PROTECTION OF MATERIALS AND STRUCTURES FROM THE SPACE ENVIRONMENT
PROTECTION OF MATERIALS AND STRUCTURES FROM THE SPACE ENVIRONMENT

ICPMSE-7

Edited by

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This publication presents the proceedings of ICPMSE-7, the Seventh International Conference on Protection of Materials and Structures from Space Environment, held in Toronto May 10–13, 2004.

The ICPMSE series of meetings became an important part of the LEO space community since it was started in 1991. Since then, the meeting has grown steadily, establishing itself as the only North American event covering the various aspects of materials protection in LEO and attracting a large number of engineers, researchers, managers, and scientists from industrial companies, scientific institutions and government agencies in Canada, USA, Asia, and Europe, thus becoming a true international event. The ICPMSE-7 meeting continued the tradition of the previous meetings including in the program the topics on protection of materials in GEO and Deep Space.

The conference was organized by Integrity Testing Laboratory Inc. (ITL), and hosted by the University of Toronto’s Institute for Aerospace Studies (UTIAS). The meeting was sponsored by:

a) The Materials and Manufacturing Ontario (MMO) and the CRESTech, two Ontario Centres of Excellence that from April 1, 2004 joined under the Ontario Centres of Excellence Inc. (OCE Inc) a not-for-profit, member-based corporation dedicated to establishing Ontario as the place to be for innovation;
b) MD Robotics;
c) The Integrity Testing Laboratory (ITL) and
d) The University of Toronto Institute for Aerospace Studies (UTIAS).

Over 80 people from countries covering the American, European and Asian continents registered for the conference representing the major space agencies and the major companies, institutions and government organizations involved in space activities, indicating a further increase in international co-operation in this critical area of protection of materials in space.

The papers in the proceedings were organized into six major sections as follows:

Session O: Opening Session
Session A: Space Environmental Effects: Radiation and Charging
Session B: Space Environmental Effects: Synergism of AO/VUV/TC
Session C: Space Environmental Effects: Synergism of AO/VUV/TC
Session D: Space Environmental Effects: Instrumentation and Calibration
Session E: New Materials and Processes
Session F: Modeling and Computer Simulations

In addition, poster sessions were organized that covered the same subjects.

Jacob Kleiman
Chairman/Organizing Committee/ICMSE-7
Integrity Testing Laboratory Inc.
20 January, 2005
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Jacob Kleiman
Integrity Testing Laboratory Inc.
Conference Chairman
ORGANIZATION

7th International Conference on “Protection of Materials and Structures from Space Environment”
ICPMSE-7
May 10–13, 2004
Toronto, Canada

Chairperson: Dr. Jacob Kleiman, ITL Inc./UTIAS, Canada

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Opening Session
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Session A: Space Environmental Effects: Radiation, Charging and UV Effects
Moderator: Kim K. DeGroh, NASA, Cleveland, USA

Session B: Space Environmental Effects: AO/VUV/TC/Micrometeoroids Effects (Ground Simulation and Flight Experiments)
Moderator: Dave Edwards, NASA, Houston, USA

Session C: Materials and Processes I
Moderator: Gary Pippin-Boeing, Seattle, USA

Session D: Materials and Processes II
Moderator: Bruce Banks, NASA, Cleveland, USA

Session E: Modeling and Computer Simulations
Moderator: Tim Minton, Montana State University, USA

Session F: Space Environmental Effects: Instrumentation and Calibration
Moderator: Alan Chambers, University of Southampton, UK
Abstract. Radiation effects of protons and electrons on the backfield silicon solar cells were investigated. The samples without cover glass were irradiated by the protons and electrons with 30–180 keV and a given flux of $1.2 \times 10^{12}$ cm$^{-2}$·s$^{-1}$ for various fluences at 77 K. Experimental results show that the short circuit current decreases gradually with increasing the proton fluence, while the open circuit voltage degrades severely under lower fluences. No obvious changes appear in the electric properties before and after the irradiation by electrons, and there exists a recovery effect in the in situ measurement for the irradiated samples. The effect of the combined radiation of protons and electrons does not show simple additivity. The damage extent of proton radiation is larger than that of combined radiation under lower electron fluences, while the combined radiation results in more severe damage under higher fluences. The DLTS analysis verified that the primary defects induced by protons were the H1 or [V+B] type at the energy level of +0.45 eV, which would result in formation of a resistance layer in the base region and degradation of the backfield Si solar cells.

Key words: Radiation effects, Protons, Electrons, Solar cells

1. Introduction

Since solar cells are key elements to provide spacecraft with electric energy in orbit, the degradation in their properties could directly influence the working condition and lifetime of spacecraft. The electric properties of solar cells would be degenerated under the space radiations [1]. It is important to improve the radiation resistance of the solar cells [2–5]. In order to evaluate the performance of the solar cells in the geostationary Earth orbit, it is necessary to characterize the effects of charged particles with the energy less than 200 keV, which exist in large amount in the Earth’s radiation belts. Also, when spacecraft passes into the Earth shadow, the solar cells are subjected to the effect of low temperatures. The
The aim of this study was to examine the change in electric properties of the silicon solar cells under the radiations of protons and electrons with $<200$ keV at 77 K, as well as the radiation damage mechanism.

2. Experimental

The sample of the backfield silicon solar cell is schematically shown in figure 1, which is 250 μm thick and has the base layer resistivity of 10–12 Ω·cm. The samples with the size of $20 \times 20 \text{ mm}^2$ were not covered with glass. The phosphorus doped Si emitter junction depth from the surface is 0.2 μm. The parameters of samples before irradiation are shown in table 1.

The ground-based simulation equipment used in this study can simulate the radiations of solar electromagnetic rays, electrons and protons in orbit, independently and simultaneously. The irradiation energy of protons and electrons was chosen as 60–180 keV, the flux $1.2 \times 10^{12} \text{ cm}^{-2} \cdot \text{s}^{-1}$ and the fluence from $2 \times 10^{13}$ to $2 \times 10^{16} \text{ cm}^{-2}$. The homogeneity of the irradiation flux is more than 95% in the area of $100 \times 100 \text{ mm}^2$ by scanning the proton and electron beam. During the irradiations, the chamber was kept at vacuum $10^{-4}$ Pa and temperature of 77 K. The electric properties of the samples were characterized by $I-V$ curves, which were measured before and after the irradiations. In order to analyze the radiation-induced defects, DLTS analysis (deep level transient spectroscopy) was carried out in the temperature range of 77–450 K.

<table>
<thead>
<tr>
<th>$I_{sc}$ (mA)</th>
<th>$V_{oc}$ (mV)</th>
<th>$P_{m}$ (mV)</th>
<th>FF</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>138.7</td>
<td>552</td>
<td>59.97</td>
<td>0.78</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 1. The parameters of the samples before irradiation

Figure 1. Schematic diagram of the samples

I. Ohmic contact region on back surface;  
II. $p^+$ doped region;  
III. p base region;  
IV. pn junction region;  
V. $n^+$ top region;  
VI. Attenuating reflection coating;  
VII. Gate electrode
3. Results and Discussion

3.1. Changes in Electric Properties Under Proton Radiation

Figure 2(a) and 2(b) show the $I$–$V$ curves for the samples irradiated with 60 and 170 keV protons, respectively. The changes in the normalized short-circuit current $I_{sc}/I_0$ and the normalized open-circuit voltage $V_{oc}/V_o$ are given as a function of fluence of protons with various energies, as shown in figures 3(a) and 3(b). With increasing both fluence and energy, the short-circuit current $I_{sc}$ decreases gradually. The irradiation of protons also leads to an obvious decrease of the open-circuit voltage $V_{oc}$, but the degradation extent depends on the fluence and energy of the protons. After the irradiation by protons with 150–170 keV, the $V_{oc}$ is noticeably degraded at lower fluences, and then remains almost unchangeable.

Figure 3. Changes in the normalized $I_{sc}$ (a) and normalized $V_{oc}$ (b) with fluence for the samples irradiated with 60, 150, and 170 keV protons
### TABLE 2. Variation of the characteristics for the samples before and after 60 keV proton irradiation (AM0)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>$V_{oc}$ (V)</th>
<th>$I_{sc}$ (mA)</th>
<th>$J_{sc}$ (mA.cm$^{-2}$)</th>
<th>FF</th>
<th>EFF (%)</th>
<th>$R_s$ (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before irradiation</td>
<td>0.5299</td>
<td>159.80</td>
<td>39.94</td>
<td>0.725</td>
<td>11.2</td>
<td>0.42</td>
</tr>
<tr>
<td>60 keV, $1 \times 10^{16}$ cm$^{-2}$</td>
<td>0.2823</td>
<td>128.56</td>
<td>32.14</td>
<td>0.511</td>
<td>4.19</td>
<td>3.39</td>
</tr>
</tbody>
</table>

with the increase of fluence or even shows a recovery after a fluence higher than $5 \times 10^{15}$ cm$^{-2}$. Table 2 shows that after the irradiation by protons with 60 keV to a fluence of $1 \times 10^{16}$ cm$^{-2}$, all the characteristics including the $V_{oc}$, $I_{sc}$, $J_{sc}$, FF, and EFF decrease, while the internal resistance in series increases remarkably (almost 10 times higher). This implies that the concentration of carriers inside the samples is obviously reduced due to the proton irradiation.

### 3.2. CHANGES IN ELECTRIC PROPERTIES UNDER ELECTRON RADIATION

Figure 4 shows the $I$–$V$ curves for the samples before and after irradiation by 60 and 180 keV electrons. It is obvious that there is very little change in the $I$–$V$ curves. However, the situation is quite different, if the $I$–$V$ curves are examined in situ during the exposure. With increasing the electron fluence, the normalized $V_{oc}$ gradually decreases (see figure 5(a)), while the normalized $I_{sc}$ increases until the fluence less than $1 \times 10^{16}$ cm$^{-2}$ (see figure 5(b)). Figures 6(a) and 6(b) show the changes in the $V_{oc}$ and $I_{sc}$ with time in vacuum after the electron irradiation, respectively. It is demonstrated that with increasing the time, the $V_{oc}$ rises and the $I_{sc}$ drops again. Both the $V_{oc}$ and $I_{sc}$ tend to return gradually to the original level for the unirradiated samples. This phenomenon implies that a recovery must be considered in evaluating the electron radiation effect for the backfield Si solar cells in orbit.

![Figure 4. Variation of $I$–$V$ curves for the samples before and after electron irradiation](image)
RADIATION EFFECTS OF PROTONS AND ELECTRONS

Figure 5. The normalized $V_{oc}$ (a) and normalized $I_{sc}$ (b) measured in situ as a function of fluence for the samples irradiated with 170 keV electrons.

3.3. CHANGES IN ELECTRIC PROPERTIES UNDER THE COMBINED RADIATION OF PROTONS AND ELECTRONS

Figure 7 shows the normalized $I-V$ curves for the samples under the proton, the electron and the combined irradiations with 170 keV. Notice that the damage effect of protons is much larger than that of the electrons (see curves 1, 2, and 4). The effect of the combined radiation of protons and electrons does not show simple additivity. The degradation extent due to the proton radiation is larger than that of the combined radiation under the same proton fluence and lower electron fluence (see curves 3 and 4). In contrast, the combined radiation results in more severe damage under the same proton fluence and higher electron fluence (see curves 4 and 5).

Figure 6. The normalized $V_{oc}$ (a) and normalized $I_{sc}$ (b) measured in situ as a function of time in vacuum after electron irradiation with 170 keV.
3.4. ANALYSIS ON RADIATION-INDUCED DEFECTS

Figure 8 shows the DLTS spectra for the samples irradiated with 150 keV protons for various fluences. With increasing fluence, the DLTS signals are reduced and the peak width increases. The effect of proton energy on the DLTS spectrum is shown in figure 9. The DLTS spectrum shows a more symmetrical distribution for the 60 keV proton irradiation, while exhibits an obvious asymmetry after the irradiation with 150 keV protons. In addition, the DLTS signals in the temperature range of 125–230 K are increased noticeably. The change in the DLTS peak height can be related to the variation of the concentration of the defects at deep energy levels due to proton irradiation. According to the DLTS analysis results, the
primary defects induced by the protons are believed to belong to the H1 type with the +0.45 eV energy level. The H1 type defects are generally referred to as the combination of radiation-induced vacancies with boron atoms, namely the \([V+B]\) defects [6]. Under the <200 keV proton irradiation, a large amount of vacancies could be formed in the base region close to the pn junction of the backfield Si cell samples, and the vacancies would interact with the nearby boron atoms in the silicon, forming the \([V+B]\) type defects. The interaction of the radiation-induced vacancies with boron atoms can provide the thermodynamic driving force for the segregation of boron atoms in the base region close to pn junction. As a result, a resistance layer with high concentration of the \([V+B]\) defects near the pn junction could be formed due to the proton radiation. The formation of such a resistance layer can contribute to the decrease in electric properties for the backfield Si solar cells irradiated with <200 keV protons.

4. Conclusions

Solar cells are key elements of the system providing the electric energy in spacecraft. It is of theoretical and practical significance to thoroughly study the damage effects of charged particles on solar cells under space environment. The samples for the backfield Si solar cells were irradiated by protons and electrons with energy of <200 keV. It is found that the proton irradiation leads to remarkable decreases in the short-circuit current and open-circuit voltage. No obvious changes appear in the electric properties after irradiation by electrons. The radiation effects of the electrons are recoverable after the irradiation. The effect of the combined radiation of protons and electrons does not show simple additivity. The damage extent of
proton radiation is larger than the combined radiation under the same proton and the lower electron fluence. In contrast, the combined radiation could result in more severe damage if the electron fluence is higher. The damage of the backfield Si solar cells is primarily caused by the protons, and could be related to the formation of the [V+B] type defects at +0.45 eV level and the resistance layer in the base region close to the pn junction.

Acknowledgment

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References

SOLAR ARRAY ARcing IN LEO

How Much Charge is Discharged?

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Abstract. It is often said that only the solar array or spacecraft surfaces that can be reached by an arc plume are discharged in a solar array arc in LEO (low Earth orbit). We present definitive results from ground test experiments done in the National Plasma Interactions (N-PI) facility at the NASA Glenn Research Center that this idea is mistaken. All structure surfaces in contact with the surrounding plasma and connected to spacecraft ground are discharged, whether the arc plasma can reach them or not. Implications for the strength and damaging effects of arcs on LEO spacecraft are discussed, and mitigation techniques are proposed.

Key words: solar arrays, low Earth orbit, arcing, plasma interactions, arc plumes, mitigation

1. Background

Modern solar arrays have areas of tens of square meters, and they operate with bus voltages exceeding 100 V. Electrostatic discharges (arcs) are undesirable and detrimental events for spacecraft function, and preventing these events and/or mitigating their consequences are of primary importance for spacecraft designers. There are two types of arcs that may occur in space. The first, the primary or trigger arc, is a transient event that discharges some spacecraft capacitance. The second type, the sustained arc, can occur between two solar array strings, and may be powered by the array’s current generating capacity. In this paper, we consider only the transient trigger or primary arcs.

Ground tests of small samples of large solar arrays have been used to provide the necessary information regarding arc inception voltages and expected arc damage for an entire array during its lifetime in space. However, the volume of the space plasma and the size of the test arrays that may be simulated in ground tests...
is limited by the size of the test vacuum chamber, and this fact necessitates the installation of additional capacitance between the sample and ground to simulate the actual capacitance of a spacecraft and its solar array discharging through the arc plasma. The magnitude of the capacitance to be added has been the subject of discussions for many years (see for example, [1]). If the discharge of a space solar array capacitance is caused by an arc plasma front propagating along the array surface (see [2, p. 31]), this magnitude is limited to about 1 μF, because the array capacitance is approximately 0.25 μF·m⁻², and the propagation distance of the dense arc plasma is less than a few meters under the conditions of a typical LEO plasma.

On the other hand, if the entire array discharges through a current channel created by an arc, this capacitance can even reach 10³ μF. The amplitude and width of an arc current pulse are both increasing functions of the capacitance discharged, and that is why the damage inflicted on the solar array by an arc depends on the capacitance discharged in the arc. Is it the capacitance reached by the dense arc–plasma front, or is it the much larger capacitance of the coverglasses of the entire array that is discharged?

The experiments described below confirm that the entire array capacitance discharges through the arc current channel even under conditions when the arc–plasma front is prevented from propagating along the sample surface. Thus, the proper value for an additional capacitor must be high (∼10³ μF) for ground tests of arrays in order to properly simulate the damaging effects that may occur for arcs on spacecraft with large arrays.

2. Experimental Setup

All of our tests were done in the National Plasma Interactions Facility (N-PI Facility) at the NASA Glenn Research Center, Cleveland, Ohio. In our tests, the LEO space plasma was simulated in a large vacuum chamber (2 m in diameter and 3 m high) equipped with four oil diffusion vacuum pumps that provided a background pressure about 0.5 μTorr (66.6 μPa). One Kaufmann-type plasma source generated a xenon plasma with an electron temperature of 1–1.3 eV, an electron number density of (4–5) × 10⁵ cm⁻³, and a neutral gas pressure of about 50 μTorr (6.67 mPa).

Two solar array samples (on fiberglass) were mounted on an aluminum sheet and installed vertically in the middle of the chamber (figure 1). One sample (strings 1, 2, and 3) represented a silicon solar array with UVR coverglasses of 300 μm thickness that corresponds to a capacitance of 4344 pF·string⁻¹. Another sample (strings 4, 5, and 6) had a capacitance of 7020 pF·string⁻¹ because of its thinner coverglasses (150 μm). The additional capacitor was chosen to have a capacitance of \( C = 0.03 \mu F \) (±10%) for the convenience of measurements—such a choice provided comparable currents in all branches of the bias circuit. However,
Some measurements were done with a higher capacitance (0.25 μF) to reveal the dependence of the arc current pulse characteristics on the value of this capacitance. Four current probes provided measurements of discharge currents flowing in essential branches of the circuit (figure 2). For the second series of measurements, a grounded aluminum plate was installed between the samples to prevent the propagation of the arc–plasma front from one sample to the other.

2.1. EXPERIMENTAL RESULTS

All four current pulse waveforms were registered by a four-channel digital oscilloscope and stored in a computer for further processing. Twenty events (arcs) were observed for each configuration (positions of keys 1–4, and capacitance $C$). That amounted to 260 files, one of which is shown in figure 3. Each file was used to obtain the following data: (1)$I_p$—peak arc current; (2)$\tau_{0.5}$—pulse width at 0.5 of the peak current value; (3)$\Delta q_i$—net electrical charge flowed through the corresponding branch; and (4)$t_{ij}$—time interval between current pulse peaks in the different circuit branches.

The magnitude of the net electrical charge flowing through a branch was calculated as

$$\Delta q_i = \int I_i(t) \, dt$$  (1)
Four current probes were used to measure the discharge currents in four different branches of the circuit. The additional capacitance was chosen to be 0.03 \( \mu F \) to obtain comparable current magnitudes for all probes. A few measurements were done with \( C = 0.25 \mu F \).

Then, the average and standard deviation over several measurements were calculated, and the resultant value was compared with the theoretically predicted value. For example, the ratio of charges for string #1 (\( \Delta q_1 \)) and capacitor (\( \Delta q_2 \)) was calculated by

\[
\frac{\Delta q_1}{\Delta q_2} = \frac{C_{\text{string}}}{C}
\]  

(2)

One example of an arc pulse current sequence for \( C = 0.03 \mu F \), and for switches K1 and K2 in the closed position. CP1 is the most positive current. The arc was initiated at time \( t = 0 \).
TABLE 1. Measurement results and theoretical estimates

<table>
<thead>
<tr>
<th>No.</th>
<th>Key # closed</th>
<th>Arc on string #</th>
<th>( \frac{\Delta q_1}{\Delta q_2} ) Measured</th>
<th>( \frac{\Delta q_1}{\Delta q_2} ) Estimate</th>
<th>( \frac{\Delta q_{arc}}{\Delta q_2} ) Measured</th>
<th>( \frac{\Delta q_{arc}}{\Delta q_2} ) Estimate</th>
<th>Bias (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>None</td>
<td>1</td>
<td>0.25(0.03)</td>
<td>0.234(0.02)</td>
<td>1.186(0.11)</td>
<td>1.379(0.05)</td>
<td>300</td>
</tr>
<tr>
<td>2</td>
<td>None</td>
<td>6</td>
<td>0.17(0.03)</td>
<td>0.145(0.015)</td>
<td>1.077(0.04)</td>
<td>1.379(0.05)</td>
<td>300</td>
</tr>
<tr>
<td>3</td>
<td>K</td>
<td>1/2</td>
<td>0.25(0.024)</td>
<td>0.234(0.02)</td>
<td>1.41(0.08)</td>
<td>1.52(0.06)</td>
<td>300</td>
</tr>
<tr>
<td>4</td>
<td>K1</td>
<td>6</td>
<td>0.16(0.02)</td>
<td>0.145(0.015)</td>
<td>1.22(0.08)</td>
<td>1.52(0.06)</td>
<td>300</td>
</tr>
<tr>
<td>5</td>
<td>K1&amp;K2</td>
<td>2/3</td>
<td>0.25(0.026)</td>
<td>0.234(0.02)</td>
<td>1.4(0.08)</td>
<td>1.67(0.07)</td>
<td>300</td>
</tr>
<tr>
<td>6</td>
<td>K1&amp;K2</td>
<td>6</td>
<td>0.217(0.06)</td>
<td>0.434(0.04)</td>
<td>1.49(0.07)</td>
<td>1.67(0.07)</td>
<td>300</td>
</tr>
<tr>
<td>7</td>
<td>K1&amp;K2</td>
<td>2/3</td>
<td>0.26(0.034)</td>
<td>0.234(0.02)</td>
<td>1.43(0.1)</td>
<td>1.67(0.07)</td>
<td>280</td>
</tr>
<tr>
<td>8</td>
<td>K1&amp;K2</td>
<td>6</td>
<td>0.21(0.05)</td>
<td>0.434(0.04)</td>
<td>1.46(0.1)</td>
<td>1.67(0.07)</td>
<td>280</td>
</tr>
<tr>
<td>9</td>
<td>All</td>
<td>4/5</td>
<td>0.19(0.05)</td>
<td>0.234(0.02)</td>
<td>1.85(0.06)</td>
<td>2.14(0.1)</td>
<td>280</td>
</tr>
<tr>
<td>10</td>
<td>All</td>
<td>2/3,6</td>
<td></td>
<td></td>
<td>1.85(0.06)</td>
<td>2.14(0.1)</td>
<td>280</td>
</tr>
</tbody>
</table>

It should be noted that the possible errors in the calculations of string capacitances could not be estimated properly because of unknown errors in the corresponding geometrical and electrical parameters. However, the consistency of all our final results is a very convincing argument that the calculations of array capacitances were done with an error of less than 10%. Also, the following ratio:

\[
\frac{\Delta q_{arc}}{\Delta q_2} = \sum \frac{C_{string}}{C} + C
\]

was verified for all events when the experimental setup made it possible to do so. This equality means that the array capacitance that discharged through the arc current channel is independent of the distance between the arc site and other strings, and the array discharged fully with or without an aluminum plate installed between the two samples.

The results of our measurements and theoretical estimates are compiled in table 1. Standard deviations (1σ) of the measurements are shown in parenthesis.

The numbers shown in table 1 demonstrate a very good agreement between the measured parameters and their theoretical estimates. We believe that some insignificant differences can be explained by our poor knowledge of the string capacitances, possibly by a somewhat incomplete discharge of the panels, and possibly by a somewhat inhomogeneous plasma potential distribution. However, the considerably smaller-than-expected discharge of string #6 observed during two different runs (run numbers 6 and 8 above) cannot be explained to date. These results look particularly strange if one takes into account the very good agreement between the measurements for strings #2/3 and their estimated values (run numbers 5 and 7 above), because these two runs were supposed to be symmetrical to each other.
TABLE 2. Experimental results with aluminum panel installed

<table>
<thead>
<tr>
<th>No.</th>
<th>Key # closed</th>
<th>Arc on string #</th>
<th>$\frac{\Delta q_1}{\Delta q_2}$ (Measured)</th>
<th>$\frac{\Delta q_1}{\Delta q_2}$ (Estimate)</th>
<th>$\frac{\Delta q_{arc}}{\Delta q_2}$ (Measured)</th>
<th>$\frac{\Delta q_{arc}}{\Delta q_2}$ (Estimate)</th>
<th>Bias (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>K1&amp;K2</td>
<td>2/3</td>
<td>0.21(0.03)</td>
<td>0.234(0.02)</td>
<td>1.32(0.07)</td>
<td>1.67(0.07)</td>
<td>450</td>
</tr>
<tr>
<td>2</td>
<td>K1&amp;K2</td>
<td>1</td>
<td>0.2(0.02)</td>
<td>0.234(0.02)</td>
<td>1.59(0.07)</td>
<td>1.67(0.07)</td>
<td>450</td>
</tr>
<tr>
<td>3</td>
<td>K1&amp;K2</td>
<td>2/3</td>
<td>0.03(0.004)</td>
<td>0.028(0.003)</td>
<td>0.956(0.02)</td>
<td>1.08(0.05)</td>
<td>400</td>
</tr>
<tr>
<td>4</td>
<td>K1&amp;K2</td>
<td>1</td>
<td>0.028(0.002)</td>
<td>0.028(0.003)</td>
<td>1.084(0.04)</td>
<td>1.08(0.05)</td>
<td>400</td>
</tr>
<tr>
<td>5</td>
<td>K1&amp;K2</td>
<td>2/3</td>
<td>0.191(0.02)</td>
<td>0.234(0.02)</td>
<td>1.39(0.06)</td>
<td>1.67(0.07)</td>
<td>400</td>
</tr>
<tr>
<td>6</td>
<td>K1&amp;K2</td>
<td>1</td>
<td>0.203(0.024)</td>
<td>0.234(0.02)</td>
<td>1.63(0.1)</td>
<td>1.67(0.07)</td>
<td>400</td>
</tr>
</tbody>
</table>

In the second stage of the experiment, an aluminum panel was installed between the two samples to prevent the propagation of the arc plasma from the arc site to the other sample (figure 1). Measurements were done with the same additional capacitor (0.03 μF, ±10%) and with another capacitor (0.22 μF, ±5%) connected in parallel with the first one. The results are shown in table 2.

It can be seen from the data in tables 1 and 2 that those strings that were not arcing discharged fully in both cases—with or without the aluminum panel between the samples. Thus, the mechanism of discharge of an entire array can only be explained by an electron current flowing from the negatively charged conductor (or semiconductor) to the surrounding plasma through the arc–plasma conductive channel. The positive charge of the coverglass is neutralizing by ambient plasma electrons that are attracted by the positive potential of the coverglass.

The dependences of the arc current pulse width and amplitude on the net capacitance were found from the experiments shown in table 1. However, the narrow range of capacitances used (0.042–0.064 μF) and large deviations in the measured values did not allow us to confirm (or to reject) any expected square root dependence (figure 4). For a discussion of the square root dependence, see [3].

For some measurements (shown in table 2), a bigger additional capacitor (0.25 μF) was used, and this provided the opportunity to verify the expected dependence of the pulse width on the capacitance (figure 5). It turned out that this dependence is slower than an expected (about 0.3 in power-law index, rather than the expected 0.5 as Snyder depicted in [4]).

One more interesting feature of the discharge process is a time delay between the instant of the peaks in the arc–current pulse and in the discharge current of those strings not arcing (figure 3). We believe that this delay is caused by a changing plasma potential during the discharge process (which corresponds to the spacecraft potential for LEO orbit). In actuality, in the simple situation when all keys (K1–K4) are open, and the arc occurs on string #1, the relaxation current
Figure 4. Arc current amplitudes and pulse widths vs. net capacitance are shown for the experiments without a conducting plate between the samples. Pulse width measurements are at top and peak current measurements are at bottom. Units are as in the legend at top.

on string #6 satisfies the following equation (eq. (4)):

\[
\frac{dI_4(x)}{dx} + I_4(x) = -\frac{C_{str}}{C} I_1(x)
\]  

where \( x = t/\tau_{str} \), and \( \tau_{str} \) is the string relaxation time.

The solution of the eq. (4) with the initial condition \( I_4(0) = 0 \) can be written as

\[
I_4(x) = -\frac{C_{str}}{C} \exp(-x) \int_0^x I_1\left(\frac{C_{str}}{C} t\right) \exp(t) dt
\]  

Figure 5. In spite of large deviations, a square root dependence of pulse width on capacitance can be excluded. The actual dependence is closer to a \( C^{1/3} \) dependence.
If the arc current pulse is simulated by two exponents or by a Gaussian curve, the solution of eq. (5) is shown in figure 6.

The measured time delay between current peaks in strings 1 and 6 was

1. with 280 V, no plate, 0.03 capacitor—2.6 (0.8) μs;
2. with 450 V, plate, 0.03 capacitor—4.88 (1.68) μs.

3. Conclusion

The results of our current experiments and their analysis confirm the necessity of using a large additional capacitance (0.3–0.5 of the expected entire spacecraft solar array capacitance) in ground tests in order to adequately simulate the consequences of arcing on solar arrays in orbit. Spacecraft solar arrays that have very large capacitances connected to spacecraft ground may be damaged by even transient arcing events unless mitigation techniques are used. For example, a spacecraft solar array with a 300 V power system and 10 μF surface capacitance may be subject to arcs of more than 1000 A peak strength and total energies greater than 0.4 J, even if the arcs do not become sustained by the array power. Miller [5] showed that even arcs of 40 A peak strength may severely damage solar cell interconnects.

4. Mitigation (reprinted from [2, p. 38])

The design of a solar array must consider the plasma environment and interactions with that environment. Arc prevention is extremely important. The following techniques have been shown in ground and flight tests to prevent arcs or minimize their damage: