LeRC
HIGH EFFICIENCY WRAPAROUND CONTACT SILICON CELL	14.5% AVG, BOL PILOT	1979	LeRC
LOW COST SILICON CELL TECHNOLOGY	$5/W TECH. READY	1980	LeRC
GALLIUM ARSENIDE CELL RESEARCH	< 25% RAD. DAM. AFTER 30Y IN GEO	1980	LaRC

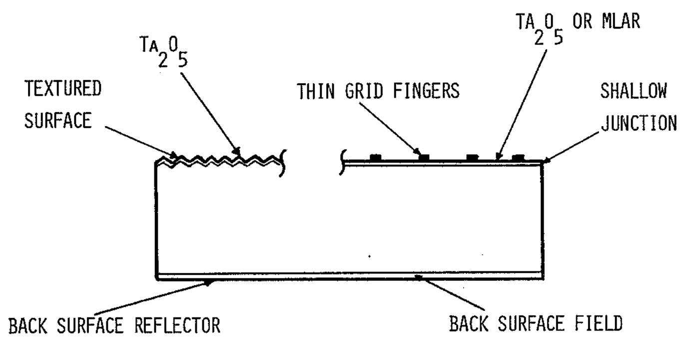


Figure 1. - Features of modern silicon solar cells.

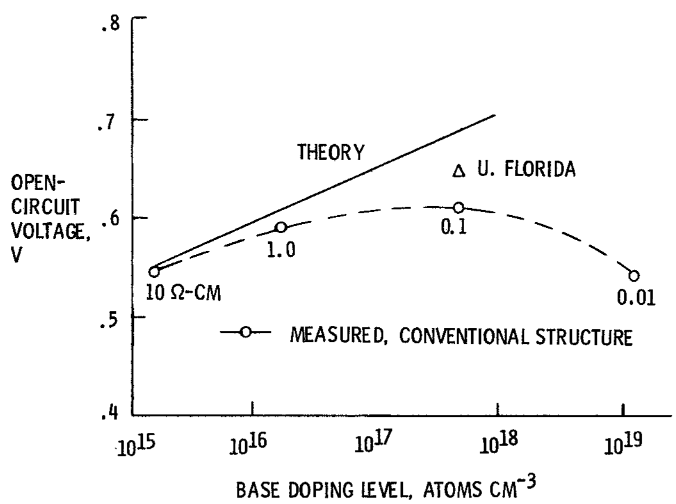
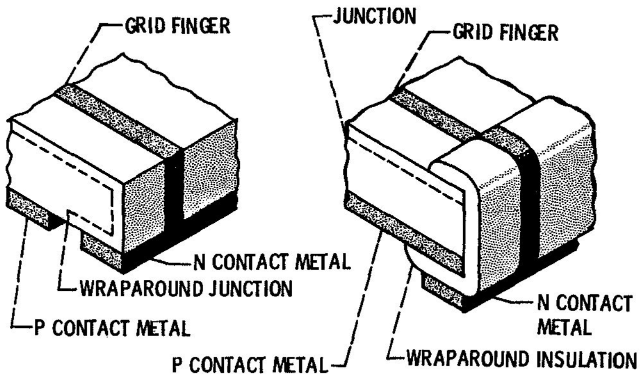


Figure 2. - Experimental and predicted open-circuit voltage dependence on base doping levels.



JUNCTION WRAPAROUND　　　　INSULATOR WRAPAROUND

FIGURE 3. - TYPES OF WRAPAROUND CONTACT SOLAR CELLS. CLOSE-UP VIEW OF CELL CORNER.

SPONSOR: AFAPL

CONTRACTOR: SOLAREX

STATUS: LABORATORY R&D
BOL EFFICIENCY 14% AMO
DEGRADES AT HALF THE RATE OF PLANAR SILICON CELLS UNDER 1 MEV ELECTRON IRRADIATION

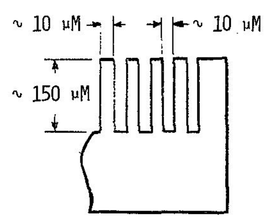


FIGURE 4. - NONREFLECTING VERTICAL-JUNCTION SILICON SOLAR CELL.

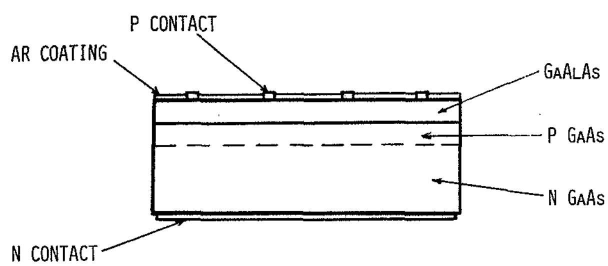


FIGURE 5. - DIAGRAM OF A GaAlAs-GaAs SOLAR CELL.