Electron Induced Charging and Arcing of Multilayered Dielectric Materials

JR Dennison, Gregory Wilson, Amberly Evans and Justin Dekany

USU Materials Physics Group
Utah State University, Logan, Utah 84322-4415

Abstract

Measurements of the charge distribution in electron-bombed, thin-film, multilayered dielectric samples showed that charging of multilayered materials evolves with time and is highly dependent on incident energy. This is driven by electron penetration depth, electron emission and material conductivity. Based on the net surface potential’s dependence on beam current, electron range, electron emission and conductivity, measurements of the surface potential, displacement current and beam energy allow the charge distribution to be inferred. To take these measurements, a thin-film disordered SiO2 structure with a conductive middle layer was charged using a 200 eV and 5 keV electron beam with regular 15 μC pulses of ±100 kA/cm². Results show that there are two basic charging scenarios which are consistent with simple charging models; these are analyzed using independent determinations of the material’s range, energy, and conductivity. Large negative net surface potentials led to electronic breakdown and large visible arcs, which have been observed to lead to detrimental spacecraft charging effects.

Experimenter

In order to investigate the charging of multilayered dielectric materials, pulsed charging experiments were conducted using multilayered dielectric materials of a SiO2 based optical coating, a conductive middle layer and an SiO2 substrate. Texts were made with the conductive layer both grounded and ungrounded. Experiments were conducted in the main USU electron emission ultrahigh vacuum test chamber, modified for observations of low intensity UV/VIS/NIR glow over a broad range of sample temperatures. Figure 1 provides a general schematic of the experimental system used.

The samples were subjected to short pulses (1−15 s) of electron bombardment using a monoenergetic electron beam with beam energies of either 200 eV or 5 keV. A low energy electron gun [Einh-K-10] was used, that can deliver a well-characterized, low-flux pulsed beam (typically 500 kA/cm²) over an energy range of 20 eV to 5 keV. The defocused electron beam produced a beam profile at the sample with a uniform beam current density over an ~3 mm diameter beam spot. Beam fluxes were monitored with a Faraday cup. Beam current densities of 251±6 kA/cm² at 200 eV and 2.74±1 kA/cm² at 5 keV were used for the experiments reported here, with an exposed sample area of 4.90±0.2 cm².

Four experiments are considered as depicted in Fig. 6. The experiments differ in terms of the incident energy and flux, and as we will see below, produce dramatically different results. To interpret the results of the experiments, we consider three physical phenomena—the electron range, electron yield and conductivity—and how they are affected by the experimental conditions.

Fig. 1. Block diagram of instrumentation for collecting the pulse charging surface voltage and displacement current data. Schematic drawing of a large-area electron bombardment. Instrumentation includes a vacuum chamber, electron beam source, beam current monitor, secondary electron detector, UV/VIS/NIR spectrometer, charge sensitive camera, and a NR video camera for optical measurements.

Results

Surface Dielectric Deposition–Ungrounded

For a 200 eV monenergetic electron beam the electron range in disordered SiO2 is approximately 3 nm, as shown in Fig. 2(a). At this depth, the electrons just penetrate into the first layer, but do not reach the conductive layer. From Fig. 2(b) the total yield for disordered SiO2 at this energy is 1 μC, which leads to a low surface potential response. Thus, in this incident energy range, net charge should see a low-limiting net deficit of electrons; this agrees with the sign of the measured net surface potential as measured in Fig. 7(a).

Surface Dielectric Deposition–Grounded

For a 200 eV electron beam with a grounded conductive layer, we expect similar behavior for the surface voltage as seen for the ungrounded sample. Positive surface voltage is observed in Fig. 7(b), as expected.

Conductive Layer Deposition–Ungrounded

For a 5 keV electron beam with an ungrounded conductive layer, we again deposit charge in the conductive layer. We also have a total electron yield less than unity as before. Because the conductive layer is ungrounded there will be no fast charge dissipation mechanism. Thus, because there is no limiting behavior from re-attraction of secondary electrons, we see a high net negative potential. This is confirmed in Fig. 7(c). For this scenario, after higher negative net surface potentials were reached, breakdown and arcing was observed.

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Theory

Backscattered electrons undergo a quasi-elastic collision near the surface and backscatter, imparting no net energy to the surface. Secondary electrons are emitted by the target material generated by incident electrons that undergo collisions near the surface, which impart energy to several other electrons in the material. Some of these secondary electrons then escape the material’s surface leading to net charge loss. The primary yield is the sum of the backscattered yield and the secondary yield. When the total yield is less than unity, charging is negative. When the total yield exceeds unity, the material’s surface becomes positively charged. As the net surface potential reaches a potential of a few volts positive, some secondary electrons are re-attracted to the surface which then can recombine with electron holes creating an upper limit on the secondary yield.

Conductivity

The conductivity of a material determines how easily a deposited charge layer can move through the material in response to an electric field. The current density produced by the embedded charge layers, the depletion layer, and the positive charge between these planes in the material are modeled in Figs. 5 and 6. The measured currents will have two terms, a particle current conductivity proportional to the conductivity and a displacement current due to the change in the electric field due to charge accumulation.

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