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Injection of charge nanostructures into insulators

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ABSTRACT

The electron beam induced selfconsistent charge transport in insulators is described by means of an electron-hole flight–drift model FDM and an iterative computer simulation. Ballistic secondary electrons and holes, their attenuation and drift, as well as their recombination, trapping, and detrapping are included. Thermal and field-enhanced detrapping are described by the Poole–Frenkel effect.

As a main result the time dependent secondary electron emission rate $\sigma(t)$ and the spatial distributions of currents $j(x, t)$, charges $\sigma(x, t)$, field $F(x, t)$, and potential $V(x, t)$ are obtained. The spatial charge distributions with depth show a quadropolar plus–minus–plus–minus structure in nanometer dimensions.

1. Introduction

In electron microscopy like scanning electron microscopy (SEM) or Auger electron spectroscopy (AES), electron energy loss spectroscopy (EELS) etc., the prediction of electrical charging is essentially to interpret the measurements, see e.g. [1]. Moreover, charging of non-conductive samples has to be known in order to manage applications such as functional layers and in nanotechnology, [2].

A great number of experimental and theoretical investigations have been published on the charging of insulators due to electron bombardment and the related secondary electron emission (SEE). Only for short pulse irradiation, target charging is prevented and the real charging-free secondary electron emission yield $\sigma(E_0)$ as a function of the primary electron energy E_0 can be measured as well as has

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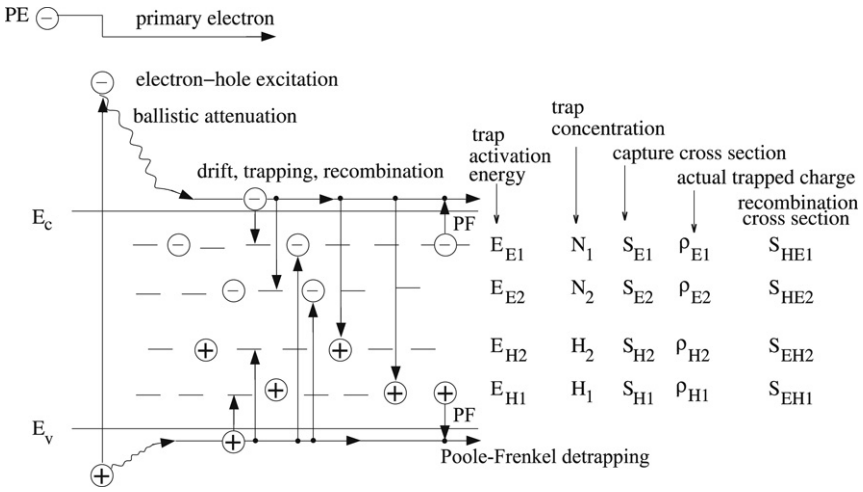

Fig. 1. Scheme of the flight–drift model (FDM) including the excitation of ballistic electrons and holes, their flight and attenuation, followed by drift or diffusion, trapping or recombination and/or Poole–Frenkel (PF) release, see Eqs. (3)–(5).

been determined theoretically for various insulators [3,4]. However, the charging behaviour under permanent electron irradiation is not yet fully understood and the stationary final state is still very complex to describe. Indeed, the total yield approach ($\sigma \gtrless 1$) is often used to predict the sign ($\pm$) of charging in the case of stationary electron irradiation, but experimental results are not fully consistent with these predictions [1,5].

It is of importance to determine the types of theory that have been led to enlighten this phenomenon. One of the first attempts was the planar (1-dimensional) selfconsistent charging simulation of our co-author (HJF) already in 1979, [6], later improved on in Refs. [7–10]. These authors use field-dependent attenuation lengths $\lambda(F)$ for the ballistic transport of electrons and holes which had been found experimentally by means of electron beam induced current (EBIC) measurements.

The present paper will extend the model of ballistic electron and hole transport to drift processes, recombination and charge trapping processes, as has already been shown in Ref. [10]. Thus, spatial charge profiles in nanoscale dimensions are built up in insulating samples. The results will be presented in particular for silica SiO_2 similar to what has been shown earlier for alumina Al_2O_3 [8–10], but can be easily adapted to any insulator using the relevant material data available in the literature.

2. Theoretical background

The various processes of electron beam charge injection into a dielectric target are demonstrated in Fig. 1. Incident electrons (so-called primary electrons PE) with initial energy E_0 and current density j_0 penetrate the insulator target up to the maximum range $R(E_0)$. The injection of primary electrons (PE) and their creation of secondary electrons (SE) and holes (H) are very similar for silica SiO_2 and alumina Al_2O_3 as we have described already in Ref. [10]. The resulting PE current density in dependence on the target depth x and the PE initial energy E_0 was found:

$$j_{PE}(x, E_0) = j_0(1 - \eta_B) \exp\left[-4.605 \left(\frac{x}{R(E_0, Z)}\right)^{p(Z)}\right], \tag{1}$$

with j_0 as impinging PE current density and the material parameters for SiO_2 and Al_2O_3: $\eta_B \approx 0.2$ the backscattering coefficient, $p = 2$ the transmission exponent. An appropriate formula for the maximum range $R(E_0)$ of electrons reached by 1% of PE in dependence on their initial energy E_0 was deduced from experimental data in [11] for the relevant energy region $1 < E_0 \leq 30$ keV with:

$$R_{SiO_2} = 33.7\ (E_0/\text{keV})^{1.55} \tag{2a}$$