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Plasma Chamber Testing of Advanced Photovoltaic Solar Array Coupons

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Introduction

HISTORICALLY, power systems on U.S. spacecraft have operated at the nominal 28 V dc inherited from the aircraft industry, a choice made feasible by their typically small size and relatively low power requirements. As satellites and other spacecraft have steadily become larger, heavier, and more sophisticated, solar arrays and other power sources have begun to be operated at higher voltages to minimize the system currents. The major advantage of higher operating voltages is the lower mass of the cabling required to transmit electrical power from the power sources efficiently.

The advent of high-voltage systems poses a number of challenges to the spacecraft designer. In particular, the interaction of materials and systems with space plasma, negligible at 28 V, now becomes important. Materials and design practices which have been standard for low-voltage systems are susceptible to various plasma interactions and in some cases will prove unsuitable when high voltages are employed. The Solar Array Module Plasma Interactions Experiment (SAMPIE)'" is a Space Shuttle experiment designed to investigate and quantify these high-voltage plasma interactions.

Results from SAMPIE will play a key role in the design and construction of high-voltage space power systems. Among its various experiment samples, a number of solar cell coupons (representing design technologies of current interest) will be biased to high voltages to measure both arcing and plasma current collection. One of the principal objectives of the experiment is to test the performance of the Advanced Photovoltaic Solar Array (APSA).[4]

APSA is characterized principally by the use of very thin (60 μ) solar cells mounted on a flexible deployable blanket. The resulting array has very high specific power, exceeding 130 W/kg beginning of life (BOL) even using silicon solar cells. On SAMPIE, a flexible, deployable geometry is not practical and the cell coupon must be hard-mounted to a piece of aluminum. It was expected that the mounting scheme would have no impact on the plasma interactions SAMPIE is designed to test since all cells, interconnects, and bus bars are on the front side. A further assumption, valid at the traditional 28 V bus voltage, was that the material properties of the array blanket are not important to the electrical performance of the array. Since APSA arrays are now being designed using several blanket materials which are not strong electrical insulators, this assumption is questionable for high-voltage operation. To test the role of different blanket materials under high-voltage conditions, three twelve-cell prototype coupons of 2-cm by 4-cm silicon cells were constructed and tested in a space simulation chamber.

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Sample Construction

Originally designed for deployment in geosynchronous Earth orbit (GEO), APSA initially used a flexible blanket of carbon-loaded Kapton® mounted in an external frame. The carbon-loaded material provides a blanket which is slightly conducting and serves as an active charge control measure in geostationary applications where spacecraft charging is the prime concern. The first test sample was therefore constructed on a 15.24-cm by 17.78-cm (6-in. by 7-in.) carbon-loaded Kapton blanket. The outer 1.27-cm (0.5-in.) perimeter was covered front and back with Kapton tape to increase mechanical strength leaving an active area of 12.7 cm by 15.24 cm (5 in. by 6 in.) of exposed carbon-loaded material. The solar cells were wired as three parallel strings each having four cells in series. The module was suspended from its four comers by four nonconducting bands in a frame made from nonconducting material.

A second coupon was constructed using standard Kapton-H, which we will henceforth refer to simply as "Kapton." The module was constructed on a 15.24-cm by 17.78-cm (6-in. by 7-in.) piece of Kapton which was then bonded to an aluminum substrate using a nonconductive adhesive. The aluminum substrate was anodized on the top and conversion coated on the back, rendering the top surface insulating and the bottom surface conducting. The effect of this is to electrically isolate the solar array from the underlying substrate. The coupon was wired as three parallel strings each having four cells in series.

The final coupon, more appropriate for use in low Earth orbit (LEO), has a blanket of germanium-coated Kapton for protection from atomic oxygen attack. The germanium coating provides a higher resistance than carbon loading but is still weakly conductive. Unlike the carbon-loaded material, for which conductivity is a bulk property, this material uses germanium as a thin film deposited on a substrate of Kapton. The cells were mounted on a piece of 12.7-cm by 15.24-cm (5-in. by 6-in.) Kapton with 150 nm of germanium coating on both sides. It was then bonded to an aluminum substrate as above and wired as a single-series string.

In all three cases, electrical wires were attached to the two busbars and shorted together to allow for the application of bias voltage. Exposed busbars are a major source of plasma current collection. All busbars were made from .32-cm- (1/8-in.) wide strips but differed slightly in length because of the different wiring schemes. General layout of the cells, spacing between them, and number, size, and placement of interconnects was as close to being the same for all three as possible. These properties are summarized in Table 1.

Test Facility and Procedures

Testing was done in the Plasma Interaction Facility (PIF) at the Lewis Research Center. All measurements were made in a space simulation chamber offering a cylindrical volume 1.8 m (6 ft) in diameter by 1.8 m long. A 91.4-cm (36-in.) diffusion pump provided an initial pumpdown to approximately 5×10^{-7} torr. Plasma was generated by a hollow cathode discharge source with a continuous flow of argon. Pressure in the tank during operation of the plasma source was approximately 5×10^{-5} torr.

An electrometer, a Keithley model 237, was used to apply a bias voltage to the test sample and measure the resulting collected current. Ion currents were measured with applied biases from 0 to -200 V in 10-V increments while electron currents were measured with applied biases from 0 to $+600$ V in 25-V increments. Ion and electron current collection sweeps were made separately, always beginning with zero volts bias and increasing the applied voltage magnitude. The negative bias range was restricted to −200 V to avoid arcing and possible damage to the sample. A complete data set consisted of ten runs which were averaged to smooth random fluctuations in plasma density. Plasma density during the operation of hollow cathode sources is characterized by a relatively stable mean value with random fluctuation ranging from a few percent to occasional bursts which can exceed 15 or 20%. Additional precautions were taken to account for the small systematic drifts in plasma density caused by changing conditions in the plasma source. To this end, plasma density was monitored using a 1.9-cm (¾-in.) Langmuir probe and a second electrometer. At the beginning of each data run, the plasma source was adjusted to result in a current of 1.65 mA when this probe was biased to +100 V. Plasma conditions corresponding to this value were measured and are shown in Table 2. The procedure effectively normalizes all data to the plasma density indicated.

Results and Discussion

All measurements reported here were made with the solar cell arrays and their blankets electrically isolated from ground and, in the case of the two hard-mounted samples, from their underlying substrates. Clearly, if the blankets have any significant electrical conductivity and were to be grounded, direct leakage to ground will be a significant contribution to the total measured current. Extensive measurements of leakage currents were made but are not reported here since they show no unexpected results. They are reported in detail elsewhere:

The data is summarized in Figs. 1 and 2. As mentioned previously, each data point is the arithmetic mean of ten individual runs. All results were highly reproducible with standard errors running generally well under one percent. We therefore do not show error bars since they are so small that they would not be distinguishable from the data point. Figure 2 presents electron collection and shows the effects of snapover in the steep increases in current that follow the sudden onset of this now well-known effect. The electrometer used for the measurements has a maximum current capacity of 10 mA. The data displayed in Fig. 2 exceeds this value at high voltages and saturates the instrument. Fig. 1 shows that ion current, as is expected, is generally linear with bias. Comparing the behavior of the three coupons, we see that the same trend is present for both electron and ion collection. In particular, the highly insulating Kapton, despite the slightly larger size of the surrounding blanket, collects the least current while the carbon-loaded material, which has the least resistance, collects the most. The germanium coupon is a more complicated case. For ion collection, germanium is about midway between Kapton and carbon, collecting approximately three times as much current as Kapton. For electron collection, it behaves as an insulator up to about 100 V, being indistinguishable from Kapton. Above this potential, current increases rapidly and the germanium coupon collects substantially more than the Kapton blanket array. We note at this point that examination of the data confirms the conventional assumption that the choice of blanket material is unimportant, as far as plasma interactions are concerned, at the traditional 28-V bus voltage.

In understanding these results we point out that the highly insulating Kapton will tend to remain near plasma potential at all points on its surface. The other two materials, since they are weakly conducting, will support potential distributions that are complicated by the geometry but in general will be close to the bias potential in the vicinity of the cell array and busbars while dropping to the plasma potential further away. Such a potential distribution on the surface of the blanket may result in two different effects that can contribute to the enhanced current flow. First, charge may be simply collected by the blanket and conducted through the material to the busbars. A relative measure of the effective conductivity may be obtained by attaching a ground clip to one comer of each coupon and measuring the resistance between the clip and a busbar approximately 1 in. away. When this is done, the carbon coupon shows 1 megohm, the germanium coupon 150 megohms, and the Kapton coupon 600 megohms. Second, such potential distributions will be expected to modify the plasma sheaths. For the Kapton case, the sheath is not likely to extend much beyond the area occupied by the actual cell array while for the two conducting coupons it may well cover the entire blanket. The effect of a large plasma sheath may be to funnel a significant current to the busbars and cell interconnects.

Our data are not able to quantitatively distinguish between these two effects which are undoubtedly both occurring. We will argue qualitatively, however, that the phenomena is primarily a plasma effect. One may gain some insight into this by attaching

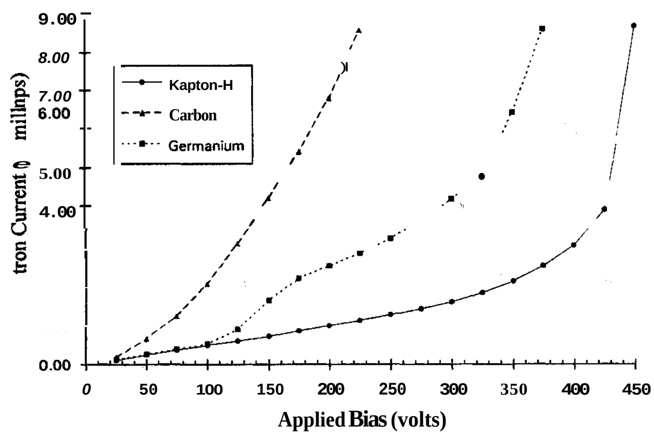

Fig. 1 Ion current vs bias.

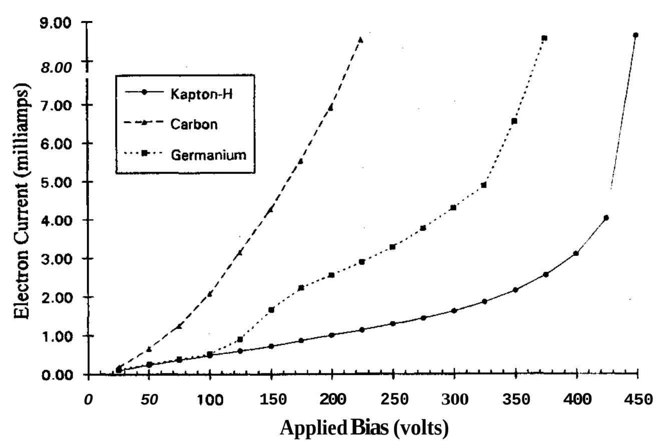

Fig. 2 Electron current vs bias.

Table 1 Coupon parameters

	Blanket properties		Array parameters	
Material	Thickness, 10^{-5}m	Exposed, area cm^2	Wiring scheme	busbar area, mm^2
Kapton H	5.08 (2 mil)	145.7	series parallel	775
Carbon-loaded	7.62 (3 mil)	Front: 70.3 Back 189.2	series/ parallel	775
Ge-coated	5.08 (2 mil)	76.8	series	692

Table 2 Plasma parameters

Electron density	7.96×10^5 $^{-3}$
Electron temp	1.75 eV
Ion temp	0.56 eV
Plasma potential	4.83 eV

the ground clip to each coupon, as described earlier, and repeating all of the measurements. These measurements are reported in detail elsewhere: but the key result is that while a significant difference is observed for the carbon coupon due to its very low resistance, no difference in current collection was observed for the germanium or Kapton coupons. If conduction through the material were important, a measurable enhancement would be expected. We believe, therefore, that our results point to what is primarily a plasma sheath effect.

Conclusions

The results reported here are the first experimental demonstration that the electrical properties of a solar array blanket can significantly impact the performance of the system. For the designer of real power systems, the relative importance of the two physical mechanisms discussed above may well be academic. Regardless of what is eventually shown to be the exact mechanism involved, it is clear that the use of weakly conductive blankets can lead to enhanced plasma current collection. This is true even if the material has what is normally considered to be a large resistance, as does the germanium coating reported here. This enhanced current collection appears as a power loss to the system and is obviously of importance to the designer.

The magnitude of the loss that a photovoltaic power system may expect to incur as a result of this effect depends on its design. In particular, spacecraft are generally grounded to the negative end of the solar array which means that the majority of the system, including the spacecraft structure, will float negative with respect to the plasma and therefore collect ions. As our data shows, ion collection is enhanced with weakly conductive coatings but, as is always true of ion collection, the absolute magnitudes are small and the overall effect may be negligible. The use of a negative ground with a high-voltage system, however, has serious implications for the final floating potential of the spacecraft? as has been amply demonstrated with Space Station Freedom (SSF). In the case of SSF, a plasma contactor had to be added to the baseline design to control potentially severe arcing and sputtering resulting from the grounding scheme. The final potential distribution on the solar arrays and structure resulting from the interplay of such a device with the power system is extremely complicated and beyond the scope of the present work, but we will point out that this is one case when large areas on the array can be driven to large positive potentials. Such a potential distribution will obviously also occur in the case of a positively grounded system. It is in such situations, however they occur, that our results will need to be considered and the use of such coatings carefully evaluated.

One research community affected by these results deals with atomic oxygen protective coatings. It was for this purpose that the germanium was initially added to the APSA coupon. Such coatings are not routinely tested for the effects we report and our results argue that they should be. For traditional low-voltage systems this may not be necessary, but for solar arrays which will operate in LEO at 100 V or more there is a clear potential for such coatings to lead directly to losses on the array.

Acknowledgments

All of the solar cell coupons used in this work as well as the flight versions for SAMPIE were fabricated for NASA by TRW Engineering & Test Division, One Space Park, Redondo Beach, CA.

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Cercignani-Lampis-Lord Gas-Surface Interaction Model: Comparisons Between Theory and Simulation

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Introduction

IN recent years, many facets of physical modeling within the context of the direct simulation Monte Carlo (DSMC) method' have received increased attention. The general goal of this effort is to implement more sophisticated, realistic models for certain microscopic phenomena, without loss of accuracy at the macroscopic level, to increase the versatility of the DSMC method and to create greater confidence in the solutions produced by its users. One facet of this is the phenomenon of gas–surface interaction with incomplete momentum or energy accommodation.*

In dealing with this issue for a given study, investigators using DSMC generally assume diffuse reflection with complete momentum and energy accommodation, specular reflection (zero accommodation), or complementary fractions of each (Fig. 1). This basic model is called the "Maxwell" model.[3] Usually, an "accommodation coefficient" for some function of velocity $Q(V)$, denoted by σ_Q or α_Q, is defined as

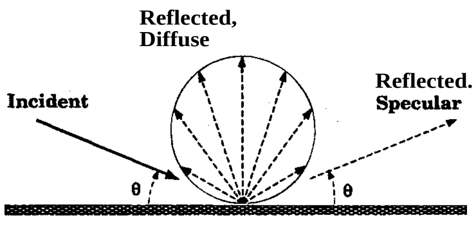

Fig. 1 Schematic representation of the angular distribution of gas molecules reflected from a solid surface for diffuse and specular models.

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