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Arc Inception Mechanism on a Solar Array Immersed in a Low-Density Plasma

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ARC INCEPTION MECHANISM ON A SOLAR ARRAY IMMERSED IN A LOW-DENSITY PLASMA

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Abstract

In this report, results are presented of an experimental and theoretical study of arc phenomena and snapover for two samples of solar arrays immersed in argon plasma. The effects of arcing and snapover are investigated. I-V curves are measured, and arc and snapover inception voltages and arc rates are determined within the wide range of plasma parameters. A considerable increase in arc rate due to absorption of molecules from atmospheric air has been confirmed. It is shown that increasing gas pressure causes increasing ion current collection and, consequently, arc rate even though the effect of conditioning also takes place. Arc sites have been determined by employing a video-camera. It is confirmed that keeping sample under high vacuum for a long time results in shifting arc threshold voltage well below –300 V. The results obtained seem to be important for the understanding of arc inception mechanism.

1. Introduction

Previous experience has shown that electrical discharges (arcs) occur on the surfaces of a high voltage solar array with high negative potential relative to the surrounding plasma. The most probable site for an arc inception is a triple junction: metallic interconnect, coverglass, and plasma (*Stevens, 1980*; *Ferguson*, 1989; *Jongeward&Katz*, 1998). In spite of the continuously growing volume of collected experimental data there are only two theoretical models of the arcing phenomena so far. The first one is based on the hypothesis of a thin insulating layer formation on the surface of negatively charged conductor (interconnect) that is undergone to the electrostatic breakdown when the electric field strength becomes high enough (*Parks et al., 1987*). The second one takes into consideration the formation of a strong electrical field on the site of a triple junction- metal, dielectric, and plasma (*Hastings et al., 1990; Cho&Hastings, 1993; Mong&Hastings, 1994*). This model provides a quite good qualitative agreement with some measurements, but it can not be considered an adequate model when quantitative results are needed. The weakest point in this theory is the hypothesis of prime electrons emitted from the conductor due to Fowler-Nordheim cold emission mechanism. This hypothesis works well for high-voltage discharges (*Litvinov et al., 1983*), but the electric field strength in the case of a solar array is two-three orders of magnitude lower, and this contradiction causes the adoption of one more hypothesis of a very high field enhancement factor (about 500) that looks rather improbable. Recently, a correction to this model of arc inception has been elaborated (*Jongeward&Katz, 1998*). This last model can explain the threshold behavior of arc inception, and it predicts increasing arc rate with increasing ion flux to the array. However, this model also can not explain the inception of ion avalanche supporting the high arc current. In all models described above the common and the most important part is the metallic cathode (usually, silver plated copper) that acquires a high negative potential relative to the surrounding plasma. Electron emission from this cathode provides primary electrons that may initiate a gas desorbtion and an ionization avalanche in this gas. In the case of cold emission an electron current density depends exponentially on the metal work function; thus, one can expect considerable variations of arc inception voltages and arc rates for the different metals. On the contrary, these characteristics of arcing are almost identical for copper and gold in spite of difference in work functions about 1 eV (*Vayner et al., 2001*). The chemical composition of desorbed gas and the mechanism of desorbtion are also unknown.

Thus, the fundamental physical problem can be formulated as the following: what is the physical mechanism of arc inception in the case of low electric field strength? To achieve some progress in solving the problem we have performed measurements of parameters for a specially designed solar array samples immersed in argon plasma (current collection, arc rates, and arc current).

2. Experimental setup

All our experiments were performed in a small vacuum tank (45 cm diameter and 75 cm height) installed at the NASA Glenn Research Center (Fig.1). Vacuum equipment provides pressure as low as 10^{-7} Torr. One Penning source generates an argon plasma with the electron density n_e=(2-20)10^5 cm^{-3} , temperature T_e=2-5 eV, and neutral argon pressure p=(5-80)10^{-5} Torr which can be adjusted during the experiment. Two solar array samples consisting of nine Si cells each were prepared. These 2x4 cm cells are connected in three parallel branches with three cells in series for each one. All cells are mounted on the fiberglass base (Fig.2). One of the two samples is mounted vertically in the center of the chamber, and it is biased by a high voltage power supply through the resistor of R=10 kΩ (Fig.3). Diagnostic equipment includes one spherical Langmuir probe with diameter d=2 cm, one current probe to measure arc current, a voltage probe, and a video camera for recording arc images and arc sites. The exposed sides of contacts and connecting wires were insulated by RTV and Kapton strips. Because the sample itself has a low capacitance, an additional capacitor was installed between the sample and ground. This allowed us to locate arc sites visually. To determine the dependence of arc pulse parameters on the capacitance (scaling) five sets of measurements have been performed with different capacitors C=0.01, 0.11, 0.22, 0.44, and 1.0 μF. To avoid damaging of a sample the bias voltage was limited to –600 V.

3. Experimental results

Both samples represent a small part of working solar array. Measuring I-V curves for both samples (Fig.4) proofed it. Even though the second set of I-V curves was measured after each sample experienced about one hundred discharges, no sign of any damage to the cells was found. Two solar array samples were tested to determine arc rates and arc sites. Both samples were arcing with almost equal rates (Fig.5). The only difference between these two samples is the frequency in occurrence of small discharges: sample with small "huts" on coverglasses demonstrated low current discharges with higher rate. First arc was registered during 30-min time interval at bias voltage -190 V. According to plasma diagnostics data (Fig.6) floating potential is equal to -20 V; thus, electric field strength

$$E = \frac{U_{fl} - U_{bias}}{d} = \frac{170V}{190\mu m} = 0.9\frac{MV}{m} \qquad (1)$$

The electric field strength ≈1 MV/m can be achieved if the conductivity of coverglass is low enough:

$$\sigma < \frac{j_{0i}}{E} \approx 10^{-13}\,(Ohm \cdot cm)^{-1}$$

where j_{0i}≈3-10 nA/cm^2 is thermal ion current.

This estimate is close to the upper limit of conductivity for the most polymers (*Frederickson et al., 1986*). Unfortunately, no data are available regarding the conductivity of coverglass/adhesive for tested samples. It seems useful to note that ion flux is 13-130 nA/cm^2 in LEO plasma.

The result (1) is in a good agreement with our previous estimate of the critical field magnitude (*Vayner et al., 2001*), and it is 2-6 times lower than the field causing surface flash-over in a vacuum (*Andersen&Brainard, 1980*). It is worth noting, that vacuum arc (pressure ≈3μTorr) could not be initiated on both samples even at bias voltage –600 V.

There are three time scales that have to be estimated for better understanding of experimental results. First, coverglass charging time τ_c that defines time interval for establishing of steady-state electric field (1).

$$\tau_c = \frac{2\varepsilon\varepsilon_0 E}{j_{0i}} \qquad (2)$$

where $\varepsilon \approx 3.5$ is the dielectric constant for coverglass, and $j_{0i} \approx 3\text{-}10$ nA/cm^2 is thermal ion current.

Substituting estimate (1) in the equation (2) one can obtain $\tau_c \approx 2\text{-}5$ s. This is in agreement with measurement of the ion collection current relaxation. Thus, the upper limit for arc rate in our experiment is

$$R_{\max} = \frac{1}{\tau_c} = 30\, arc / \min \qquad (3)$$

Of course, the measured arc rate has never been close to the limit (3).

Second, capacitor charging time τ_e that defines time interval for recovering bias potential after each discharge:

$$\tau_e = 3RC \qquad (4)$$

where R =10 kOhm is the resistance, and $C \leq 1\,\mu$F is the additional capacitance.

This time interval is very short (less than 3 ms), and it is insignificant for the further analysis.

Third, the experiment time T that is time interval when measurements are performed with steady parameters (pressure, plasma density, and bias voltage). Due to the experimental conditions, this time varies from fifteen minutes (steady bias voltage) to several days (steady pressure and plasma density). It has to be taken into account when experimental results are used for the analysis of spacecraft solar array operation.

Arc rate depends not only on bias voltage but also on the neutral gas pressure also (Fig.7). This dependence has been found long time ago (*Ferguson, 1989*) but there is no satisfactory explanation yet. Three physical mechanisms can be suggested and tested: i) Paschen discharge in argon; ii) increasing adsorbed gas density due to increasing neutral molecules flux toward the dielectric surface; iii) increasing ion current collection due to specific features of Penning (and Kaufman) plasma source operation. Vacuum chamber with sample installed was tested against Paschen discharge within the pressure range 50-200 μTorr (parameter pD=(1.5-6)10^{-3} Torr·cm) with absolutely negative result. This is not a surprise because Paschen minimum for argon is pD=1 Torr·cm (*Handbook, p.61*). According to mass-spectrometry data obtained earlier, partial pressures of H_2O and N_2 reach 0.5-2 μTorr which correspond to the molecular fluxes ≈10^{13} 1/cm^{2}s. Unfortunately, the binding energy is not known but if we suggest that this energy is much higher than the surface temperature the only monolayer of adsorbed molecules can be created by this flux. Formation of the second and other layers is prevented by partial pressures that are much lower than saturation pressures for a room temperature. In addition, the mixtures of air components to the argon cannot influence on arc inception because arc rate decreases considerably during a few hours after the beginning of an experiment (so called conditioning). However, arc rate returns to the almost initial value after the sample is exposed to the normal pressure for a few hours (0.67 arc/min at –600 V before exposure, and 0.67 arc/min at –400 V after exposure). The last observation confirms the hypothesis of electron impact gas desorption as a mechanism for a discharge inception (*Pillai&Hackam, 1982*). The increase of ion current collection with increasing pressure is confirmed and measured in the experiment (Fig. 8). Thus, arc rate increases with the increase of ion current collection as it is expected from the theoretical model of *Jongeward&Katz (1998).* It should be stressed that the question of providing high electron flux toward the dielectric surface is still not answered. According to *Pillai&Hackam* (*1982*), estimate for the threshold voltage is $U_{th} \geq 2$ kV which is about one order of magnitude higher than observed threshold. The further discussion of physical processes and theoretical simulations of arc inception mechanism could be continued after the calculation of field enhancement caused by plasma sheath and mirror charge. One more argument in favor of desorped molecular gas ionization mechanism comes up from the measurements of arc current pulse widths for different additional capacitances (Fig. 9). It can be shown that the pulse width depends on the capacitance as the following:

$$\tau = \left(\frac{\gamma C U_{bias}}{\pi e}\right)^{1/2}\left(\frac{A m_p}{2kT_e}\right)^{3/4} \qquad (5)$$

where $\gamma = 10^{-7} T_e^{-1/2}$ cm^3/s is the rate of dissociative recombination (T_e in eV), T_e is the electron temperature in the arc plasma, and A is the molecular mass of desorped molecules.

To compare experimental results (Fig.9) with theoretical calculation the equation (5) can be represented in the simple form (for water molecules A=18):

$$\tau = 53 C^{1/2} T_e^{-1}\ \mu s \qquad (6)$$

where the capacitance is expressed in μF, and bias voltage is U_{bias}=500 V.

It is seen that experimental measurements and estimate (6) are in a very good agreement if plasma temperature is T_e=4.5 eV that corresponds to the published data (*Handbook, p.109*).

It seems necessary to add a few words about the possibility of the sample contamination by the diffusion pump oil. Especially performed measurements demonstrated the following changes in arc rate: 0.13 arc/min at –230 V at Feb. 13, and no arcing at –280 V at Feb.16 after the sample was kept in vacuum for over 70 hours. Thus, it can be concluded that oil contamination during the experiments does not influence on arc inception. Moreover, it is demonstrated that arc rate decreases considerably with increasing a time span when sample is kept under high vacuum: even for highest ion flux (p=140 μTorr) no arc is observed at bias voltage –320 V after 168 hours in vacuum. Effect of conditioning exhibits itself also much more definitely: arc rate drops from 1.3 arc/min for initial seven minutes to 0.2 arc/min for the next ten minutes interval (under the same pressure and bias voltage –400 V).

Snapover inception voltage is found to be close to the results obtained in previous experiments (*Ferguson et al., 1998; Vayner et al., 2000*). It is particularly important for a high-voltage solar array operating in LEO conditions where electron number density can reach (1-3)10^6 cm^{-3} (Fig. 10).

Conclusion

Conventionally designed solar array generating voltage 250-300 V can be used as a power supply for a LEO spacecraft. Electrostatic discharges can be prevented if a special care is taken concerning outgassing of dielectric surfaces exposed to the space plasma.

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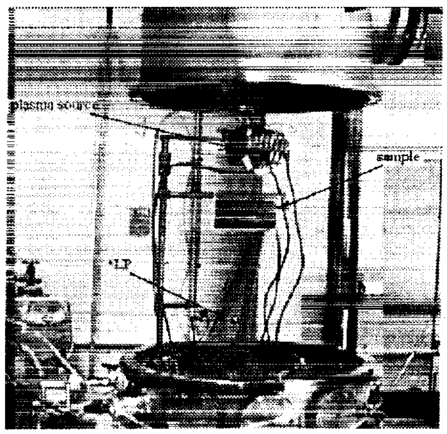

Fig.1. Small vacuum chamber is shown with sample installed

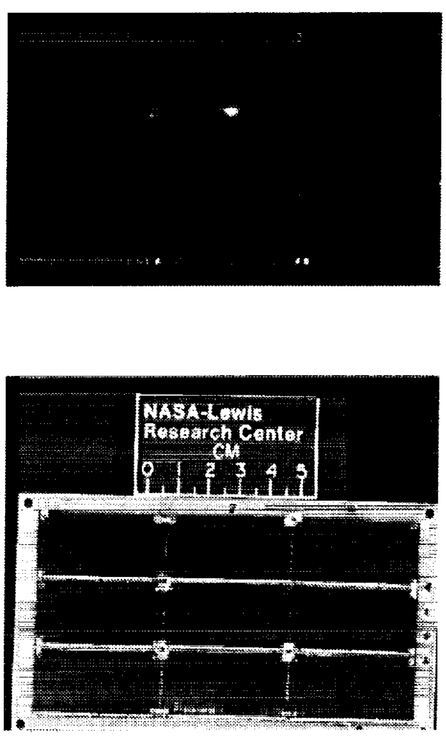

Fig.2. Solar array sample is shown arcing in chamber(top). Size of the sample is also demonstrated (bottom).

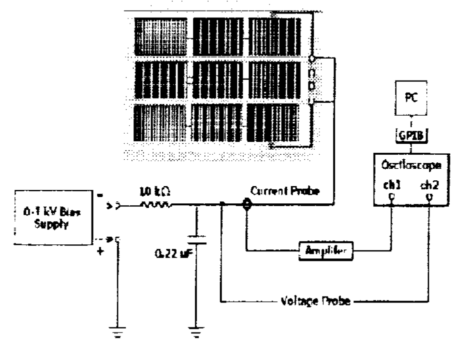

Fig.3. Circuitry diagram for the experiment.

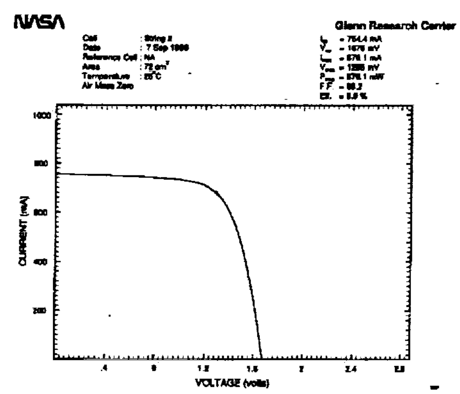

Fig.4. I-V curves are almost identical for both samples as before as after arcing.

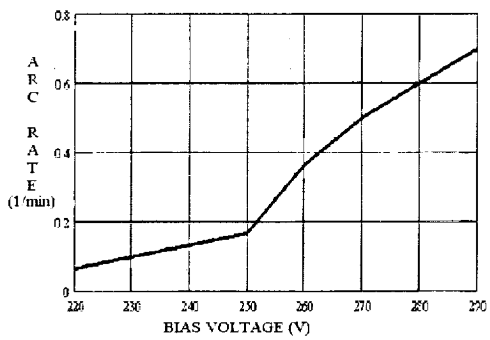

Fig.5. Initial arc rate vs. bias voltage (pressure 60 μTorr)

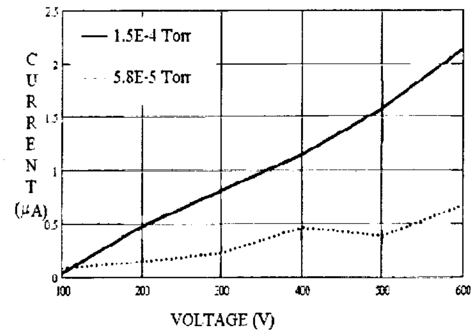

Fig.8. Ion current vs. bias voltage (negative) is shown for different argon pressures. Error bars are calculated from five independent measurements for each point.

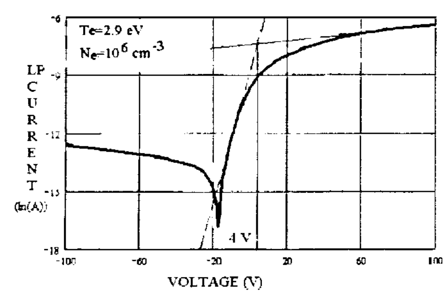

Fig.6. One example is shown of Langmuir probe diagnostics of low density plasma

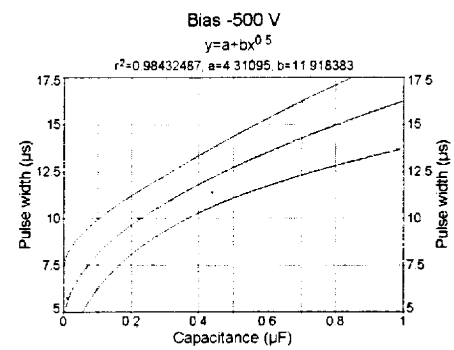

Fig.9. Arc current pulse width vs. capacitance is shown fitted to square root approximation.

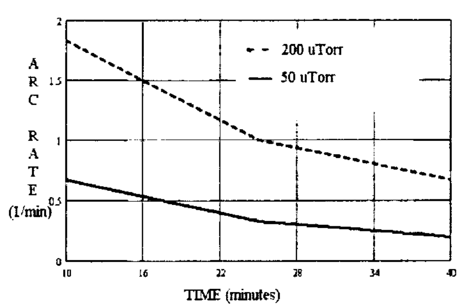

Fig.7 Decreasing arc rate (conditioning) is shown for two neutral gas pressures (bias voltage –500V).

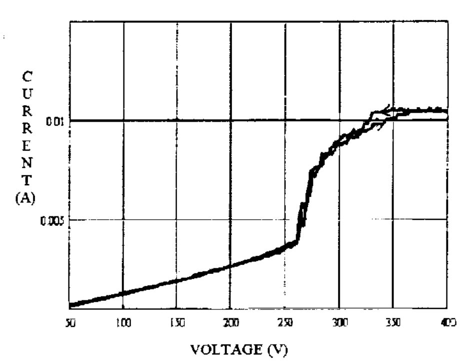

Fig.10. One example of snapover is shown (pressure 180 μTorr).

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13. ABSTRACT *(Maximum 200 words)*

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