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Electron impact secondary electron emissions from elemental and compound solids

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ABSTRACT

The Sternglass theory [Sternglass, Phys. Rev. **108**, (1957) 1] for fast-ion-induced secondary-electron emission, which is proportional to the stopping powers, from metals has been modified to calculate the electron impact secondary electron yield from both elemental and compound targets with atomic number $Z = 4–92$ for incident energy range $5 \le E_i \le 10^5$ eV. This modification includes the use of a realistic stopping power expression that involves calculations of the effective atomic electron number, effective mean excitation energies and realistic electron density distribution of the target atoms along with the effective charge of incident electron. Throughout the studied energy range, the predictions of our proposed theory are in reasonable agreement with the experimental data for *Be* to *U* elemental and six important compound targets.

1. Introduction

Secondary electrons (SEs) are those emitted when an elemental or compound solid target is irradiated by projectiles - electrons, ions and photons-having kinetic energy of $E_{SE} \le 50$ eV [1]. These SEs are easily quantified in terms of SE yields (SEY), which is defined as the ratio of the number of SEs to the number of incident electrons. Knowledge of SEY resulting from the bombardment of a solid target with a focused beam of incident projectile lies at the heart of many diversified fields. In recent years its renewing interest grows enormously in both research and applications including the studies of radiation effects in materials, plasma-surface interaction [2,3], scanning electron microscopy (SEM) [4,5], microscope images, atomic structure of a given target [6–8], and also many other applications. The theory for the SE emission (SEE) has been a subject of continuous interest and variation since the discovery at the beginning of the twentieth century, resulting in the publications of a large number of theoretical works on this topic [6–24].

Among the available studies, some are heavily dependent on fitting species-dependent parameters, some are relied on accurate oscillator strength evaluation, some are involved in evaluating the complex dielectric response function, etc. However, many of them are divided into slots for different energy and species regimes to describe SEY. For examples, Sternglass [9] in 1957 proposed a well-known theory for SEE from metals induced by energetic ions of energy greater than a few MeV. Suszcynsky and Borovsky [10], based on a knowledge of the backscattered-electron energy distribution, extended Sternglass [9] approach for the incident of fast-electrons (several keV to about 200 keV) and also accounted for the contribution of the backscattered electrons to the production of secondary electrons. Ion-impact SEE theories are also developed by Parilis and Kishinevskii [11,12] accounting for Auger recombination mechanism and also by Ghosh and Khare [14] on the basis of the relation of the SEY to the ionization cross-sections at high energy electron impact. However the formulae of [11,14] reproduced fairly accurate SEY for the incident energies 1 keV $\le$E $\le$ 100 keV. Salow

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[7], Baroody [8] and Bruining [6] have presented elementary theories for electron-induced SEE. Kanaya and Kawakatsu [15] explained the SEE from metals due to both primary and backscattered electrons by modifiing these theories using a Lenard-type power potential formalism [25]. Kanaya, Ono, and Ishigaki [16] further extended this approach to include insulators.

A comprehensive transport theory was propounded by Wolff [17] for electron-induced SEE to obtain the spectrum of emitted secondaries, and to estimate the maximum yield. This treatment was later extended by Stolz [18]. Amelio [19] evaluated the energy distribution for the secondary electrons. All these studies [17–19] concentrated on metals. Schou [20], Rösler and Brauer [22] applied transport theories to both electron and ion-impact SEE. Ashley et al. [23] evaluated the contributions to energy loss and mean free path due to removal of electrons from the inner shells of Al atoms in the solid based on atomic generalized oscillator strengths. Electron inelastic mean free paths and stopping powers for a solid medium have been computed by Tung et al. [24] using the Lindhard dielectric response function for the electron gas [26]. To the best of our knowledge, there is not a single model capable of describing the experimental SEY covering a wider energy domain from lower ($E_i < 10$ eV) to relativistic energies and the whole range of elemental solids.

The objective of the present study is to propound a formalism capable of furnishing reasonably accurate electron impact SEY from elemental (*Be - U*) and compound solids targets over a wider range of the projectile energies, $5 \leq E_i \leq 10^5$ eV, albeit simple in structure. It is obvious, and implicitly contained in earlier works, that the SEY is proportional to the stopping power of the target material [6,9–11,15–17]. Encouraged by our recent calculation [27] involving the electron impact stopping powers (ESPs) of material media including both elements and compounds in the energy range 1 eV–100 MeV, we use the same ESPs formula to propose a new semi-analytical model for SEY in the framework of Sternglass theory [9], embodying a modified factor essential for the best fit of the data. The formula for ESPs uses effective atomic electron number, effective mean excitation energies and realistic electron density distributions (DDs) of the target atoms and the effective charge of incident electron. The numerical DDs of the target electrons are evaluated numerically using the multi-configuration code of Desclaux [29], which uses the Dirac-Hartree-Fock [30] electron wave functions. These realistic DDs are then employed to calculate both the effective charges and mean excitation energies of the target elements considered herein.

The present *simple-to-use* formula is applied to calculate the SEY for 42 elemental solids and 6 important compound targets with atomic numbers $Z = 4–92$. This selection of the targets was guided by the availability of experimental data. The SEY for compounds are calculated using the Bragg-Kleeman [31,32] rule of the linear combination of the elemental SEY. Although our model is capable of calculating SEY easily for various compound targets, here only a few important targets polyimide sheet, organic and inorganic compounds, semiconductor, and metal oxides namely kapton ($C_{22}H_{10}N_2O_5$), furoin ($C_{10}H_8O_4$), ethylbenzene (C_8H_{10}), dry ice (CO_2), silica (SiO_2), and Indium tin oxide (In_2O_5Sn) are considered.

The rest of this paper is organized as follows. Section 2 describes the outline of our proposed theoretical model. In section 3 and 4, we provide, respectively, the analysis and the results of SEY calculated from our proposed theory and compare them with the experimental data. Section 5 concludes with a brief summary and future plan.

2. Outline of the proposed theoretical model

Sternglass's [9] equation for SEY for incident high speed ion is given as:

$$\Delta = \frac{1}{2}\frac{1}{\overline{E_0}}\left\langle\frac{dE_i}{dx}\right\rangle_{av}\Gamma\Lambda d_s[1+F(E_i)] \tag{1}$$

Here $\overline{E_0}$ is the mean energy loss per secondary formed. A value of 25 eV for $\overline{E_0}$ was adopted in the work of Sternglass [9,33]. This is also the average value found empirically in the analysis of SEY from metals under electron bombardment [33]. $\langle\frac{dE_i}{dx}\rangle_{av}$ is the energy loss per unit path length averaged over d_s length for the surface and is given in Refs. [9,10] as,

$$\left\langle\frac{dE_i}{dx}\right\rangle_{av} = 2\pi Ne^4 z_i^2\left[\frac{Z}{E_{eq}}\ln\left(\frac{4E_{eq}}{\bar{I}}\right)\right] \tag{2}$$

where $E_{eq} = \frac{1}{2}m_0 v_i^2 = \left(\frac{m_0}{M}\right)E_i = E_i$ (for electron). Here N is the number of atoms per unit volume and e is the electronic charge. E_i, z_i, M and v_i, are the energy, charge, mass and velocity of the incident particle, respectively. The quantity m_0 is the electronic mass, Z is the atomic number of target element and $\bar{I}$ is the mean excitation potential for the atoms.

The quantity Γ and Λ are constants, and their product $\Gamma\Lambda \simeq 0.5$ [9], which is the probability that an ionization electron liberated from a depth d_s, will reach the surface and escape. The mean escape depth of the secondary electrons is of the order of the mean free path of a slow electron. Suszcynsky and Borovsky [10] used $d_s \sim$ 5–50 Å.

According to [9], the function $F(E_i)$, shown in Eq. (1) can be written as,

$$F(E_i) \approx \left(1+\frac{E_{eq}}{100\ eV}\right)^{-1} \tag{3}$$

For the proper description of the electron impact SEY, the following modifications have been implemented:

a) In this investigation we take the average value of $d_s = 25$ Å.
b) We replace the stopping power term $\langle\frac{dE_i}{dx}\rangle_{av}$ by a slightly modified form of stopping power formula of Haque et al. [27] as

$$S = 2\pi e^4 N_0 \frac{\rho}{AE_i} z^{*2} Z^* \xi\left[\ln\frac{2.75E_i}{I^*}\right] \quad \text{eV/Å} \tag{4}$$

where e, N_0, ρ, A and ξ are, respectively, the electronic charge, Avogadro number, atomic density in g/cm^3, atomic mass and a normalization constant ($\xi = 0.529$). E_i is the electron energy in eV. The factor $2\pi e^4 N_0$ in Eq. (4), according to Haque et al. [27] and Jablonski et al. [28] is 785 $\times 10^{12}$ (eV)^2 (cm)^2 . In Eq. (4) Z^*, z^* and I^* denote, respectively, the effective charge of the target atom, the effective charge of the incident electron and the effective mean excitation energy of the target atom, and are given in Ref. [27] as.

$$Z^* = \int_{r_c}^{\infty} 4\pi r^2 n(r)dr \tag{5}$$

and