

SPACE PLASMA TESTING OF HIGH-VOLTAGE THIN-FILM SOLAR ARRAYS WITH PROTECTIVE COATINGS

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This paper gives an overview of the space plasma test program for thin-film photovoltaics (TFPV) technologies developed at the Air Force Research Laboratory (AFRL). The main objective of this program is to simulate the effects of space plasma characteristic of LEO and MEO environments on TFPV. Two types of TFPV, amorphous silicon (a-Si) and copper-indium-gallium-diselenide (CIGS), coated with two types of thin-film, multifunctional coatings were used for these studies. This paper reports the results of the first phase of this program, namely the results of preliminary electrostatic charging, arcing, dielectric breakdown, and collection current measurements carried out with a series of TFPV exposed to simulated space plasma at the NASA Glenn Plasma Interaction Facility. The experimental data demonstrate that multifunctional coatings developed for this program provide effective protection against the plasma environment while minimizing impact on power generation performance. This effort is part of an ongoing program led by the Space Vehicles Directorate at the AFRL devoted to the development and space qualification of TFPV and their protective coatings.

INTRODUCTION

State of practice (SOP) crystalline solar cell technology for space has utilized a coverglass to protect cells from the effects of space ionizing radiation^[1], space plasma^[2], atomic oxygen, and other components of orbital space environments. This coverglass adds mass to the solar array and increases solar array cost. TFPV, on the other hand, have been proven to be resistant to on-orbit radiation and therefore do not require a thick protective coverglass. Instead, only a thin-film coating made of suitable protective material is required to provide sufficient protection against the space environment^[3]. Although the efficiency of TFPV is currently low compared to crystalline cells, they are attractive at the system level due to significant increases in specific power (W/kg) and packaging efficiency^[4]. For high power applications, TFPV also have a significant impact on cost reduction of their arrays. Overall, TFPV offer great promise for power generation on future spacecraft missions.

To reach these goals AFRL initiated a comprehensive program to develop space qualifiable coatings for TFPV with properties tailored to specific DOD space missions^[5,6]. The program established a solid scientific base for modeling and fabrication of thin-film multifunctional protective coatings, their industrial scale-up, and thorough space survivability testing. The key elements of the program are: (1) design of coatings that are multifunctional in nature, i.e. provide simultaneous environmental protection, optimize optical transmittance and passive thermal management, and mitigate charging effects, (2) selection of suitable, low-temperature coating deposition techniques with high deposition rates, (3) space qualification testing, and (4) industrial scalability. Both single layer and multilayer, multi-component coatings have been investigated.

The principal objective of the space plasma test program is to study the degradation mechanism of TFPV and their modules under simulated LEO and GEO space plasma environments and propose design strategies for mitigation of harmful effects of the space environment on their performance. The specific objectives of this program are: (1) to characterize plasma-induced current leakage and arcing effects during high voltage biasing, (2) to characterize material properties of TFPV and their protective coatings, which are relevant to the space plasma environment interactions, (3) to validate models of plasma interaction with TFPV modules, (4) to develop a predictive capability for on-orbit performance at LEO and GEO, and (5) to increase TRL (Technology Readiness Level) for TFPV at the cell level and at the array level.

Arcing through the layer of protective coating can result in electromagnetic interference, solar cell damage, induced currents in the power systems, optical emission, and an enhanced local plasma density. The suitable remedial strategies fall into two basic groups, namely implementation of suitable protective materials and array design. The results of these studies will provide feedback into the selection of suitable protective coating materials and help to propose design strategies for mitigation of deleterious effects of the space environment on TFPV^[7, 8].

Solar Arrays are composed of a number of strings of cells connected in both series and parallel configurations. The solar array is designed to supply the needed power for a given spacecraft or mission. Furthermore, solar arrays are typically grounded to the negative end of the spacecraft. It is the negative grounding scheme coupled with the plasma environment that is responsible for all solar array/spacecraft interactions. While cell thickness and composition play some role, it is not the only (nor the most important) factor in determining how the array will interact with its ionospheric environment. The single most important factor in determining the magnitude of the interactions with the plasma environment lies with the operating potential of the array. The maximum operating voltage gradient of the array investigated in this work is 280 Volts as measured with respect to the plasma.

PLASMA TESTS EXPERIMENTAL CONDITIONS

TFPV modules investigated in this work were assembled by Lockheed-Martin. Each test module consisted of an aluminized kapton blanket, stretched on a 1 x 1 m aluminum frame. Single cells and strings of cells were mounted on the “kapton” side of the blankets and interconnected with copper traces. Each cell or string of cells was individually wired with coaxial cables allowing each of them to be measured independently in-situ during the plasma exposure experiments. In addition, these individual connections provided flexibility for biasing the cells during the tests and allowed simulation of high-voltage bias conditions between the cells. Optically active areas of these cells were protected with multifunctional thin-film protective coatings. The exposed electrical connectors were protected with kapton tape and silicone adhesive to produce a “conformal” protective overcoat over the entire area of the interconnected module. This interconnect scheme was as “flight-like” as possible. The configuration of test modules is depicted in Figure 1 and photographs of the coupons are shown in Figure 2.

The TFPV investigated in this work include amorphous silicon (a-Si) and copper-indium-gallium-diselenide (CIGS) technologies coated with two types of thin-film proprietary protective coatings. The TFPV devices were acquired from United Solar Ovonic Corp. (USOC), Global Solar Energy Inc. (GSE), and Iowa Thin Film Technologies (ITFT). Both single cells and strings of interconnected cells were investigated. The interconnect technologies include copper traces, shingled interconnects, and monolithic integration. Flexible substrates include stainless-steel foil and kapton.

The typical high-voltage plasma test conditions were accomplished by slowly biasing the cell negative with respect to the chamber wall to the expected operation voltage of 280V or until the breakdown voltage of the coating was reached. Biasing was accomplished under current limited conditions starting at -100 V at increments ranging from 25 V up to 100 V, for dwell times ranging from 15 minutes to 30 minutes. The voltage steps and dwell times varied depending on observed current collection conditions. Since the protective coatings were extremely thin, it was necessary to test first whether the coatings acted as conductors or insulators, and also to measure the leakage current from each cell. The resistivity of thin-film coatings often changes dramatically after exposure to the plasma.

Measurements of electrical and optical performance of TFPV were conducted prior to and after exposure to the simulated plasma environment. Electrical characterization consisted of current-voltage (I-V) measurements under simulated Air Mass Zero (AM0) conditions using a Large Area Pulsed Solar Simulator (LAPSS) system. Test modules, as well as individual cells and strings of cells were also inspected visually, using an optical microscope, for the presence of pinholes prior to plasma testing and after plasma testing.

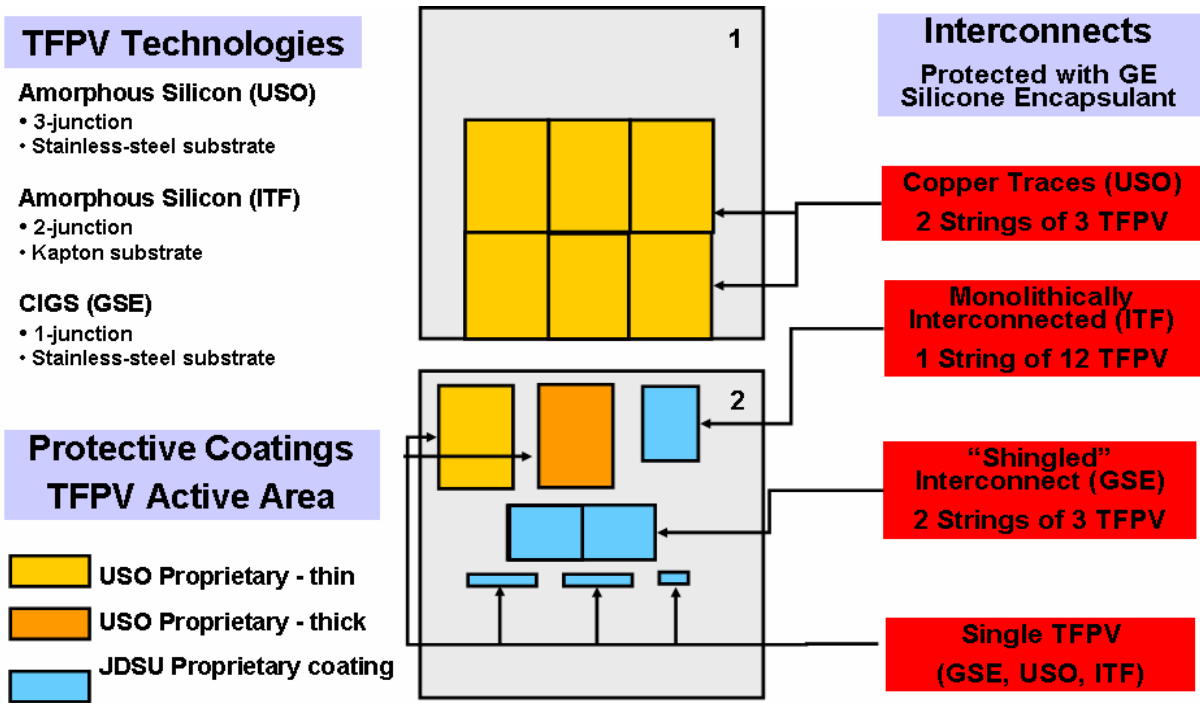


Figure 1. Schematic diagram showing configurations of TFPV and strings on two test modules.

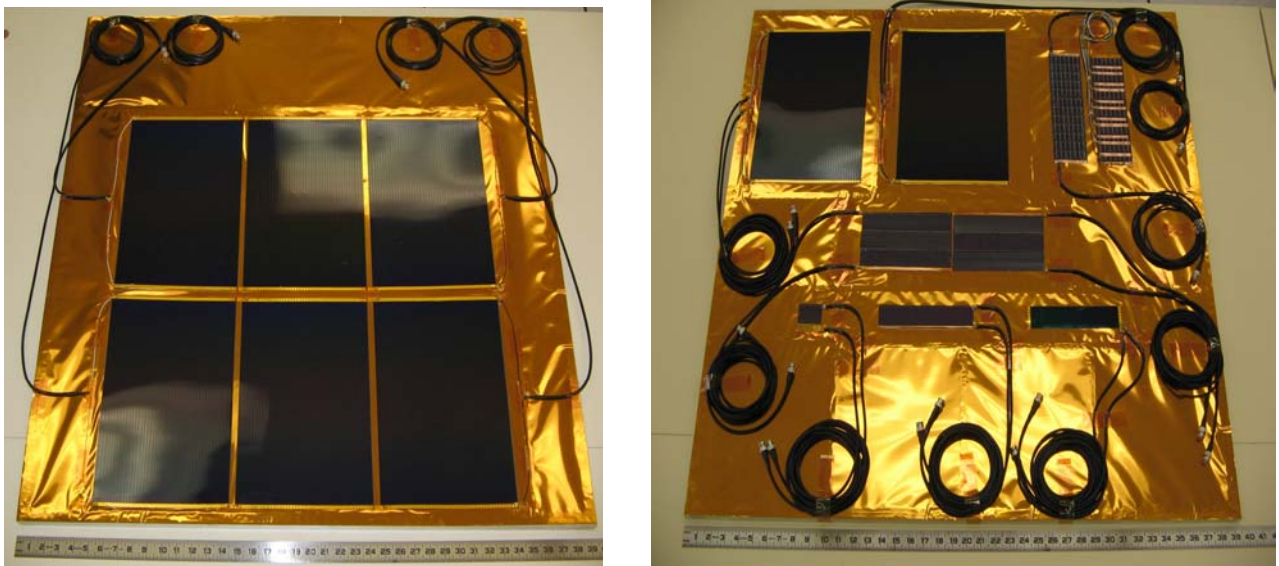


Figure 2. TFPV space plasma test modules; module 1 (left) and module 2 (right). Details are presented in Figure 1.

Initial plasma exposure experiments were carried out in a horizontal vacuum chamber (2 m diameter and 3 m long) equipped with four oil diffusion pumps providing a background pressure of about 1 micro Torr (Figure 3). All measurements were conducted under Xenon plasma with an electron temperature of 1.1 eV, a number density $(2-3) \times 10^5 \text{ cm}^{-3}$, and a background pressure 35-40 micro Torr. All conductive areas of the test modules were covered with kapton tape. The electric circuit diagram for arc testing is shown in Figure 4. Current collection measurements were carried out by biasing each sample with a power supply. Collection current density varied from sample to sample but on average the magnitude was about ten times lower than for a bare conductor. To measure breakdown voltage each sample was biased negatively with respect to the chamber starting from -100 V.



Figure 3. Plasma test chamber at the Plasma Interaction Facility at NASA Glenn.

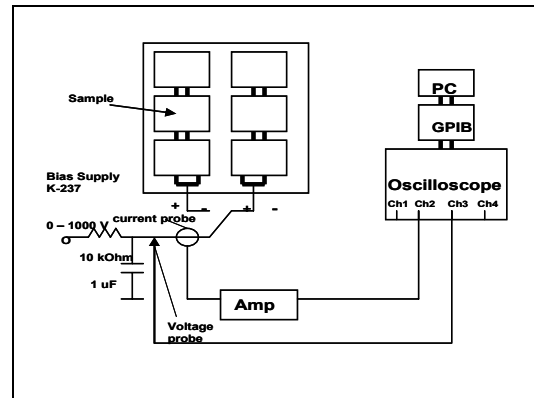


Figure 4. Electric circuit diagram for the arc test.

RESULTS OF ARCING THRESHOLD MEASUREMENTS FOR TFPV

Results presented in this paper conclude the first phase of the space plasma testing program for TFPV. A total of ten samples of coated TFPV were tested under a simulated space plasma environment characteristic of LEO. The samples included single cells and strings of cells based on a-Si and CIGS technologies and coated with two types of proprietary coatings. Collection currents were measured for all the samples before and after observed onset of the electrostatic breakdown. Samples were biased under current limited conditions to prevent catastrophic degradation. To measure the breakdown voltage each sample was biased negatively with respect to the plasma, starting at -100 V, and then the voltage was increased stepwise at increments ranging from 25 V up to 100 V, for dwell times ranging from 15 minutes to 30 minutes.

Generally, two kinds of discharge events were observed during the space plasma exposure tests. The first kind of observed discharge event appeared as a short, not very intense arc followed by relatively minor changes in both the current and the voltage. Several examples of these, so called surface “flashovers”^[9], are presented in Figure 5. The second kind of discharge event appeared as an intense arc, followed by a sharp increase in collected current, and was typically observed at higher bias voltages. Since all the discharge measurements were performed under current limited conditions, all arcing events were promptly terminated to prevent catastrophic damage. An example of a wave form of typical arc current and a voltage pulse are shown in Figure 6. The corresponding image of the arc, as recorded using the on-board video camera, is presented in Figure 7. The results of arcing thresholds and collection current measurements are summarized in Table 1.

Overall, TFPV coated with the oxide coating demonstrated higher arcing threshold voltages than the cells coated with the polymer coating of comparable thickness. Moreover, the thicker polymer coating demonstrated a higher arcing threshold voltage than the thinner one. The quantitative relationship between the coating thickness and the arcing threshold can not be ascertained based on the results of these measurements. Additional tests will be performed in the very near future to assess this relationship.



Figure 5. An example of a series of several flashes recorded via an on-board video camera during simulated LEO plasma test.

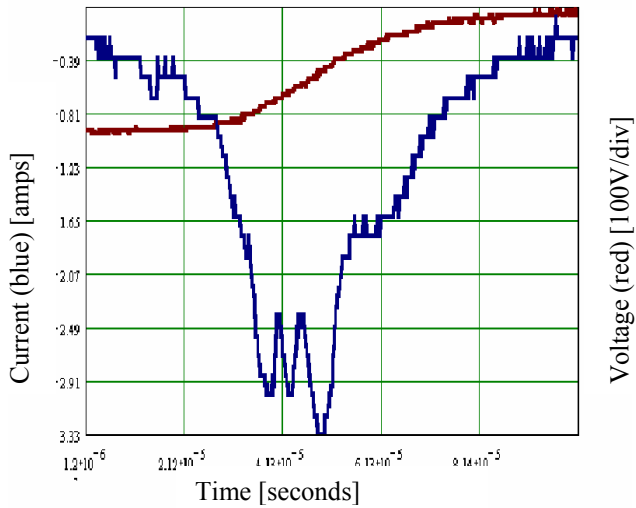


Figure 6. Example of wave forms of an arc current and voltage pulses corresponding to an arc event presented in the photograph in Figure 7.

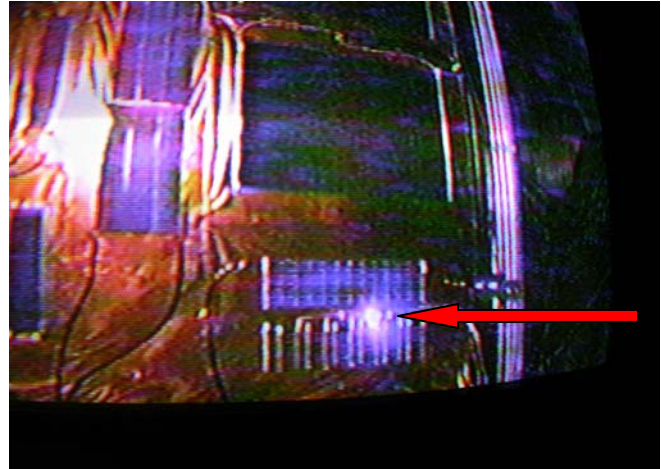


Figure 7. An image of an arc event at - 200 V bias recorded by the on-board video camera.

Table 1. Results of arcing thresholds and collection current measurements for a series of TFPV with protective coatings.

TFPV Description	Coating Description	Arcing Threshold [Volts]	Current Collection [microamps]
a-Si	Polymer – thick film	> 200	330
a-Si	Polymer – thin film	100 – 125	295
a-Si	Oxide/ITO	< 100	290
a-Si/1	Oxide/ITO	150 – 200	250
a-Si/2	Oxide/ITO	> 400	250
a-Si	Oxide/ITO	300 – 350	250
CIGS	Oxide/ITO	> 400	280
CIGS	Oxide/ITO	> 400	280
CIGS	Oxide/ITO	300 – 400	290
CIGS	Oxide/ITO	200 – 250	240

DISCUSSION AND CONCLUSIONS

Emerging TFPV technology offers major improvements in power for space missions by providing a high specific power, enhanced space radiation resistance (as compared with their crystalline counterparts), and an excellent ability to anneal the radiation-induced performance degradation. To provide protection from other components of the space environment including the space plasma, dielectric protective coatings have to be implemented. Results of the initial measurements presented in this paper have demonstrated that both the polymer based and the oxide based thin-film protective coatings provide effective protection for the TFPV from the effects of the simulated LEO space plasma environment. The following is a brief discussion of the test results and concluding remarks.

Implementation of robust dielectric coatings, both polymer and oxide based, provide effective protection of TFPV under the effects of the simulated LEO space plasma environment. In general, there are two major remedial strategies aimed at protecting TFPV arrays from harmful effects of space plasma, including the implementation of robust coating materials, and the sound engineering design of the entire TFPV array. Therefore, in order to prevent space plasma-induced catastrophic degradation of TFPV arrays, one must design the spacecraft arrays and power system to keep the differential charging caused by plasma well below the breakdown potential, or implement materials, that can tolerate the resulting electrostatic discharges.

The estimated values of the electric field strength encountered within the thin-film coatings during high-voltage biasing reached values closely approaching the dielectric strength limits for the materials used for these coatings. Although it is too early to draw final conclusions based only on the results of initial measurements, it should be emphasized that the results of this effort are very encouraging considering that these proprietary coatings were relatively thin. The design of these coatings was optimized to provide the best optical transmissivity, thermal emissivity, dielectric strength and mechanical strength.

The surface properties and the thickness uniformity of both the oxide based and the polymer based protective coatings used in these studies are strongly dependent on their surface area. In addition, the coatings showed the presence of structural imperfections such as pinholes and microcracks. Results of these studies have demonstrated that the aforementioned structural imperfections were likely responsible for initiation of electrostatic discharges. In addition, these structural imperfections affected not only the onset of the arcing events but also the extent of the time-dependent, arc-induced performance degradation. Detailed analysis of this relationship and the proposed remedial strategies will be carried out in the second phase of this program.

The simulated space plasma testing program presented in this paper provided on-ground test data on the interaction of coated TFPV with space plasma and will contribute to an on-orbit predictive capability. In addition, it will provide feedback for the design of future flight hardware. Initial data presented here clearly demonstrate the enhanced resistance of the coated solar cell to a simulated LEO plasma environment.

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