The secondary electron emission yield of muscovite mica: Charging kinetics and current density effects

G. Blaise, F. Pesty, and P. Garoche
Laboratoire de Physique des Solides, CNRS-UMR8502, Univ Paris-Sud 11, F-91405 Orsay cedex, France

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Using a dedicated Scanning Electron Microscope (SEM), operating in the spot mode, the charging properties of muscovite mica have been studied in the energy range 100–8000 eV. The intrinsic yield curve $\sigma_0 (E)$, representing the variation of the yield of the uncharged material with the energy $E$, has been established: the maximum value of the yield is 3.92 at $E = 300$ eV and the two crossovers corresponding to $\sigma_0 (E) = 1$ are respectively at energies $E_I < 100$ eV and $E_{II} = 4850$ eV. At a given energy and under a low current density $J \leq 100$ nA/cm$^2$, the yield varies with the electron fluence from its intrinsic value $\sigma_0$ up to the value corresponding to the Self Regulated Regime (SRR) for which $\sigma = 1$. This variation is independent of $J$. The fluence dependence of the yield $\sigma(D)$ is due to the internal field produced by the accumulation of charges that blocks the emission when the charging is positive and enhances it when it is negative. At room temperature, the relaxation time of stored charges is estimated to be of the order of 250 sec for holes and 150 sec for electrons. Three current density effects have been observed when $J \geq 400$ nA/cm$^2$. (i) The variation of $\sigma(D)$ with the fluence $D$ depends on $J$. (ii) Negative charging is obtained at high current density in the energy range $(E_I, E_{II})$ where the material is normally positively charged at low current density. (iii) Electron exo emission (bursts of electrons) is produced at low energy when the net stored charge is positive. The interpretation of the current density effect on $\sigma(D)$ is based on the high rate of charging, the effect relative to negative charging is due to the expansion of the electron distribution, while the exo-emission effect is due to the collective relaxation process of electrons. © 2009 American Institute of Physics.

[I. INTRODUCTION]

Muscovite mica is one of the most common insulators being used in power electronics capacitors because it exhibits outstanding insulation properties, combined with good mechanical and thermal properties. It is a highly reliable material exhibiting low ionizing radiation-induced conductivity and resistant to electrical micro discharges that cause instabilities in electronic circuits and are precursors of electrical breakdown. Muscovite mica exhibits a rather high relative permittivity, $\varepsilon_r \approx 7$ in the samples used, compared with solid polymers ($\varepsilon_r \approx 2–3$) also used in high voltage capacitors. Its dielectric strength, $\approx 100$ MV/m, is rather good and its resistivity $\approx 10^{17} \Omega \cdot \text{cm}$ lies near or above the maximum of the resistivity range of insulators ($10^9–10^{15} \Omega \cdot \text{cm}$). The energy loss factor $\approx 0.2 \%$, is extremely low.

For many years it has been recognized that the field strength of an insulator is relevant to the formation of a space charge. As a consequence, a number of methods have been developed for characterizing the charging properties of dielectric materials. Among them those in which the sample is subjected to the irradiation of a dedicated electron beam (energy, intensity, spot size...) are of a particular interest because they do not require electrode deposition and they allow a large investigation of the charging parameters. In fact this potentiality was not really exploited in the past. Most of the studies were focused only on the measurement of the energy dependence of the intrinsic SEE yield, $\sigma_0 = f(E)$, that is the yield of the uncharged material.\footnote{Author to whom correspondence should be addressed. Electronic mail: pesty@lps.u-psud.fr} For that it is necessary to maintain the surface potential close to zero in order to avoid the undesirable effect of charging on the emission of secondary electrons. As early as 1954, Bruining recommended the use of a pulse injection method. Since that time various compensation methods were developed, the most popular being the use of a flooding electron gun to prevent the sample from positive charging.\footnote{Electronic mail: pesty@lps.u-psud.fr}

Stranger enough, no intensive work on mica has been carried out in order to elucidate the reasons of its good dielectric properties. One of the most recent work on the subject is that of Hopman et al.\footnote{Electronic mail: pesty@lps.u-psud.fr} who proposed a compensation pulse method by alternating the magnitude of the voltage applied to the sample in such a way that the surface positively charged for one pulse becomes negative for the next one. This method presents a specific interest for our work since it was applied to mica.

For a few years we have been developing a scanning electron microscopy method for the characterization of insulating dielectrics based upon the...
The experiments are carried out in the spot mode by defocusing the electron beam on an area much larger than the penetration depth. This simple planar geometry allows the surface potential and the internal field to be estimated easily. Let \( Q_{SC} \) be the total stored charge on the disc of diameter \( \Phi \). Assuming the net stored charge density \( D_{SC} = Q_{SC}/(\pi \Phi^2/4) \) is uniform on the irradiated area, the potential and the field along the axis of the disc can be expressed in a simple way using the image theory.

Let \( e \) be the thickness of the mica sample and \( \Phi \) the diameter of the irradiated area. The potential \( V_S \) at the mica surface can be assimilated to the potential in the centre of the charged disc, that is:

\[
V_S = V_S^\infty \left[ 1 + \frac{4e}{\Phi} \left( 1 - \left( 1 + \frac{\Phi^2}{16e^2} \right)^{1/2} \right) \right]
\]

with:

\[
V_S^\infty = \left[ 2\varepsilon_0 \left( 1 + \varepsilon_r \right) \right]^{-1} \Phi \ D_{SC}
\]

Here, \( V_S^\infty \) is the surface potential of a sample of infinite thickness \( e \). The second part in Eq. (3) is a correcting factor depending on the ratio of the sample thickness to the diameter of the irradiated area. In practice the numerical expression for mica, with \( \varepsilon_r = 6.9 \), is:

\[
V_S^\infty = 7.16 \times 10^{-5} \Phi \ D_{SC}
\]

where \( D_{SC} \) is expressed in pC/cm² and \( \Phi \) in \( \mu \)m.

In the same way, the field inside the disc, just beneath the surface, is expressed as:

\[
\sigma = \frac{\Delta Q_{SB} + \Delta Q_{SC}}{\Delta Q} \sigma_{measured after the induced charge measured on the sample holder collector through the SiO₄ tetrahedral layer. The LEED diffraction (001), composed of half the potassium layer, lying onto the oxygen atoms in the successive sheets, there is only one symmetry element for the diffraction pattern: the plane which is perpendicular to either the 013 direction, according to whichever face is being observed after cleavage (there are two non equivalent sheets in the lattice cell).

The muscovite crystals used in this work are obtained from industrial insulators for power electronics (transistor mounting washers). The muscovite crystals have been air-cleaved, then annealed at 300°C for one hour, prior to introduction into the vacuum chamber of the microscope. Measurements have been carried out under 7.10⁻⁷ mbar. The electron beam direction is normal to the basal plane (001) of the muscovite.

B. Experimental setup

The experimental set up for measuring the SEE yield is a Scanning Electron Microscope equipped with two complementary detectors surrounding the sample, as shown in Fig. 1. The charge \( \Delta Q_{SB} \) of secondaries and backscattered electrons is collected on the secondary backscattered (SB) detector held at a -100 V bias voltage, in order to prevent any electron from returning to the sample surface when the latter is positively charged. The charge \( \Delta Q_{SC} \) stored in the insulator is measured on the sample holder collector through the induced charge \( \Delta Q_{IC} = -\Delta Q_{SC} \). The complementary collection of the two detectors imposes:

\[
\Delta Q_{SB} + \Delta Q_{IC} = \Delta Q
\]

where \( \Delta Q \) is the real charge delivered to the sample by the electron beam.

The average SEE yield \( \bar{\sigma} \) measured after the injection of the charge \( \Delta Q \) is then given by:

\[
\bar{\sigma} = \frac{\Delta Q_{SB}}{\Delta Q} = \frac{\Delta Q_{IC}}{\Delta Q}
\]
In the following, the variation of the SEE yield $\sigma(D)$ is plotted as a function of the fluence $D = Q(\pi/4)\Phi^2$ expressed in pC/cm$^2$ ($Q$ being the injected charge in pC). The correct measurement of $\sigma$ as a function of the fluence injected all along the pulse, implies that during each time increment $\tau$ the SEE yield varies from a quantity less or equal to the accuracy with which $\sigma$ is measured. This mandatory condition implies to adjust the injected fluence to the required measurement. The measurement of the intrinsic yield $\sigma_0$, i.e., the yield of the uncharged material, requires a very low fluence: typically 100 to 1000 pC/cm$^2$. Fluence ten times higher has to be injected to study the charging kinetics. The asymptotic behavior of $\sigma$ requires the fluence to be a hundred times larger. The complete evolution of the SEE yield versus the fluence is obtained by the succession of at least three pulses corresponding to the three mentioned fluence values.

In Fig. 2a the $\sigma(D)$ evolution was recorded on the same irradiated zone during two successive shots delivered at a 200-eV primary energy. The fluence was 0.3 nC/cm$^2$ in the first one and 1.5 nC/cm$^2$ in the second one. During each fluence increment, respectively of 1.2 pC/cm$^2$ and 6 pC/cm$^2$, the relative variation of $\sigma$ is less than 0.5 %. As it is much less than the precision of the measurement (1–3 %), it is concluded than the $\sigma(D)$ variation is representative of the charging kinetics of mica. In particular, the measurement of the intrinsic yield $\sigma_0$ deduced from the upper plateau is $\sigma_0 = 3.36 \pm 0.03$.

In Fig. 2b the injected fluence was about 200 nC/cm$^2$ on a virgin area, different from the one irradiated in Fig. 2a. The fluence increment is 735 pC/cm$^2$. Referring to Fig. 2a the yield has dropped by about 30 % after the injection of this fluence. Clearly the conditions are inadequate for measuring the intrinsic yield correctly. This is why the initial yield $\sigma_0 = 2.83$ is much less than the real intrinsic yield measured before. Conversely, when the variation of $\sigma(D)$ is slow, at the end of the pulse, the asymptotic steady value $\sigma_\infty = 1 \pm 0.01$ is well established.

The charge surface density $D_{SC}$ stored at the time $t$ of injection during the pulse of duration $T$ is obtained by integrating the induced current $I_{IC}$ according to Eq. (9)

$$
\frac{\Phi^2}{4} D_{SC}(t) = \int_0^t I_{IC}(t) dt
$$

(8)

The variation of $D_{SC}$ with the fluence is shown in Fig. 3 for 200-eV electron injection. At the very beginning of irradiation (insert in Fig. 3) the initial slope of the curve is zero, which corresponds to the upper plateau $\sigma_0$ in Fig. 2a. This feature guaranties the good value of the intrinsic yield $\sigma_0$. At the end of the pulse the total stored charge is $D_{SC} = 2.3$ nC/cm$^2$. It is obvious that increasing the irradiation time, the stored charge would have still increased. This point will be examined further.
FIG. 3: Variation of the positive stored charge density $D_{SC}$ as a function of the electron fluence $D$ at 200 eV. Same conditions as in Fig. 2. The graph in inset displays the initially horizontal slope of the charging curve, which corresponds to the measurement of the intrinsic yield $\sigma_0$ in Fig. 2a.

III. DEPENDENCE OF THE INTRINSIC YIELD $\Sigma_0$ WITH ENERGY

The measurements of $\sigma_0$ were carried out under the conditions mentioned above, that is: low current density $J \approx 12$ nA/cm$^2$, fluence $\leq 1200$ pC/cm$^2$ with 20 pA primary current on an area of diameter $\Phi = 456$ μm. The values of $\sigma_0$ in Fig. 4 are the average of measurements on three different samples taken from the same muscovite mica. Three measurements were carried out on each sample, on three virgin areas 2 mm away from each other in order to avoid any influence of the charging of one spot on the electron emission of the other one. The precision on $\sigma_0$ is 2-3 % when energy is less than 800 eV and about 1 % above.

The maximum yield $\sigma_{0\text{max}} = 3.92 \pm 0.1$ is obtained at the energy $E_m = 300 \pm 25$ eV. A more accurate value of $E_m$ would require a series of measurements on both sides of the maximum, which is very sample consuming for a minor interest. By extrapolating the $\sigma_0$ curve at very low energy, we can estimate the crossover energy $E_i$, for which $\sigma_0(E_i) = 1$, to be in the range 50 to 100 eV. As well, the interpolation of $\sigma_0$ between 4000 and 6000 eV leads to the energy value $E_{II} = 4850 \pm 25$ eV for the second crossover for which $\sigma_0(E_{II}) = 1$.

IV. CHARGING DYNAMICS OF MICA

A. Time stability of the stored charges

The time stability of the stored charges can be easily appreciated by delivering two shots on the same area, separated by a time interval $\Delta t$. If the $\sigma$ response to the second shot is exactly in the continuity of the first one, it is concluded that charges are stored on fixed sites at the time scale $\Delta t$. For example, at room temperature charges in silica, alumina and magnesia single crystals are permanently trapped on fixed sites. If the $\sigma$ response to the second shot overlaps the response to the first one in part, it is concluded that a fraction of charges stored during the first shot have disappeared from the implantation zone where they were produced. In other words a relaxation process, not specified for the moment, has occurred during the time $\Delta t$, that eliminates charges from the implanted area.

FIG. 4: Intrinsic yield $\sigma_0$ of muscovite mica as a function of the primary electron energy (in keV). With a calibrated primary current $I = 20$ pA on an area of diameter $\Phi = 456$ μm, with a current density $J = 12$ nA/cm$^2$ and fluence $\leq 1.2$ nC/cm$^2$. Maximum yield at 300 eV, crossover energies: $50 < E_i < 100$ eV and $E_{II} = 4850$ eV. Each point is the average of 9 measurements. Precision 2-3 % for $E < 800$ eV, 1 % above.

The $\sigma$ response to the two shots is represented in Fig. 5 for mica irradiated at 500 eV (as $\sigma > 1$, mica is positively charged). During the first shot, 0.6 nC/cm$^2$ were delivered to the sample. The final value of the SEE yield was $\sigma_f = 1.80$ and the stored charge $D_{SC} = 750$ pC/cm$^2$. At the onset of the second shot, triggered 5 min after the first one, the initial yield $\sigma_i = 2.27$ is greater than $\sigma_f$. This means that a certain amount of charges stored during the first shot has disappeared from the implanted area. By superimposing the two curves, it is deduced that the remaining positive charge amount was 102 pC/cm$^2$ just before the second shot. In other words 85 % of the positive charges have vanished in 5 min.

FIG. 5: Variation of $\sigma$ as a function of the fluence at 500 eV during two shots delivered at 5 min time interval, on the same area. Experimental conditions: calibrated intensity 20 pA, diameter of the irradiated area $\Phi = 456$ μm, current density $J = 12$ nA/cm$^2$. The yield $\sigma_i > \sigma_f$ means that a large amount of charges (about 85 %) have vanished from the implanted zone during the 5 min stop between the two shots.
The fine study of the charge relaxation consists of charging the sample with a high electron fluence, some tens nC/cm², then proceeding to the measurement of σ by injecting a very low fluence of the order of 50 pC/cm², at increasing time intervals. At low energy, between $E_I$ and $E_{II}$, where the net stored charge is positive, the relaxation of holes is studied and at high energy, above $E_{II}$, where the net stored charge is negative, it is that of electrons. To a first approximation the time charge relaxation can be fitted by an exponential function from which the relaxation constant time is deduced. In mica the relaxation time of holes is about 250 sec and that of electrons about 150 sec. From a practical point of view one can consider that the irradiated area has recovered its neutrality after about 15 min.

**1. Positive charging**

The variation of σ with the fluence, at a 300-eV energy, is given in Fig. 6a. The curve was obtained by merging the responses to two shots: the first one of low fluence, 1.2 nC/cm², allows us to follow the rapid decrease of σ from its intrinsic value $\sigma_0 = 3.92$; the second one of higher fluence, 120 nC/cm², delivered a few seconds after the first one, gives the variation of σ up to the steady value $\sigma_{st} = 1$. In Fig. 6a note the change in the fluence increment between the two shots, which passes from 2.4 pC/cm² to 240 pC/cm² from the first one to the other one. When the steady value $\sigma_{st} = 1$ is reached, the yield does not vary any more with the fluence. This is the Self-Regulated Regime (SRR) in which one “secondary plus backscattered” electron is emitted in the average per incoming electron.

This apparent neutrality of the implanted area suggests that charges diffuse in the volume of the sample until they are evacuated through the contact with the metal sample holder. If it were not the case, very rapidly the sample would be inappropriate for further charging experiments, due to its macroscopic charging.

**B. Charging kinetics of mica**

The fluence dependence of σ is always recorded with a low current density $J = 12$ nA/cm² (20 pA electron beam current on a 456-μm diameter area).

![FIG. 6: (a) Variation of σ as a function of the fluence at 300 eV. Experimental conditions: calibrated intensity 20 pA, diameter of the irradiated area $\Phi = 456 \text{ μm}$, current density $J = 12$ nA/cm². Note in the insert the change in the fluence increment that passes from 2.4 pC/cm² for the first shot to 240 pC/cm² for the second one. (b) Variation of the stored charge with the fluence. Once the Self-Regulated Regime is reached, $\sigma_{st} = 1$, the stored charge saturates at the value $D_{SSR} \approx 6.6$ nC/cm².](image)

This variation of the stored charge with the fluence is given in Fig. 6b. Clearly, the charged sample saturates at the value $D_{SSR} \approx 6.6$ nC/cm² when the SRR is established. Under a low current density, mica accumulates a finite amount of charges as all materials do, in which charges are fixed or relax very slowly.

Under the SRR ($\sigma_{st} = 1$), the surface potential calculated from Eqs. (3) to (5) is $V_{SSR} \approx 62$ V for a 40-μm thick sample. Therefore electrons impact the surface at the real energy $E_{SSR} = 300 + 62 = 362$ eV which is an energy much less than the crossover energy $E_{II} = 4850$ eV for which the intrinsic yield equals unity. This result refutes the opinion according to which the steady value $\sigma_{st} = 1$ is obtained when the beam energy is shifted to the crossover energy $E_{II}$.\(^{27}\)

The internal field at the SRR, calculated from Eqs. (6) to (8), is $F_{SSR} \approx 44$ kV/m. It is extremely low as compared to the field strength of mica which is of the order of 100 MV/m.

The charging kinetics described above is observed under low electron fluence, at any energy between $E_I = 50-100$ eV and $E_{II} \approx 4850$ eV where mica charges positively. Only the maximum density of stored charges $D_{SSR}$ at the SRR varies with energy. The variation of $D_{SSR}$ and $\sigma_0$ with energy is represented in

![FIG. 7: Variation of the intrinsic yield $\sigma_0$ (open squares) and the stored charge $D_{SSR}$ at the self-regulated regime (filled triangles), as a function of the electron beam energy, showing the strong correlation between the two parameters. Insert: variation of $D_{SSR}$ with the electron beam energy showing the strong increase of the negative charging beyond the second crossover $E_{II} = 4850$ eV (note the increase in the units by two orders of magnitude).](image)
Fig. 7. The strong correlation between the two parameters is evident: both are maxima at 300 eV and decrease on either side until \( \sigma_0 = 1 \) and \( D_{SRR} = 0 \) at the two crossover energies.

**TABLE. 1: Parameters characterizing the Self-Regulated Regime.** \( E \) is the nominal energy of the electron beam, \( V_{SRR} \) is the surface potential calculated from Eq. (3), \( E_{SRR} \) is the real impact energy of the beam, \( F_{SRR} \) is the internal field calculated from Eq. (6). Experimental conditions: beam current 20 pA; diameter of the irradiated area \( \Phi = 456 \mu \text{m} \); sample thickness \( e = 40 \mu \text{m} \).

<table>
<thead>
<tr>
<th>( E ) (eV)</th>
<th>( D_{SRR} ) (nC/cm²)</th>
<th>( V_{SRR} ) (V)</th>
<th>( E_{SRR} ) (eV)</th>
<th>( F_{SRR} ) (kV/m)</th>
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The values of the surface potential \( V_{SRR} \) with the beam nominal energy are indicated in Table 1. For positive charging the energy shift is always much less than the value of the nominal energy.

**2. Negative charging**

When the beam energy is greater than the energy of the second crossover, the intrinsic yield \( \sigma_0 \) is smaller than unity and mica charges negatively. For example at 6 keV (Fig. 8) the yield starts from its intrinsic value \( \sigma_0 = 0.83 \), increases slowly with the fluence up to the steady value \( \sigma_0 = 1 \) of the SRR.

At the energy of 5 keV just a little bit higher than the crossover energy \( E_{h} \), the fluence of about 12 nC/cm² is sufficient to reach the SRR, at 6 keV energy the SRR is reached after the injection of 2 \( \mu \text{C/cm}^² \) (Fig. 8) and at 8 keV it is 7.2 \( \mu \text{C/cm}^² \). The stored charge density at the SRR is given in Table 1 for these three energies, as well as the resulting surface potential. At a 5 keV energy the surface potential is slightly negative \( (V_{SRR} = -2.3 \text{ V}) \), so that the real beam energy at the impact is very close to the nominal energy. At 6 keV, \( V_{SRR} = -1.3 \text{ kV} \), so that the real beam impact energy is only 4.7 keV. What to think about the repulsive potential of -8.2 kV facing the beam of nominal energy 8 keV? This point will be discussed further in Sec. VI.B.

**V. CURRENT DENSITY EFFECTS**

Keeping the beam current constant, the current density is changed by varying the size of the spot. In Table 2 are given the current densities obtained with 20 pA current in four spots of different sizes. The current density varies by a factor of 8500. Three current density effects were observed.

**A. Internal field induced current density effect**

At 300 eV the same charge \( Q = 2 \text{ pC} \) was delivered on four virgin areas of respective diameter 456, 79, 32.6 and 5 \( \mu \text{m} \) (Table 2). The current densities \( J \) the stored charge densities \( D_{SRR} \) and the initial yields \( \sigma_i \) are indicated in Table 2.

It is clear from Fig. 9 and Table 2 that the SEE yield \( \sigma \) strongly depends on the current density \( J \): by increasing the current density, the initial yield \( \sigma_i \) is lowered and the maximum stored charge \( D_{SRR} \) at the SRR drops strongly. Under the maximum current density \( J = 102 \text{ \mu A/cm}² \) \( (\Phi = 5 \mu \text{m}) \), the decrease of \( \sigma \) is so steep that just two measurements are differing from unity and the stored charge \( D_{SRR} \approx 12 \text{ pC/cm}² \) is at the limit of detection.

Under the low current density \( J = 102 \text{ \mu A/cm}² \) \( (\Phi = 456 \mu \text{m} \text{ in Fig. 9}) \), the fluence increment \( \Delta D \approx 4.8 \text{ pC/cm}² \) is sufficiently low for the condition imposed in Sec. II to be fulfilled in order to obtain the right fluence-dependence of \( \sigma \). The \( \sigma \) curve in Fig. 9 for \( J = 12 \text{ nA/cm}² \) is considered as the standard curve of the SEE yield at a 300-eV energy.

The fact that \( \sigma \) depends on the current density means that during the injection of each fluence increment the SEE yield has varied. This variation is due to the rise of the internal electric field during injections: the higher the current density, the stronger the rise of the field and the lower the measured \( \sigma \) value.

Let \( \overline{\sigma}_1 \) be the average yield measured after injection of the fluence \( D_1 \) on the area of diameter \( \Phi_1 \), under the current density \( J_1 \) and \( \overline{\sigma}_0 \) the average yield obtained under the standard condition, after injection of the fluence \( D_0 \) on the area of diameter \( \Phi_0 \). The identity between the two average values \( \overline{\sigma}_1 = \overline{\sigma}_0 \) is postulated when the internal fields are of equal value in both experiments. Integrating Eq. (2), the stored charge density is expressed as:

\[
D_{SC} = D \left( \sigma - 1 \right)
\]
And the identity between the two fields reads from Eq. (6):

\[
\left(1 + \frac{\Phi_{FS}^2}{16e^2}\right)^{-1/2} D_1 = \left(1 + \frac{\Phi_{SRR}^2}{16e^2}\right)^{-1/2} D_0
\]

To illustrate the procedure, \(D_0\) is the fluence delivered under the standard condition \(J_0 = 12 \text{ nA/cm}^2\) \((\Phi_0 = 456 \mu\text{m})\) and \(D_1\) the fluence delivered under the current density \(J_1 = 408 \text{ nA/cm}^2\) \((\Phi_1 = 79 \mu\text{m})\). In Fig. 9, the first dot gives \(\overline{\sigma}_1 = 2.81\) for the fluence increment \(D_1 = 326 \text{ pC/cm}^2\) \((0.016 \text{ pC in Fig. 9})\). With \(e = 60 \mu\text{m}\), calculation using Eq. (10) yields a fluence \(D_0 = 665 \text{ pC/cm}^2\). Considering the standard curve in Fig. 9 this fluence corresponds to the injected charge \(Q = 1.09 \text{ pC}\) from which the average yield \(\overline{\sigma}_0 = 2.67\) is deduced. Taking the precision into account, this value is in good agreement with the value 2.81 measured under the current density \(J_1\). This procedure has been used to recalculate the \(\sigma\) values at high current density in Fig. 10. The good agreement proves that the current density effect observed is really due to the internal field. This feature has some consequence on the contrast of images (see Sec. V.I.D).

Table 3. Values of the current density effect parameters obtained at 300 eV, in a mica sample of thickness \(e = 40 \mu\text{m}\), after positive charging. \(\Phi\) is the diameter of the irradiated area, \(J\) the current density calculated for 20 pA beam current, \(\sigma_{\text{min}}\) is the minimum SEE yield measured in Fig. 12, \(D_{\text{SRR}}\) is the stored charge density deduced from the curves in Fig. 12. \(V_{SRR}^\text{FS}(\Phi)\) and \(F_{SRR}^\text{FS}(\Phi)\) are respectively the surface potential and the internal field calculated from Eqs. (3) and (6). \(V_{SRR}^\text{FS}(\Phi) = V_{SRR}^\text{FS}(\Phi = 456 \mu\text{m}) + V_{SRR}^\text{FS}(\Phi)\) is the resulting potential on the axis, \(F_{SRR}^\text{FS} = F_{SRR}^\text{FS}(\Phi = 456 \mu\text{m}) + F_{SRR}^\text{FS}(\Phi)\) is the resulting field on the axis.

<table>
<thead>
<tr>
<th>(\Phi) ((\mu\text{m}))</th>
<th>(J) ((\mu\text{A/cm}^2))</th>
<th>(\sigma_{\text{min}})</th>
<th>(D_{\text{SRR}}) (nC/cm(^2))</th>
<th>(V_{SRR}^\text{FS}(\Phi)) (V)</th>
<th>(V_{SRR}^\text{FS}(\Phi)) (kV/m)</th>
<th>(F_{SRR}^\text{FS}) (kV/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>456</td>
<td>0.012</td>
<td>---</td>
<td>6.5</td>
<td>+62</td>
<td>---</td>
<td>+44.9</td>
</tr>
<tr>
<td>79</td>
<td>0.408</td>
<td>0.925</td>
<td>-3.0</td>
<td>-8.65</td>
<td>+54</td>
<td>-56.9</td>
</tr>
<tr>
<td>32.6</td>
<td>2.4</td>
<td>0.88</td>
<td>-16.8</td>
<td>-35.3</td>
<td>+27</td>
<td>-340</td>
</tr>
<tr>
<td>5</td>
<td>102</td>
<td>0.58</td>
<td>-1780</td>
<td>(-628)</td>
<td>(-566)</td>
<td>(-370 000)</td>
</tr>
</tbody>
</table>

**B. Current density effect induced by the primary electron “pressure”**

Another phenomenon occurs as the following experimental procedure is used. Firstly, a virgin area is positively charged at low energy by bombarding the surface with a low current density until the SRR is reached \(\sigma_{\text{SRR}} = 1\). Secondly, the spot size is reduced in order to increase the current density. Results obtained at 200 eV are displayed in Fig. 11. Firstly, under the low current density \(J = 12 \text{ nA/cm}^2\), mica is positively charged on an area of diameter \(\Phi = 456 \mu\text{m}\). Once the SRR is reached with \(\sigma_{\text{SRR}} = 1\), the spot diameter is then reduced to the size \(\Phi = 5 \mu\text{m}\), corresponding to the high current density \(J = 102 \mu\text{A/cm}^2\), i.e., about \(10^4\) times higher in density. That time, the yield starts from the value close to unity, drops below unity and passes through the minimum of 0.6 before progressively rising to unity (Fig. 11). A new SRR is achieved with a negative charging that time, instead of the previous positive one obtained under low-current density.

This feature was observed in the energy range 120-800 eV. It is important at low energy (120 to 300 eV), and vanishes rapidly above, until it is hardly detectable at 800 eV. It has been studied in details at 300 eV. After having positively charged the sample on a large area \((\Phi = 456 \mu\text{m})\) under the low current density \(J = 12 \text{ nA/cm}^2\), the central area is negatively charged under the three current densities indicated in Table 3. In Fig. 12 the \(\sigma\) variation corresponding to the negative charging is represented. In these experiments the large charge increment of 0.2 pC encompasses in one measurement the dropping part of the curve represented in Fig. 11. But the negative stored charge is fully collected. Note in Table 3 that the minimum yield is lower as the current density is higher.

In these three experiments the disc of diameter \(\Phi = 456 \mu\text{m}\) is positively charged under the low current density with its central zone (diameter \(\Phi = 79, 32.6\) and 5 \(\mu\text{m}\)) negatively charged under the specified high current densities. Assuming that the positive and negative charge distributions are superimposed, surface potential and field can be calculated according to Eqs. (3) to (6) once the SRR is reached (sample thickness \(e = 40 \mu\text{m}\) in Table 3). It is noticed that in the central area of diameter \(\Phi = 79\) and 32.6 \(\mu\text{m}\) the surface potential \(V_{SRR}^\text{FS}\) remains slightly positive, but the resulting field becomes negative. This field inversion is due to the fact that the screening of the central negative charge by the positive induced charges is quasi nil.
when the diameter of the central area is 79 and 32.6-μm. Figures relative to the 5-μm area are irrelevant: the strong negative potential (–566 V) is incompatible with the 300 eV electron beam, and the field exceeds the field strength of mica (= 100 MV/m) by almost four times. To rationalize these results it is necessary to consider the lateral and in depth expansion of the negative charge distribution. The situation is similar to that observed under negative charging at high energy.

C. High current density induced electron exo emission

A beam, 300 eV energy and 20pA current, has been directed onto a virgin area of diameter \( \Phi = 5\mu m \), delivering 1.2 pC charge under the current density \( J = 102\, \mu A/cm^2 \) (Fig. 13). Two additional features are observed:

i) The initial yield is high (\( \sigma_i = 3.20 \)), close to the intrinsic yield \( \sigma_0 = 3.92 \), instead of being closer to unity as previously observed under the same conditions (see Fig. 10 for \( \Phi = 5\mu m \)). It results that the SRR requires a rather larger amount of stored charges than in Fig. 10.

ii) During injection two strong emission peaks are produced. The stored charge curve in Fig. 13 correlates very well the two peaks. Instead of increasing monotonously, the stored charge progresses by steps, each of them ending at the occurrence of a peak. The bursts of electrons were observed during four successive shots on the same area, separated by about one minute stop. Each time the initial yield was decreasing until the response to the fifth shot is completely flat.

When the flux of incident electrons becomes very high, the field around the space charge distribution rapidly increases and reaches a value that exceeds the detrapping field. Charges are released from their trapping site and scattered into the bulk, leading to the strong expansion of the charge distribution. This feature explains why it is so difficult to bring under control the charging of an insulator by using a focused beam.
and the irradiated area 1 mm$^2$, the screening of the

\[ \sigma \]

maximum yield, according to the rule: the higher

maximum value of the yield also explains the very low

microscope does not work below 100 eV). The high

cannot be determined accurately because the

value is certainly below 100 eV and above 50 eV (it

produced at the maximum yield, calculated from

holder is very strong. The maximum surface potential

close to zero. In fact as their mica sample is 1

negatively, in order to maintain the surface potential

(Fig. 1). They use a compensation method by

In their experiments the sample is held at a negative

energy dependence of the intrinsic

yield $\sigma_0$

The muscovite mica whose average atomic

number is $<Z> = 9.43$, exhibits a singular SEE yield with respect to materials having a comparable atomic

number and density as SiO$_2$ ($<Z> = 13$), Al$_2$O$_3$ ($<Z> = 10$). The maximum yield occurs at low energy

(300 eV) as in polymers,$^{19}$ but the maximum yield

$\sigma_0(\text{max}) \approx 4$ is twice as high as the one of oxides. Normally with a maximum yield at a very low energy, the second crossover $E_{II}$ should also be at a low energy. In fact it is close to 5000 eV, which is much higher that the one measured in amorphous and polycrystalline light oxides.$^{18}$ The high value of $E_{II}$ is related to the high

maximum yield, according to the rule: the higher

$\sigma_0(\text{max})$, the higher $E_{II}$. As for the crossover $E_{I}$, its value is certainly below 100 eV and above 50 eV (it
cannot be determined accurately because the microscope does not work below 100 eV). The high maximum value of the yield also explains the very low
crossover energy $E_{I}$.

A recent work on the energy dependence of the intrinsic SEE yield $\sigma_0$ of mica has been published by Hopman et al.$^{13}$ They proceed by steps of 2 eV up to 2000 eV. Their current density is 20 times higher than the one used in our experiments, but current density effects can still be neglected at this density. The fluence of 5 pC/cm$^2$ is of the same order as the fluence injected in our experiments for the measurement of $\sigma_0$. In their experiments the sample is held at a negative potential to prevent secondary electrons from returning to the surface as we did by a positive bias voltage applied in front of the sample on the SB collector (Fig.1). They use a compensation method by alternating pulses in which mica charges positively and negatively, in order to maintain the surface potential close to zero. In fact as their mica sample is 1 $\mu$m thick and the irradiated area 1 mm$^2$, the screening of the positive charges by charges induced in the sample holder is very strong. The maximum surface potential produced at the maximum yield, calculated from

Eqs. (3)–(4), is of the order of 0.3 V. Therefore the

charging at each step measurement of $\sigma_0$ is negligible, but the charge accumulation during the 1000 steps up to 2 keV would give rise to a potential of several tens of volts that would affect the secondary electron emission.

Hopman found the maximum yield $\sigma_{0\text{max}} = 5$ at 500 eV. These two figures are a little higher than those obtained in the present work ($\sigma_{0\text{max}} = 3.92$ at 300 eV). More important is the difference of the yield at 2 keV ($\sigma_0 = 3$ in Ref. 13 against 1.7 in the present work).

One reason of the difference in the yields could be due to the negative bias voltage applied to the sample in order to vary the energy of incident electrons (their electron gun operates at a constant negative voltage). This procedure makes the beam diameter to vary at the impact. Therefore as the impact energy decreases from 2 keV to zero, the beam diameter is enlarged which tends to increase the yield.

VI. DISCUSSION

A. The energy dependence of the intrinsic yield $\sigma_0$

FIG. 12: Variation of the SEE yield with the injected charge $Q$ at 300 eV energy, at three current densities corresponding to $\Phi = 79, 32.6$ and 5 $\mu$m. The experiment is similar to that in Fig. 11. Only the negative charging produced by the second shot is represented.

FIG. 13: Variation of the SEE yield with the injected charge $Q$ at 300 eV showing two exo electron emission peaks and correlated variation of the stored charge $D_{EC}$. Each peak corresponds to a strong electron emission that reduces the stored charge. Experimental conditions: calibrated intensity 20 pA, diameter of the irradiated area $\Phi = 5 \mu$m, current density $J = 102 \mu A/cm^2$, 2 pC charge delivered to the sample. Insert: variation of the SEE yield with the injected charge at 300 eV energy, combining two current density effects: the exo electron emission peak is followed by a negative charging.

B. The fluence dependence of $\sigma$ and the Self-Regulated Regime (SRR)

The variation of $\sigma$ with the fluence is due to the internal electric field that develops beneath the surface as charges accumulate. When $\sigma_0 > 1$ as represented in Fig. 6a, the net stored charge is positive and the electric field, directed outwards, is opposed to the coming out of electrons. As a result, $\sigma$ decreases with the dose. It is the opposite under negative charging at energies beyond $E_{II}$.

The conventional interpretation of the regulation of the SEE yield at the value $\sigma_{IR} = 1$, called the Self-Regulated Regime (SRR), has been attributed to the variation of the surface potential as the material charges.$^{27,28}$ Two causes contribute to the regulation according to this interpretation:

The positive surface potential, produced when the material charges positively, creates in the vacuum,
in front of the sample, a field that makes low energy electrons to return to the sample. This effect does not really constitutes a physical phenomenon inherent to the charging properties of insulating materials since it can be avoided by applying an extracting field outside the sample with a positive bias voltage (Fig. 1).

The second cause is the energy variation of the incident beam due to the surface potential that drifts the beam energy to the crossover energy $E_{pl}$. According to this interpretation, when $\sigma_0 > 1$ the positive charging increases the beam energy to the value $E_{pl}$ and by symmetry, when $\sigma_0 < 1$ the negative charging reduces the beam energy to the value $E_{pl}$.

In fact the calculation of the surface potential from the real amount of stored charges provides evidence that this interpretation is not correct. Of course, under positive and negative charging the beam energy shift is higher as the difference $|\sigma_0 - 1|$ is higher, but much less than the energy difference $|E_{pl} - E|$. For example, at the maximum yield $\sigma_{max}$ at 300 eV, the energy drift is about 62 eV whereas $E_{pl} - E = 4850 - 300 = 4550$ eV. It is the same under negative charging. The energy drift at 5000 eV is just a few eV, much less than the difference $5000 - 4850 = 150$ eV.

Beyond $E_{pl}$ the negative charge amount required to reach the SRR increases very rapidly with energy (see Table 1), leading to the unrealistic value of $E_{pl} = -8.2$ kV compared to the nominal energy of 8 keV. It is obvious that the beam will be reflected long before the potential reaches the value $-8.2$ kV. In fact, as negative charges accumulate, the repulsive potential they produce scatters the beam progressively until it is fully reflected (this is the mirror effect). When the beam is reflected and collected by the secondary electron detector SB, a pseudo SRR with $\sigma = 1$ is obtained. But this is not actually a secondary electron emission yield because no electron penetrates the sample. This is just an apparent yield.

Before being reflected the beam is laterally scattered by the high negative surface potential. Then the sample is irradiated out of the delimited zone of diameter $\Phi$ and charges continue to be stored on an area much larger than expected, so that the surface potential in absolute value can be maintained below the nominal potential of the beam. This is what happens at 6000 eV where the beam is just strongly scattered.

In conclusion, the variation of the yield during the injection process is due for a small part to the energy drift and for a major contribution to the internal field created by the accumulation of charges. For example at 300 eV where the yield is maximum, the 62 eV drift in the beam energy changes the yield by a few %. The rest of the variation up to the SRR is due to the blocking of secondary electrons by the internal field. It is the same at any energy.

C. Charge relaxation

Charge relaxation in insulators is in relation with their conductive properties. In most dielectrics holes are not mobile, or very little, at room temperature. Therefore their neutralization is due to the mobile electrons of the material that come and neutralize them. On the other hand, electrons injected can leave the implantation zone by a direct diffusion process.

The slow relaxation of holes and electrons in muscovite mica suggests this material contains a small density of mobile carriers at room temperature. Under permanent irradiation the charge relaxation gives rise to a permanent current, usually called leakage current, which is a spurious effect in high voltage applications. The slow charge relaxation in mica could explain its very good insulation properties in high voltage capacitances because the slow elimination of charges limits the energy loss and reduces the risk of electric breakdown by an excessive accumulation of charges.

The property to exhibit a low conductivity is typical of insulators having resistivities in the $10^{12} - 10^{14}$ $\Omega$cm range. They are called low conductive insulators. Another example of this type of material is yttria-stabilized zirconia in which the relaxation time of charges is a little bit longer than in mica, about 30 min. Materials such as $\text{Al}_2\text{O}_3$, $\text{MgO}$, $\text{SiO}_2$ single crystals, in which no charge relaxation is observed at room temperature, have resistivities in the $10^{15} - 10^{18}$ $\Omega$cm range. They are called trapping insulators.

The elimination of charges by a relaxation process requires expressing the charge conservation law under the SRR as the following:

\[\text{INCOMING CHARGES} = \text{GOING OUT CHARGES} + \text{FLOWING CHARGES},\]

and the yield at the SRR is expressed as:

\[\sigma_{SRR} = \text{GOING OUT CHARGES} / \text{(GOING OUT CHARGES + FLOWING CHARGES)}\]

If no charge is flowing as in trapping insulators, the induced current falls of to zero under the SRR and the yield $\sigma_{SRR} = 1$. If charges flow, a permanent current is established in the induced circuit. It is negative for the positive charge relaxation (neutralization of holes by the mobile electrons of the material) and $\sigma_{SRR} > 1$; it is positive for the negative charge relaxation (electron diffusion) and $\sigma_{SRR} < 1$. In low conductive materials such as mica, where the charge relaxation requires several minutes, the flowing charge rate is much less than the incoming charge rate, under the above mentioned experimental conditions. Therefore the material seems to behave like a trapping insulator. This is why $\sigma_{SRR} = 1$ is obtained. To observe a steady yield different from unity in mica, the flux of incoming electrons should be divided by a factor one hundred at least, which is beyond the experimental capabilities.

D. Discussion on current density effects

As the brightness of images depends on the secondary electron emission, the contrast will depend on the internal field produced on each pixel during the dwell time of the beam. To make the presentation simple, it is assumed that the sample surface is
perfectly flat and composed of areas having different yield values. It is also assumed that a negative bias voltage is applied to the sample in order to prevent electrons from returning to the surface when it is positively charged. In the present case of mica, for example, about +100 V is sufficient.

Let us consider a beam of intensity $I_0$ scanned at a rate such that the dwell time on each pixel is $t_{pix}$. Using Eqs. (1), (2) and (10), the secondary plus backscattered charge $Q_{SB}(t_{pix})$ issued from the pixel is expressed as:

$$Q_{SB}(t_{pix}) = I_{0}t_{pix} \sigma(t_{pix})$$

where:

$$\sigma(t_{pix}) = \int \{\sigma(t) - 1\} dt$$

We define the contrast $C_{12}$ between two pixels 1 and 2 as the ratio of the two charges $Q_{SB}$ given by Eq. (11), that is:

$$C_{12} = \frac{\sigma_1(t_{pix})}{\sigma_2(t_{pix})}$$

The contrast between the two pixels will depend on the charge accumulation on these pixels during the dwell time of the beam $t_{pix}$.

Suppose the scanning is so slow (to take the image) that the Self-Regulating Regime is reached on the two pixels. The contrast, independent of the dwell time, will be in the ratio of the maximum charging on the two pixels:

$$C_{12} = \frac{Q_{SRR}(1)}{Q_{SRR}(2)}$$

In between these two cases the contrast will depend on the dwell time on the pixels.

It is reported in the literature that under permanent irradiation, negative charging is often observed at energies under the crossover $E_{II}$ where the insulator should be positively charged.$^{28,32-36}$

Although the experiments presented in this paper are carried out by pulses, the procedure used is similar to a permanent injection since injections of very long duration (about 1 min) delivering doses up to several $\mu$C/cm$^2$ can be achieved. The decomposition of a long time injection into a sequence of appropriate short pulses allows the various aspects of the charging process and their incidence on the SEE yield, to be revealed.

It results from our experiments that the charging kinetics described in Sec. IV.B is well respected at any energy, provided the current density is low enough, typically $J \leq 100$ nA/cm$^2$.

Then, the anomalies mentioned in the literature are probably relevant to the current density effects described in Sec. V. In particular the negative charging observed in a regular positive-charging energy range comes probably from the “pressure” effect mentioned in Sec. V.B.

Two antagonistic field effects have to be considered to explain the “pressure” effect of the current density: the first one is due to a dominant positive field that prevents electrons from escaping, which makes the yield to drop below unity, and the second is a dominant negative field that enhances the electron emission, allowing the yield to rise up to the SRR.

To understand this dual-action of the fields, we consider the double layer formed by positive holes concentrated at the surface and primary electrons concentrated in deeper layers, as described by Derjagin.$^{37,34}$ The balance of the fields produced by these two charge distributions determines the orientation of the field acting on the electron emission: if the balance is positive the field has a blocking effect, if it is negative the escaping of electrons is favored. To simplify the presentation it is assumed that holes are much more stable than electrons. Taking the experimental parameters of Fig. 12, that is, 20 pA current delivered on $\Phi = 5 \mu$m diameter area during one second, that is 20 pC, the electron density stored around their average penetration depth is $5 \times 10^{14}$ electrons/cm$^2$. In fact, the maximum electron concentration that a dielectric can sustain in a stable way is a few ppm,$^{28}$ that is some $10^9$ electrons/cm$^2$. Clearly even if injected electrons are spread over some tens of atomic layers around the average penetration depth, their concentration remains much higher than that the material can accept. The consequence is that the negative stored charge becomes unstable. It expands laterally where the field is stronger and perpendicularly until a new equilibrium is achieved. The lateral spreading of the electron charge makes the negative field to decrease in the escape depth region of electrons, so that the positive field becomes dominant, making the yield to decrease below unity (Fig. 12). But the negative charging is continuing as injection proceeds, so that, at the end, the negative field becomes dominant, making the yield to increase up to the SRR.

The expansion of the negative charge is due to the detrapping by an effect similar to the Poole-Frenkel field effect.$^{29}$ But it is also possible that once incoming electrons are thermalized, they diffuse over long distances under the internal field before finding a trapping site outside the irradiated area. This last process will become very efficient if in the central irradiated area the electron trap concentration is exhausted.

The electron exo emission is usually observed at energies higher than the crossover energy $E_{II}$ where the net stored charge is negative.$^{28}$ It is a violent phenomenon accompanied by an irreversible damage of the material. In mica the exo emission is produced at very low energy (for example 300 eV) where the net stored charge is positive. It is much less intense than at high energy. Its suddenness and briefness suggest that it is relevant to a collective relaxation process in the region where primary electrons are concentrated. The storage of electrons distorts the lattice, forming locally
a metastable structure. When the current density is high, the incoming electron rate can surpass the rate of expansion of the charge distribution, making the charge concentration to increase until the metastable structure collapses. A burst of electrons is released, some of them forming the exo emission, the others being dispersed in the bulk. The appearance of exo emission and the peak frequency are characteristic of the mechanical and electrical performances of dielectrics.

VII. CONCLUSION

The simultaneous acquisition of the induced and secondary currents allows the measurements to be free of the primary beam drift. As a result, the precision on the calculated values of $\sigma$ from Eq. (12) is much better than that derived from the expression $\sigma = I_{SB} / I_0$, where $I_0$ is the calibrated primary current.

The precision of about 1% makes the SEE yield to become appropriate for physical studies of dielectric materials. However, for these studies to be carried through, they must be treated with cautions:

i) The fluence and current density must be adapted to the parameter to be measured: intrinsic yield, stored charge, time relaxation of charges, etc. It is more convenient to use the spot mode rather than the scanning mode to achieve these works because the current density to be accounted for is that of the electron probe, not that of the scanned area.

ii) Measurements must be carried out on spots distant a few mm to avoid any electric influence from one spot to another. The number of measurements on one sample must be limited to about 10 spots per cm² and the total integrated dose to some $10^5$ pC/cm² to avoid a global potential effect.

Provided the current density is low enough, the rule stating that charging is positive when $\sigma > 1$ and negative when $\sigma < 1$ suffers no exception. It was tested on a number of insulators as single crystals and polycrystalline oxides, composite materials, glasses, solid polymers. Any deviation from this rule is due to current density effects.

The variation of the yield with the dose, up to the regulation at the value $\sigma_{SB} = 1$ (Self-Regulated Regime) is not due to the variation of the primary beam energy up to the crossover energy $E_0$ as stated in many papers. It is mainly controlled by the internal electric field that develops during the injection process, as evidenced by the experiments carried in Sec. V.A.

With the experimental device sketched in Fig. 1, the time stability of stored charges under low electron beam fluence can be studied from a few seconds up to several hours. It is characteristic of the conduction properties of insulators and allows the distinction between “trapping insulators” such as Al₂O₃, SiO₂, MgO single crystals and solid polymers in which charges are stable at room temperature over a quasi infinite time and “conductive insulators” like the mica used in this study and zirconia stabilized with 9% yttrium (single phase), in which charges relax at a time scale of a few minutes or less.

Current density effects are the more striking features of insulators subjected to electron irradiation. Their quantitative study is very difficult because they mix up. For example, the experiment shown in the insert in Fig. 13 has been performed under conditions similar to the ones reported in Fig. 13. But the response is slightly different. It combines two current density effects: the exo emission peak is followed by a negative charging. Experiments in which one current density effect is dominant have been selected to clarify the presentation. If the field effect (Sec. V.A) is well established, the “pressure effect” in Sec. V.B is not yet quantitatively investigated nor the exo emission process in Sec. V.C.

Mica materials are minerals mostly composed of Si, O, H, Al, K and Mg, organized in a basic tetrahedral structure. Thus, it is reasonable to assume that most micas exhibit similar features under electron irradiation, with some nuances due to their specific composition. In that sense, this study of the muscovite species can contribute to the understanding of the good performance of this material in high voltage applications. It is suggested in the literature that the SEE yield is in relevance with the hold-off of insulators. Our study shows that the high value of the intrinsic yield $\sigma_0$ in the low energy range is not a limitation to the performance of mica. The slow charge relaxation indicates a low mobility which explains the low energy loss coefficient favorable to the performance. From this point of view, mica seems to be a good compromise between large gap dielectrics, the performance of which being limited by a strong charge trapping that trigger the breakdown process, and high permittivity dielectrics, the high conduction of which leading to an energy loss too high to be exploitable under high field. Last point, the electron exo emission disruptive process, similar to the partial discharges observed just before breakdown, is sufficiently soft to prevent any damaging that could weaken the material.


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