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Analytical model of secondary electron emission yield in electron beam irradiated insulators

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ABSTRACT

The study of secondary electron emission (SEE) yield as a function of the kinetic energy of the incident primary electron beam and its evolution with charge accumulation inside insulators is a source of valuable information (even though an indirect one) on charge transport and trapping phenomena. We will show that this evolution is essentially due, in plane geometry conditions (achieved using a defocused electron beam), to the electric field effect (due to the accumulation of trapped charges in the bulk) in the escape zone of secondary electrons and not to modifications of trapping cross sections, which only have side effects.

We propose an analytical model including the main basic phenomena underlying the space charge dynamics. It will be observed that such a model makes it possible to reproduce both qualitatively and quantitatively the measurement of SEE evolution as well as to provide helpful indications concerning charge transport (more precisely, the ratios between the mobility and diffusion coefficient with the thermal velocity of the charge carrier).

1. Introduction

The relatively recent increase of interest in charge accumulation inside insulators, as achieved by electron irradiation in a scanning electron microscope (SEM), may lead one to believe that the understanding of the microscopic mechanisms governing transport, charge accumulation and associated processes (relative to the generation of free carriers, to their transport and to trapping and de-trapping effects) represents a new field of endeavor.

In recent years, numerous techniques have been developed to elucidate such phenomena in the characterization of dielectrics (Damamme et al., 1997; Blaise and Le Gressus, 1991; Cazaux, 2010; Gross and de Oliveira, 1974; Ehrenberg and Gibbons, 1981). Our work mainly focused on the so-called induced current method (ICM) (Thome et al., 2004; Damamme et al., 2016; Zarbout et al., 2008). In this method, charging is achieved via irradiation using a SEM and is investigated by the induced current in the sample holder (due to the influence of electrostatic effects) which is measured throughout the irradiation time. The evolution of the induced current stemming from image charges was directly associated with that of the amount of trapped charges, which can also be deduced by the backscattered and secondary electron emission (SEE) currents via charge conservation.

To complete these studies, several theoretical models have been established or adapted to reproduce and understand the underlying mechanisms responsible for charging inside dielectrics during electron irradiation. In spite of the considerable amount of theoretical work done, no specific approach has yet been able to provide a complete and coherent interpretation of the observed phenomena. Such approaches include those of Renoud et al. (Renoud et al., 2004) and Ding et al. (Ding et al., 2001), which are based on Monte Carlo (MC) simulations, which make it possible to monitor, in an efficient manner, the variation in secondary emission yield throughout the creation of the charge. This type of method becomes computationally very expensive and unreliable when long-range potential and long-time dynamic behavior are considered.

Le Roy & Teyssèdre (Le Roy et al., 2006) and Raftari (Raftari et al., 2015) have proposed a self-consistent drift-diffusion-reaction (DDR) equation but they assume static parameters in their works. Fitting & Kortov (Galvatskikh et al., 2001; Meyza et al., 2003), then the Saint-Etienne group, (Aoufi and Damamme, 2011) performed computer simulations of secondary electron emission and the related self-consistent charge transport by introducing a twin flux method (ballistic model) for electrons and holes.

The present paper constitutes an extension of previous studies. We focus on modeling charge generation, transport and trapping phenomena in insulators which are one of the causes of breakdown

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phenomena (through their mobility, their concentration and their distribution within the material). On the other hand, a simple modeling is suggested to provide SEE evolution versus trapped charges in the sample. We attempt here to predict the observed charge accumulation evolution in these materials following a defocused electron beam irradiation in a SEM via an analytical model and to give additional information on the analysis of secondary electron emission evolution.

The use of such irradiation conditions will enable a simplified description, since the planar geometry requirement will be met. Moreover, interference from more complex phenomena, such as microbreakdowns or ageing, will be prevented.

In the first part, we begin by recalling the principle of the ICM. As previously reported, the experimental results are better identified by plotting the logarithm of secondary electron emission yield, $\ln(\sigma_{EES})$, as a function of the total trapped charge Q_T leading to the build-up of an electrostatic field in the material.

In the second part, our proposed model will be presented introducing the main elementary phenomena underlying the space charge dynamics (generation, transport and trapping of charges and secondary electron emission) in the framework of the drift-diffusion-reaction (DDR) model in plane geometry (Le Roy et al., 2006; Raftari et al., 2015; Galvatskikh et al., 2001). One of the goals of this paper is to outline the main factors that may influence SE yield evolution and in particular the mobility and trapping terms.

In the third part, a comparison of experimental results and calculations obtained for different insulators is developed. We conclude by trying to clarify what can be measured in a SEE experiment.

2. Principle of the ICM: experimental results

Charge implantation in the sample is carried out in a SEM with a monoenergetic primary electron beam and specially equipped to measure the SEE current (the current generated by secondary and backscattered electrons emitted) via a detector set to a voltage of $V_c = 100$ V (Thome et al., 2004; Zarbout et al., 2008). Since the current beam intensity (I_{prim}), varying from several pA to several μA, and the irradiation time t, varying from 10^{-3} to 1 s, are known, the amount of injected charges is perfectly controlled. From a practical view point, this charge implantation is usually performed with primary energy values (E_{kin}) varying from 3 10^2 to 3 10^4 eV.

Furthermore, when the specimen is continuously irradiated, the trapped charge $Q_T(t)$ produces an induced charge Q_{ind} (with opposite sign) mainly concentrated in the metal sample holder, expressed as follows: $Q_{ind} = KQ_T$, where K is the electrostatic influence factor that depends on dielectric permittivity, on the thickness of the sample and on the electrical characteristics of the media surrounding the sample. The time variation in Q_T in the sample during irradiation creates an induced current I_{ind} between the grounded metal electrode and ground, given by, $I_{ind} = K\frac{dQ_T}{dt}$ (see Fig. 1).

When an insulator is bombarded with an incident electron beam (defined by E_{kin}, I_{prim}), the slowdown of the electrons generates a great number of electron/hole pairs close to the sample surface, and initially causes the emission of secondary electrons, leaving behind a thin layer of positive charges. In fact, SEs, with low energies (few electron volts) and backscattered electrons BSEs are emitted in the vacuum and form a secondary electron emission current I_{SEE}; $I_{\text{SEE}} = \sigma_{\text{SEE}} I_{\text{prim}}$, where σ_{SEE} is the total electron emission yield. Next, incoming electrons penetrate deeper into the sample and undergo complex diffusion, and transport in the internal electric field and are finally trapped about a certain depth $R_p(E_{kin})$ known as the maximum electron penetration depth (Cazaux, 2010; Gross and de Oliveira, 1974; Galvatskikh et al., 2001). As a function of E_{kin}, we give here the Kanaya and Okayama expression of penetration depth beyond which there is less than 1% of primary electrons (Kanaya and Okayama, 1972):

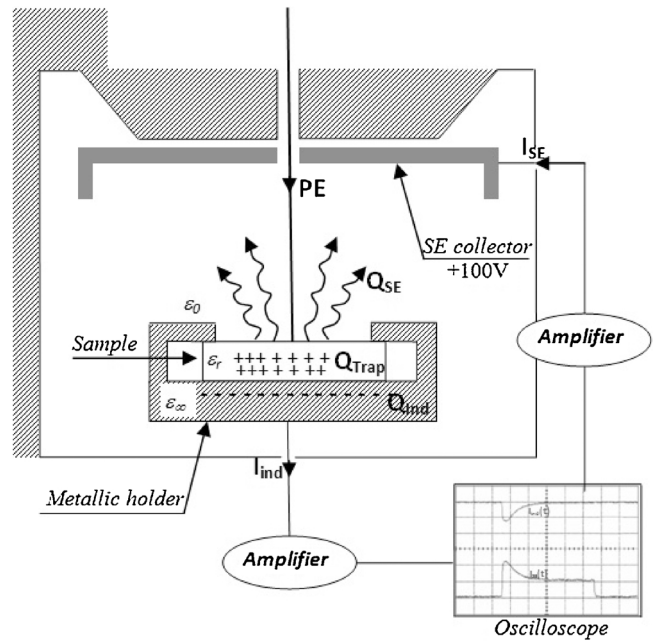

Fig. 1. The experimental set up for the measurements of the secondary electron current and induced current. The secondary electron collector (diameter 15 cm) is positioned at a distance L ≈ 2 cm from the sample surface. The recorded current curves reflect the sample positive charging.

$$R_p(E_{kin}) = \frac{27.6 \cdot A}{\rho \cdot Z^{8/9}} \cdot E_{Kin}^{5/3} \tag{1}$$

(where A is the mean atomic mass in g, Z the mean atomic charge, ρ the density in g cm^{-3} and E_{kin} is in keV).

Consequently, the conservation of charges can be written as follows:

$$I_{prim} = \sigma_{SEE} I_{prim} + \frac{dQ_T}{dt}$$

The primary electron current density J_{prim} (in A per surface unit) has been chosen weak enough to neglect interaction between the different cascades of electron-hole pairs created. Consequently, the main physical parameter in such an experiment is the total quantities of charges injected per $Q_{inj}^S(t) = \int_0^t J_{prim} dt$ per unit surface area,

During irradiation, $\text{Ln}\sigma_{\text{SEE}}(t) = \text{Ln}\left(\frac{I_{SEE}(t)}{I_{prim}}\right)$ as a function of trapped charge per surface unit, $Q_{trapp}^S(t) = \int_0^t (J_{SEE}(t) - J_{prim})dt$ has been measured for different energies of the electron beam. In turn, $Q_{trapp}^S(t)$ generates an electric field at the sample surface. Consequently, to the extractor electric field initially present in the sample (resulting from the application of the positive voltage to the SE collector set at $V_c = 100$ V (see Fig. 1)) will be added, as charges are accumulated, the electric field due to electrons and holes trapped in the sample bulk. Henceforth, the electric filed satisfies the Coulomb's law given as: $div\ \varepsilon F = \rho$ and $\overrightarrow{F} = -\overrightarrow{grad}\, V$.

At the sample surface, the total electric field F_{surf} can be written, for a plane geometry when $R_p << e$,

$$F_{surf} = \frac{e}{e + \varepsilon_r L} \frac{Q_{trapp}^S}{\varepsilon_0 \varepsilon_r} - \frac{V_C}{e + \varepsilon_r L} \tag{2}$$

Where e and L represent, respectively, the specimen thickness and the working distance between the sample surface and the collector, ε_0 is the vacuum permittivity and ε_r is the relative dielectric permittivity (see Fig. 2).

This electric field $F(z)$ will be the key parameter that increases or decreases according to its orientation the SEE in the escape layer. In order to facilitate the interpretation of results, the conditions for planar

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