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Formulae for secondary electron yield from insulators and semiconductors

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Abstract The processes and characteristics of secondary electron emission in insulators and semiconductors were studied, and the formulae for the maximum yield (δ_m) at $W_{p0m} \leq 800$ eV and the secondary electron yield from insulators and semiconductors δ at the primary incident energy of $2\ \text{keV} \leq W_{p0} < 10\ \text{keV}$ ($\delta_{2\text{–}10}$) and $10\ \text{keV} \leq W_{p0} \leq 100\ \text{keV}$ ($\delta_{10\text{–}100}$) were deduced. The calculation results were compared with their corresponding experimental data. It is concluded that the deduced formulae can be used to calculate $\delta_{2\text{–}100}$ at $W_{p0m} \leq 800$ eV.

Keywords Maximum secondary electron yield · Insulators and semiconductors · Secondary electron yield

1 Introduction

Secondary electron yields from different materials have interested many authors [1–4]. The secondary electron yield from insulators and semiconductors (δ) has found increasing applications in various areas, such as information technology, accelerator, scanning electron microscope, space flight, etc. [5–7] However, due to the high resistance of insulators and semiconductors, it is difficult to overcome their surface charge problem and measure the secondary electron yield [8–10]. Thus, available δ measurement data on insulators and semiconductors are not rich [11], especially in the incident energy range of 10–100 keV. Instead, many authors deduced formulae for key parameters to deduce δ of insulators and semiconductors [12–16]; But up to now, no formulae are available for the incident energy range of 2–10 keV ($\delta_{2\text{–}10}$) and 10–100 keV ($\delta_{10\text{–}100}$), and for W_{p0m}, the incident energy at which δ is maximized (δ_m).

In this study, based on secondary electron emission processes in insulators and semiconductors and the formulae of $\delta_{2\text{–}10}$, $\delta_{10\text{–}100}$, and the maximum yield δ_m at $W_{p0m} \leq 800$ eV were deduced, involving the primary range of $10\ \text{keV} \leq W_{p0} \leq 100\ \text{keV}$ ($R_{10\text{–}100}$) and $2\ \text{keV} \leq W_{p0} < 10\ \text{keV}$ ($R_{2\text{–}10}$), the atomic number Z, and the high energy back-scattering coefficient r, apart from the different forms of secondary electron yield. For compounds, Z represents average atomic number of compounds, for example, $Z = (20 + 8)/2$ for CaO; and r represents back-scattering coefficient in the energy range of $W_{p0} \geq 10$ keV.

2 Methods

2.1 Formula for δ_m

When electrons enter an insulator or semiconductor, secondary electrons are generated due to energy deposition of the primary electrons. Suppose that $N(x, W_p)$ is the number of secondary electrons produced at a depth x and primary electron energy of W_p, $N(x, W_p)$ is proportional to average loss of primary electrons per unit path length [17, 18]:

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$$N(x, W_p) = -\frac{dW_p}{dS}\frac{1}{\varepsilon}, \tag{1}$$

where W_p is primary energy at given depth in insulator or semiconductor, S is the path length of primary electrons, and ε is the average energy required to produce an internal secondary electron in an insulator or semiconductor.

The probability of an internal secondary electron reaching the surface of the insulator or semiconductor and passing over the surface barrier into vacuum can be written as [17, 18]:

$$f(x) = B\exp(-\alpha x), \tag{2}$$

where α is the absorption coefficient (and $1/\alpha$ is mean escape depth of secondary electrons), and B is the probability that an internal secondary electron escapes into vacuum upon reaching the surface of insulator or semiconductor.

From Eqs. (1) and (2), the yield due to primary electron can be written as [19]:

$$\delta_p = \int_0^R N(x, W_p)B\exp(-\alpha x)dx = -\frac{B}{\varepsilon}\int_0^R \frac{dW_p}{dS}\exp(-\alpha x)dx. \tag{3}$$

According to Seiler [17], the maximum yield due to primary electron δ_{pm} is at $R = 2.3/\alpha$. Then, δ_{pm} can be written as [19]:

$$\delta_{pm} = -\frac{B}{\varepsilon}\int_0^{\frac{2.3}{\alpha}} \frac{dW_p}{dS}\exp(-\alpha x)dx. \tag{4}$$

At $W_{p0m} \le 800$ eV, the primary range R can be expressed as [20]:

$$R = 2\times10^{-9}\, A_\alpha W_{p0m}/\left(\rho Z^{2/3}\right), \tag{5}$$

where ρ is material density, Z is atomic number, and A_α is atomic weight.

It can be assumed that the R at $W_{p0m} \le 800$ eV approximately equals the corresponding S for deducing the formula for δ_m. Thus, the energy loss per unit path length of the primary electrons at $W_{p0m} \le 800$ eV can be obtained by differentiating Eq. (5):

$$dW_p/dS = -\rho Z^{2/3}/\left(2\times10^{-9}\, A_\alpha\right). \tag{6}$$

The δ_{pm} at $W_{p0m} \le 800$ eV can be obtained by combining Eqs. (4) and (6):

$$\delta_{pm} = \left(e^{2.3}-1\right)B\rho Z^{2/3}/\left(2\times10^{-9}\, A_\alpha\alpha e^{2.3}\varepsilon\right). \tag{7}$$

Relation between δ_m and δ_{pm} can be written as [21]:

$$\delta_m = (1+1.26r)\delta_{pm}. \tag{8}$$

For a given material, r is a constant [22]. The δ_m can be obtained by combining Eqs. (7) and (8).

$$\delta_m = (1+1.26r)\left(e^{2.3}-1\right)B\rho Z^{2/3}/\left(2\times10^{-9}\, A_\alpha\alpha e^{2.3}\varepsilon\right) \tag{9}$$

2.2 Formula for δ_{10-100}

When primary electrons of 10 keV $\le W_{p0} \le$ 100 keV enter an insulator or semiconductor, R_{10-100} can be expressed as [20]

$$R_{10-100} = \frac{3.02\times10^{-11}A_\alpha W_{p0}^{5/3}}{\rho Z^{8/9}}. \tag{10}$$

It can be assumed that the R_{10-100} approximately equals the corresponding S for deducing the formula for δ_{10-100}. Thus, the following expression can be obtained by differentiating Eq. (10):

$$\frac{dW_p}{dS} = -\frac{\rho Z^{8/9}}{5.03\times10^{-11}A_\alpha W_p^{2/3}}. \tag{11}$$

The R_{10-100} is much larger than the maximum escape depth of secondary electrons T. For example, using Eq. (10) in Si ($Z = 14$, $\rho = 2.35$ g/cm^3, and $A_\alpha = 28.1$) [13] at $W_{p0} = 10$ keV, we have $R_{10} = 16{,}055$ Å and $T = 41$–54 Å [23]. Thus, most of the primary energy is dissipated outside T, and the primary energy changes little inside T. Then, the energy loss of primary electrons in the energy range of 10 keV $\le W_{p0} \le$ 100 keV per unit path length inside T can be approximately written as:

$$\frac{dW_p}{dS} = -\frac{\rho Z^{8/9}}{5.03\times10^{-11}A_\alpha W_{p0}^{2/3}}. \tag{12}$$

The δ_p in energy range of 10 keV $\le W_{p0} \le$ 100 keV can be obtained by combining Eqs. (3) and (12):

$$\delta_p = \frac{B}{\varepsilon}\frac{\rho Z^{8/9}}{5.03\times10^{-11}A_\alpha W_{p0}^{2/3}}\int_0^R \exp(-\alpha x)dx. \tag{13}$$

The R_{10-100} is much larger than T. The internal secondary electrons excited outside T cannot be emitted into vacuum [23], and T approximately equals $5/\alpha$ [23]. Thus, the definite integral [0, R] of Eq. (13) can be replaced with [0, $5/\alpha$]. Then, we have:

$$\delta_p = \frac{\left(e^5-1\right)}{e^5}\frac{B}{\alpha\varepsilon}\frac{\rho Z^{8/9}}{5.03\times10^{-11}A_\alpha W_{p0}^{2/3}}. \tag{14}$$

The δ is composed of δ_p and yield due to backscattered electrons δ_r, i.e. [24]

$$\delta = \delta_p + \eta\delta_r = (1+\beta\eta)\delta_p, \tag{15}$$

where β is the ratio of the mean secondary electron generation of one backscattered electron to that of one primary electron, and η is the back-scattering coefficient at W_{p0}. The β is greater than one [17], because the larger average emission angle of backscattered electrons is more favorable for the excitation of secondary electrons than the normal incidence of primary electrons, and the mean energy of backscattered electrons is less than W_{p0}.

According to theoretical and experimental results, for $10\ \text{keV} \leq W_{p0} \leq 100\ \text{keV}$, β of metals is about 2 ($\beta_{10\text{–}100\ \text{metal}} \approx 2$) [25–28]. Because the average emission angle and mean energy of backscattered electrons from insulator or semiconductor are similar to those from metals [28, 29], we assume $\beta_{10\text{–}100\ \text{insulator}} \approx 2$ for $10\ \text{keV} \leq W_{p0} \leq 100\ \text{keV}$. Therefore, we have:

$$\delta_{10-100} = (1 + 2r)\delta_p. \tag{16}$$

The δ in energy range of $10\ \text{keV} \leq W_{p0} \leq 100$ keV and $W_{p0m} \leq 800$ eV can be obtained by combining Eqs. (9), (14) and (16)

$$\delta_{10-100} = \frac{43.9(1+2r)Z^{2/9}\delta_m}{(1.1.26r)W_{p0}^{2/3}}. \tag{17}$$

2.3 Formula for $\delta_{2\text{–}10}$

When primary electrons of $2\ \text{keV} \leq W_{p0} < 10\ \text{keV}$ enter an insulator or semiconductor, $R_{2\text{–}10}$ can be expressed as [20]:

$$R_{10-100} = \frac{1.03 \times 10^{-10} A_\alpha W_{p0}^{3/2}}{\rho Z^{5/6}}. \tag{18}$$

It can be assumed that the $R_{2\text{–}10}$ approximately equals the corresponding S during for deducing the formula for $\delta_{2\text{–}10}$. Thus, we have Eq. (19):

$$\frac{dW_p}{dS} = -\frac{\rho Z^{5/6}}{1.545 \times 10^{-10} A_\alpha W_p^{1/2}}. \tag{19}$$

The $R_{2\text{–}10}$ is much larger than T in energy range of $W_{p0m} < 800$ eV. For example, for Si ($Z = 14$, $\rho = 2.35$ g/cm^3, $A_\alpha = 28.1$) [13], at $W_{p0} = 2000$ eV, calculated with Eq. (18) we have $R_2 = 1222$ Å and $T = 41$–54 Å [23]. Thus, most of the primary energy is dissipated outside T; the primary energy only has a little change inside T. Then, the energy loss of primary electrons in the energy range of $2\ \text{keV} \leq W_{p0} < 10$ keV per unit path length inside T can be approximately written as:

$$\frac{dW_p}{dS} = -\frac{\rho Z^{5/6}}{1.545 \times 10^{-10} A_\alpha W_{p0}^{1/2}}. \tag{20}$$

Based on Eqs. (3) and (20), δ_p in energy range of $2\ \text{keV} \leq W_{p0} < 10$ keV can be written as:

$$\delta_p = \frac{B}{\varepsilon} \frac{\rho Z^{5/6}}{1.545 \times 10^{-10} A_\alpha W_{p0}^{1/2}} \int_0^R \exp(-\alpha x)dx. \tag{21}$$

$R_{2\text{–}10}$ is much larger than T in energy range of $W_{p0m} < 800$ eV, the internal secondary electrons excited outside T cannot be emitted into vacuum [23], and $T \approx 5/\alpha$ [23]. Thus, the definite integral [0, R] of Eq. (21) can be replaced with [0, $5/\alpha$], i.e.,

$$\delta_p = \frac{(e^5 - 1)}{e^5} \frac{B}{\alpha\varepsilon} \frac{\rho Z^{5/6}}{1.545 \times 10^{-10} A_\alpha W_{p0}^{1/2}}. \tag{22}$$

From Eqs. (8) and (15), we have $\delta_p/\delta_r = 1/(1.26r)$ for $W_{p0m} \leq 800$ eV, and from Eqs. (15) and (16), we have $\delta_p/\delta_r = 1/(2r)$ for $10\ \text{keV} \leq W_{p0} \leq 100$ keV. There is the tendency that η increases with W_{p0} for $W_{p0} \leq 10$ keV [17], so there is the tendency that the δ_p/δ_r decreases with W_{p0} for $W_{p0} \leq 10$ keV. Thus, the δ_p/δ_r ratio for $2\ \text{keV} \leq W_{p0} < 10$ keV is in the range of [1/(1.26r), 1/(2r)], and we assume $\delta_p/\delta_r = 1/(1.5r)$ for $2\ \text{keV} \leq W_{p0} < 10$ keV. Then, approximately, the δ for $2\ \text{keV} \leq W_{p0} < 10$ keV can be expressed as:

$$\delta = (1 + 1.5r)\delta_p. \tag{23}$$

Combining Eqs. (22) and (23), we have:

$$\delta_p = \frac{(e^5 - 1)}{e^5} \frac{B}{\alpha\varepsilon} \frac{\rho Z^{5/6}(1 + 1.5r)}{1.545 \times 10^{-10} A_\alpha W_{p0}^{1/2}}. \tag{24}$$

From Eqs. (9) and (24), the δ for $2\ \text{keV} \leq W_{p0} < 10$ keV and $W_{p0m} \leq 800$ eV can be expressed as

$$\delta_{2-10} = \frac{14.29(1+1.5r)Z^{1/6}\delta_m}{(1+1.26r)W_{p0}^{1/2}}. \tag{25}$$

3 Results and discussion

Several approximations were made in deducing Eqs. (17) and (25). For example, for $2\ \text{keV} \leq W_{p0} < 10$ keV, energy loss of primary electron per unit path length inside T is from approximation. The energy loss decreases with W_p [4, 30]. The $R_{2\text{–}10}$ is much larger than T for $W_{p0m} < 800$ eV. Thus, most of the primary energy is dissipated outside T; the primary energy changes little inside T. Therefore, the energy loss of primary electron can be calculated Eq. (20).

The $\delta_{10\text{–}100}$ and $\delta_{2\text{–}10}$ calculated with Eqs. (17) and (25), respectively, and the δ_m [31, 32], Z, W_{p0} and r are given in Table 1. It can be seen that the calculation results of $\delta_{10\text{–}100}$ and $\delta_{2\text{–}10}$ agree well with the experimental data [31, 32].

Table 1 Comparison of the calculated δ for insulators and semiconductors with the experimental data

Materials [17, 21]	δ_m	W_{p0} (keV)	Calculated	Measured
Si ($Z = 14$, $r = 0.22$)	1.594 [31]	3.0 [31]	0.6723	0.769 [31]
		5.0 [31]	0.5207	0.49 [31]
		10 [31]	0.3056	0.3431 [31]
		20 [31]	0.1925	0.216 [31]
		30 [31]	0.1439	0.138 [31]
Te ($Z = 52$, $r = 0.41$)	1.63 [31]	3.0 [31]	0.875	0.891 [31]
		5.0 [31]	0.6777	0.706 [31]
		10 [31]	0.4451	0.376 [31]
		20 [31]	0.2804	0.319 [31]
		30 [31]	0.214	0.174 [31]
	0.819 [11]	2.0 [11]	0.5384	0.495 [11]
		2.4 [11]	0.4915	0.418 [11]
Ge ($Z = 32$, $r = 0.35$)	1.142 [33]	2.0 [33]	0.688	0.696 [33]
		2.5 [33]	0.6154	0.54 [33]
		3.0 [33]	0.5618	0.53 [33]
		3.5 [33]	0.52	0.49 [33]
		4.0 [33]	0.4865	0.45 [33]
		4.5 [33]	0.4587	0.42 [33]
		5.0 [33]	0.4352	0.42 [33]
	0.743 [11]	2.0 [11]	0.4477	0.398 [11]
		3.0 [11]	0.3655	0.312 [11]
		4.0 [11]	0.3165	0.264 [11]
	1.62 [31]	5.0 [31]	0.6174	0.649 [31]
		20.0 [31]	0.2458	0.228 [31]
C ($Z = 6$, $r = 0.1$)	1.56 [31]	5.0 [31]	0.434	0.501 [31]
		20 [31]	0.1475	0.125 [31]
	1.136 [33]	2.0 [34]	0.5	0.527 [34]
		2.5 [34]	0.447	0.442 [34]
		3.0 [34]	0.408	0.4 [34]
		4.0 [34]	0.3533	0.316 [34]
		5.0 [34]	0.316	0.315 [34]
Indium tin oxide ($Z = 35.7$, $r = 0.36$)	2.52 [32]	2.0 [32]	1.5477	1.55 [31]
		3.0 [32]	1.2637	1.31 [32]
		5.0 [32]	0.9789	1.03 [32]
		7.0 [32]	0.8273	0.72 [32]
		10 [32]	0.6356	0.73 [32]
Indium zinc oxide ($Z = 29$, $r = 0.34$)	2.67 [32]	2.0 [32]	1.581	1.61 [32]
		3.0 [32]	1.291	1.31 [32]
		5.0 [32]	1.0	1.02 [32]
		7.0 [32]	0.845	0.86 [32]
		10 [32]	0.6278	0.72 [32]
Al_2O_3 ($Z = 10$, $r = 0.18$)	6.23 [35]	2.0 [35]	3.025	3.83 [35]
		3.0 [35]	2.47	2.44 [35]
V_2O_5 ($Z = 12.3$, $r = 0.2$)	1.216 [36]	2.01 [36]	0.6114	0.718 [36]
		2.54 [36]	0.5439	0.669 [36]
		3.044 [36]	0.4968	0.578 [36]
		3.572 [36]	0.4586	0.53 [36]
		4.034 [36]	0.4316	0.487 [36]
		5.056 [36]	0.3855	0.389 [36]
		5.571 [36]	0.367	0.347 [36]

So, Eq. (17) can be used to calculate $\delta_{10\text{–}100}$, and the assumption that $\beta_{10\text{–}100\ \text{insulator}} \approx 2$ is reasonable. Also, for 2 keV $\leq W_{p0} <$ 10 keV, Eq. (25) can be used to calculate $\delta_{2\text{–}10}$ and the assumption that the ratio of $\delta_p/\delta_r \approx 1/(1.5r)$ is reasonable.

The secondary electrons inside an insulator or semiconductor lose their energy in electron–electron collisions. Classically, only electrons with a kinetic energy $E > \chi_{real}$ can escape into vacuum [37], where χ_{real} is the real electron affinity and E is the energy measured from the bottom of conduction band of insulator and semiconductor. The minimum energy (for secondary electrons to escape) increases with the χ_{real}. The electrons that are created in shallower depths suffer fewer collisions and survive with sufficient energy to escape. In other words, volume in the insulator or semiconductor from which electrons escape decreases with increasing χ_{real}, and from this reduced volume only hot electrons emerge. As a result, a decrease in $1/\alpha$ is expected. With the increase of χ_{real}, the minimum energy for secondary electrons to escape increases, and B decreases. Therefore, from Eq. (9), δ_m increases with decreasing χ_{real}.

For an insulator or semiconductor, different sample preparation techniques can lead to different χ_{real}, hence different δ_m, and different $\delta_{2\text{–}10}$ and $\delta_{10\text{–}100}$, from Eqs. (17) and (25). These can be seen clearly for Te and Ge shown in Table 1 From above, it is concluded that the formulae for $\delta_{10\text{–}100}$ and $\delta_{2\text{–}10}$ can be used to calculate $\delta_{2\text{–}100}$ in the energy range of $W_{p0m} \leq$ 800 eV.

4 Conclusion

Based on the processes and characteristics of secondary electron emission, formulae for $R_{10\text{–}100}$ and $R_{2\text{–}10}$ and relationships among parameters of δ, the formulae for $\delta_{10\text{–}100}$ and $\delta_{2\text{–}10}$ were deduced, respectively. The $\delta_{10\text{–}100}$ calculated with the deduced formula for $\delta_{10\text{–}100}$ and $\delta_{2\text{–}10}$ calculated with the deduced formula for $\delta_{2\text{–}10}$ were compared with their corresponding experimental data, and the results were analyzed. It is concluded that the deduced formulae for $\delta_{10\text{–}100}$ and $\delta_{2\text{–}10}$ can be used to calculate $\delta_{2\text{–}100}$ in the energy range of $W_{p0m} \leq$ 800 eV.

Different sample preparation of an insulator or semiconductor can lead to different χ_{real}, $1/\alpha$, B, δ_m, $\delta_{2\text{–}10}$ and $\delta_{10\text{–}100}$.

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