BRIEF REPORTS AND COMMENTS

This section is intended for the publication of (1) brief reports which do not require the formal structure of regular journal articles, and (2) comments on items previously published in the journal.

Secondary electron emission for layered structures

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Semiempirical theory for secondary electron emission is extended to cover the layered structure. Secondary electron emission for the two-layered structure, i.e., a thin film on a substrate, is calculated and compared with the experiment. Good agreement between the two indicates the usefulness of this theory for the layered structure.
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These days, thin layers are widely used as a secondary electron emission (SEE) layer in many electron amplifying devices, such as a microchannel plate (MCP)[1] or an MCP-incorporated field emission display.[2,3] Although there have been a number of SEE experiments for a thin film on the substrate,[1,4–8] relatively little attention has been paid to the theoretical aspect of the thin film.

In this brief report, the SEE theory for the layered structure is studied in order to narrow the gap between the theories and experiments. Due primarily to the simplicity of the theory, the semiempirical elementary SEE theory[4] was chosen to cover the layered structure.[9] The constant loss scheme—approximately constant energy dissipation of electrons throughout the sample—is used in this derivation due to its physical clarity and supporting experiments.[4,5,10] Under the assumption that the electron replenishment from the reservoir through the multilayer and to the surface is sufficient to supply the emitted secondary electrons (SEs), i.e., no charge accumulation within the sample, the calculation is derived.

Following the elementary theoretical approach summarized in Ref. 4, the secondary electron emission yield (SEEY, δ) for the multilayer[11] (Fig. 1) as a function of the initial energy of the primary electron E_0 can be written as the summation of each δ_i within the layer i, i.e., within the domain $D_i=[X_{i-1},X_i]$:

$$\delta=\sum_i \delta_i=\sum_{i=1}^{l}\int_{D_i} dx\, n_i(x,E_{i-1}) f_i(x), \tag{1}$$

where $E_{i-1}\equiv E_{i-1,0}=E_{i-1}(x=X_{i-1})$ is the initial kinetic energy of electrons entering the domain D_i, i.e., the energy at $x=X_{i-1}$. After losing its energy through the layer i, the electron moves to the next layer $i+1$ with the initial energy E_i again, and finally stops at the last layer l. $n_i(x,E_{i-1})dx$ is the average number of secondary electrons produced in a layer of thickness dx at a position of x within the domain D_i per incident primary electron, and $f_i(x)$ represents the probability for a SE to migrate and escape to the surface direction.

It is generally assumed that $f_i(x)=B_i e^{-\alpha_i x}$, where B_i represents a constant of the order of unity ($\leqslant 1$) and α_i represents the absorption coefficient of SEs within the layer i. $n_i(x,E_{i-1,0})$ is assumed to be $-(1/\epsilon_i)(dE_i(x)/dx)$, i.e., proportional to the average energy loss per unit path length, where ϵ_i is the average energy required to produce a SE within the layer i[9] and the subscripts i of all the symbols indicate the symbols within the ith layer. Following the constant loss scheme illustrated in Ref. 4:

$$-\frac{dE_i(x)}{dx}=\frac{E_{i-1,0}}{R_i}, \tag{2}$$

which leads to

$$E_i(x)=E_{i-1,0}\times\left(1-\frac{x-X_{i-1}}{R_i}\right). \tag{3}$$

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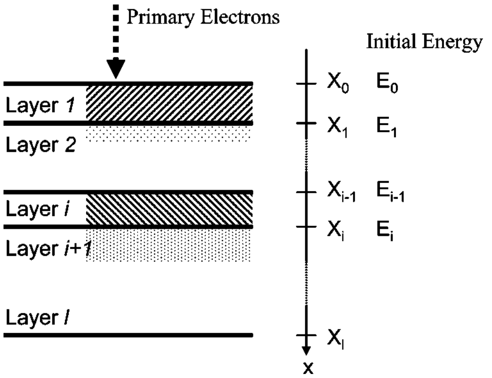

FIG. 1. Schematic diagram of an arbitrary l-layered structure. The 0th layer is assumed to be a vacuum and the lth layer is assumed to be infinitely thick, leading to the stop of incident electrons at the lth layer.

R_i of the penetration depth of electrons entering into the layer i is expressed from Young's experiments,[1,12] i.e.,

$$R_i=\frac{(E_{i-1,0})^n}{nA_i}, \tag{4}$$

where n is an arbitrary power to be determined later, and A_i is a constant depending on the material characteristics of the layer i. Then performing the integration of Eq. (1), SEEY becomes:

$$\delta(E_0)=\sum_{i=1}^{l} e^{-(\alpha_i X_{i-1})}\left(\frac{B_i}{\epsilon_i}\right)\left(\frac{nA_i}{\alpha_i}\right)^{1/n}\left[\frac{1-e^{-\alpha_i(\Delta X_i)}}{z_i^{n-1}}\right], \tag{5}$$

where $z_i^n=\alpha_i R_i$ and $\Delta X_i=X_i-X_{i-1}$. In the above derivation, the boundary values at the last layer l, are defined as $\Delta X_l \equiv R_l$, because the incident electrons stop in the last layer with the penetration depth of R_l.

However, when the thickness of each layer is too thick, the multilayer effect will shrink due to the exponential feature in the above derivation. Here, the calculation is performed for a two-layered structure, which is the most common experimental situation, i.e., $l=1$, and is compared with the experiments. The above equation can be expressed as:

$$\begin{aligned}\delta &= \delta_1+\delta_2\\ &=\left(\frac{B_1}{\epsilon_1}\right)\left(\frac{nA_1}{\alpha_1}\right)^{1/n}\left[\frac{1-e^{-\alpha_1 X_1}}{z_1^{n-1}}\right]+e^{-(\alpha_2 X_1)}\left(\frac{B_2}{\epsilon_2}\right)\\ &\quad\times\left(\frac{nA_2}{\alpha_2}\right)^{1/n}\left[\frac{1-e^{-\alpha_2 R_2}}{z_2^{n-1}}\right],\end{aligned} \tag{6}$$

where the thickness of the first layer is d, and $(X_0=0, X_1=d$, and $\Delta X_1=X_1=d)$. The initial energies at the layer 0 and 1 are E_0 and $E_1=E_{1,0}=E_1(x=X_1)=E_0[1-(d/R_1)]$, respectively. From Young's experiment,[1,12] the constant n is chosen to be 1.35.

The calculation is performed for the thin SiO_2 layer on the Si substrate. The input parameters for Si and SiO_2 used in this calculation are $\rho(Si)=2.33$, $\rho(SiO_2)=2.20$, $E_{0,\max}(Si)=0.30$, $E_{0,\max}(SiO_2)=0.35$ eV, $\delta_{\max}(Si)=1.15$, and $\delta_{\max}(SiO_2)=3.55$, which are obtained from Ref. 5 for Si and this experiment for SiO_2, respectively. In order to verify the above derivation, SiO_2 films of five different thicknesses were grown on a Si substrate (p type, boron doping with a resistivity of 300 Ω cm) by thermal oxidation at 930 °C. The thickness of the SiO_2 films was measured using ellipsometry. 20 and 60 min grown films were 77 and 160 Å, respectively, but 5, 7, and 10 min grown films were too thin to be accurately measured using ellipsometry. The SEEY measurement was done in a vacuum chamber (high 10^{-8} Torr) with an electron gun (Kimball Physics, EFG-7) by applying a small negative voltage to the sample. The experimental details can be found in Refs. 7 and 13.

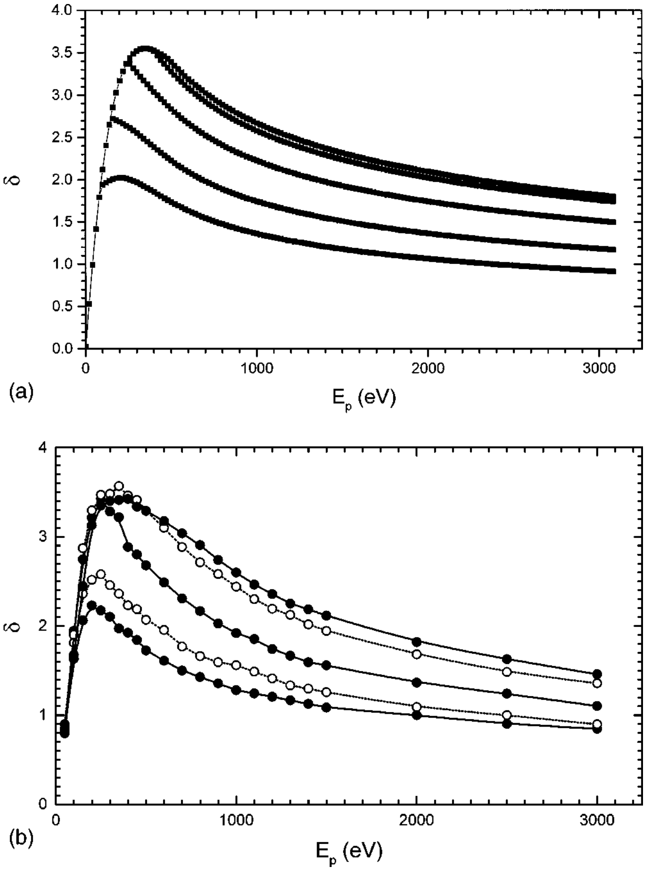

FIG. 2. (a) Calculated SEEY for SiO_2/Si as a function of the primary electron's energy E_p. From the bottom, the thickness of an SiO_2 layer is 20, 40, 80, 150, and 200 Å, respectively. (b) Measured SEEY for SiO_2/Si as a function of electron energy. From the bottom the curves correspond to the samples of 5,7, 10, 20, and 60 min oxidation at 930 °C, respectively.

The overall shape of the calculated SEEY curves in Fig. 2(a) agrees well with those of the measured SEEY curves in Fig. 2(b) and those in Ref. 1. The sharp discontinuity at low energy in Fig. 2(a) is caused by the ideal assumptions in the current model which does not include experimental imperfections such as the flawed interface between the layers. The low SEEY for the thinner samples reflects the fact that most of the SEs are produced within the Si substrate where SEEY is lower than that of SiO_2. As the thickness of a SiO_2 layer becomes larger, the SEEY also becomes larger due to the larger contributions from the SiO_2 layer. Eventually, when the SiO_2 layer becomes thick, the SEEY value will approach that of bulk SiO_2.

The current model considers only the penetration and escape depth of electrons, together with the thickness of the layer. One of our assumptions that can result in the deviation from the experiment is the unlimited electron replenishment from the reservoir to avoid charge accumulation. Charge accumulation becomes serious when the oxide layer becomes thick.[7,14] Thus, applying the current model to a thicker layer should be avoided.

In summary, by extending the elementary theory, we have derived the SEEY for a multilayered system. The calculation and experiment were compared for a series of thin SiO_2 layers on a Si substrate, i.e., a two-layered system, from which reasonably good agreement was obtained. The limitation of this derivation, due mainly to neglecting the charge accumulation, was also discussed.

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