ELECTRON-BEAM CHARGING OF PLASMA-COATED SPACECRAFT DIELECTRICS

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Abstract

Research results are described on the charge accumulation and arc discharging of coated dielectric sheets exposed to a 20 keV electron beam. The dielectric sheet substrates are Kapton and Mylar, and the coatings are plasma-deposited amorphous hydrogenated silicon (a-Si:H), silicon nitride (P-SiN), and silicon dioxide (P-SiO_2). Arc discharges are characterized by their current pulse shape and by their appearance as recorded using a CCD camera. Results indicate that P-SiO_2 and P-SiN coatings on Kapton prevent discharge occurrence. Other coating-substrate combinations do not prevent discharges but do modify them.

1. Introduction

Arc discharges on spacecraft dielectrics, for example on thermal blankets, result not only in irreversible damage to the material itself, but the accompanying electromagnetic interference can perturb or destroy electronic systems on board the satellites. Arc discharges, recently reviewed by Balmain [1], are believed to result from charge accumulation at some depth in the dielectric. This subject relates strongly to electret research (an electret is defined as a dielectric with quasi-permanent charge or polarization), which has been the object of many papers in journals and conference proceedings; two excellent reviews on recent progress [2,3] provide the reader with valuable guidance through this complex subject.

2. Theory

In the following, we develop a simple model based on our own and others' observations, and on the current state of knowledge about electron beam charged electrets, in order to explain discharge suppression by some types of thin coatings, as described later in this paper. This model must account for the following important and general observations which have been made on the three commercial polymers of greatest relevance to the thermal-blanket space technology being considered here, namely polyethylene-terephthalate (PET, e.g. DuPont Mylar^R), polyimide (PI, e.g. DuPont Kapton^R), and fluorinated ethylene-propylene copolymer (e.g. DuPont Teflon^R FEP).

[i] When bare films of the polymers are irradiated with monoenergetic electrons (e.g. 20 keV, typical for those encountered in geosynchronous orbit), the dielectric is charged up to the surface potential V_S at which the secondary plus back-scatter emission yield has become unity. The range of 20 keV electrons being substantially less (~4 μm in PET [4]) than the polymer films' thickness (usually 25 or 51 μm), they give rise to a narrow sheet of charge (see also below) having its centroid near the maximum electron range value. Breakdowns initiate in this embedded charge layer, and they propagate in the form of filamentary tunnels parallel to the surface, accompanied by occasional "blow-outs" of gaseous products through the polymer surface [5].

[ii] Coating the polymer with conducting or semiconducting layers (indium tin oxide ITO [6], metal [7], or hydrogenated amorphous silicon, a-Si:H [8]) modifies, but does not suppress, the tendency for arc discharges to occur.

[iii] On the other hand, plasma-deposited, thin dielectric coatings of the types described in the present paper and in our earlier reports [8,9], are very effective in suppressing arc discharges of all amplitudes.

Observations [i] to [iii] may be explained by the following model. When a dielectric is subjected to ionizing radiation, for example to an energetic electron beam, electron-hole pairs are generated in the affected portion of the dielectric, giving rise to radiation-induced conductivity (RIC) [3]. In the case of electron beam irradiation, the RIC is often assumed (for the sake of simplicity) to be depth independent up to the electron range value, and zero elsewhere (the so called "box model"). In other words, the narrow slab of polymer traversed by the electrons (before they come to rest in a thin sheet centered at the maximum electron range value, see Figure 1a) may be considered like a field-free, virtual electrode region, at least as a first-order approximation [3]. If internal leakage is small (certainly the case for PET and FEP) and less than the incoming electron flux, the electric field in the space charge region will exceed a critical value for discharge initiation, as already described above.

Now, consider the case when a thin layer of dielectric material (P-SiO_2, P-SiN, PP HMDSO, for example) is deposited on the front surface of the polymer film. Since the layer is usually very thin (≤ 0.5 µm) and composed of low atomic number elements, the maximum range of 20 keV electrons remains close to the above-mentioned value (~4 µm) beneath the free surface. All these plasma-deposited coating materials contain at least 20 or more atomic % of hydrogen [10], much of it chemically bonded, but some "free" [11]. Under the influence of the energetic electrons transiting through the coating, some hydrogen is ionized, and the resulting protons are drawn to the polymer/coating interface by the developing negative space charge field, and they become trapped at this interface. In somewhat analogous experiments, we have recently confirmed such protonic conduction in PI/P-SiO_2 double layer dielectric samples [12], and have obtained convincing evidence for deep trapping of the protons at the polymer/coating interface, most recently by CV measurements [13]. The creation of protons by the transiting electron beam is accompanied by little or no negative charging in the coating, as recently reported by Günther for the case of thin SiO_2 layers [14]. The field created by the positive space charge (that is, the trapped protons at the coating/polymer interface) can attract back some of the electrons deposited in the polymer, thanks to the high conductivity in the RIC region. On account of this reverse electron current, the electronic space charge density in the polymer remains below the critical value for initiation of arc discharges, and this results in the observed suppression of discharging (see Figure 1b).

Now consider conducting or semiconducting coatings, which do not suppress discharging, for example the case of a-Si:H. Most of the features described above for plasma deposited dielectrics apply also to a-Si:H, such as the presence of hydrogen which can be converted to free protons. A major difference, however, is the fact that free electrons in the coating can readily neutralize the protons, thus preventing formation of the positive space charge at the coating/polymer interface. In other words, this situation resembles that of the bare polymer, Figure 1a.

3. Charging/discharging experimental procedure

The dielectric sheets under test were mounted over a flat copper substrate and under a copper aperture-mask. The aperture was a circular opening with a 4.5 cm diameter and bevelled edges. Initially the test specimen was heated under vacuum to reduce surface moisture and then cooled to room temperature, the cycle taking 1 hr. to rise to 50°C, 1/2 hr. at or over 50°C, and 1-1/2 hr. to cool. The vacuum was maintained at a pressure less than 3×10^{-6} Torr throughout the 3 hr. heating and cooling period, and also during the subsequent electron beam exposure.

The electron beam was incident normally on the flat specimen, and the beam density was spatially uniform to within ± 10%. The procedure involved exposure for 20 min. at 1 nA/cm^2 followed immediately by 20 min. at 15 nA/cm^2. During exposure the beam stability was ± 18% at the lower current and ± 3% at the higher current.

When an arc discharge occurred, the resulting currents were monitored as they passed from the substrate to ground through 2.5 ohm resistor and from the mask to ground through a 2.6 ohm resistor. The current impulses were measured by recording the resistor voltage drops using a 400 MHz bandwidth dual-beam oscilloscope. The substrate current pulse was positive, corresponding to electron blowoff from the specimen; the mask current was negative, corresponding to electron collection by the mask. The mask current magnitude was lower than the substrate current due to a fraction of the blowoff electrons bypassing the mask and going directly to ground via the metal walls of the vacuum chamber.

The arc discharge pattern could be monitored photographically or visually through a glass port with a direct view of the specimen. The problem of how to record the arc appearance was solved by the use of a CCD camera (Tektronix C1001) and videotape recording, followed by display of the desired frames on a monitor and photographic recording. The CCD camera had a luminous sensitivity of 2 Lux and a 3dB spectral range of 400-600 nm.

4. Experimental results

A preliminary experiment was conducted on uncoated Mylar 51 μm thick with an incident beam density of 20 nA/cm^2, in order to test the recording system and to verify that the discharges observed were consistent with past experience. The measured mask and substrate current impulses are shown in Figure 2, with respective peak currents of 15.5 A and 44.4 A, and half-height durations of 18 ns and 114 ns. Both mask and substrate currents show an initial sharp peak, while the substrate remains higher for a longer period, presumably because the later-time electron blowoff goes preferentially to the vacuum chamber walls rather than moving sideways to the mask.

The videotaped arc discharge pattern on the Mylar test specimen is shown in Figure 3. The Lichtenberg figure appearance is strongly in evidence, and bright spots are visible at sites of arc punchthrough of the specimen. The visible arc tracks cover most of the specimen, suggesting that most of the accumulated charge has been removed by the arc. These results are entirely consistent with past experience, and also demonstrate the utility of the CCD camera and videotape system for this type of experiment. It was also demonstrated that the CCD camera output could be stored in computer memory for later processing.

The main objective of the experimental program was to determine arc strength and occurrence on coated specimens. Each specimen was tested on its coated side and then tested on its uncoated side for comparison as an experimental "control" case. As already indicated, sample preparation involved a 3 hr. heating and cooling cycle under vacuum to reduce the possibility of surface moisture effects. Also, a 3 hr. room temperature pumpdown and a 1.5

hr. room temperature pumpdown were employed, with a full set of tests carried out under each set of conditions. No strong differences in results were observed, indicating that surface moisture absorption does not play a dominant part in discharge occurrence.

The coatings tested all had a nominal 0.5 μm thickness. Three coating types were evaluated: SiN, SiO_2, and a-Si:H. These coatings were applied (using the plasma process) to polymer sheets of Kapton and Mylar, with thicknesses of 51 μm and 25 μm. Most cases of arc occurrence were at a beam current density of 15 nA/cm^2 and only a few were noted at 1 nA/cm^2 in the short 20 min. observation period that was used: no clear pattern of occurrence at 1 nA/cm^2 was noted. The main features of arc occurrence and non-occurrence are summarized in Table 1.

Table 1. Arc Occurrence on Coated and Uncoated Polymers

Coating/Polymer	Arcs: – none; * some; ** very strong	
	Coated side	Control(uncoated)
SiN / 51 μm Kapton	–	*
SiO_2 / 51 μm Kapton	–	*
a-Si:H / 51 μm Kapton	**	*
SiO_2 / 25 μm Mylar	*	*
SiN / 25 μm Mylar	*	*

5. Discussion of experimental results

The most prominent feature of the results shown in Table 1 is the complete absence of arc occurrence for SiN and SiO_2 on 51 μm Kapton. This result tends to support the idea that proton mobility and electron immobility in the coating material combine to reduce charge accumulation in the underlying polymer. The Kapton arcs appeared similar to Figure 3, with no central punchthroughs, only edge initiation.

However, for the thinner 25 μm Mylar, arc prevention due to coating did not occur. What was observed in the coated Mylar cases was a strong tendency for arc punchthrough to occur, the punchthrough sites then acting as initiation points for the Lichtenberg figure class of discharge tracks, just as in the case of uncoated Mylar. Because the Mylar is half the thickness of the Kapton the internal fields are higher, so the beneficial effects of the coating apparently are reduced. Furthermore, experience shows that Mylar has a greater tendency to experience punchthrough arcs than Kapton, for the same thickness.

The performance of the semiconductor a-Si:H coating was especially noteworthy, first because of the occurrence of arcs on the coated side, and second because these arcs were very strong, having more than twice the highest peak currents observed with all other specimens, either coated or control. The measured current pulses were smooth and short, with a typical 14 to 15 ns half-height duration, suggesting an arc propagation velocity of 1.5×10^6 m/s. The appearance of the discharges was also different, as can be seen in Figure 4.

The arc photograph in Figure 4 shows a diffuse discharge with no sign of the Lichtenberg figure pattern which occurred in all other coating/polymer combinatons. It is postulated that the semiconductor coating provides enough lateral conductivity to reduce charge buildup near the mask edge and to smooth out charge buildup elsewhere allowing more charge to accumulate before the arc initiates at the point of greatest electrical weakness. In partial support of this, Figure 4 shows some darkening near the mask edge, as well as relatively uniform brightness elsewhere.

6. Conclusions

Under 20 keV electron beam exposure, the tendency of Kapton to exhibit arc discharges can be reduced to zero by the application of a plasma-deposited surface coating of either SiN or SiO_2 which are insulators. A semiconducting coating, a-Si:H, does not prevent discharges but rather produces much stronger discharges that have a relatively uniform and diffuse appearance quite different from those commonly observed resembling Lichtenberg figures.

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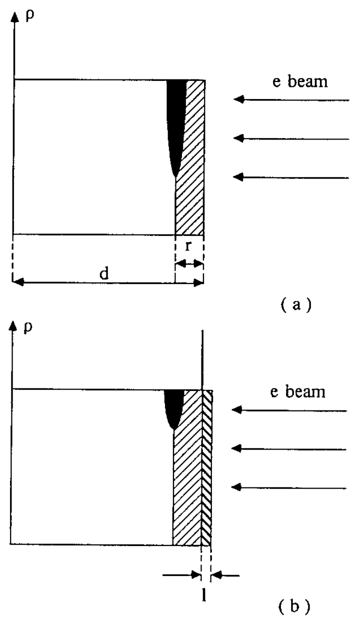

Fig. 1. Schematic representation of charge density distributions ρ in electron beam irradiated polymer films of thickness d. Radiation induced conductivity (RIC) exists in the layer of thickness r (the maximum electron range in the polymer), shown hatched. (a) bare polymer case; (b) polymer coated with a thin, plasma-deposited layer of dielectric material (thickness *l*, $l \ll d$).

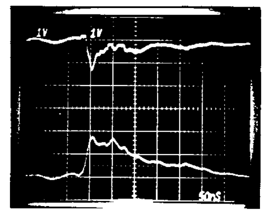

Fig. 2. Arc discharge currents on bare 51 μm Mylar. Top: mask current, 15.5A peak. Bottom: substrate current 44.4A peak. Horizontal: 50 ns/major division.

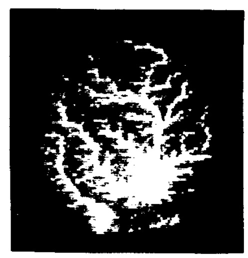

Fig. 3. Image of arc discharge on bare 51 μm Mylar.

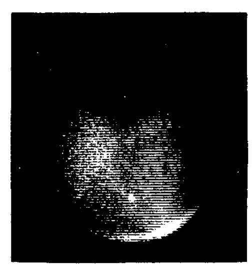

Fig. 4. Image of diffuse arc discharge on 51 μm Kapton coated with 0.5 μm a-Si:H.