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Electron Energy Dependent Charging Effects of Multilayered Dielectric Materials

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Abstract

Measurements of the charge distribution in electron-behondared, 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 the incident electron penetration depth, electron emission and material conductivity. Based on the net surface potential, displacement current at beam end, electron current, 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 deposited SiO$_2$ structure with a conductive middle layer was charged using 200 eV and 5 keV electron beams with regular 15 eV pulses at 1 nC/m$^2$. 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 electron range, yields, and conductivity. Large negative net surface potentials led to electronic breakdown and large visible arcs, which have been observed to lead to detrimental spacecharge effects.

Experimentation

In order to investigate the charging of multilayered dielectric materials, pulsed charging experiments were conducted using multilayered dielectric materials of SiO$_2$ based on the coating, a conductive middle layer and an SiO$_2$ substrate. Samples were made with the conductive layer both grounded and ungrounded. Experiments were conducted in the main USU electron emission and thin-film vacuum test chamber, modified for observations of low intensity UV/VIS/IR glow above a broad range of sample potentials. Figure 1 provides a general schematic of the experimental system used.

The samples were subjected to short pulses ($\leq 500$ s) of electron bombardment using a monochromatic electron beam with beam energies of 300 eV and 5 keV. A low energy electron gun (UET, EK-51k) was used, that can deliver a well-characterized, low-flux pulsed beam (90μA/cm$^2$ to 1 μA/cm$^2$) over an energy range of 20 eV to 6 keV. The delivered electrons were focused into a beam profile at the sample with about 30μA/cm$^2$ uniformity over an ~3 cm diameter beam spot. Beam fluxes were monitored with a microammeter for current measurements and UV/VIS and IR spectrometers, an SRL CCD still camera, and a NIM video camera for optical measurements.

Backscattered electrons undergo a quasi-electrostatic collision with the surface and backscatter, imparting no net charge into the material. Secondary electrons are generated by incident electrons that undergo collisions near the surface, which impart energy to several other electrons in the material. This produces a displacement current at beam end, which leads to the generation of net charge at the surface leading to net charge loss. The total 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 critical potential of a few volts, some secondary electrons are emitted from the surface which then recovers and backscatter with electron holes creating an upper limit on the net surface potential.

Conductors

The conductivity of a material determines how easily deposited charge layer can move through the material in response to an electric field. The electric field at a position inside the material produced by the embedded charge layers, the depletion layer, and the conductive layer is the material as modeled in Eqs. 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.

Theory

Four experiments are conducted as depicted in Fig. 6. The experiment differs in terms of the incident energy and flux, and as we will see below, produces dramatically different results. To interpret the experiment, we use the three physical phenomena—the electron range, electron yield and the electron transport (conductivity) of the material—and how they are affected by the experimental conditions.

Surface Dielectric Deposition—Ungrounded

For a 200 eV monochromatic electron beam the electron range in disordered SiO$_2$ is approximately 3 nm, as shown in Fig. 2(a). At this depth, the electrons just penetrate into the first layer, and do not reach the conductive layer. From Eq. (6), the total yield for disordered SiO$_2$ at this energy is ~0.5, which is a positive net surface potential yield. Thus, we should see a small limiting potential at a net surface potential due to a 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 monochromatic electron beam with a grounded backplane, we expect similar behavior for the surface voltage as seen for the ungrounded scenario. Positive surface potentials is observed in Fig. 7(c), as expected.

Conductive Linear Deposition—Ungrounded

For a 5 keV monochromatic electron beam the electron range in disordered SiO$_2$ is ~580 nm, as shown in Fig. 2(b). Therefore, the electrons penetrate through the surface dielectric and into the conductive layer. The total yield for disordered SiO$_2$, at this energy is ~1, which should lead to a negative net potential in Fig. 7(b).

Conductive Linear Deposition—Grounded

For a 5 keV monochromatic electron beam with an ungrounded conductive layer, we again expect positive charge added to the conductive layer. Also we also have a total electron yield less than unity as before. Because the conductive layer is ungrounded there will be no fast charging depolarization mechanism. Therefore, there is no limiting behavior from extracation of secondary electrons, we should see a high net negative potential in Fig. 7(c). For this scenario, after higher negative net surface potentials were reached, breakdown and arcing was observed.

Results

Fig. 4. Diagram of incident electron flux impinging on a generic material, $\gamma_{0,SK}$ denotes the backscattered yield and $\gamma_{0,SK}$ denotes the secondary yield. The total yield is the sum for all electron energy groups to the net secondary yield $\gamma_{0,SK}'$.

Fig. 5. Electric fields arise due to embedded charge layer(s) and grounded planes. The resulting electric field can lead to charge transport. Using the embedded charge layer and displacement currents resulting from charge migration to the grounded planes. Conductivity determines how fast embedded charges can move.

Fig. 6. Measurements of surface potentials vs. time (a, e, f) and test electrodes and conductive layers vs. time (b, d, h) for: (a, b) surface dielectric deposition with low energy electron beam and ungrounded conductive layer; (c, d) surface dielectric deposition with low energy electron beam and grounded conductive layer; (e, f, g) diode structures with high energy electron beam and ungrounded conductive layer; and (h, i) diode structures with high energy electron beam and grounded conductive layer. $\delta$ in the figures refers to the current vs. bias based on Eq. 5 with $b = 0.95$, $r = 0.95$, $\tau = 507$ s, (i) conductive layer $r = 0.95$, $\tau = 507$ s, (j) electron beam $r = 0.95$, $\tau = 507$ s, (k) electron beam $r = 0.95$, $\tau = 507$ s, (l) electron beam $r = 0.95$, $\tau = 507$ s.