SURFACE DISCHARGES ON SPACECRAFT DIELECTRICS IN A SCANNING ELECTRON MICROSCOPE

K.G.Balmain,* M.Orszag,† and P.Kremer‡

Department of Electrical Engineering
University of Toronto, Toronto, Canada

Abstract

The scanning electron microscope (SEM) is shown to be a useful device for the study of surface electrical discharges on spacecraft materials. Discharges were observed on specimens of Kapton, Kapton-fiber glass laminate, Kevlar-fiber glass laminate, and Teflon, the observations involving primarily measurements of secondary-electron emission and specimen-current frequency spectrum. The spectra of all these materials were similar, with a constant amplitude of -45 to -50 dBm at 300 kHz bandwidth, flat up to 100 MHz, and dropping off above that. With Teflon, however, the frequency of discharge occurrence was several times that of the other materials. Discontinuities in secondary-electron SEM photographs suggest discharge "cleanoff" of a large fraction of the deposited charge, and a mechanism of discharge propagation through the submerged charge layer is proposed to explain this effect.

Presented in part as Paper SA69 at the Spring Annual Meeting of the AGU (cosponsored by AIAA), Washington D.C., June 16-19, 1975. The research was supported by the Communications Research Centre, Department of Communications, Canada, under Department of Supply and Services Contract No.DSS 36100-4-0235. Permission by the Department of Communications to publish the results of this study is acknowledged. Support was also provided by the National Research Council of Canada, under Grant No. A-4140. Discussions with R.E.Barrington are gratefully acknowledged.

*Professor of Electrical Engineering.
†Post-doctoral Assistant.
‡Engineering Technologist.

Introduction

There is now little doubt that a satellite in synchronous orbit can accumulate electric charge in large quantities, in the presence of the high-energy electrons associated with magnetic storms and in the absence of sufficient charge drainage by mechanisms such as photoemission. Because the exposed surface of a typical satellite is composed largely of insulating materials (dielectrics), and because the charge buildup and drainage effects vary over the surface, the whole-satellite charging, already mentioned, must be accompanied by strong differential charging. Subsequent local discharge by electrical breakdowns and arcs is clearly a possibility and could have led to the satellite operational anomalies which have been observed. Synchronous-orbit observations and also some relevant laboratory experiments have been reviewed thoroughly by Rosen[1], making unnecessary any further general remarks here.

Let us turn now to the specifics of laboratory simulation of spacecraft-charging conditions. The necessity for simulation in a vacuum chamber is a crucial limitation because the larger the chamber, the better the simulation ought to be. On the other hand, the smaller the chamber, the more inexpensive the experiments become, and the easier it is to make changes. A small, highly functional, experimental vacuum chamber complete with electron-beam source is provided by a typical scanning electron microscope (SEM), whose normal mode of operation involves measuring secondary-electron emission and using this measurement to create an image by synchronization with the incident beam scan. Such secondary-electron images have been used by Balmain[2] to display charge-accumulation patterns on spacecraft dielectrics and to provide tentative evidence for the existence of impulsive discharge events on Kapton and Kapton-fiber glass laminate, events indicated by momentary increases in secondary-electron emission. The further development of SEM simulation of spacecraft dielectric discharges is described in the remainder of this paper.

Experiments

The Scanning Electron Microscope

Each test specimen of spacecraft dielectric material was mounted in the SEM vacuum chamber as shown in Fig. 1. Experiments involved measurement of secondary electrons and measurement of current passing through the specimen to the copper plate beneath it. For secondary-electron imaging, the signal

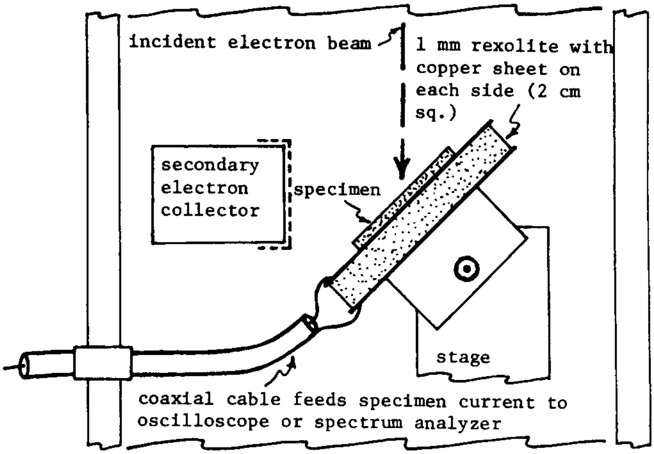

Fig. 1 Arrangement of components in specimen vacuum chamber of scanning electron microscope.

from the electron collector intensity-modulates a cathode-ray tube (CRT) whose beam position is synchronized with the position on the specimen of the SEM incident electron beam, which is scanned in a left-to-right raster going from top to bottom (with reference to the CRT display). Consequently, the resulting photographs must be thought of not only as recordings in space but also as recordings in time.

Secondary-Emission Photography

One effect of negative-charge accumulation on a small specimen is to deflect the incident electron beam toward the edge of the specimen. However, the SEM image records the intended, rather than the actual point of contact of the beam with the specimen. Therefore, on a negatively charged specimen, two identifiable points on either side of the center of the specimen will appear to be closer together than is actually the case, and any decrease in the amount of charge will cause the apparent separation between the two points to increase. This is illustrated in Fig. 2, in which two straight scratches on a Kapton sample suddenly appear to jump apart. This discontinuity in the photograph is accompanied by a white streak, indicating a sharp increase in electron emission from the specimen. The increase in electron emission clearly is consistent with the reduction in surface charge, so it is definite that we can think in terms of "discharge events" occurring on the specimen. The locations on the specimen of white streaks, which are actually events in time rather than space. Furthermore, the discharges need not occur at a

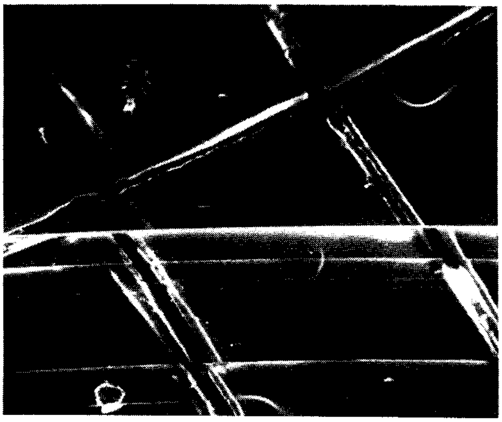

Fig. 2 Secondary-electron photograph of Kapton at 20-kV beam voltage and x 280, showing discharge events.

well-defined point but in some sense could be distributed over the specimen surface. Such a view is supported by the observation that many of the discharge events restore the apparent scratch separation essentially to the uncharged separation, indicating "cleanoff" of a large fraction of the accumulated charge at each event.

The discharge events just described were observed on Kapton, Kapton-fiber glass laminate, and Kevlar-fiber glass laminate. The appearance of the events in the photographs ranged from a few heavy streaks, as in Fig. 2, to a "snowstorm" of very short streaks. Discharge events were never observed on typical solar cell cover glass (5% CeO-doped, with MgO coating), on which the short decay time of accumulated charge (a few seconds) apparently did not permit the buildup of strong differential charge in the SEM environment, even with a beam accelerating voltage of 30 kV.

Specimen Current

The specimen current was measured first by connecting the stage (on which the dielectric was mounted) to the "specimen current amplifier" on the SEM and recording the result. A typical result for Kapton is shown in Fig. 3 along with a corresponding measurement of secondary emission. In this case, the specimen current has a background value of about 10^{-10} A caused mainly by displacement current accompanying the slow temporal buildup of electric charge on the surface of the di-

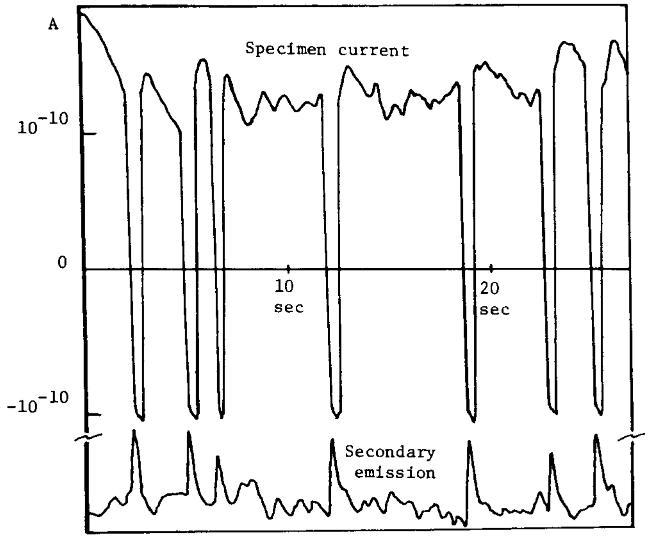

Fig. 3 Discharge events indicated by specimen current and secondary emission, for Kapton 0.1 mm thick and 20-kV beam voltage.

electric. From time to time there is a discharge event producing the burst of secondaries already discussed. Simultaneously, there is a reversal of specimen current, driving the amplifier to saturation in the negative direction, which is the direction of electrons flowing upward toward the specimen surface, or positive charges flowing downward. Such an effect could be entirely capacitive, the upward release of specimen surface electrons being accompanied by the downward release of positive charge previously attracted to the specimen stage by the slow accumulation of charge on the specimen surface. Conduction through the dielectric can be ruled out as an explanation for the current pulses, because such conduction would have to involve the passage of surface electrons downward through the specimen.

To get a better idea of the rise and fall times of the specimen current pulses, the experiment was repeated using a 25-MHz storage oscilloscope. The negative pulses were observed as before, rising to several volts for a 1-MΩ oscilloscope input resistance. The fall time of the pulse was determined by the time constant of the oscilloscope input resistance and the total capacitance (oscilloscope + cable + specimen stage). However, the rise time was "instantaneous", independent of the time constant, as one might expect from the "instantaneous" release of charge from the specimen stage. As measured in a

250-MHz oscilloscope, the "instantaneous" rise times turned out to be between 4 and 8 nsec, as did the fall times when using a 50-Ω load. On rare occasions, strong positive pulses were observed with the 25-MHz oscilloscope, suggesting breakdown through the 125-μm thickness of the Kapton specimen. However, the vast majority of discharge events appear not to penetrate the specimen but rather to occur at or close to its surface.

Spectrum Analyzer Measurements

The specimen current discharge pulses were measured first by setting the spectrum analyzer at various fixed frequencies and, at each one, taking note of the amplitude of the strongest pulse in a 1-min interval, using a 10 kHz bandwidth. For this experiment, the SEM was not scanned but rather the spot beam was moved slowly back and forth by hand-adjustment of the deflection controls. This procedure gave many times more discharges per unit time than did the rapid beam scan used previously.

The results for Kapton and Kevlar-fiber glass laminate are shown in Fig. 4. The two spectra are essentially the same: flat up to 100 MHz followed by a dropoff of between 30 and 40 dB/decade of frequency. Such a spectrum with the 40 dB/dec-

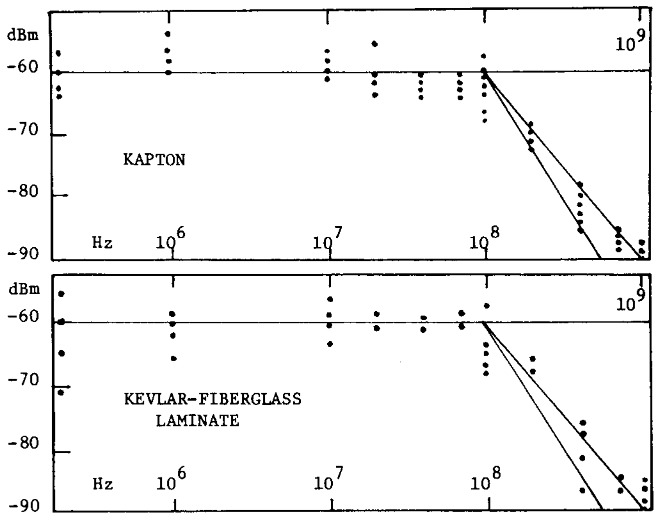

Fig. 4 Discharge spectra for specimens with 1 cm^2 area. Each dot is amplitude of strongest discharge pulse in 1 min interval. Lines indicate dropoff rates of 30 and 40 dB/decade of frequency. An intermediate frequency bandwidth of 10 kHz was used, with a 10-kHz low-pass video filter.

ade dropoff figure is characteristic of continuous-function pulses with rise and fall times of the order of a few nanoseconds.[3,4] Sharper pulses involving step-discontinuities produce slower dropoff rates.

A second type of spectrum analysis experiment involved using a wider bandwidth of 300 kHz and sweeping the frequency slowly from 100-1100 MHz while recording the detected discharge pulses on a storage oscilloscope. The materials tested were Kapton, Kevlar-fiber glass laminate, and Teflon. The spectral dropoff rates were similar in all cases: 30-40 dB/decade from 200-500 MHz and a somewhat slower, more irregular dropoff up to 1100 MHz. The results for the Kevlar-fiber glass laminate were indistinguishable from those for the Kapton. The Teflon, however, exhibited a frequency of discharge occurrence 5-6 times higher than the Kapton while giving pulse amplitudes 15 dB lower than the Kapton.

It should be mentioned that the SEM beam accelerating voltage threshold for the observation of discharge events was normally 16-18 kV for all materials, with essentially no change in measured spectrum from 20 to 30 kV. The addition of a large amount of contaminant to the dielectric surface, such as a smear of diffusion pump oil, merely raised the discharge threshold to between 20 and 25 kV. Variation in specimen surface area from 1 mm^2 to 250 times that had no effect on the spectrum in this type of measurement. Also, specimen thickness variations from 0.1 to 0.5 mm had no effect. In some cases, however, beam incidence on the edge of the specimen produced increased frequency of discharge occurrence. In addition, the light output from the discharges was photographed, the results indicating that the brightest part of each discharge is highly localized at the point of beam incidence. An electrically floating vacuum-deposited layer of gold, about 200-Å- thick, completely stopped the discharges in a sequence of experiments on Teflon.

In order to determine the effect of incident-beam current density, the beam was defocused by varying the "working distance" as measured below the final aperture of the instrument. A working distance set to give focus 15 mm above the specimen produces a beam diameter somewhat greater than 1 mm and a current density of the order of 10 nA/cm^2 (as expected in synchronous orbit under storm conditions); whereas a working distance adjusted close to focus on the specimen surface produces a current density of the order of 10^4 times as great (all of the experiments described heretofore employed a focused electron beam). Some of the results for Teflon are

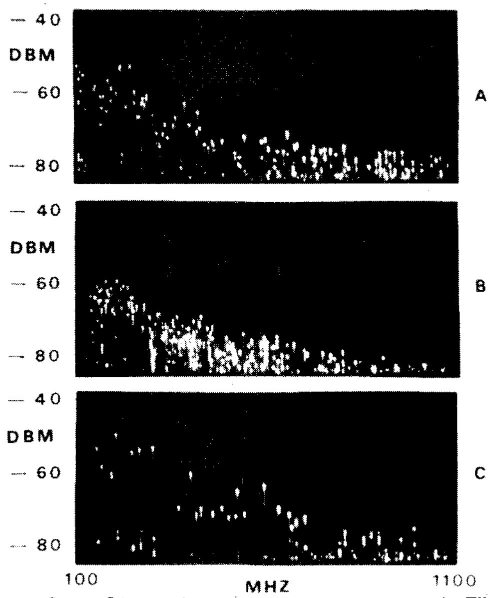

Fig. 5 Spectrum of Teflon discharges at 20 kV, for a 200-sec time interval and 300-kHz-IF bandwidth. Location of beam focus relative to specimen: (a) 25 mm below, (b) at surface, and (c) 15 mm above (effective beam diam ~ 1 mm).

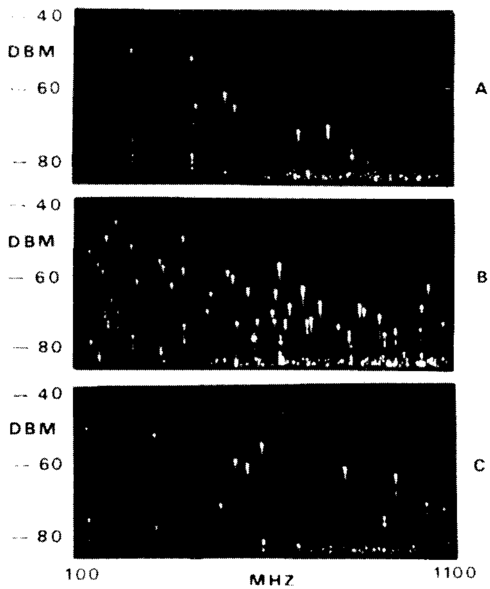

Fig. 6 Spectrum of Kapton discharges at 30 kV, for a 400-sec time interval and 300-kHz-IF bandwidth. Location of beam focus relative to specimen: (a) 15 mm below, (b) at surface, and (c) 11 mm above (effective beam diameter ~ 1 mm).

shown in Fig. 5, from which it is clear that a focused beam produces 3-4 times the frequency of discharge occurrence but 10-dB lower amplitude, compared to the defocused beam. For Kapton, as shown in Fig. 6, the effect on frequency of occurrence is the same, but the spectrum amplitude is unaffected. This latter point is especially worthy of note because it suggests that spectrum amplitude measurements on Kapton in an SEM are directly applicable to large-scale situations with broad incident beams. Applicability of the Teflon results is much less certain, but an approximate procedure would be simply to add 10 dB to the spectrum amplitudes obtained with a focused beam. It is interesting to note that such a 10-dB-adjustment brings the flat part of the Teflon spectral amplitude up to -50 dBm, fairly close to the Kapton level of -45 dBm.

Interpretation

For each electron incident on a sample of spacecraft dielectric, a net negative charge is deposited because, on the average, less than one secondary electron is emitted. This occurs provided that the incident-beam energy is above a threshold value (the "second crossover" on the yield vs energy curve). This threshold value is about 2000 eV for Teflon and 500 eV for Kapton, as reported by Willis and Skinner.[5]

High-energy (2 MeV) experiments have been reported by Gross on borosilicate glass[6] and Plexiglas[7], showing that the charge accumulates at a well-defined depth, and if the dielectric surface is pressed with a grounded needle, a discharge results. The discharge damage reveals that the path of the discharge is first "vertical" from the needle to the charge layer, and then "horizontal" through the charge layer in a feathery pattern (Lichtenberg figure). A lower-energy version of such a discharge could be triggered by the SEM electron beam, causing local breakdown between the submerged negative-charge layer and the dielectric surface (which would be slightly positive because of secondary emission). This initial breakdown, which has been discussed by Meulenberg,[8] then could be followed by a propagating discharge through the submerged charge layer. These ideas are illustrated in Fig. 7.

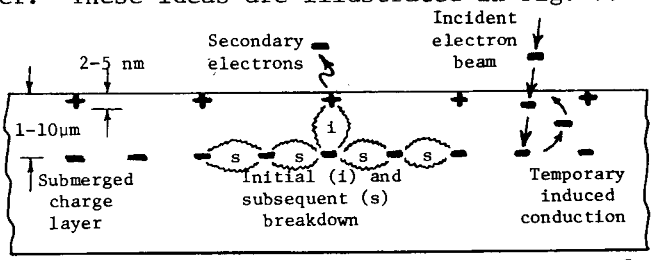

Fig. 7 Charging and discharging in a cross section of a dielectric specimen: illustration of some possible mechanisms.

If this discharge mechanism were operative, a thin layer of surface metallization would not stop the discharges. However, such a deduction ignores the phenomenon of beam-induced temporary conductivity (both "prompt" and "delayed" components)[9], which could drain at least part of the submerged charge to the surface metallization. Certainly much more experimentation needs to be done to establish clearly the effects of surface metallization, partly because these effects relate to a possible cure for the discharge problem, and partly because they help to reveal the nature of the discharge mechanism.

Conclusions

Surface discharges on thin specimens of spacecraft dielectric have been observed in the SEM by measuring secondary-electron emission and specimen current. The discharge currents have rise times of a few nanoseconds and fall times apparently determined by the external circuitry. The corresponding frequency spectra have a "knee" at about 100 MHz and are remarkably similar in amplitude and shape for different materials such as Kapton, Kapton-fiber glass laminate, Kevlar-fiber glass laminate, and Teflon (the Teflon amplitudes are about 5 dB lower than the other materials). However, Teflon exhibits a frequency of discharge occurrence which is several times higher than the other materials.

The discharge spectra (specimen-current measurements) have maximum levels from -45 dBm to -50 dBm for a 50-Ω input impedance and a 300-kHz bandwidth, strong enough to be classified definitely as sources of interference. It should be emphasized that these discharges are confined near the dielectric surface and are not dielectric-to-metal or metal-to-metal arcs. It is not clear yet how highly localized the surface discharges are, but there is some evidence for charge "cleanoff" over an appreciable area, possible via discharge propagation through the submerged layer of accumulated charge. No optically-visible discharge tracks have been observed yet, but SEM examination of much-used specimens reveals regular patterns of deep-seated alteration that could be either structural damage or long-lived charge accumulation.

References

[1]Rosen, A., "Large Discharges and Arcs on Spacecraft," Astronautics & Aeronautics, Vol.13, June 1975, pp. 36-44.

[2]Balmain, K.G., "Charging of Spacecraft Materials Simulated in a Scanning Electron Microscope", Electronics Letters, Vol.9, Nov.15, 1973, pp. 544-546.

[3]Reference Data for Radio Engineers, H.W.Sams & Co. Inc., Indianapolis, 1968, pp. 42.5-42.7.

[4]Bracewell, R., The Fourier Transform and Its Applications, McGraw-Hill, New York, 1965.

[5]Willis, R.F., and Skinner, D.K., "Secondary Electron Emission Yield Behavior of Polymers," Solid State Communications, Vol. 13, No. 6, 1973, pp. 685-688.

[6]Gross, B., "Irradiation Effects in Borosilicate Glass," The Physical Review, Vol.107, July 15, 1957, pp. 368-373.

[7]Gross, B., "Irradiation Effects in Plexiglas", Journal of Polymer Science, Vol. 27, 1958, pp. 135-143.

[8]Meulenberg, A., "Evidence for a New Discharge Mechanism for Dielectrics in a Plasma," Spring Annual Meeting of the American Geophysical Union, Paper SA70, Washington, D.C., June 16-19, 1975.

[9]Gross, B., Sessler, G.M., and West, J.E., "Charge Diagnostics for Electron-Irradiated Polymer Foils," Applied Physics Letters Vol. 22, April 1, 1973, pp. 315-316.