SUMMARY OF SILICON HIGH EFFICIENCY SOLAR CELL WORKSHOP

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It was agreed that the maximum practical silicon solar cell efficiency was 20 percent (AM0) with the hopes that 18 percent could be achieved by the end of CY80. (The role played by a NASA RFP that sought to develop an 18-percent cell by that same time in this assessment may never be known.) It was agreed that open-circuit voltage was the final limiting barrier to achievement of this goal. The list of voltage limiting mechanisms was not shortened; in fact, additions such as the need to match dopant to lattice, minority carrier diffusivity, and band narrowing due to junction field were made to the mechanisms outlined at previous workshops. The growing list of mechanisms underscored the need for a focussed attack on the problems. The participants did believe that 0.7 V is still a reasonable goal.

The quality of the available silicon material was thought to be adequate to achieve 18 percent efficiency now. However, before 20 percent could be achieved, improvement in minority carrier lifetime and in reduction of unwanted impurities such as carbon and oxygen would have to be made.

A number of device structures thought capable of achieving 18 percent efficiency surfaced. It is clear in any of these structures that the design of emitters and base structures must be carefully controlled to achieve high performance. The use of 0.1 Ω-cm material with or without back surface field was still recommended, although concerns were expressed about the radiation resistance of this structure. The use of n^+-p-p^+ structures with p-base resistivities above 0.1 Ω-cm were thought to also be practical. However, care must be taken in both design of the emitter (including HLE structures) and in achieving a perfect p^+ layer before these structures can reach 18 percent. Also, the use of thin cells (∿50 μm) was an integral part of this discussion. Perhaps the cell that culminated this trend was the thin n-i-p cell (50 μm) that should have the aforementioned advantages of the n^+-p-p^+ structures plus radiation resistance due to the use of intrinsic silicon. In addition to these somewhat conventional structures, both the interdigitated back contact with either a tandem junction or a front surface field and the vertical junction cell under development by the U.S. Air Force were felt capable of achieving 18 percent AMO efficiencies.

One high performance cell design that was discussed incorporated the following features: use material of about 20 Ω-cm resistivity with a 1.0-msec lifetime and thickness <100 μm; form an n^+-n-p-p^+ structure keeping all surface concentrations below 10^{19} cm^{-3}; process with "cool" processing steps — i. e., those that do not require long times at high temperatures — such as various pulsed processing procedures; use a mirror back surface; passivate surface with a charged oxide or silicon oxide-nitrides; use low metal coverage on the surface (<1 percent coverage). This structure served to focus the discussion and led to surfacing of the variety of mechanisms and approaches listed previously. Whether the design is feasible or not is speculative at this time. Most of the basic features of this structure were aimed at eliminating the adverse mechanisms and effects thought to limit the performance of present devices.

It was agreed that high beginning-of-life efficiency and high end-of-life efficiency were not incompatible. Specific cell designs that might encompass both of these diverse demands were the n-i-p cell and the vertical junction cell.

Several R&T areas were surfaced. The need to develop low carbon and oxygen silicon (with concentrations below 10^{15} cm^{-3}) was stressed. The need for a materials repository that could serve as a common, controlled source of materials for investigators was also noted. As mentioned previously, there is a need to develop "cool", clean processes that do not harm the lifetime in the good material. The absorptivity problem leading to increased orbital temperatures was highlighted as a need that could be solved by the development of better antireflection coatings. As a corollary, a means for comparing competing cell designs by determining performance at orbital temperatures was desired so that the benefits of an improved technology could be realized in flight. Finally, the need for a measurement round-robin was surfaced. An error of 5 percent in performance measurement spells the difference between an 18-percent cell and a 17-percent cell. Thus, verification of the achievement of an 18-percent cell will require a careful measurement program. The round-robin was envisioned as a first step in this process.

WORKSHOP QUESTIONS

HIGH EFFICIENCY SILICON SOLAR CELLS

- WHAT IS MAXIMUM PRACTICAL EFFICIENCY (AMO) OF SILICON SOLAR CELLS?
- WHAT MECHANISM(S) IS PRIMARILY LIMITING THE VOLTAGE?
- DO WE SEE ANOMALIES SUGGESTING A NEW MECHANISM?
- DO WE NEED HIGHER QUALITY SILICON TO ACHIEVE 18% EFFICIENCY?
- WHAT APPROACHES LOOK BEST TO ACHIEVE 18% BEGINNING OF LIFE EFFICIENCIES?
- CAN WE GET BOTH 18% BOL AND HIGH END-OF-LIFE EFFICIENCY?
- WHAT RESEARCH ON OTHER SILICON DEVICES HAS A POTENTIAL IMPACT ON SILICON SOLAR CELLS?
- WHAT AREAS OF RESEARCH OR TECHNOLOGY SHOULD GET MORE ATTENTION?

Figure 1

AN INTERIM REPORT ON THE NTS-2 SOLAR CELL EXPERIMENT*

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SUMMARY

Solar cell modules on the NTS-2 satellite have experienced more than 642 days of orbital time in a planned 3 year mission in a 20,190 km (10,990 NM) circular orbit at an inclination of 63.5 degrees. Complete I-V curve data are obtained from the fourteen solar cell modules together with a record of panel temperature and sun inclination. The data are corrected for sun angle, solar intensity, and cell temperature effects. No instrumental problems have occured, and only one solar cell module has failed completely.

INTRODUCTION

The Navigation Technology Satellite-Two (NTS-2) is the second in a series of developmental satellites that are forerunners of the DOD NAVSTAR Global Positioning System (GPS). NAVSTAR GPS is being developed to provide extremely accurate navigation information on a 24 hour basis with worldwide coverage in all types of weather conditions. NTS-2 was launched on 23 June 1977 into a circular orbit of altitude 20,190 km at an inclination of 63.5°.

The purpose of the solar cell experiment is to obtain flight data on (1) state-of-the-art solar cell configurations which embody improvements in solar cell efficiency through new silicon surface and bulk technology, (2) improved coverslip materials and coverslip bonding techniques, and (3) short and long-term effects of ultraviolet rejection filters vs. no filters on the cells. In addition, it is deemed important to obtain (4) comparative degradation data on a developmental type of liquid epitaxy gallium-aluminum-arsenide solar cell, and (5) confirmation of the predicted space radiation effects in this orbit.

DESCRIPTION OF EXPERIMENTS

The NTS-2 solar cell experiment contains 13 modules of

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*This work is supported by the Space Applications Branch of the Naval Research Laboratory, by the Air Force Aero Propulsion Laboratory, and by the Space and Missile Systems Organization.

silicon cells and 1 module of gallium-arsenide solar cells. Each module consists of five 2 x 2 cm cells connected in series. The modules are mounted on two 1/4-inch thick aluminum homeycomb panels, as shown in Figure 1. There is also an experimental blocking diode which is a 1 x 2 cm planar device with a polished aluminized surface. Experiment 12 is comprised of this diode in series with experiment 11. The panels are thermally isolated from the spacecraft structure; therefore, in order to allow for heat dissipation which can only be accomplished by thermal radiation from the front panel surface, the modules were evenly spaced on the panel and the intervening regions were coated with a white thermal control coating, Dow Corning 92007, which covers 52 percent of the panel surface.

Temperatures are monitored at the rear surface of four cells by means of three thermistors and one wire resistance thermometer. The thermistors are accurate to within ± 3 degrees C up to 100 degrees C, and the wire thermometer is accurate to within ± 2 degrees C to above 120 degrees C.

The experimental panels are continuously illuminated by the sun (except during the biannual eclipse season of 25 days). The experiment is mounted on the satellite surface which faces the direction of travel about the earth, and twice during each orbit the satellite is rotated 180 degrees in yaw so that the paddles (and experiment) face the sun. Figure 2 shows the location of the panels on the spacecraft.

Table I gives a brief description of the experiments showing the type and thickness of the solar cell, the type and thickness of the coverslip, the nature of the coverslip to cell bonding, the interconnect material, and the beginning-of-life (BOL) cell efficiency.

EXPERIMENTAL RESULTS

This report includes data through 642 days in orbit. This period began 7 July 1977 until 14 April 1979.

The current-voltage characteristics of the solar cell arrays are telemetered in real time as the satellite passes over the tracking station at Blossom Point, Maryland. The electronic circuit measures the I-V curve for each module in sequence reading out current-voltage values for evenly-spaced points from I_{sc} to V_{oc}. Each cell module is short-circuited except when it is being stepped through the I-V curve. The average value of I_{sc} measured in space on the first day of exposure agreed with the solar simulator values to 1.41 ± 0.99 percent. The agreement between V_{oc} on initial space exposure and the solar simulator values was 1.24 ± 2.02 percent. The average error between P_m measurements on the ground and the first day in orbit was 3.33 ± 3.17 percent.

Unpredicted Module Degradation

Several modules exhibited unusual and unpredictable behavior in orbit. The first observation was in the I-V curve of the gallium-arsenide module on the first day in orbit. It was observed that the P_M had decreased 12.3 percent from the pre-launch value, as V_{OC} had dropped 6.8 percent. Because of the good agreement among the other modules with ground data, we did not think this was due to measurement error. We believed there was a possibility for physical change in the cell module in the time between the last ground calibration with a solar simulator and the space measurement (145 days). Between day 1 and day 80 in orbit the GaAs cell module showed a significant amount of P_M and V_{OC} recovery, which we believe is related to the method of interconnection of the GaAs cells. They were series-connected by means of a metal-filled epoxy, rather than by soldering or welding a metal interconnect. Figure 3 shows the space performance of the GaAs module. The performance of Hughes gallium arsenide cell has generated a great deal of interest. The gallium arsenide cell is a high-efficiency solar cell whose efficiency is less affected by high temperature than are silicon cells. GaAs is expected to be harder to radiation and is therefore ideal for space applications. The problems of surface recombination and low lifetime in the diffused region are largely overcome by the addition of a GaAlAs window.

Three experiments have sustained unpredictably large degradations. The first of these, the Solarex Space Cell, Experiment 8, experienced an open-circuit of the module on the 69th day, causing the complete loss of subsequent data. Fortunately this failure occurred during a time while data were being recorded, allowing the abrupt manner in which it failed to be observed. Analysis of the data acquisition system showed that no single point failure of the data system could result in both voltage and current data loss. Therefore it is presumed the module open-circuited.

A second anomaly was the sudden onset of increased degradation rate in the Solarex vertical junction cell, Experiment 7 (Figure 4). At this time there have been four sudden drops in the maximum power output of the vertical junction cells. These large decreases have occurred around day 20 in orbit, near day 180, then day 300, and finally day 540. Investigations performed at AFAPL suggest that these unusually large losses in maximum power are the result of cell surface disintegration due to thermal cycling of adhesive-bonded coverslipped cells. The data in Figure 4 seem to support this hypothesis. The abnormal drops in power occur at approximately the same time as the maximum duration of the eclipse. As the cells experience increasingly longer periods of extreme cold, more of the junction is destroyed resulting in power loss. The breakdown of the junction is thought to be related to the type of adhesive used to bond the coverslip. Following each drop in P_M the power output stabilizes quite well until the next maximum duration of the eclipse. The decrease in P_M output of the vertical junction cell by day 642 was 66.6 percent.

The third unusual occurrence is the large degradation rate for Experiment 5, the COMSAT CNR cell covered with a 12 mil (0.305 cm) fused silica coverslip which has no ultraviolet cut-off filter. The COMSAT textured cell was flown both with and without an ultraviolet rejection filter in order to evaluate the effect of the filter. The P_M of this cell has decreased to 37.6 mW after 642 days, while Experiment 6, an identical module except for the addition of the ultraviolet cut-off filter on the coverslip, has a P_M of 53.8 mW (Fig. 5). Laboratory measurements at COMSAT Laboratories did not show a substantial difference with or without a filter. If the degradation seen in the I_{SC} of these cells were caused by particle radiation in the cell, the V_{OC} would be severely degraded. Also, the curve fill factor would be smaller than it is for the less damaged cell. However the V_{OC} of the cells with and without the uv filter is not markedly different, and the fill factor at day 642 is identical at 100 degrees C. Therefore we conclude that coverslide adhesive darkening may be a prime cause in this degradation. The degradation appears to be caused by an optical transmission loss factor, not a p-n junction effect.

Predictable Radiation Degradation of Solar Cell Modules

The remaining eleven cell modules have operated very satisfactorily; the rate of degradation which we attribute primarily to radiation damage has been greater than was predicted from several trapped radiation models. We have made estimates of the space radiation fluence based upon solar cell parameter degradation in four modules, namely Experiment 1, the OCLI conventional cell; Experiment 2, the Spectrolab Helios cell; Experiment 3, the Spectrolab textured hybrid cell and Experiment 10, the OCLI violet cell.

Among the experiments of primary interest is the Spectrolab "Helios" back field cell, Experiment #2. This cell was space qualified as one of the experiments aboard the NTS-1 satellite. The "Helios" cell is presently in use as the main power source on NTS-2 and is in use in other satellite programs. As of day 642, the maximum power output of the Spectrolab Helios cell (NTS-2) has decreased by 23.3 percent. Interestingly, although the Spectrolab Helios cell degraded less than a conventional cell in I_{SC} and P_M, it has degraded more in V_{OC}. This behavior has been reported previously for solar cells with a p^+ layer at the back contact in laboratory studies.The power output of the Helios p^+ solar cell, Experiment 2, is plotted along with the predicted degradation in Fig. 6. It is readily observed that the cells are degrading slightly faster than predicted.

The 1-MeV electron equivalent fluence shown in Table 2 was obtained by fitting solar cell parameter to radiation damage curves (ref. 1) for generic types of solar cells. The equivalent fluence values obtained from this experiment are all substantially higher than the equivalent fluence listed in reference 1, which bases fluence calculation on the AE4 trapped electron model. For 12 mil fused silica shielding and infinite backshielding, reference 1 lists a 2 MeV electron equivalent fluence of 3.3×10^{13}e/cm^2-year.

Experiments 3 and 4 were designed to distinguish between cell degradation effects due to adhesive bonding vs. FEP Teflon bonding. There is an improvement with the Teflon bonded coverslip (17.6 percent P_M degradation) using "as sawn fused silica" instead of the traditional polished and uv filtered Corning 7940 fused silica (degradation in P_M 20.6 percent). These data are presented in Figure 7.

Another coverslip evaluation is made in Experiments 1 and 13 which use an OCLI conventional cell, Experiment 1 with an adhesive bonded Corning 7940 fused silica coverslip and Experiment 13 with an electrostatic bonded Corning 7070 glass coverslip. There was a substantial initial loss in BOL P_M with the electrostatic bonding technique at the time the module was fabricated. A direct comparison between the final results is therefore not valid.

A more complete listing of parametric data as a function of radiation fluence may be obtained in reference 2. An abridged data table is included as Table III.

In experiments of this type, there is a compelling urge by the observer to make an overall comparison and a list of cells in the order of their "best performance". Best performance cannot be simply defined to be a universally acceptable criterion. What we have done is prepare a bar graph (Fig. 8) which shows the maximum power of each cell type as measured on the solar simulator before launch and space data after 642 days. The cells are arranged in decreasing order according to power at day 642. It is readily seen that this does not imply that the original efficiency of the cells is in the same order.

CONCLUSIONS

The overall performance of the flight experiment and the data acquisition system continue to be excellent. Several important conclusions which have been reached concerning the new cell technologies are listed below.

1. The Spectrolab Helios p^+ (Exp. 2) cell with an adhesive-bonded 0.0254 cm ceria microsheet coverslip is an excellent solar cell for the GPS natural environment. The Spectrolab textured hybrid cell (Exp. 4) with an FEP bonded 0.0152 cm "as-cut" quartz coverslip is equally satisfactory for this orbit.

2. There are three other types of silicon cells which can be classed as production cells, or nearly production, whose P_M exceeds the Helios (Exp. 2) and hybrid (Exp. 4) output. These are in ascending order of P_M: the Spectrolab textured HESP, no p^+ (Exp. 14) with adhesive-bonded 0.030 Corning 7940 coverslip; the OCLI violet cell (Exp. 10) with an adhesive-bonded 0.030 cm Corning 7940 coverslip; and the Spectrolab textured Helios p^+ (Exp. 9), with a back surface reflector and an FEP bonded 0.030 cm as cut quartz coverslip.

3. The FEP Teflon bonded "as-cut" quartz coverslip permits very high cell power output, with no evidence of any problems, performing as well as adhesive-bonded Corning 7940 with uv filter for radiation shielding and optical transmission.

4. The GaAs cell (Exp. 15) is fourth in rating of power output at day 642. Despite the difficulty with low V_{OC} and P_M during the first month after launch, it has recovered sufficiently to show its value in this radiation environment. However more reliable interconnect than epoxy is obviously needed.

5. Lithium-doped p-on-p solar cells show better P_M output than 2 ohm-cm n-on-p cells in this space electron environment. This was not expected, since p/n (Li) cells have not annealed as well for electron exposures in the laboratory as they have for heavy particle exposures such as protons and neutrons. The high panel temperature (100 degrees C) may have produced partial annealing of the radiation damage.

Some unresolved findings that are of sufficient importance to justify further investigation are:

1. Unexpectedly large I_{SC} loss in the COMSAT CNR cell with the adhesive bonded coverglass of Corning 7940 having no uv filter.

2. Thermal cycling damage in the vertical junction solar cell.

REFERENCES

1. H. Y. Tada and J. R. Carter, Jr., "Solar Cell Radiation Handbook," Pasadena, CA; Jet Propulsion Lab., JPL Pub. 77-56, November 1977.

2. D. H. Walker and R. L. Statler, "Results of the Solar Cell Experiments Aboard the NTS-2 Satellite After 447 Days in Orbit," NRL Memorandum Report 3935, 9 March 1979.

Table I — NTS-2 Solar Cell Experiments

Exp. No.	Cell Type	Thickness (cm)	Coverslip (cm)	Coverslip Bond (cm)	Interconnect	Efficiency 28°C (%)
1	OCLI Conventional, 2 ohm-cm	0.025	Corning 7940, AR and UV, (0.030)	R63-489	Cu/Ag	10.7
2	Spectrolab “Helios” p^+ 15-45 ohm-cm	0.0228	Ceria microsheet w/o AR, (0.025)	DC 93-500	Moly/Ag (.0025)	11.5
3	Spectrolab Hybrid Sculptured 7-14 ohm-cm	0.020	Corning 7940, AR and UV, (0.0152)	DC 93-500	Moly/Ag (.0025)	10.5
4	Spectrolab Hybrid Sculptured 7-14 ohm-cm	0.020	Corning 7940, w/o AR or UV, (0.0152)	FEP Teflon (0.0051)	Moly/Ag (.0025)	11.1
5	Comsat Non-Reflecting, p^+ Textured, 1.8 ohm-cm	0.025	Corning 7940, AR, w/o UV (.030)	R63-489	Ag, thermo-compression bonding	14.5
6	Comsat Non-Reflecting, p^+ Textured, 1.8 ohm-cm	0.025	Corning 7940, AR and UV (.030)	R63-489	Ag; thermo-compression bonding	14.6
7	Solarex Vertical Junction, p^+, 1.5 ohm-cm	0.030	Ceria microsheet w/o AR (.0152)	Sylgard 182	Ag mesh	13.0
8	Solarex Space Cell, p^+ 2 ohm-cm	0.025	Ceria microsheet w/o AR (0.0152)	Sylgard 182	Ag mesh	12.8
9	Spectrolab “Helios” p^+ Sculptured, BSR, 10 ohm-cm	0.030	Corning 7940 (.030) w/o AR or UV	FEP teflon (.003)	Ag mesh (.003)	14.2
10	OCLI Violet, 2 ohm-cm	0.025	Corning 7940 (.030) AR and UV	R63-489	Cu/Ag	13.5
11	Spectrolab P/N Li-doped 15-30 ohm-cm, Al contacts	0.020	Corning 7940, AR and UV, (0.015)	Silicone	Aluminum (.0025) Ultra-sonic welding	10.8
12	Spectrolab Planar Diode in series with Exp. 11	NA	NA	NA	NA	NA
13	OCLI Conventional, 2 ohm-cm	0.025	Corning 7070 (.028)	Electrostatic bonding	Cu/Ag	10.2
14	Spectrolab HESP, no p^+, Sculptured, 2 ohm-cm	0.030	Corning 7940, AR and UV (0.0305)	R63-489	Moly/Ag (.0025)	13.6
15	Hughes Gallium-Aluminum Arsenide	0.0305	Corning 7940, AR and UV, (0.0305)	DC 93-500	Aluminum GPD (.0025), epoxy	13.6

Table II.— NTS-2 Equivalent Fluence (1 - MeV e/cm^2) Predictions*

OCLI Conventional 2 Ω-cm, 10 mil cell, 12 mil FS Coverslip

BOL		Fluence at 200 days	Fluence at 1 yr	Fluence at 3 yr
I_{sc}	136.0 mA	1.5×10^{14}	2.7×10^{14}	8.2×10^{14}
V_{oc}	548 mV	3×10^{13}	5.5×10^{13}	1.6×10^{14}
P_m	56.5 mW/4 cm^2	1.3×10^{14}	2.4×10^{14}	7.1×10^{14}

Spectrolab Helios, 10 Ω-cm, 9 mil cell, 10 mil Ceria Coverslip

BOL		Fluence at 200 days	Fluence at 1 yr	Fluence at 3 yr
I_{sc}	154 mA	1.3×10^{14}	2.4×10^{14}	7.1×10^{14}
V_{oc}	545 mV	1×10^{13}	1.8×10^{13}	5.5×10^{13}
P_m	60.5 mW/4 cm^2	9×10^{13}	1.6×10^{14}	4.9×10^{14}

Spectrolab Textured Hybrid, 8 mil cell, 6 mil FS Coverslip

BOL		Fluence at 200 days	Fluence at 1 yr	Fluence at 3 yr
I_{sc}	156 mA	5.0×10^{14}	9.1×10^{14}	2.7×10^{15}
V_{oc}	522 mV	5.0×10^{14}	9.1×10^{14}	2.7×10^{15}
P_m	53.8 mW/4 cm^2	3.3×10^{14}	6.0×10^{14}	1.8×10^{15}

OCLI Violet

BOL		Fluence at 200 days	Fluence at 1 yr	Fluence at 3 yr
I_{sc}	166 mA	1×10^{13}	1.8×10^{14}	5.5×10^{14}
V_{oc}	552 mV	2×10^{13}	3.7×10^{13}	1.1×10^{14}
P_m	67.5 mW/4 cm^2	7.5×10^{13}	1.4×10^{14}	4.1×10^{14}

*Cell data at 50°C

Table III. NTS-2 SOLAR CELL EXPERIMENT

MAXIMUM POWER (MW)*

EXP NO.	CELL TYPE	PRE-LAUNCH	DAY 1	DAY 642	% LOSS FROM PRE-LAUNCH	FILL FACTOR AT 100 C
1	OCLI 2 ohm-cm	53.1	56.3	40.2	24.3	.674
2	SPECTROLAB Helios (NTS-2)	57.9	60.6	44.4	23.3	.644
3	SPECTROLAB Text. Hybrid	52.4	53.5	41.6	20.6	.595
4	SPECTROLAB Text. Hybrid, FEP	54.6	55.4	45.0	17.6	.637
5	COMSAT CNR No filter	72.8	74.7	37.6	48.4	.672
6	COMSAT CNR	70.1	72.0	53.8	23.3	.672
7	SOLAREX VJ	63.1	62.2	21.1	66.6	.435
9	SPECTROLAB Text. Helios BSR	66.6	70.0	51.6	21.8	.690
10	OCLI Violet	67.5	66.6	50.8	24.7	.645
11	Lithium, P/N	53.2	55.8	42.5	20.1	.682
13	OCLI 2 ohm-cm ESB coverslide	47.0	46.8	37.0	21.3	.559
14	SPECTROLAB HESP	63.3	63.8	47.0	25.8	.677
15	HRL AlGaAs	70.0	61.4	50.0	28.6	.752

*The power data are corrected to 50°C and one sun intensity air mass zero.