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Calculation of the angular dependence of the total electron yield

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ABSTRACT

Secondary electron emission plays an important role in many applications such as scanning electron microscopy, space applications and accelerator technologies. Secondary electron yield $\delta(E)$ at normal incidence of a primary electron beam is frequently modelled by the well-known semi-empirical law. However, this model is not used in a consistent way to predict the angular dependence. Additionally, neglecting the energy reflection has particular influence on the angular dependence of the secondary electron yield and therefore cannot be ignored. We propose here a simple approach to calculate $\delta(E)$ for any incident angle based on the experimental result achieved at normal incidence. The secondary electron yield is calculated according to the universal semi-empirical law, while a fraction of the electron energy deposited into the sample is calculated using a Monte Carlo simulation. A simple modification of the original model for calculating a total electron yield (i.e. the sum of the 'true' secondaries and backscattered electrons) is also presented. Very good agreement is observed between measurements and the calculation as long as the roughness is not significant. The model works very well for both, low Z and high Z materials. In the case of rough samples this approach cannot predict the angular dependence of the total electron yield.

1. Introduction

Secondary electron yield (SEY) defined as the number of secondary electrons emitted per incident electron is one of the basic magnitudes describing secondary electron emission. This phenomenon is of great interest in many areas such as electron microscopy, accelerator technologies (e.g., in the formation of e-cloud that deteriorates the primary beam [1]), fusion [2], charged particle detectors [3] and space technologies due to the multipacting of spacecraft on-board RF devices [4].

The limited reliability and reproducibility of SEY measurements, which have been performed for over 80 years [5], is mainly related to surface cleanliness, roughness [6], or experimental problems [7]. Additionally, it is sometimes neglected that SEY strongly depends on the incident angle of the primary beam, whilst the experiments are performed almost exclusively at normal incidence [8]. However, the angular dependence is of high relevance in the case of e-cloud formation, spacecraft charging or charged particle detectors.

The influence of the incident angle on the energy dependence of secondary electron yield $\delta(E)$ has been studied since the very beginning of the experimental investigation of secondary electron emission [9]. This investigation is hindered by the influence of a sample surface topography on measurements, which is why there are only few proposed models based on very simple assumptions or purely empirical formulae. Usually, approaches are focused on predicting angular dependence of a maximum yield δ_m, *and the corresponding primary beam energy* E_m [10–13].

A typical approach originally introduced by Salehi and Flinn [11], is based on the assumption that all secondary electrons are generated at single depth equal to the range of primary electrons, R. In other words, the depth distribution of the stopping power is approximated by a δ-function at the position of the intensive peak in the Bragg curve [14]. Starting from this assumption, it was shown that the ratio between the secondary electron yields (SEY) at oblique incidence and at normal incidence is $\delta(\theta)/\delta(0^\circ) = \exp[R/\lambda\cdot(1-\cos\theta)]$, where θ is the incident angle measured with respect to the surface normal, and λ is the escape depth of secondary electrons. Additionally, assuming that the primary electron range

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vs. their energy obeys the power law $R = b \cdot E^n$, *E_m depends on the incident angle as* $\ln(E_m) = \text{const} - \ln(\cos\theta)/n$. In some cases experimental results showed very good agreement with the model [10,11]. However, it should be emphasized that the starting assumption concerning the stopping power distribution is far from the realistic situation, which is certainly the reason why the overall shape of $\delta(E)$ at any incident angle calculated by this model does not agree with the experimental results.

Particularly popular nowadays is the model introduced by Kirby and co-workers [12], which is basically a simplified version of the work of Salehi and Flinn [11]. The final result of this model is the expression $\delta(\theta)/\delta(0^\circ) = \exp[b \cdot E_m^n/\lambda \cdot (1 - \cos\theta)]$, in which E_m is considered to be constant i.e. independent on the incident angle. The latter is however not the case, as pointed out in Ref. [10] for instance.

Finally, there are some purely empirical models such as that of Vaughan described as $\delta_m(\theta)/\delta_m(0^\circ) = 1 + k_s \cdot \theta^2$ and $E_m(\theta)/E_m(0^\circ) = 1 + k_s \cdot \theta^2/2$, where k_s is a fitting parameter used to describe the surface roughness [13].

Secondary electron emission from uniform samples at normal incidence of a primary electron beam is frequently and in many cases successfully modelled by the well-known semi-empirical law [10,14]. The latter is based on the assumption of the constant stopping power along the sample depth, which is a rather good approximation close to the sample surface [14]. Therefore, it seems reasonable to use this approach as a starting point to develop a model for description of the angular dependence of $\delta(E)$. Additionally, at higher incident angles, a considerable amount of the primary electron energy is reflected back into the vacuum and thus, not utilized to create secondary electrons. The fraction of the reflected energy can be estimated using Monte Carlo simulations.

In this work we propose a simple approach to determine $\delta(E)$ for any incident angle based on the experimental result achieved at normal incidence i.e. for $\theta = 0^\circ$. The secondary electron yield is calculated according to the universal semi-empirical law, while a fraction of the electron energy deposited into the sample is determined using the well-known Monte Carlo simulation Casino, ver. 2.42 [15]. A simple modification of the original approach for calculating a total electron yield (TEY), i.e. the sum of the 'true' secondaries and the backscattered electrons, will be also presented. Finally, the calculations are performed and compared with the experimental result obtained for silver and graphite. The agreement between the calculation and the experiment is discussed as well as the possibilities for further refining the model.

2. Experimental

Most of the TEY measurements were performed on the CELESTE facility at ONERA laboratory in Toulouse, described in detail elsewhere [16]. This experimental setup is entirely dedicated and designed to the study of secondary electron emission. A dry turbomolecular pump associated with an oil-free primary pump allows the system to be maintained at a vacuum level down to 5×10^{-9}mbar. The tank is grounded and collects emitted secondary electrons. The sample holder permits to rotate the sample from 0° (normal incidence angle) to 90° and the sample can be independently positively or negatively biased. The sample current, measured with a help of a Faraday cup, is monitored using a 200 MHz TDS3034B oscilloscope connected to a Femto-DHPCA-100 high speed and low noise current amplifier. An ELG2 Kimball electron gun with an option of microsecond electron beam pulsing was used as the electron source. Short electron pulses (about 5 μs) were used to avoid electron beam induced surface modification. In the TEY measurement configuration, the sample is negatively biased at −18 V in order to prevent the recollection of the emitted electrons or the stray electrons generated at the inner vacuum chamber shells.

TEY measurements at ONERA lab were performed on four different samples: two of high purity silver, and two more of graphite having different roughness. The silver samples (99.99% pure, provided by Goodfellow Company (Ag00470/31)) were exposed for more than 3 years to ambient atmosphere. The roughness of the samples was 160 nm (flat silver) and about 5 μm (rough silver), respectively. Rough graphite sample of 99.9% purity and estimated roughness of about 10 μm, purchased from Goodfellow, was also investigated. We used highly oriented pyrolytic graphite (HOPG) as a model for flat graphite sample. According to atomic force microscopy measurements, the surface roughness is estimated to be 0.9 nm, obtained in a 5×5 μm^2 scan.

Additionally, the measurements on HOPG were repeated in the Surface Science laboratory at Universidade Nova de Lisboa. Simple system for TEY measurements based on the collection method, similar to the one described by Lapington and co-workers [3], was realized in the frame of a multipurpose apparatus for surface analysis described elsewhere [17]. The system is designed to measure $\sigma(E)$ in the energy range 50–1000 eV at different incident angles. The primary current was kept at few nA and the beam spot had area of 3–5 mm^2. The sample was freshly cleaved just before performing the measurements, which were acquired at a working pressure in the low 10^{-6}mbar range obtained using a dry vacuum system. Sample cleanliness was checked using X-ray photoelectron spectroscopy before and after the sample measurement. The surface composition of the sample before and after the TEY measurement was identical showing less than 5% of impurities, consisting mainly of saturated hydrocarbons.

The relative measurement error of TEY is about 2% on both experimental setups.

3. The model description

We shall now introduce a simple model providing angular dependence of the secondary or total electron emission based on the SEY/TEY experimental results measured at normal incidence. It should be emphasized that once the necessary information is extracted from the experimental results, the procedure is exact i.e. without introducing any free parameters. The starting point is the semi-empirical law, which is based on the following assumptions [14]:

a) The trajectories of all incident electrons are straight lines. All electrons have the same range determined by their primary energy using the power law: $R = b \cdot E^n$ ($1 < n < 2$, b is a material constant).
b) The number of secondary electrons created is proportional to the stopping power S, which has uniform depth distribution i.e. $S = E/R = 1/(b \cdot E^{n-1})$. This assumption, which ignores the depth dependence of the stopping power, is quite reasonable knowing that all emitted secondary electrons are created in the first few nanometers and considering the scattering of incident electrons [18]. Therefore, the obtained energy dependence $\delta(E)$ should represent a rather good approximation.
c) The escape probability of electrons created at depth z is $0.5 \cdot \exp(-z/\lambda)$. The probability to overcome the potential barrier is not considered in the frame of this approach, since it should not affect significantly the modelling procedure.

Starting from the hypotheses given above, SEY at normal incidence is given as