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MODEL FOR BREAKDOWN PROCESS IN DIELECTRIC DISCHARGES*

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ABSTRACT

A heuristic model is presented to explain the blowoff of charge during an electron-induced dielectric discharge. It is proposed that blowoff of charge is not an independent breakdown mechanism but is a consequence of a breakdown initiated by a punchthrough or a flashover. As the trapped charge funnels toward the punchthrough or flashover point, the $\tilde{V} \times \tilde{B}$ force on the moving electrons and the local electric field between the trapped charge and the free surface of the dielectric force electrons outward. Part of the moving charge goes directly to the substrate but the remainder breaks through the surface of the dielectric near the breakdown point, which is weakened by I^2R heating, and escapes from the dielectric. The discharge time is assumed to be governed by an LC time constant where L is the inductance of the electrons flowing in the branches of the Lichtenberg figures at an electron range below the irradiated surface and C is the capacitance between the trapped electrons and the substrate for the discharged area. Experiments are proposed to verify that blowoff is a consequence of punchthrough or flashover and to test the assumed relation for the discharge time.

INTRODUCTION

During the discharge of a thin dielectric over a grounded conducting substrate, it has been noted that the current through the ground lead during the discharge corresponds to electrons flowing from ground to the substrate (references 1,2,3,4,5). This sign of the return current is consistent with electrons being blown off the dielectric surface during the discharge. This outward emission of electrons, and possibly even ions, during discharges has also been observed directly (references 2,5). The amount of charge that is emitted outward in a typical discharge has been measured to be about 50 percent of the trapped charge that is lost in the discharge, as measured by the change in the surface potential (references 1,5). The experimental evidence also indicates that breakdowns appear to start at localized points on the dielectric, and the trapped charge at an electron range below the irradiated surface flows toward the breakdown point in Lichtenberg trees that form in the plane of the trapped charge (reference 5).

In order to understand the existing data, to plan additional logical experiments, and to make reasonable predictions of the coupling of discharges into

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satellite systems, it is necessary to have a reasonably accurate model of the discharge process. Some of the features that a complete discharge model should contain are the discharge mode (punchthrough, flashover, blowoff); the initiation, spreading, and quenching mechanisms for the discharge current distribution; the total charge released, pulse width, and peak current as a function of the discharge area; and the effect of sample material, size, and boundaries in determining the details of the discharge.

Thusfar there has been relatively little published work which attempts to model the breakdown process for spacecraft charging conditions. At a previous Spacecraft Charging Conference, Meulenberg presented a model for the blowoff of charge during a discharge which relied on a high electric field between the trapped electrons and the surface of the dielectric, which was assumed to have a thin layer of positive charge due to the high surface rate of secondary emission (reference 4). Unfortunately this model is basically one-dimensional and does not seem to be consistent with the observation that at least part of the breakdown process involves charge funneling toward one discharge point. More recently, Sellen and Inouye have proposed a mechanism for the initiation and propagation of a dielectric surface discharge based on a propagating surface wave and secondary electron multiplication on the surface of the dielectric (reference 6). Other attempts to characterize the discharge parameters have been mainly empirical curve fitting of experimental peak currents and pulse widths versus discharge area (reference 7). While such empirical relations can be useful for some engineering applications, they usually give little information on the basic physical processes in the discharge and can even lead to serious errors if extrapolations are attempted well beyond the range of the experimental parameters and/or if data from different experimental conditions or materials are indiscriminantly mixed together.

In the present paper, a model is proposed which postulates mechanisms for the initiation and the spreading of the discharge, the blowoff of charge, the maximum charge release per unit area, and the variation of pulse width with sample area and thickness. It does not contain specific details on the effects of sample boundaries or the discharge quenching (area limiting) mechanisms, but it probably contains the ingredients for the area-limiting mechanism if the basic physical parameters could be accurately determined. Experiments are proposed which would verify that blowoff is a consequence of punchthrough or flashover and which would measure the punchthrough current and the variation of discharge time with the sample area and thickness.

PROPOSED MODEL

In many of the discussions of dielectric discharge, three different independent breakdown mechanisms are assumed or implied - punchthrough, flashover, and blowoff. The main thrust of the present paper is that blowoff is not an independent breakdown mechanism but is a consequence of a breakdown that is initiated either by a punchthrough or a flashover. It is proposed that all breakdowns on thin dielectrics with conducting substrates are initiated either by punchthrough of the trapped electrons through the bulk of the dielectric or by flashover of the trapped electrons to a conducting contact on or near the boundaries of the dielectric.

When a punchthrough or flashover process is initiated, the high conductivity region near the breakdown point causes the ground potential of the conductor to be extended to a local point in the plane of the trapped electrons inside the dielectric. Positive image charge accumulates at this point and causes a large electric field in the plane of the trapped electrons which pulls the trapped electrons from their traps. These previously trapped electrons then flow in the trapping plane toward the breakdown point, and the discharge area spreads out as more and more of the trapped charge moves toward the discharge point. The exact mechanism for spreading of the discharge area is not clear, but perhaps the position of the ground potential moves outward from the breakdown point in the plane of the trapped charge and is always close to the electrons that are still trapped.

Initially, the trapped charge that moves toward the discharge point goes directly to the substrate, either via the punchthrough path or by flashover to a ground contact that is connected to the substrate. Because the samples of interest are very thin, this initial flow of charge directly to the substrate causes negligible return current in the ground lead. As the electrons in the trapped layer and the positive image charges in the substrate move toward the breakdown point, a magnetic field is created between the moving electrons in the dielectric and the substrate. The resulting $\tilde{v} \times \tilde{B}$ force on the electrons is in the direction to force the electrons toward the surface of the dielectric. The geometry of the situation before and during a bulk punchthrough is illustrated in figure 1. The magnitude of the $\tilde{v} \times \tilde{B}$ force in a typical discharge can be estimated by the following calculation. Assume that a uniformly charged circular sample with the radius of 10 cm breaks down at the center of the sample when the trapped charge has a density of $\sigma = 2 \times 10^{-7}$ coul/cm^2. ($E \simeq 2 \times 10^6$ V/cm through the sample, which is typical of the breakdown strength of spacecraft dielectrics.) If the total trapped charge ($Q = \pi r^2 \sigma = 628 \times 10^{-7}$ coul) is released in 10 ns, the peak current is about $I = 6280$ A. At a distance of 0.1 cm from the punchthrough point, the magnetic field due to the current I is

$$H = \frac{I}{2\pi(0.001 \text{ m})} = 10^6 \text{ A/m}$$

Using an electron velocity of $\tilde{v} = 10$ cm/10 ns $= 10^9$ cm/sec, the equivalent electric field due to the $\tilde{v} \times \tilde{B}$ force is

$$E = \mu_o \, v \times H = 4\pi \times 10^{-7}(\text{h/m})(10^7 \text{m/sec})(10^6 \text{ A/m})(10^{-2} \text{ m/cm})$$

$$\cong 1.2 \times 10^5 \text{ V/cm}$$

The electric field from the trapped charge to the surface of the dielectric due to the Meulenberg effect also forces the electrons toward the surface of the dielectric. The magnitude of this field has not been measured and its theoretical magnitude is uncertain due to uncertainties in the amount of radiation-induced conductivity. In the region of the breakdown, the high current density increases the I^2R heating and weakens the dielectric sufficiently so that the $\tilde{v} \times \tilde{B}$ force, which is maximum close to the punchthrough point, and the Meulenberg electric field can force some of the electrons through the surface of the dielectric. Once the electrons break through the surface, the negative surface potential, which usually exists on an electron-irradiated dielectric, forces the emitted electrons further away from the dielectric. The net result is blowoff of electrons shortly after the initiation of the punchthrough or flashover breakdown. This blowoff of charges causes an approximately equal return current in the ground lead, in contrast to the negligible return current due to the direct punchthrough or flashover currents. The maximum amount of charge that can be released in one discharge is the amount of charge required to produce the initial breakdown field, which is determined by the breakdown strength of the material or the flashover voltage, which is geometry dependent.

It is also proposed that the duration of the discharge pulse is governed by an LC time constant where L is the inductance of the electrons flowing in the Lichtenberg figures in the plane of the trapped electrons toward the breakdown point and C is the capacitance between the trapped electrons and the substrate for the discharge area, A. The inductance of the Lichtenberg trees is estimated to be considerably larger than the inductance of a uniform sheet of charge moving toward one punchthrough point. Since C is proportional to A, and L probably varies as a power of A less than 0.5, the discharge pulse width should go as A to a power somewhat greater than 0.5. Moreover, since C depends inversely on the thickness of a dielectric and L has only a logarithmic dependence on the distance from the Lichtenberg trees to their images in the substrate, the discharge pulse width should vary approximately as the dielectric thickness to the power (-0.5).

POSSIBLE VERIFICATION EXPERIMENTS

The following proposed experiments should clearly demonstrate whether or not blowoff of charge is a consequence of punchthrough or flashover and also provide repeatable data to verify the variation of pulse width with sample area and thickness. The experimental setup is illustrated in figure 2. A thin dielectric with a grounded conducting substrate is irradiated as in most discharge experiments with low energy electrons (≈20 keV), which typifies the surface charging component of the space electron environment. The edges of the sample would be shielded to prevent edge breakdown or the electron beam could be rastered to cover only the central portion of the sample. The difference between the present and previous discharge experiments is that a small area of the substrate is removed and a conducting stylus is inserted a slight ways into the backside of the dielectric through the area where the substrate was removed. The stylus is connected to the substrate by a lead with minimum inductance that is instrumented to measure transient currents. This lead has a switch that can be remotely controlled.

In the first experiments, the switch between the stylus and the substrate would be closed, and the sample would be irradiated with electrons until a spontaneous breakdown occurred. Presumably this breakdown would be a punchthrough from the trapped electrons to the stylus due to the enhanced electric fields around the point of the stylus when it is grounded. It is recognized that the threshold potential for this breakdown should be less than the potential for bulk punchthrough without the stylus. However, once the punchthrough discharge is initiated, it is felt that the dynamics of the discharge should be similar with and without the stylus. In this experiment, the punchthrough current time history will be measured directly through the stylus lead. Also, the occurrence of blowoff can be inferred from the current through the ground lead and by direct measurements with one or more fast Faraday cups and possibly a charged particle analyser. If the present model is correct, a blowoff of charge should occur more-or-less simultaneously with the measured punchthrough. The sum of the punchthrough charge and the blowoff charge (as measured most accurately by the current through the ground lead) should agree with the total charge lost in the discharge, as measured by the change in the sample surface potential.

Even if a blowoff of charge is observed with every punchthrough, it could be argued that this was just coincidence and that blowoff was still an independent discharge mechanism. To investigate this possibility further, the experiments would be repeated, except that the switch from the stylus to the substrate would be open while the sample was irradiated to a slightly larger fluence than was required above to cause discharge with the switch closed during the irradiation. Since electric field lines do not concentrate around the stylus with the switch open, the sample will presumably not break down by punchthrough at this fluence with the switch open. Also, presumably a blowoff discharge will not occur. When the desired fluence has been delivered to the sample, the electron beam would be turned off and then the switch from the stylus would be closed. If the deposited fluence was somewhat greater than the fluence which caused a punchthrough with the stylus closed during the irradiation, closing the switch should induce a punchthrough. Also, if the present model is correct, a blowoff of charge should also occur almost simultaneously with the punchthrough. This sequence of events would demonstrate conclusively that the blowoff followed as a result of the punchthrough. It would also show that the electron plasma from the electron gun and the secondary emission was not essential to a blowoff discharge. Experiments of this kind are presently being designed, but results are not available as yet.

Another advantage of the stylus-stimulated discharges is that it should be possible to obtain more consistent and repeatable data and thus to determine more accurately the variation of discharge time and peak current with sample parameters, such as area and thickness. In these experiments, the location of the discharge point will be controlled relative to the nearest boundaries of the sample. Without the stylus, the discharges can occur randomly over the surface of the sample, depending on where the discharge channels are initiated, so the distance to the sample edges will vary from discharge to discharge, which could noticeably affect the discharge characteristics. In order to check the predicted (-0.5) power dependence of discharge time on sample thickness, one has to be able to distinguish factors-of-2 differences in discharge time for a realistic four-fold variation in sample thickness.

Another prediction of the model is that the ratio of blowoff charge to total charge lost during a discharge could vary with the energy of the electron beam. This result would occur if the probability that the total Lorentz force $e(\underset{\sim}{E} + \underset{\sim}{v} \times \underset{\sim}{B})$ can force the electrons through the surface depends on the depth of the trapped electrons below the surface. For example, for higher energy electrons which are trapped closer to the substrate than the irradiated surface, most of the discharge would probably go directly to the substrate and very little would be blown off. Since the return charge from ground is essentially proportional to the blowoff charge, changing the fraction of the blowoff could affect the interpretation of peak return currents as a function of sample area when data for different beam energies are compared. Thus, until this dependence is determined, caution should be used when comparing data for different beam energies.

A final advantage of the stylus-stimulated discharges is that the "true" discharge time would be measured directly. The pulse width of the return current from ground, which is the basis for the previous estimates of the discharge time, is always the slower of three characteristic blowoff discharge times – the time for the charge to just escape from the dielectric surface, the transit time for the blowoff electrons to reach the walls of the test chamber, and the circuit time constant of the sample, ground lead, and measuring system. The last two times are dependent on the experimental setup and chamber geometry and are not representative of the basic discharge process. Moreover, the transit time should be essentially independent of sample size. Thus, if any measured ground-lead currents are limited by transit time, it is misleading to draw a single curve through such data points and other data points where the discharge time varies significantly with area.

SUMMARY

It is proposed that blowoff of charge from electron-charged dielectric is a consequence of a punchthrough or flashover discharge. According to the model, the physical process which forces the electrons outward through the dielectric surface is the $\underset{\sim}{v} \times \underset{\sim}{B}$ and electric field forces on the electrons. The model predicts a variation of discharge time on the sample area and thickness and a possible dependence of the return current from ground during a discharge on the energy of the electron beam. Stylus-stimulated discharges would provide a direct measurement of the punchthrough current time history and would verify whether or not blowoff occurs only as a result of punchthrough or flashover.

REFERENCES

1. N. J. Stevens, R. R. Lovell, and V. Gore, "Spacecraft-Charging Investigation for the CTS Project," Progress in Astronautics and Aeronautics, Vol. 47, 1976, pg 263.

2. R. C. Adams and J. E. Nanevicz, "Spacecraft-Charging Studies of Voltage Breakdown Processes on Spacecraft Thermal Control Mirrors," Progress in Astronautics and Aeronautics, Vol. 47, 1976, pg 225.

3. K. G. Balmain, M. Orszag, and P. Kremer, "Surface Discharges on Spacecraft Dielectrics in a Scanning Electron Microscope," Progress in Astronautics and Aeronautics, Vol. 47, 1976, pg 213.

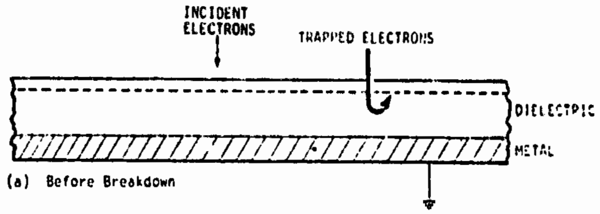
4. A. Meulenberg, Jr., "Evidence for a New Discharge Mechanism for Dielectrics in a Plasma," Progress in Astronautics and Aeronautics, Vol. 47, 1976, pg 237.

5. E. J. Yadlowsky, "Laboratory Simulation of Irradiation-Induced Dielectric Breakdown in Spacecraft Charging," Annual Status Report under NASA Research Grant No. NSG-3145, with Colorado State University, May 10, 1978.

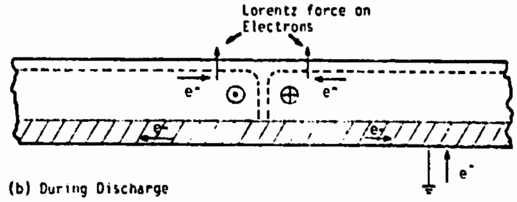
6. G. T. Inouye and J. M. Sellen, Jr., "A Proposed Mechanism for the Initiation and Propagation of Dielectric Surface Discharges," Proc. of 1978 IES Symposium on the Effects of the Ionosphere on Space and Terrestrial Systems.

7. K. G. Balmain, P. C. Kremer, and M. Cuchanski, "Charged-Area Effects on Spacecraft Dielectric Arc Discharges," Proc. of 1978 IES Symposium on the Effect of the Ionosphere on Space and Terrestrial Systems.

(⊙ AND ⊕ ARE DIRECTIONS OF H FIELD, OUT OF AND INTO PAPER, RESPECTIVELY)



(a) Before Breakdown



(b) During Discharge

FIGURE 1. ILLUSTRATION OF BREAKDOWN MECHANISM

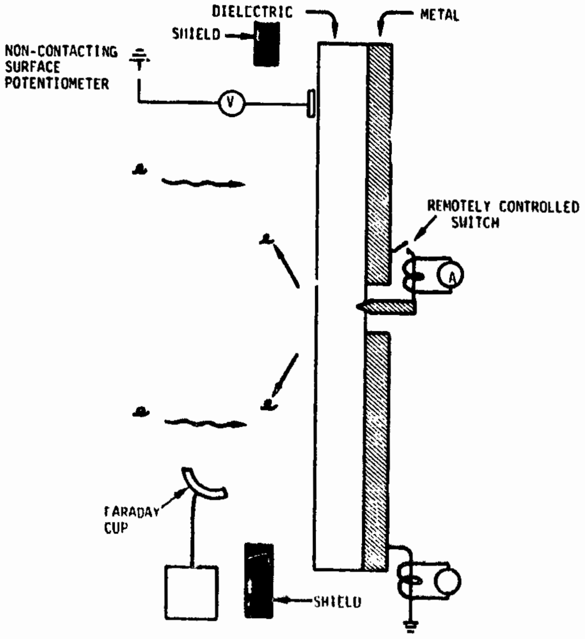


FIGURE 2. EXPERIMENTAL SETUP FOR STYLUS - STIMULATED DICHARGES