Studies of Microdamage in Dielectric Discharges

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Electrical discharges on electron beam irradiated dielectrics have been studied to understand the possible nature of discharges that may occur on differentially charged satellite surfaces. The microdamage associated with these discharges has been investigated using optical and scanning electron beam microscopy and chemical etching techniques to assess the degradation in the optical and structural properties that can occur and to identify the current carrying channels discharging the surface. This paper reviews the microdamage characteristics that have been observed and attempts to correlate the salient characteristics of the damage with prominent material properties and electrical characteristics of the discharge. The results indicate that two or more distinct discharge processes are required to account for the various surface and subsurface microdamage observed.

Introduction

MAGNETIC substorm activity in space produces fluxes of energetic electrons which can differentially charge spacecraft dielectric surfaces relative to the average spacecraft potential. Such charging can result in electrical breakdowns producing electrical surges that may interfere with system operations and microdamage to the dielectric materials which may degrade the operational characteristics of the dielectric. In many cases, silver-backed dielectrics such as Teflon® and Kapton are used as passive thermal surfaces whose utility depends on proper optical transmissivity and infrared emissivity.

The study of microdamage due to electrical stress can provide an insight into the discharge processes that may occur on various dielectrics and thereby provide a basis for the prediction of the types and severity of discharges which may occur in a space environment. Such studies also demonstrate the effect of microdamage on the long-term physical properties of materials, and the possible nature of particulates that may be generated during a discharge. Since most experimental studies have been concerned primarily with ascertaining the electrical threat discharges pose to a spacecraft, the reports of microdamage have been treated as secondary in nature and little analysis of the physical impact has been undertaken.

In general, two basic types of experimental procedures have been used to study dielectric breakdown and material damage. The first, for which a large body of literature exists, is experiments in which the electrical stress on dielectrics is provided by high-voltage electrodes. Such studies have long been used to study materials for high-voltage cables, capacitors, and many other standard applications of dielectrics as electrical insulators. Such studies are referenced here only for comparison with experiments which approximate the charging characteristics of spacecraft more closely; namely, those experiments in which electron beams are used to charge various dielectrics.

This paper will be in the nature of a review. The next section will chronicle the different types of material microdamage that have been observed. The following section will try to correlate the electrical properties and material damage that occur and will compare the results with models of electrical breakdowns and discharge propagation that have been proposed in the literature.

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Microdamage Studies

The microdamage resulting from surface flashover and puncture discharge on electron beam irradiated dielectric films has been studied using optical microscopes, scanning electron microscopes (SEM), and Auger spectrometers. The studies reveal the existence of subsurface tunnels, blow-out holes, punch-through holes, surface channels, surface contaminants, and erosion of the metallized backing on these thin film samples. Similar damage studies have been carried out on dielectric spacers sandwiched between electrodes electrically stressed to induce a breakdown on the dielectric. Again surface damage tracks have been observed which represent erosion of the dielectics by the arc. The characteristic features of these damage tracks can be classified to yield information about discharge propagation processes along dielectric surfaces and the contamination of the surface by the ejected material. In related microdamage studies, the growth of subsurface "treeing" induced by nonuniform electrical stresses at the tip of a biased, pointed electrode has been investigated. The results of these stress studies provide information about the growth of subsurface cracks that can initiate discharges through the dielectric material. An overview of these various studies is presented subsequently.

Figure 1 shows one type of damage pattern observed following discharge on an electron beam irradiated dielectric sample.[1] In general, a hole is observed in the material extending from the front surface to the rear metallized backing (referred to as a punch-through or puncture). Irregular subsurface tunnels in the form of trees radiate from the punch-through hole to form a Lichtenberg pattern.

The spatial relationships of the subsurface tunnels to the puncture hole are shown in Fig. 2. The sketches were obtained from stereo microscope views at various depths in the polymer coatings. The top sketch in Fig. 2 shows the main lateral channels for a nonpenetrating electron beam to be near the exposed sample surface with finer channels extending downward into the material. The bottom sketch in Fig. 2 shows that the main channels for a penetrating electron beam emanate from the silver backing at the base of the puncture. The authors also observed punctures surrounded by a limited network of fine tunnels (center sketch) with no major lateral tunnels.

Similar punctures with lateral subsurface tunnels have been observed by others on dielectric samples.[2-8] The optical micrograph in Fig. 3a shows the subsurface tunnels produced by a discharge on a 75-μm Teflon® sample whose edge was shielded from direct irradiation by the electron beam.[2] The tunnels are estimated to be 6-8 μm below the sample surface corresponding closely to the calculated range (6.4 μm) of the 26-keV electrons used in the study. The extent of the damage is

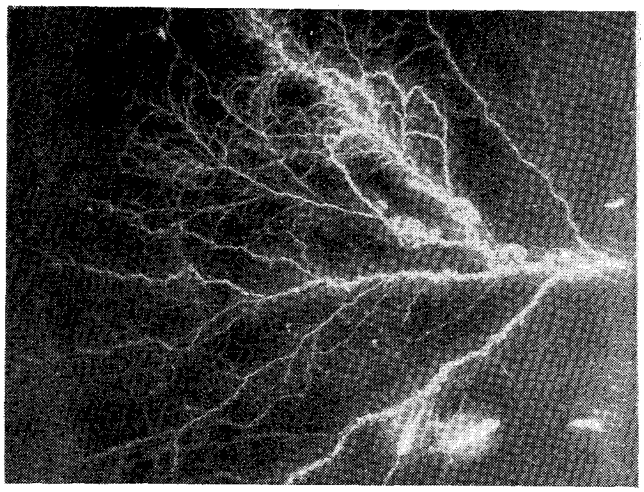


Fig. 1 Optical micrograph of microdamage on a 125-μm silvered FEP Teflon sample irradiated by a 35-keV electron beam.[1]

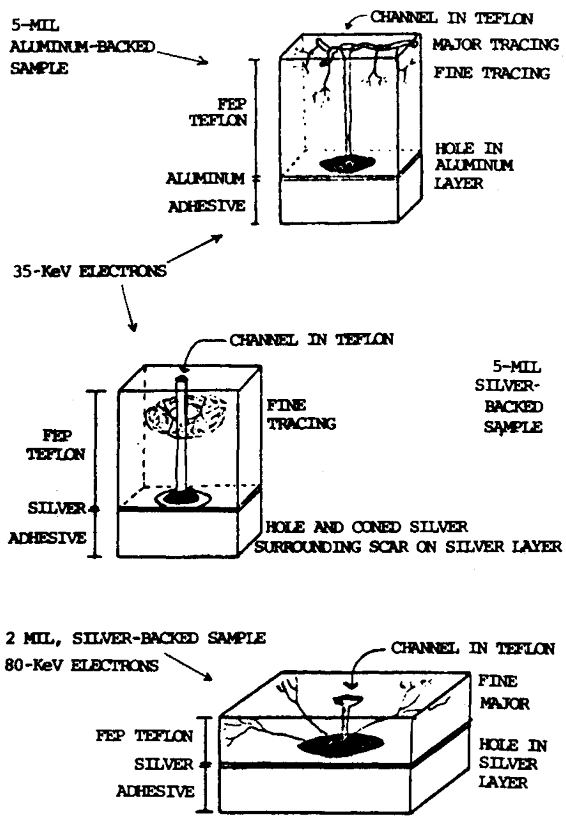
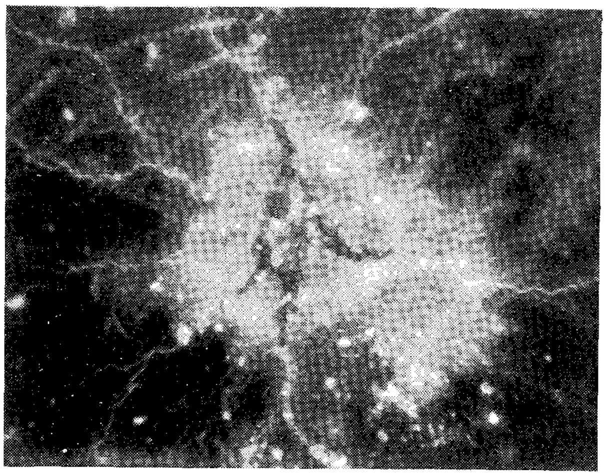
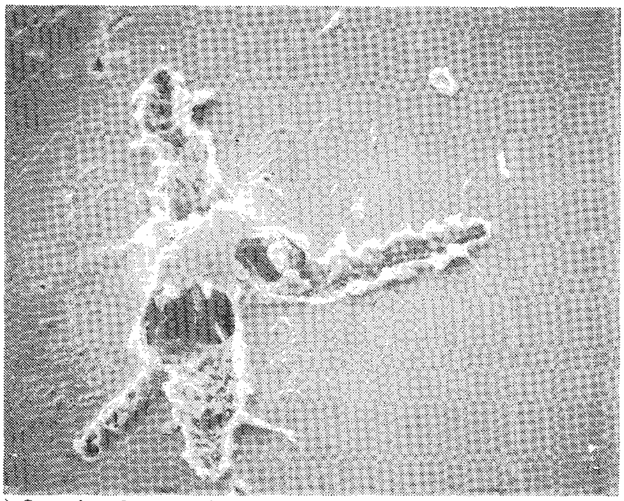


Fig. 2 Sketch of discharge tunnels and vaporized metal backing in FEP Teflon.[1]

further demonstrated in the SEM micrograph of the same region (Fig. 3b). The current in the discharge has ruptured the top of the tunnels where they coalesce to form the puncture while ejecting molten Teflon® in the process. Other blowout holes through the sample surface are observed at other locations along the subsurface tunnels. Balmain and Dubois[3] have reported similar punch-through holes and tunnel networks on Teflon®. They noted that the number of puncture sites is much smaller than the number of discharge events and that the holes occur most frequently near the mask shielding the sample edges. The authors report the diameter of the major tunnels to be 1 μm, lying about 4-8 μm below the surface. The puncture usually results in the vaporization of the metallized backing in the vicinity of the hole.



a) Optical micrograph showing subsurface filamentary structure (75×).



b) Scanning electron micrograph of breakdown site shown in Fig. 3a (190×).

Fig. 3 Microdamage on 75-μm silvered Teflon samples irradiated by a 26-keV electron beam.[2]

In addition to the subsurface tunnels which form irregular patterns, surface channels having very regular patterns have been observed on irradiated dielectrics.[3,7,9,10] The optical micrograph in Fig. 4 reveals the regularity of the tracks, and the SEM micrographs in Fig. 5 demonstrate the surface nature of the tracks.[10] Straight tracks, often a few centimeters in length, are observed to lie along a preferred direction with cross tracks occurring at an angle of approximately 30 deg to the main tracks. Leafy projections protrude from the long straight tacks in Fig. 5.

These linear surface channels occur together with puncture sides having subsurface tunnels on samples with edges shielded from direct irradiation by the electron beam.[3,10] In fact, Balmain and Dubois[3] observed the merging of surface channels with subsurface tunnels on Kapton® samples which indicated to them a similar production process. On the other hand, subsurface tunnels were not seen on Teflon® samples with an edge exposed to the irradiating beam. In these studies only linear surface channels were observed.[9]

In addition to grooves, tunnels, and punctures, localized changes in surface quality were observed by Berolo[5] who attributed the effect to a depolymerization of the surface material followed by a repolymerization. In the same study, outsputtered material in the form of 50×150 μm rods having two distinct phases was observed. This surface deposition was observed on samples irradiated by an electron beam whose energy was rapidly swept between 15 and 30 keV but not on samples irradiated by a constant energy beam. Other researchers have observed surface erosion on metallic surfaces coated by thin oxide films,[11] contamination of the surface by adhesives used to apply the polymer films[12] and a darkening of the dielectric material which leads to an increase in the solar absorptance (from 0.24 to 0.49).[13]

Studies of surface flashover in high-voltage switch geometries reveal irregularly shaped surface damage tracks resembling trees on the dielectric separating the electrodes, as shown in Fig. 6.[14] In general, the trunk of the tree at the cathode end is a deep surface channel that becomes shallower as more branches are formed toward the anode end. Partial discharges have been observed with emission and damage patterns that stop and start on the dielectric without extending to either electrode.[14] The surface damage was most severe on polymer dielectrics with minimal damage occurring on alundum. No subsurface tunneling was observed in these flashover studies.

In related studies, the growth of subsurface cracks induced near the sharp tip of the biased electrode was investigated.[15,16] The Lichtenberg patterns formed this way resemble trees having some similarities to the irregular subsurface tunnels observed in the irradiation studies. Figure 7a presents one of these electrically induced trees and Fig. 7b presents a view of the inside of one of these tree channels. These point electrode studies were directed at determining the electric field gradient required to induce electromechanical stresses of sufficient magnitude to cause microvoids in the material to grow. The studies indicate that the breakdowns occur preferentially along the crystalline interfaces in semicrystalline polymers.[16]

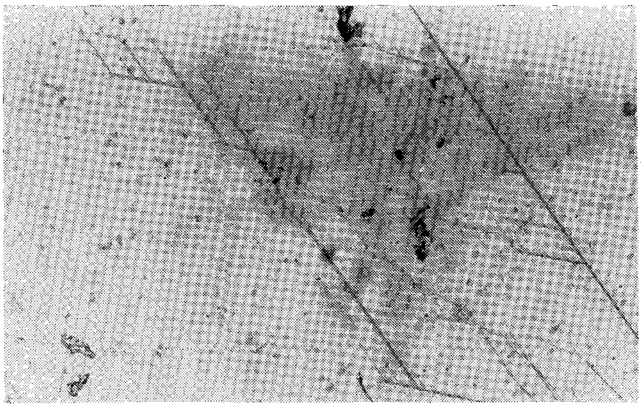


Fig. 4 Optical micrograph of surface channels on Mylar film showing regularity of damage tracks. Scale: 50 μm (Ref. 10).

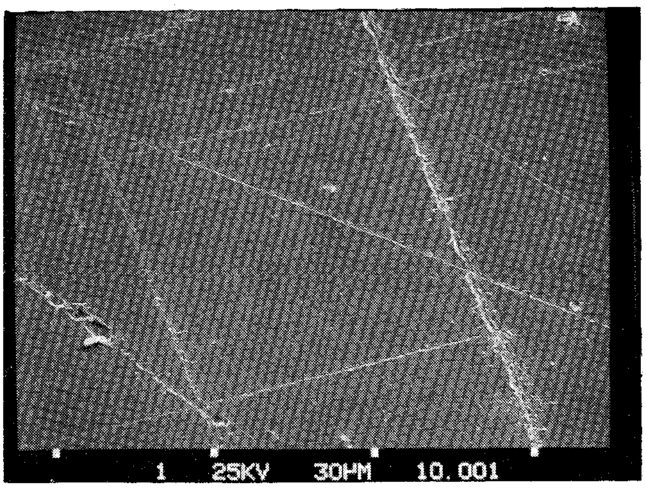
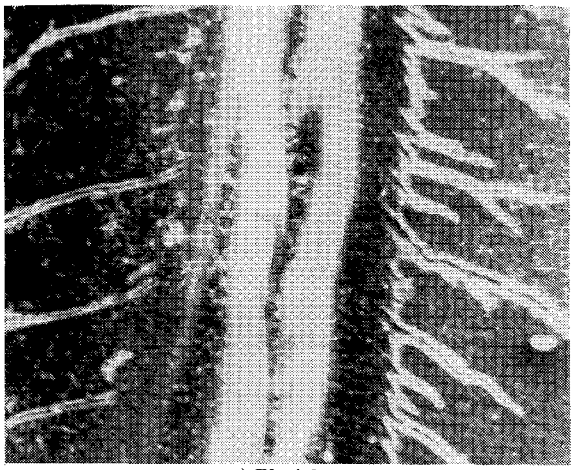


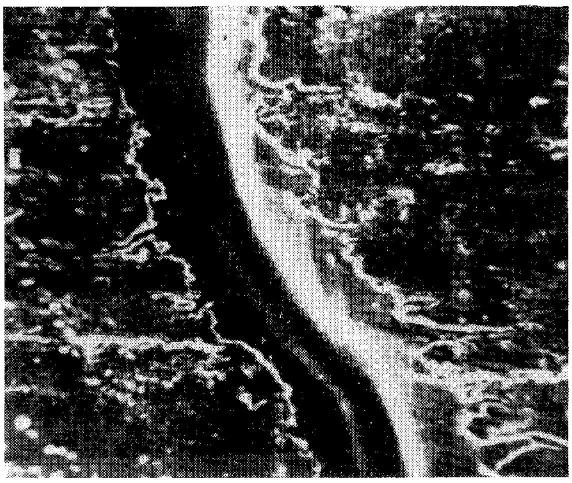
Fig. 5 Scanning electron micrograph of surface channel on Mylar film.[10]

Correlation of Damage Characteristics with Discharge Features and Material Properties

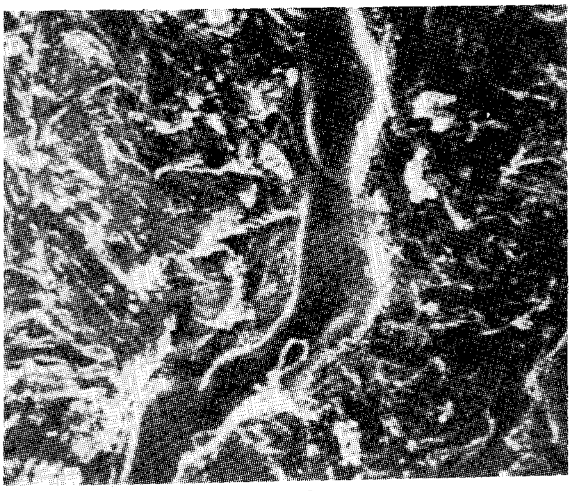
Although the microdamage studies do reveal injury to the material which can affect the performance aboard spacecraft, the primary value of these studies lies with the insight they provide about the breakdown process on irradiated dielectrics. In this regard, it is important to compare the discharge characteristics with the microdamage patterns to see what features appear to be common to a particular class of



a) Plexiglas.



b) Teflon.



c) Polyethylene.

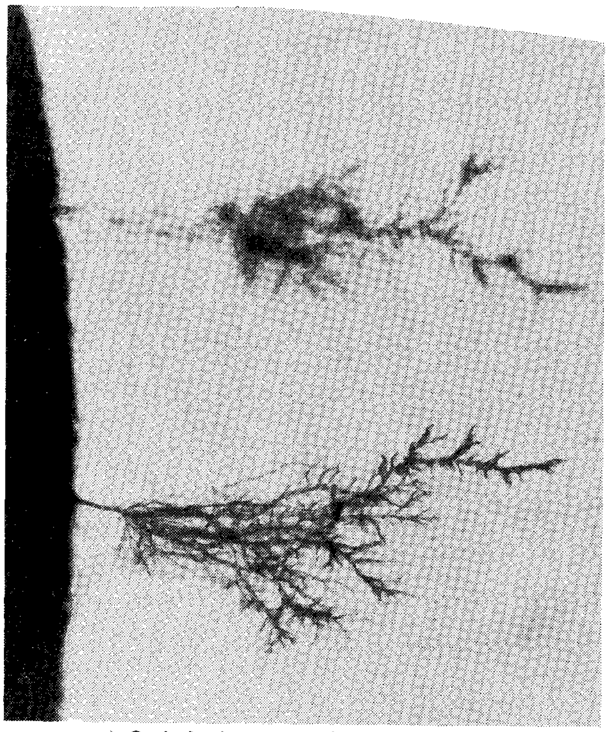
Fig. 6 Channels on thermoplastic dielectric samples after 20 flashovers, dc voltage: (100×).

breakdown. Unfortunately, most of the experimental studies were not conducted with only one discharge event per sample to allow a one-to-one correlation to be made. Numerous discharge events result in a composite of breakdown patterns. In spite of these limitations a number of broad discharge categories appear to emerge.

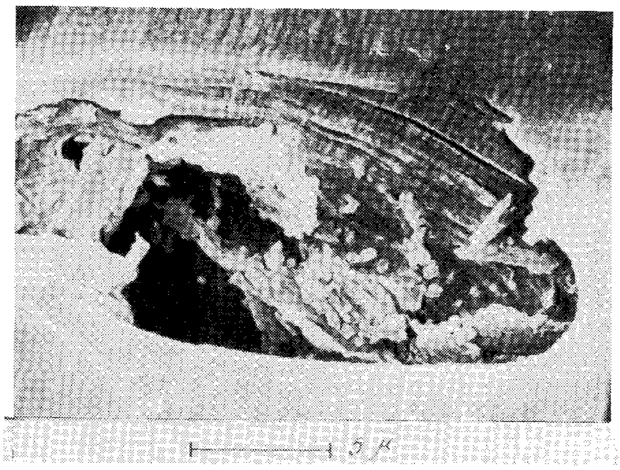
It is clear that discharges occur that do produce microdamage tracks. In these cases the similarities between the damage patterns and the optical emission patterns suggest that the damage tracks are formed by the arc currents which discharge the sample. It is unclear whether discharges occur on irradiated dielectrics that do not produce damage tracks, but there is some evidence which suggests this is the case. First, the number of individual damage patterns observed on samples subject to repeated discharges is far fewer than the number of discharge events.[2,7] Visual observations indicate that every discharge event is accompanied by an optical emission pattern. After a number of puncture sites are established, there is an equal probability for a given site to be the terminus for a breakdown with a number of sites taking part in some discharge events simultaneously.[2,8] The fluctuations in orientation of the visual patterns indicate the relative absence of repeated discharges along a pre-existing damage track. The puncture site surrounded by a limited mesh of fine subsurface channels, shown in the middle sketch of Fig. 2, which has no tracks farther out could be an example of such a discharge that produces little or no microdamage. Finally, the observation that wiping motion used to clean a surface can affect the optical emission pattern suggests that surface contaminants could be very important in some discharge events.[17] The absence of any surface damage that follows the emission patterns provides further evidence of breakdown without damage. Although these results indicate a trend, the absence of visual cracks and tunnels is not proof that damage on a finer scale did not occur. Water trees are examples of subsurface "cracks" that fill up under a combination of water pressure and electrical stress that disappear after the stresses are removed.[15] It is possible that the cracks and tunnels produced during a breakdown close up in a similar fashion, and are not readily detected optically as suggested by Frederickson.[18] Further work is required along these lines.

The microdamage observed can be classified into punctures, irregular subsurface tunnels, and relatively regular surface channels. The orientation of the surface channel appears to be correlated to the material properties. Amore and Eagles[19] observed microsize voids (50-100 nm in diameter), lying in rows just below the surface of the materials, that are related to stresses during manufacture. For Mylar® materials with a single stretch direction, the voids lie along straight parallel rows with crosslinking rows that resemble a brick and mortar pattern. For materials having two stretch directions, a lamellae pattern is observed. Similar brick and mortar patterns were observed by Gossland et al.[10] on Mylar when the polymer was chemically etched. The material was observed to be optically birefringent with the slow optic axis favoring the stretch direction but not lying along it.[10] The long straight parallel surface damage channels were observed to be along the stretch direction making a 30-deg angle with the slow optic axis. These observations indicate that the stretch direction has a lower breakdown strength that could be related to the preferential growth of trees along crystalline interface observed in bulk dielectric breakdown studies.[16]

The conditions under which surface channels and subsurface tunnels are observed should be mentioned. Yadlowsky et al.[9] have reported that they observed the surface channels on Teflon® samples which have an edge exposed to the irradiating beam. However, Cooke et al.[6] have reported irregular subsurface tunnels in 12.7-mm polymethylmethacrylate irradiated with 3-MeV electrons with holes drilled in the samples.[6] Both irregular tunnels and regular surface channels have been observed on samples whose edges have been shielded from the irradiating beam[2,3] with transitions from one mode to another



a) Optical micrograph of one type of tree.



b) Scanning electron micrograph of channel interior.

Fig. 7 Electrical trees in insulators.[10]

observed in some cases.[3,6] Subsurface tunnels are observed to bridge a 5-mm-wide unirradiated strip separating two irradiated areas but not to bridge a 7-mm gap. The puncture sites on thin films are observed right up the mask shielding the edges, whereas the subsurface channels on thicker samples without edge shields do not extend to the edges of the sample.[6] Finally, on thin films with exposed edges, the discharge tracks go directly to the edge of the sample. Evaluation of arc propagation characteristics from damage track measurements indicates that the propagation velocity increases as the sample is charged to higher potentials and that the direction of propagation is from the puncture site toward the leafy end of the tree.[6]

A number of physical mechanisms have been proposed to explain the variety of damage tracks and discharge characteristics observed. Models based on the propagation of an ionizing front have been suggested to describe the formation of a conducting plasma column which provides a current path to ground for removing the excess charge.[3,6,20] When the energy deposited in the current channel is sufficiently large, a permanent visible tunnel is formed with melting, blowout holes, and ejection of molten dielectric occurring. This physical picture is similar to the models proposed for treeing in bulk dielectrics where electromechanical stresses on voids in dielectrics result in crack formation through rupturing. Electrical discharges then occur in the gases liberated within the crack volume and result in a propagating streamer through the material.[16] A different type of breakdown process has been suggested by Inouye and Sellen[21] wherein secondary electrons emitted in the gradient of a potential wave are accelerated and returned to the sample surface. The process can result in a lateral surface current carried by the secondary electrons if the emission coefficient is greater than one. This type of breakdown process is not unlike the models developed to describe surface flashovers for vacuum insulators spanning the gap between high-voltage electrodes. Here the secondary electrons emitted at the cathode return to the insulator after being accelerated by the interelectrode fields and liberate absorbed gas from the surface. The interelectrode breakdown then takes place via a discharge through the evolved gas.[14] This type of surface breakdown process could account for optical emission patterns on irradiated dielectrics that follow the wiping pattern used to clean the sample surface.

Summary

Microdamage studies of electron beam irradiated dielectrics reveal a variety of damage characteristics that include punctures, blowout holes, subsurface tunnels, surface channels, material darkening, surface deposition of ejected material, and evaporation of the metallized backing near punchthroughs and rivets. These results indicate that the microdamage can adversely affect the quality of mirror surfaces and thermal control surfaces. Of particular interest in this regard is the deterioration of the irradiated surface by outsputtering of material that was observed on samples irradiated with a swept energy beam that was not observed when the beam was monoenergetic. Additional studies are required to determine how seriously the surface might be deteriorated during the lifetime of a typical satellite.

The microdamage studies provide considerable insight into the propagation characteristics of these breakdowns. The irregular subsurface tunnels propagate from a puncture toward the leafy tree with a velocity that depends on the initial voltage of the irradiated surface. The discharge can jump gaps of unirradiated region and change from a surface damage mode to a subsurface damage mode. Although there is evidence for breakdowns which do not produce material damage, additional studies are required to determine whether or not damage has resulted on a very fine scale that has not been observed to date.

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