THIN FILM PHOTOVOLTAIC DEVELOPMENT at PHILLIPS LABORATORY

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ABSTRACT

Various political and economic forces have, in the last three years, driven the Air Force to reassess its space power generation technologies. In the area of photovoltaics, increasing emphasis is being placed on material, production, and life cycle costs in order to increase the "economic survivability" of systems. In response to these new priorities, Phillips Laboratory is directing a three phase program designed to evaluate, improve and make available to the user community, an advanced thin film solar cell capable of replacing state of the art solar cells while reducing overall costs. This paper describes the work that has already taken place and outlines the future direction of the program.

1. Technology Readiness

1.1. Overview

The effort entitled *Technology Readiness in Thin Film Solar Cells* was carried out by the Jet Propulsion Laboratory, California Institute of Technology, as directed by the U.S. Air Force Phillips Laboratory. Over a period of about two years, 175 thin film solar cells were procured from various vendors and subjected to various tests to measure AM0 current-voltage (I-V) characteristics, spectral response, electron and proton radiation susceptibility, annealing potential, thermal variance, photon degradation, and mechanical ruggedness.

The cells procured are described in Table 1 with cross sectional diagrams in Figure 1. Testing was done in two steps; a limited preliminary group of cells followed by an expanded population.

Table 1: *Thin film solar cells procured*

Cell Type	Measured Average Efficiency (AM0)	Number Procured	Cell Area
Boeing CIS	8.7%	10	2cm x 2cm
Boeing CIS	8.4%	30	2cm x 2cm
ISET CIS	8.8%	10	4cm x .915cm
ISET CIS	8.1%	29	4cm x .905cm
Solarex a-Si	6.6%	10	4cm x 4cm
Solarex a-Si	7.2%	31	1.75cm x 4cm
Solarex a-Si	5.4%	19	1.75cm x 4cm

In addition, 20 Photon Energy CdTe/CdS cells were included in the preliminary testing. These cells, however, were deposited on a thick non-radiation resistant glass superstrate and so were not included in the secondary testing. A 16 cell module of CIS cells from Siemens was also included in the preliminary testing.

1.2. Test Procedures

Light I-V curves were performed using a Spectrolab X-25 Mark II solar simulator as the AM0 light source. The beam intensity from the simulator was set by using solar cell standards that had been calibrated on a high altitude balloon. The intensity was set for the a-Si cells by using a crystalline silicon solar cell (calibrated in 1987) with a KG-5 Schott infrared absorption filter. This combination produces a standard cell spectral response closely resembling a-Si solar cells. The balloon flight standard used for measurement of the CIS cells was a Boeing CIS cell calibrated on the 1991 flight. The temperature of the cells under test was maintained at 28°C during the I-V measurements by using a thermo-electric heating/cooling system. Special probes were designed to accommodate the various contact schemes and sometimes fragile cell materials.

Spectral response measurements were made on all thin film cells using a prism monochromator. A white bias light consisting of a tungsten halogen lamp with an intensity of approximately one half that of AM0 was used to illuminate the solar cells during S/R measurements. The triple junction cells were measured one junction at a time and the three responses added.[2]

Proton irradiations were performed on the CalTech tandem Van de Graff accelerator. The target plane remained at room temperature with no need for active thermal control at the low flux rates used. Electron irradiations were performed at the JPL Dynamitron accelerator with the samples held at 28°C. Whenever measurements could not be made immediately after irradiation, the cells were either packed in dry ice or placed in a freezer to minimize annealing.

During the long term photon exposure tests, the cells were exposed to an AM0 light source consisting of a Spectrolab X-25L. Throughout these tests, the cells were exposed in air while in an open circuit condition. The cells were removed from their test blocks at various times for electrical measurements. Light I-V curves were measured using the Spectrolab X-25 Mark II described above. If changes in I_{sc} were observed during these measurements, the spectral response of the cell was also measured before returning it to the photon flux.[1]

1.3 Test Results

I-V measurements as a function of temperature (-40 to 80°C) were performed on a Boeing, ISET and Siemens CIS cell from the first procurement. The temperature coefficients are very similar and nearly linear over the range of temperatures tested. The values in Table 2 were determined by measuring the slopes of each parameter versus temperature and have been normalized for an active cell area of 4cm^2. The temperature coefficient for the a-Si cell was not observed to be linear and so was calculated for three separate sub-ranges and normalized to an active cell area of 4 cm^2.

Table 2: *Temperature coefficients at AM0*

Cell Type	I_{sc} (mA/°C)	V_{oc} (mV/°C)	P_{max} (mW/°C)
Boeing CIS	0.023	-1.92	-0.31
ISET CIS	0.038	-1.99	-0.29
Siemens CIS	0.020	-1.98	-0.23
Solarex a-Si -40 to 0°C	0.031	-4.03	+0.14
Solarex a-Si 0 to 40°C	0.019	-6.95	-0.04
Solarex a-Si 40 to 80°C	0.019	-8.28	-0.11

Four sets of thin film cells were selected for proton testing. Each set consisted of three each of the Boeing, ISET and Solarex Lot I, and two of the Solarex Lot II cells. Proton fluences ranged between 1x10^9 and 2x10^{12} p/cm^2, with energies of 0.5, 1.0, and 3.0 MeV for all cell types. In addition, a low energy tailored to each cell type was included. These low energies were 300 keV for the Boeing cells and 240 keV for the ISET cells. They were chosen such that the protons would stop after penetrating most of the way through the topmost semiconductor layer, where they are expected to produce the maximum amount of damage in the cell. The energy chosen for the Solarex cell was 115 keV; calculated to stop in the center of the topmost junction. These low energies were based on material and thickness information obtained from the manufacturers, and the errors made in the calculation will vary as the thickness tolerances and material densities vary. Results (including some annealing data) are presented in Figures 6-11.

Similar sets of thin films were also subjected to electron radiation at 0.7, 1.0, and 2.0 MeV energies. Fluences were cumulatively increased from 3x10^{13} to 1x10^{16} e/cm^2 in half order of magnitude steps. Figures 12-17 show the damage sustained along with a crystalline silicon damage curve for comparison.

Samples of all three cell types also underwent long term exposure to AM0 photons for a period of 580 hours. The cells were held at a temperature of 25 +/- 2°C and I-V curves taken after exposures of 21, 90, 158, 275, 443, and 580 hours. Proton irradiated, electron irradiated, and non-irradiated samples were all used. Figures 2 and 4 show results of this test.

Contact pull strength tests were completed on the Boeing CIS and the Solarex a-Si cells. The configuration of the aluminum contacts on the ISET cells did not permit the attachment of pullable contacts leads and so these cells were not pull tested. Even though the cells tested are probably best described as "prototype", the contacts were sufficiently robust to be considered satisfactory.

1.4. Conclusions

In general, the cells tested showed the expected radiation tolerance, and low temperature annealing may mitigate all but the worst radiation damage. The thin film efficiencies are low in comparison with crystalline silicon and GaAs technologies (the highest measured thin film efficiency being 9.5%). However, even at these preliminary efficiencies very high specific power is possible. In addition, these cells were purchased from research laboratories and experienced an amount of variability to be expected from cells made in such an environment. The most interesting result of this work is the possibility of photon degradation in some CIS cells. A more statistically relevant sample needs to be tested to determine the extent of this effect.

2. Contracted R&D

2.1. Motivation

One of the conclusions made apparent by the *Technology Readiness* effort described above is that thin film solar cells need to be produced in greater quantities as well as improved in certain key areas before DoD satellite designers will be willing to consider them as a technology option. In order to address both of these concerns, PL/VTPC has funded two contractual efforts through the Broad Area Announcement 91-01. The Martin Marietta Astronautics Group and the Boeing Company, Space and Defense Systems, were chosen as being the most likely to make a significant contribution to the field in the two year period of performance allowed. Because each contract was initiated in October 1992, only the goals of the programs will be discussed here.

2.2. CIS at Boeing

This program seeks to build on the ten years and ten million dollars already invested in the Boeing CIS device. The program involves four main tasks.

Task 1 is to evaluate and select optimum lightweight substrate materials. In addition to being lightweight, a suitable substrate for the CIS cell must also satisfy several other conditions. A partial list would include a relatively smooth surface to prevent shunting defects in the thin film device, a thermal expansion coefficient close to that of the deposited thin film layers to avoid creating high mechanical stresses, ruggedness to avoid cell and array fabrication losses, and the high temperature (450-550°C) in-vacuum compatibility required by the CIS fabrication process. The candidate materials to be considered include thin glass, thin metal foils, and polymeric materials.

In Task 2 Boeing will modify their existing solar cell device fabrication process to accommodate the selected lightweight substrate. The processing of new substrate materials would probably require the design and development of specialized tooling for many phases of the cell production. The substrate cleaning, Mo sputter deposition, Mo patterning, CIS deposition, ZnO sputtering, patterning, grid/interconnect deposition, and A/R coating steps will all have to be modified or retooled in order to accept a new substrate.

Task 3 will combine the results of the previous two tasks into the fabrication of CIS modules on the lightweight substrates. Wherever appropriate, this task will apply results generated by the DOE/NREL funded research contracts. Various quality control techniques will be utilized including Scanning Electron Microprobe (SEM) for film morphology, Energy Dispersive Spectrophotometry (EDS) for film composition, and X-ray diffraction for film orientation.

Finally, Task 4 will consist of environmental testing of the CIS cells produced. The tests will consist of thermal cycling, vacuum storage, UV exposure, and limited radiation testing.

These cells are meant to be the stand-alone photovoltaic for power generation, but can (with minor modification) be utilized in a tandem cell stack. The program will be complete in October 1994.

2.3. CdTe & CIS at Martin Marietta

Martin Marietta is investigating both CdTe technology and CIS technology. In order to develop CdTe solar cells, three main tasks focus on testing and evaluating a space worthy transparent superstrate, manufacturing and testing a 15cm x 15cm monolithically interconnected CdTe module, and addressing rigid polycrystalline thin film array issues.

The CdTe superstrate will be chosen based on optimum cost/weight, space environment survivability, and effects on cell performance. Cell manufacture will include the following steps: cleaning and preparing the transparent superstrate, sputtering of the TCO top contact, deposition of CdS, electrodeposition of CdTe, and finally sputtering of a metallic back contact. Completed cells will undergo thermal cycling for 60,000 cycles as well as electron and proton irradiation, with optimized devices eventually being fabricated.

The resulting cell-superstrate combination will be used to fabricate the monolithically integrated modules. Preliminary array concepts involving the large area (15cm x 15cm) modules will then be conceived with emphasis on maintaining the lower labor associated with implementation of larger devices. Once a design has been completed, a demonstration article illustrating possible integration schemes shall be fabricated and tested.

Similarly, CIS cells will be manufactured and tested on flexible substrates; 30cm x 30cm monolithically interconnected modules will be tested and evaluated; and any issues associated with the use of flexible photovoltaics on arrays will be addressed.

The CIS devices will be made as follows: cleaning and preparing of the flexible substrate (including titanium and aluminum foils), deposition of an insulating layer on the metallic substrates, deposition of the Mo back contact, construction of the $CuInSe_2$ absorber layer, deposition of CdS, and sputtering of a ZnO TCO top contact. As with the CdTe cells, the CIS cells will undergo equivalent environmental testing and then be monolithically integrated into the 30cm x 30cm modules. Assuming success to this point, the more complicated array issues generated by utilizing a flexible solar cell will be addressed, and a small scale panel assembled and tested.

This effort is also scheduled to finish in October 1994.

3. Future Efforts

3.1. Technology Readiness - Phase II

In order to address some of the unanswered questions generated by the first *Technology Readiness* effort, PL/VTPC will undertake a redux of the program in 1993-94. Several developments have also led to this follow-on study including the evolution of the level of the state-of-the-art, increased interest of DoD contractors in thin film photovoltaics, the availability of new PV technologies (thin films and others), and the continued demand for cheaper satellite power systems. Because Phillips Laboratory in-house facilities are now available, this program will be able to afford a larger number of each cell type.

3.2. Flight Experiments

PL/VTPC will also be able to compare the on-orbit performance of several thin films with the laboratory test results. The PASP PLUS flight experiment includes an multi-cell a-Si module. In addition, the Space Technology Research Vehicle (STRV) includes a CdTe cell, an a-Si cell, and two types of CIS cells. Both of these experiments are scheduled to launch in 1994 into high radiation orbits.

ACKNOWLEDGMENTS

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REFERENCES

[1] R. Mueller and B Anspaugh, "Technology Readiness in Thin Film Solar Cells", JPL Task Plan No. 80-3207 Final Report, 1992

[2] R. Mueller, "Spectral Response Measurements of Two-Terminal Triple-Junction a-Si Solar Cells", to be published in *Solar Energy Materials and Solar Cells*

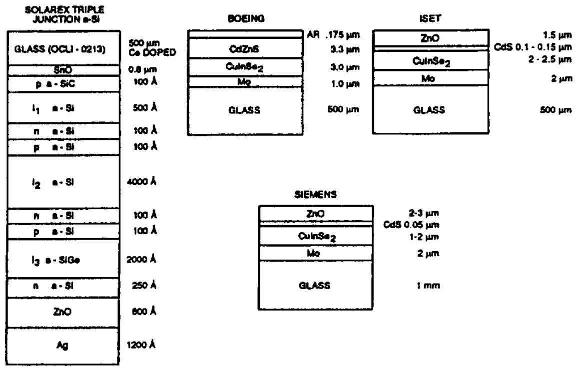

Figure 1: *Thin film solar cell cross sections*

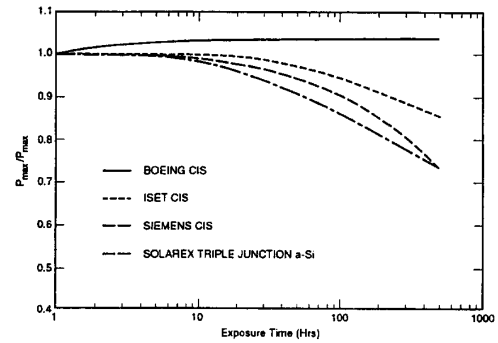

Figure 2: *Photon stability for thin films*

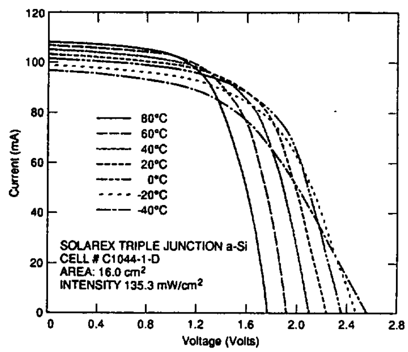

Figure 3: *Temperature curves for Solarex a-Si*

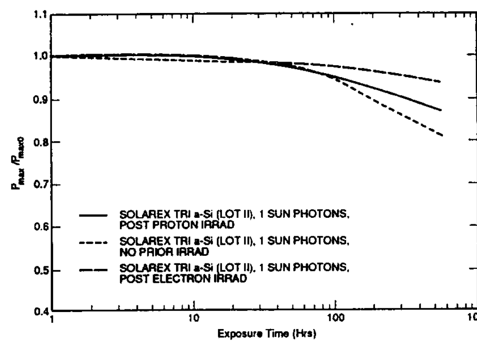

Figure 4: *Photon stability for a-Si after irradiation*

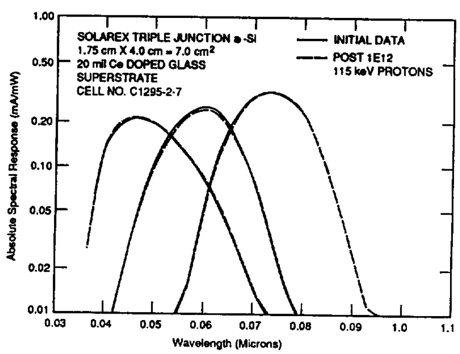

Figure 5: *Spectral response for Solarex a-Si*

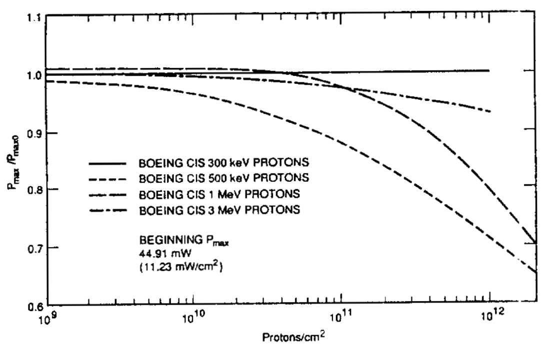

Figure 6: *Boeing CIS proton irradiation*

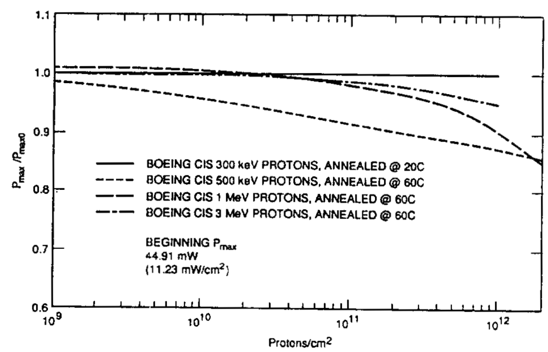

Figure 7: *Boeing CIS proton irradiation + 60 °C anneal*

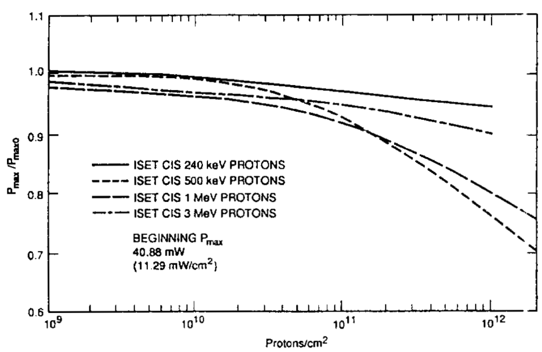

Figure 8: *ISET CIS proton irradiation*

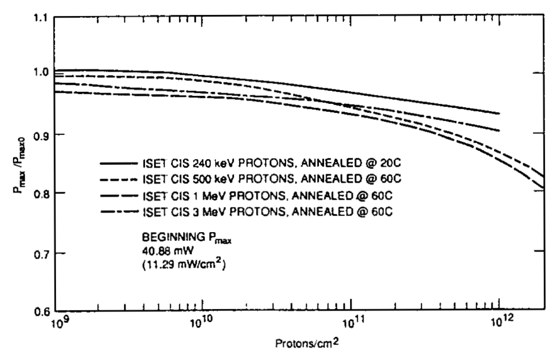

Figure 9: *ISET CIS proton irradiation + 60 °C anneal*

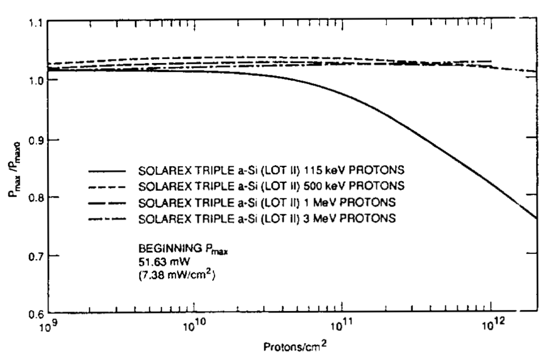

Figure 10: *Solarex a-Si proton irradiation*

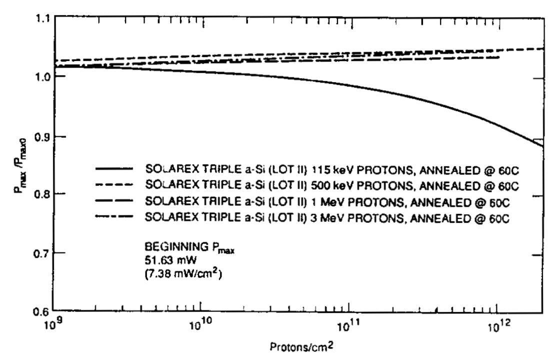

Figure 11: *Solarex a-Si proton irradiation + 60 °C anneal*

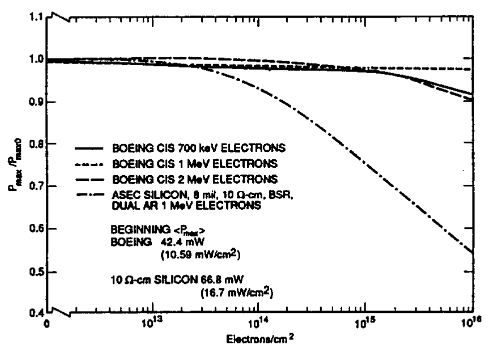

Figure 12: *Boeing CIS electron irradiation*

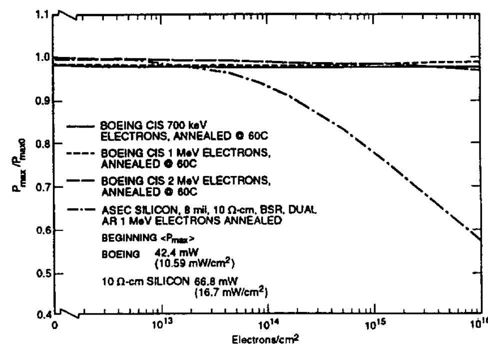

Figure 13: *Boeing CIS electron irradiation + 60 °C anneal*

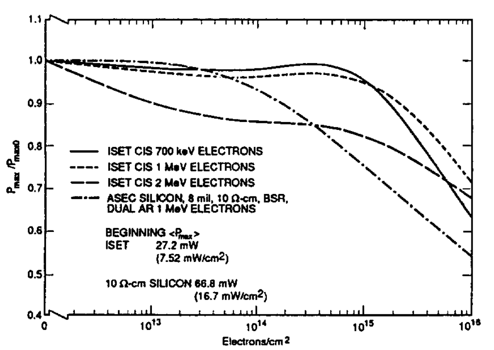

Figure 14: *ISET CIS electron irradiation*

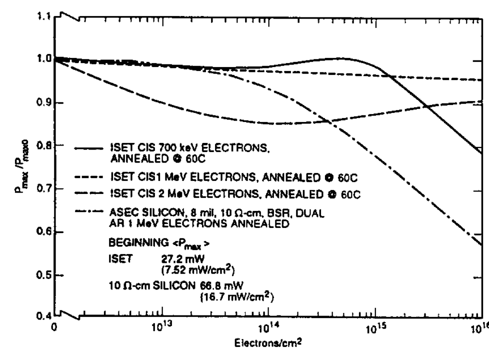

Figure 15: *ISET CIS electron irradiation + 60 °C anneal*

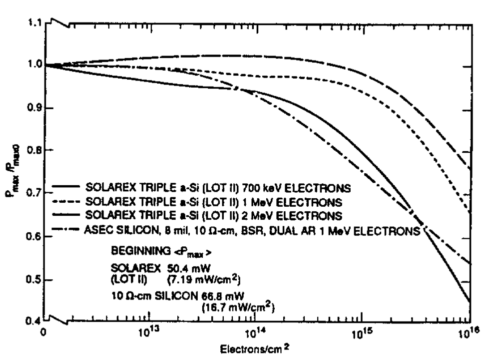

Figure 16: *Solarex a-Si electron irradiation*

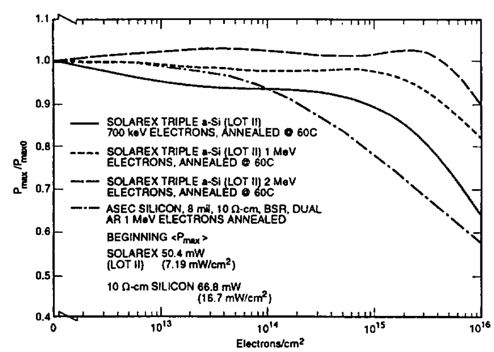

Figure 17: *Solarex a-Si electron irradiation + 60 °C anneal*