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Space Plasma Experiment for Thin-Film Solar Cells 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 AFRL. The test program is designed to simulate the interactions between TFPV arrays and plasmas characteristic of LEO and MEO environments. The response of coated amorphous silicon and copper-indium-gallium-diselenide solar cells to the simulated space plasma environment is presented. Solar cells used in these experiments were coated with two types of thin-film, multifunctional, protective coatings, which are designed to provide protection from the space environment, including space plasma, and to aid in passive thermal management of the TFPV arrays. The test coupons, which contain single cells and interconnected strings, closely resemble the actual configuration of high-voltage TFPV arrays that will be flown on the Demonstration and Science Experiments (DSX). Results of preliminary electrostatic charging, arcing, dielectric breakdown, and parasitic current measurements are presented and analyzed. The preliminary experimental data presented in this paper demonstrate that multifunctional protective coatings developed for TFPV arrays provide effective protection against the plasma environment while minimizing impact on their power generation performance. This effort is part of an ongoing development program for TFPV led by the Space Vehicle Directorate at the Air Force Research Laboratory. Plasma interaction tests were carried out at the NASA Glenn Plasma Interaction Facility.

I. Introduction

State of practice (SOP) crystalline solar cell technology for space has utilized a cover glass to protect cells from effects of space ionizing radiation, space plasma, atomic oxygen, and other components of orbital space environments. This cover glass adds mass to the solar array and increases costs. One of the advantages of thin-film photovoltaics (TFPV) is that they have proven to be relatively resistant to on-orbit radiation and therefore do not require a thick cover glass. TFPV offer great promise for power generation on future spacecraft missions. Although the efficiency of the cells is currently low compared to crystalline cells, they are attractive at the system level due to significant increases in specific power (W/kg) and stowage (W/m³). For high power applications, TFPV may also have a significant impact on cost reduction. However, these technologies require development of flexible, lightweight protective coatings to provide passive thermal management and protection from a number of space environment components including space plasma.

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To reach these goals AFRL initiated a comprehensive program to develop space qualifiable coatings for TFPV with their properties tailored to specific DOD space missions¹. 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 their nature, (i.e. simultaneously provide 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 rates², (3) space survivability testing, (4) industrial scalability and (5) ability to tailor to specific mission needs. Both single layer and multilayer, multi-component coatings have been investigated.

The principal objectives of the space plasma test program are to study the degradation mechanism of TFPV and their modules under simulated space plasma (LEO and MEO environments) and evaluate the current leakage and arcing effects during high voltage biasing^{3,4}. Arcing can result in electromagnetic interference, solar cell damage, induced currents in the power systems, optical emission, and an enhanced local plasma density. In particular, the specific objectives of the program are; (1) simulate the behavior of TFPV arrays under LEO and MEO environments, (2) validate models of plasma interaction and effects on TFPV, (3) characterize material properties of TFPV and their protective coatings, which are relevant to the space plasma environment interactions, and (4) propose design strategies for mitigation of deleterious effects of the space environment on TFPV.

II. Experimental Plan

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 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 designed 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.

Thin-film solar cells investigated in this work were assembled on two test coupons by Lockheed-Martin. The cells were mounted on an aluminized Kapton blanket and stretched on two, 1 x 1 m aluminum frames and interconnected with encapsulated 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, individual connections provide flexibility for biasing the cells during the tests and allow simulation of voltage gradients between interconnects, which closely resembles the actual configuration on the Demonstration and Science Experiments (DSX) flight experiment arrays⁵. Optically active areas of these cells have been protected with multifunctional thin-film protective coatings. The exposed contact areas are protected with a silicone adhesive in order to produce a “conformal” protective overcoat for the entire interconnected module. This interconnect scheme is similar to the expected design of the actual DSX flight experiment coupons. Figure 1 summarizes the configuration of two tests coupons.

Thin-film solar cells investigated in this work were acquired from United Solar Ovonic Corp. (USOC), Global Solar Energy Inc. (GSE), and Iowa Thin Film Technologies (ITFT). The cells include amorphous silicon (a-Si) and copper-indium-gallium-diselenide (CIGS) technologies coated with two types of thin-film proprietary protective coatings. Both single cells as well as strings of interconnected cells are 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 are accomplished by slowly biasing the cell negative with respect to the chamber wall down to the expected operation voltage or until the breakdown voltage of the coating is reached. The default value of the voltage applied will be that of the maximum array operating voltage. Because the protective coatings are extremely thin, it is necessary to test whether the film acts as conductor or insulator, and to measure the leakage current from the cell. The resistivity and the conductivity of the test cell immersed in plasma will also be measured. As is the case with some thin insulating films tested in the past the resistivity often changes dramatically after testing. TFPV will also be inspected visually using a microscope for the presence of pinholes prior to plasma testing and once again after plasma testing and photographic images will be recorded.

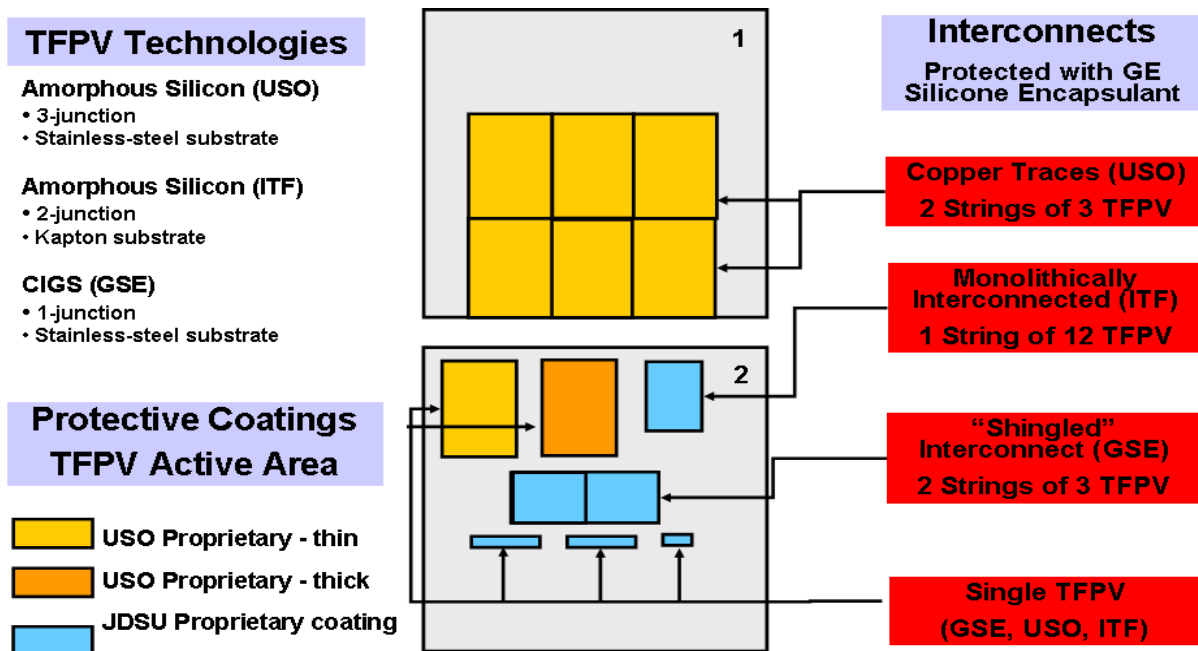


Figure 1. Schematic diagram showing configurations of TFPV and strings on two test coupons.

TFPV will be exposed to simulated space plasma conditions. Samples will be biased under current limited conditions for dwell times as specified in the test plan, sufficient to determine their performance under plasma conditions. Samples will then be tested using a combination of biasing and electron gun irradiation. Testing has been designed to determine solar array environmental interactions under conditions expected to be encountered in the DSX Flight Experiment. Electrical and optical performance of TFPVs will be measured prior to and after exposure to simulated LEO plasma environment. Electrical characterization consists of current-voltage (I-V) measurements under simulated Air Mass Zero (AM0) conditions and optical measurements consist of optical reflectivity measurements. The I-V measurements will be performed using a Large Area Pulsed Solar Simulator (LAPSS) system. Current-voltage characteristics will be measured under LAPSS system illumination and in darkness. In addition current-voltage characteristics will be measured during the plasma tests without illumination at time intervals as specified in the test plan.

III. Response of Coated TFPV to Simulated Space Plasma

Initial plasma exposure experiments were carried out in a vertical vacuum chamber (2 m diameter and 3 m eight) equipped with four oil diffusion pumps providing background pressure of about 1 micro Torr. Xenon plasma

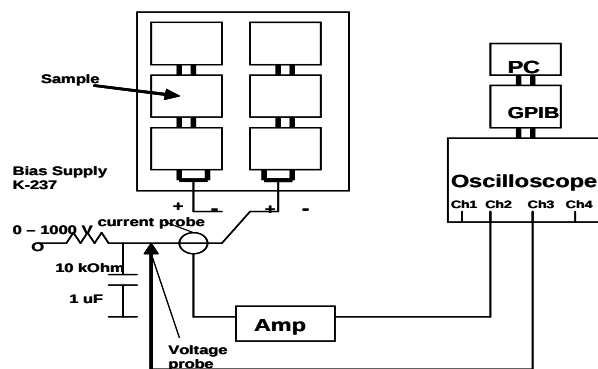


Figure 2. Electric circuit diagram for the arc test.

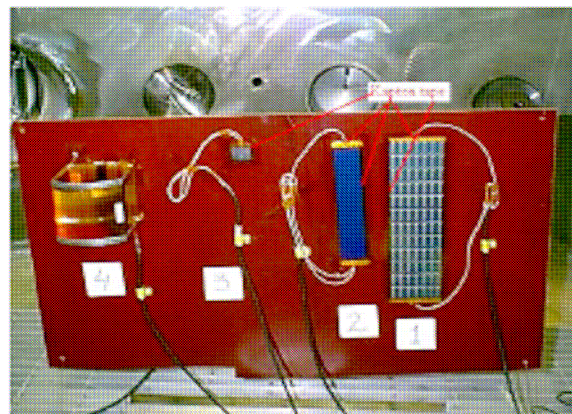


Figure 3. Fiberglass sample plate.

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 has been generated. TFPV samples were mounted on a fiberglass plate with all conductive areas covered by Kapton tape (Figure 2). The electric circuit diagram for arc testing is shown in Figure 3. Current collection was measured by biasing each sample with power supply. Collection current density varies from sample to sample but in average the magnitude is 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. Voltage steps varied from 20 to 100 V depending on observed ion collection current. The duration of each step varied between 10 and 20 minutes. The examples of wave forms of arc current and voltage pulses are shown in Figure 4 and images of arcs are presented in Figure 5.

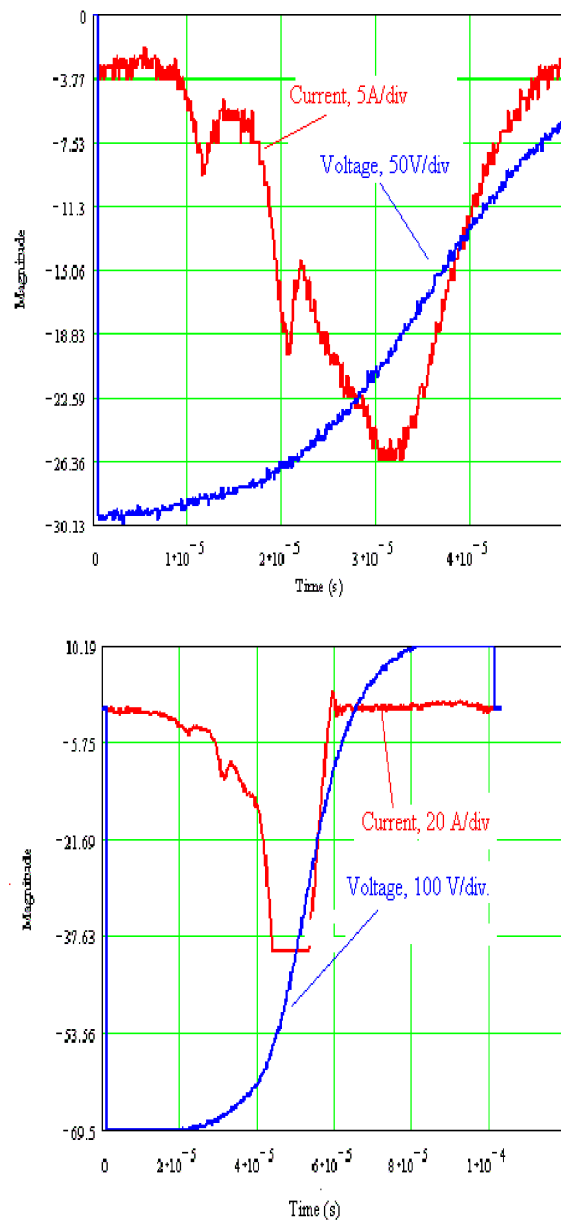


Figure 4. Typical examples of wave forms of arc current and voltage pulses: (a) arc on sample #1 and (b) arc on sample #2.



Figure 5. Images of arcs: sample #1 (top) and sample #2 (bottom.).

Results of initial performance tests demonstrated increased survivability of coated amorphous silicon TFPV in the plasma environment. The uncoated sample experienced first breakdown at voltage gradient of 300V, and the second at 450V. The coated TFPV sample, on the other hand, demonstrated higher breakdown threshold of 650V. This particular coating has been developed at AFRL/VSSV under contract with JDS Uniphase. It is a multifunctional coating that provides protection against the space environment and aids in thermal management of a solar panel while minimizing impact on solar cell performance.

IV. Conclusions

Thin-film solar cell technologies have potential for providing high specific power for space missions operating under harsh space environments including low density plasmas. Before successful technology transition can occur, TFPV performance must be characterized, understood, and modeled through on-ground testing and in-flight experiments. The simulated space plasma testing program outlined in this paper will provide on-ground test data on the interaction of coated TFPV with plasma and will lead to an on-orbit predictive capability. In addition, it will provide feedback to the design of the DSX flight experiment. Initial data presented here clearly demonstrate the enhanced resistance of the coated solar cell to a simulated LEO plasma environment.

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