

SURFACE FLASHOVER CHARACTERISTICS OF DIELECTRIC THIN FILMS IN VACUUM: A REVIEW

Hulya Kirkici

Auburn University

Electrical and Computer Engineering Department, 200 Broun Hall
Auburn AL 36849, USA

ABSTRACT

This work presents a discussion on space environmental effects and electrical insulation in space as well as experimental results of vacuum surface flashover characteristics of new dielectric materials to be used in space environment as protective coating or as dielectric materials. Specifically, experimental results of voltage and current characteristics and optical emission during the surface flashover of diamond like carbon (DLC) on silicon and polycrystalline diamond on silicon are discussed. The results are compared with the surface flashover characteristics of other materials such as quartz and Teflon™.

INTRODUCTION

Electrical insulation of high voltage (HV) power systems to be used in space environment is currently a major research area because of the interest in HV, high-power systems intended to support advanced space vehicles and modules such as earth orbiting satellites, inter-satellite modules, and interplanetary or intergalactic vehicles. As technology advances and new materials developed, there is a growing need to study the electrical integrity of these materials in space environment. These new materials can be either used in the construction of electronic components as dielectric material, or can be used as protective coating of the sub systems. In either case they are exposed to harsh space environment such as ionospheric plasmas, high-energy particle flux, solar flare, galactic or intergalactic micro-meteorites, atomic-oxygen, thermal variation, and high energy UV or other radiation effects. Also, the space environment is in reality a vacuum environment. Therefore,

the electrical insulation in space requires further consideration than the earth-bound systems operated in atmospheric pressures. One major problem with the electrical systems operating in space or vacuum is the differential charging of the individual components due to the interaction of spacecraft with the local space environment and due to the difference in dielectric properties of the materials used to construct these systems. This differential charging eventually results in surface flashover or surface breakdown of the materials, thus loss of high voltage isolation and permanent damage to the electrical systems of subsystems due electrical overloading [1]. Considering the space environmental effects and new advanced material candidate for use in space, we have tested electrical characteristics and studied surface flashover characteristics of several synthetic [2-4] materials considered to be used as productive insulating and/or protective coating in space power systems.

SURFACE FLASHOVER

Surface flashover or surface discharge across solid insulator in vacuum has been investigated for many years by various researchers [5, 6]. It is widely accepted that the surface flashover phenomena across solid insulators supporting the high voltage electrodes is due to the field emission of electrons at the cathode "triple junction" which is the intersection of electrode, insulator and vacuum interface when the applied field exceeds some threshold value.

Besides the main cause of surface flashover, other contributing factors are listed as the type and surface condition of the dielectric material [2], the type and surface condition of the electrode material, the geometry of the

electrodes, and operating environment [7]. The background and local gaseous species and pressure gradient [8] in the vicinity of the high voltage system are also important factors contribute to the surface flashover characteristics.

Regardless of the contributing factors, in general, surface flashover results from the random emission of a relatively small number of field emitted electrons which are the seed electrons, at the cathode/dielectric/vacuum interface due to the high electric field established at this interface. These seed electrons in combination with the positive charge built up on the dielectric surface act as a precursor to an electron avalanche towards the anode across the surface of the dielectric. This enhanced electric field at the triple junction further helps sustain the electron emission. Thus a surface flashover is initiated which is followed by a surface breakdown in most cases. The threshold potential for the initiation of the surface flashover is mainly depends on the factors that are listed above.

EXPERIMENTAL SET UP

Experimental set up to study the surface flashover phenomena consisted of a pump station with a ultra-high vacuum chamber, a mass spectrometer and an optical multi-channel analyzer with each computer controlled data acquisition systems, a high voltage dc power supply, and electrical (current/voltage probes) diagnostics instrumentation. A pair of copper electrodes was placed on the flat surface of the test sample as shown in Figure 1.

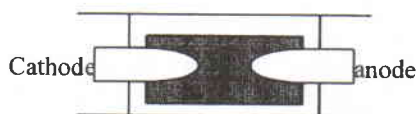


Figure 1. Top view of Electrodes and sample assembly.

The electrodes were polished to reduce surface irregularities; and the distance between them was either 1 mm or 3 mm depending on the experimental set. This electrode/sample assembly was places on a TeflonTM sample

holder and was placed in the vacuum chamber in a way that it was seen through a glass window to allow visual observation and optical diagnostics during the surface flashover phenomena.

SAMPLES AND SAMPLE PREPERATION

The thin film samples used in the experiments were polycrystalline diamond on silicon (D/Si), diamond like carbon on silicon (DLC/Si), and silicon dioxide on silicon (SiO₂/Si) substrate, free standing polycrystalline diamond (PD), single crystal diamond (SD), quartz, and TeflonTM. We also used DLC film deposited on silicon dioxide, which acted as the interface between the DLC and silicon substrate (DLC/SiO₂/Si). All the thin film samples were produced in house by microwave plasma assisted (CVD) system using proper gas mixtures depending on film type. The surface resistivity of the samples was measured by a surface probe and determined to be larger than 20 M Ω -mm. The DLC film thickness was 5 μ m and 30 μ m. The film thickness of SiO₂ was 2 μ m for both cases, as the interface or as the thin film. The polycrystalline diamond film was 5 μ m. Both the quartz and free-standing polycrystalline samples were 1 mm in thickness. All the samples, except the single crystal diamond, were 1 cm by 1 cm in surface area. All the samples had optical quality smooth surfaces except the polycrystalline diamond on silicon substrate. A sample at a time was placed on the sample holder and tests were conducted. The surface condition of each sample was examined both by an optical microscope or scanning electron microscope before and after the surface flashover experiments. Some samples seemed to have experienced permanent surface damage, and the picture of damaged region was obtained for presentation.

EXPERIMENTAL PROCEDURE

The vacuum chamber containing the sample assembly was pumped to a high vacuum level, and was kept under vacuum for several hours to reduce the outgassing effects on the surface flashover events, and all the chamber pressure was on the order of 10⁻⁵ Pa throughout experiments. A dc voltage was applied between

the electrodes, and an oscilloscope was used to record the surface flashover events. The breakdown current and voltage characteristics of the surface flashover events were recorded by using a high frequency high voltage probe and 0.1Ω current viewing resistor (CVR). The applied voltage was ramped up steadily (approximately 100V/s) until a flashover event initiated at the cathode, and the voltage was turned off immediately after the surface flashover event occurred. The same procedure was repeated several times until a steady surface flashover voltage was reached. In some cases, however, after a few shots, the breakdown voltage became unpredictable. For these samples, the experiments were terminated, and the sample was taken out of the chamber for examination and surface analysis.

EXPERIMENTAL RESULTS

It should be noted that the present experiments were conducted using a non-uniform electric field since the electrodes were rounded at the tips, but flat on the surface contacting the sample's surface (see Figure 1) to avoid any sharp structure that may enhance the field at the vacuum electrode interface. With this electrode geometry, the highest electric field was on the surface of the dielectric where the electrode separation was the smallest. Under this condition it was expected that the field emitted electrons from the cathode would follow the field lines while propagating toward the anode, and initiate a surface flashover discharge. This behavior was verified by observing the light emission during the surface flashover events, and the voltage collapse and the current increase were recorded as the evidence of the events.

Surface Flashover Voltage Waveform

The waveform data for all the samples were normalized to compare the exact shape and time evolution of the signals obtained during the surface flashover events. This comparison of voltage wave forms as a function of time for all the samples showed that the TeflonTM, quartz, free-standing polycrystalline and single crystal diamond samples exhibited the same characteristics. The breakdown event (the

voltage collapse) occurred in few (1 to 2 ns) ns. However, the duration of the surface flashover was considerable long (in the order of 7 to 8 μ s). On the contrary, although the voltage collapse time was again in few ns, the voltage recovery time (or the breakdown duration) was in the order of 100 ns for the thin films (DLC/Si, DLC/SiO₂/Si, D/Si, SiO₂/Si) on silicon samples regardless of the film thickness.

This result indicated that the film thickness was not a major effect on the surface flashover characteristics of these materials. However, having the substrate, which is a semi-conducting material, had played an important role in the duration of the breakdown. Dielectric film on semiconductor material structure seemed to have appeared to the field as a metal-insulator-semiconductor (MIS) diode, and depending on the biasing level and/or direction, a mechanism similar to an avalanche breakdown on bulk breakdown may have occurred. Also, having a dielectric interface, namely SiO₂ between DLC and Si seemed to have increased the integrity of the film to the applied field.

All these thin films including the diamond film, exhibited "conductive" nature after few surface flashover events. Furthermore, it was observed that the DLC samples were more vulnerable to the high electric fields. After few shots, only these DLC samples experienced visible permanent damage on them at the vicinity of the cathode "foot" print, where the flashover was initiated and where the field was the highest [3]. These samples were taken out of the vacuum chamber for surface analysis.

It was reported above that the polycrystalline diamond sample did not have an optical quality surface smoothness. And yet behaved the same as the DLC films in terms of vulnerability to high voltages, i.e., lost high dielectric properties, and became conducting after a few shots. However, there was no visible permanent damage on the surface of the sample. Furthermore, the breakdown voltage waveform and order of magnitude of the breakdown voltage of D/Si were same as the other thin film samples having optical quality surfaces [2]. Therefore it may be concluded that the surface condition didn't seem

to be an important factor in the initiation or time evolution of the surface flashover events.

Surface Flashover Voltage

Several sets of experiments were conducted with all the samples. Figure 2 shows the breakdown voltage of thin films (DLC/SiO₂/Si, DLC/Si, SiO₂/Si, and D/Si) for different event number.

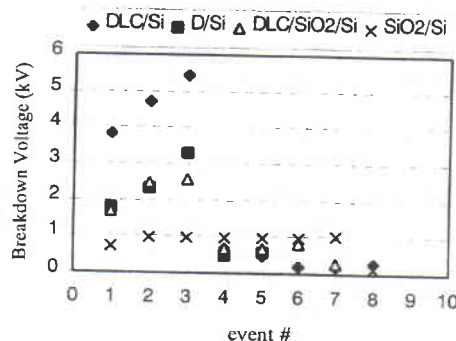


Figure 2. Breakdown voltage versus event number for four different thin-film samples. The electrode separation was 3 mm throughout these experiments.

It is seen in this data that DLC/Si seems to have the highest breakdown voltage approaching 5.5 kV, in comparison SiO₂/Si has the lowest breakdown voltage (approximately 1. kV). Further, the electrode conditioning phenomena, where the breakdown voltage increase with the event number and reaches to a steady breakdown voltage level was observed for each sample under investigation. However, after a few shots, as seen in Figure 2, (in most cases this was after the 3rd or 4th event), the samples seemed to have lost the dielectric, or high resistivity properties, and the breakdown voltage suddenly became very low. It was also observed that there was a relatively low intensity of light emission, and the breakdown voltage waveform seemed to have exhibited "micro" surface flashover events. The maximum current however was relatively low, on the order of mA. The next and the following surface flashover events occurred at much lower

voltage levels, and the tests were terminated after 7th or 8th shot for each sample. On the contrary, although the surface flashover breakdown voltage was much lower compared to the other thin film samples, the SiO₂/Si sample did not experienced similar catastrophic breakdown event, and it sustained its dielectric characteristics longer than the others.

Figure 3 shows the same plot for free-standing polycrystalline diamond and single crystal diamond samples. It should be noted that the surface of the free standing polycrystalline diamond was polished to an optical quality smooth surface.

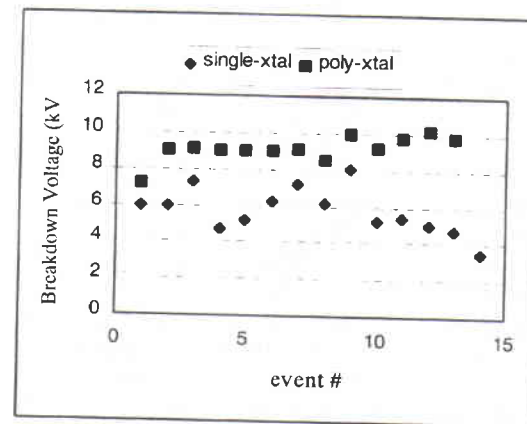


Figure 3. Breakdown voltage versus event number for single crystal and polycrystalline diamond samples. The electrode separation for these experiments was 1 mm.

In Figure 3, the surface flashover voltage seems to remain at approximate value of 9.5 kV, whereas the single crystal sample's breakdown voltage seems to oscillate around 5.8 kV range with a variation of ± 3 kV. This was an unexpected result because the surface quality of this sample was same as the polycrystalline and quartz sample. In a previous work, surface flashover characteristics of a quartz sample was studies and, it was found that the breakdown voltage increased for the first few shots and stabilized at approximately 15 kV range [7]. The polycrystalline sample's surface flashover characteristics are similar to the quartz's case.

Optical Emission Characteristics

Optical diagnostics light emission during the surface flashover events were recorded by several instruments namely, optical multi-channel analyzer (OMA) to record optical spectroscopy, CCD camera to record optical image, and photo-multiplier tube (PMT) to record the time evolution of the light emission. The CCD camera images revealed that the surface flashover starts at the cathode-dielectric-vacuum interface as a small "hot" spot and then develops to a full arc propagating across the surface of the dielectric to the anode. One needs to note that the intensity of the light emission during the surface flashover of thin-film samples was relatively low for the CCD camera to detect. Therefore, only the light emission images of the surface flashover of quartz, free-standing and single crystal samples were recorded.

An OMC was used to investigate the nature of the emission spectrum. Optical spectrum of the light emission during the surface flashover was recorded and the wavelength identification was conducted. The emission spectrum of the plasma produced during the surface flashover of quartz sample showed that the emission was mainly due to the nitrogen species. The first negative and second positive molecular emission bands were the strongest emission bands. In addition to these, there were lines belonging to SiO_2 molecule [2]. These results indicate that the residual gas present in the vacuum chamber plays an important role in the initiation of a surface flashover and in the generation of a plasma environment in the vicinity of the electrodes. Also, the lines belonging to SiO_2 molecule indicated that the applied electric field has sufficient energy to excite the bound molecules in the solid dielectric material.

The intensity of the light emission from the polycrystalline was too low for OMA sensitivity to obtain any valuable data. However, visual observation of the emission indicated that the emission was in the blue, blue-violet region of the spectrum. This is in agreement with the data in the literature that the emission from polycrystalline diamond was reported to be a broad band spectrum with highest intensity

centered at 2.85 eV (435 nm) with two side bands centered at 2.155 eV (575 nm), and 1.68 eV (738 nm) [10]. In that work, these emission lines were attributed to the deep donor acceptor pair recombination, and broad vibronic band with a zero phonon line. In comparison, we may conclude that the emission in our observation is similar to the ones given above and is a result of a zero-phonon line, which in turn is due to a nitrogen vacancy complex. Considering that the field-emitted electrons may penetrate into the material, the effect may be interpreted as electron injection into the dielectric material, and would be responsible for the light emission.

Optical spectrum of the emission from the single crystal diamond was recorded by the OMA. This spectrum showed that it was a broad band emission with a peak at 550 nm and tail towards the infrared. The mechanism for this emission was concluded to be as similar to the one seen in polycrystalline case, where the field emitted electrons are injected into the material and excited the molecular levels in the dielectric. However, studies are continuing to investigate the nature of the light emission from these materials further.

The PMT data showed that the light emission during the surface flashover for quartz sample was on the order of several micro-seconds, almost same duration as the voltage recovery time for this sample. However, the duration of the light emission from the free standing polycrystalline and single crystal diamond films was on the order of several seconds, which was much longer than the voltage recovery time. This is another reason that we believe that the light emission was result of excitation and de-excitation of the molecules/atoms within the crystalline structure.

Outgassing Effects:

Desorbing or outgassing gas molecules in vacuum can also contribute to the surface flashover initiation [2, 9]. Any surface of solid (dielectric or other) exhibit forces of attraction normal to the surface and gas is

normally adsorbed on all the surfaces, when left in atmospheric environment long enough. Under certain conditions of temperature and pressure, this gas is desorbed and constitutes one of the main sources of gas in vacuum. The material outgassing is another source of increased gas density in the vicinity of the surfaces. This molecular or atomic gas density gradient near the dielectric lowers the surface breakdown potential threshold further, because the breakdown potential depends on the operating pressure.

In search of effect of outgassing and desorption, we used a mass spectrometer to determine the gas species before and after each experimental set of each sample being investigated. These experiments showed that before the surface flashover events, the gas composition was mainly of water, nitrogen, hydrogen, oxygen, and carbon-dioxide, which are concluded to be result of adsorption of atmospheric species in the vacuum chamber. However, mass spectroscopy experiments showed no traces of gas species that might be by product of the synthetic thin film dielectric materials (DLC or polycrystalline diamond) after the surface flashover events. This may be due to the fact that the surfaces area of the samples is much smaller compared to the surface area of the vacuum chamber, and the amount of outgassing or desorbing gas from the samples is much less than the detectable level for the mass spectrometer. On the contrary, mass spectrometer analysis of TeflonTM sample after the flashover events showed traces of perfluorotributylamine (PFTBA) and trifluoroethane (C₂H₃F₃) molecules, which are most likely to be by-products of TeflonTM sample. Also, optical diagnostics of the plasma generated during the flashover showed similar results as the mass spectroscopy analysis.

CONCLUSIONS

Experiments to investigate surface flashover characteristics of material intended to be used in space environment conducted. The results showed that polycrystalline and DLC thin films might not be suitable materials for high voltage application as dielectric material in vacuum when coated onto semiconductor material. Having a dielectric interface between the DLC and silicon seemed to improve the breakdown characteristics, however it was determined that this also was not sufficient to have a reliable film for HV applications. All the thin films experienced permanent damage; therefore they were vulnerable for HV applications. The duration of the surface flashover was on the order of 10s of ns for thin films. However it was on the order of several micro-seconds for the other free standing samples. Also, there was almost no light emission during the surface flashover for thin films, where as the light emission was a long duration event for the other, free standing films. It was concluded that the light emission was due to the excitation and emission of impurities within the crystal structure for the diamond samples, whereas the light emission was due to the background gas for the case of quartz sample.

REFERENCES

- [1] M. Gollor and K. Rogalla, "HV Design of Vacuum-Insulated Power Supplies for Space Applications," IEEE Trans. Elect. Insul., vol. 28, pp 667-80, 1993
- [2] H. Kirkici, M. F. Rose, R. Ramesham, and R. F. Askew, "Surface Breakdown Characteristics of Polycrystalline Diamond Thin Films in Vacuum," 1994 CEIDP Annual Report, 94-CH3456-1, pp 699-704, October, 1994.
- [3] H. Kirkici, "Surface Flashover Characteristics of Diamond-Like-Carbon (DLC) in Vacuum," IEEE Trans. on Dielectrics and Electrical Insulation, vol. 4, pp 71-78, 1997

- [4] H. Kirkici, "Optical mission Characteristics of Polycrystalline Diamond during Surface Flashover in Vacuum," IEEE Trans. Dielectrics and Electrical Insulation, vol. 4, pp822-26, 1997.
- [5] P. H. Gleichauf, "Electrical Breakdown over Insulators in High Vacuum," J. Appl. Phys., vol. 22, pp 535-41, 1951
- [6] H. C. Miller, "Surface Flashover of Insulators," IEEE Trans. Electr. Insl., vol. 24, pp 765-86, 1989.
- [7] H. Kirkici, M. F. Rose, R. R. Criss, R. Ramesham, and R. F. Askew, "Optical Spectroscopy Studies of Surface Breakdown of Polycrystalline Diamond Thin Films in Vacuum," 1994 CEIDP Annual Report, 94-CH3456-1, pp 606-611, October, 1994.
- [8] G. Masten, T. Muller, F. Hegeler, and H. Krompholz, "Plasma Development in the Early Phase of Vacuum Surface Flashover," IEEE Trans. Plasma Science, vol. 22, pp 1034-42, 1994.
- [9] R. A. Anderson and J. P. Brainard, "Mechanism of Pulsed Surface Flashover Involving Electron-Stimulated Desorption," J. Appl. Phys., vol. 51(3), pp 1414-21, 1980.
- [10] L. H. Robins, L. P. Cook, E. N. Farabaugh, and A. Feldman, "Cathodoluminescence of Defects in Diamond Films and Particles Grown by Hot-Filament Chemical-Vapor Deposition," Phys. Rev. B, vol. 39, pp 13367-77, 1989.