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Formulae for the secondary electron yield and total stopping power from 0.8 keV to 10 keV for metals

A G XIE[1,2,*], S Y XIAO[1] and L WANG[1]

[1]School of Physics and Optoelectronic Engineering, Nanjing University of Information Science and Technology, Nanjing 210 044, China
[2]Department of Electrical and Biological Physics, Kwangwoon University, 20 Kwangwoon-gil, Nowon-gu, Seoul 139-701, Republic of Korea
*Corresponding author. E-mail: xagth@126.com

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Abstract. Based on the range–energy relationship, the characteristics of secondary electron emission, some relationship between the secondary electron yield δ and experimental results, the universal formulae for $\delta_{0.8-2}$ (the subscript indicates that the energy range of primary energy at the surface W_{po} is from 0.8 keV to 2 keV) and δ_{2-10} for metals were deduced. The $\delta_{0.8-10}$ calculated with the universal formulae and the $\delta_{0.8-10}$ measured experimentally were compared, and the scattering of δ for the same metal was analysed. Finally, we concluded that the formulae were universal for $\delta_{0.8-10}$ for metals. On the basis of some relationship between parameters of δ, we deduce a formula for expressing total stopping power $S_{0.8-10}$ as a function of S_{10-30}, $\delta_{0.8-10}$, δ_{10-30}, backscattered coefficient $\eta_{0.8-10}$, η_{10-30} and W_{po}. The calculated $S_{0.8-10}$ were compared with the values measured experimentally and it was concluded that the formula to estimate $S_{0.8-10}$ was universal for metals.

Keywords. Secondary electron yield; total stopping power; metal.

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1. Introduction

Electrical properties of solid and parameters of electrical properties are important topics [1–5]. The secondary electron yield δ is one of the most important parameters of electrical properties of solid, and many researchers have studied about δ and deduced formulae for δ [6–18]. We have deduced the universal formula for δ_{10-100} (in this paper, the subscript indicates that the energy range of primary energy at the surface W_{p0} is from 10 keV to 100 keV) [19]. Based on the range–energy relationship, the characteristics of secondary electron emission, some relationship between the parameter δ and experimental results, the universal formulae for $\delta_{0.8-2}$ and δ_{2-10} for metals were deduced in this paper. The formulae presented in this paper to estimate $\delta_{0.8-10}$ are universal for metals.

The average rate of energy loss per unit path length due to collisions with atoms and atomic electrons in which bremsstrahlung quanta are emitted is the radiative stopping power [20], and the average rate of energy loss per unit path length due to Coulomb collisions resulting in the ionization and the excitation of atoms is the collision stopping power [20]. For electrons, the sum of the collision and the radiative stopping powers is called the total stopping power S (i.e., the energy loss of the primary electrons per unit path length) [20]. S is a research tool for determining δ which is a widely studied topic [7,8,21,22]. Thus, many researchers have measured $S_{0.001-40}$ [23–26]. The ESTAR program can calculate S from 10 keV to 10000 MeV [27] and the SREM program can also calculate S [28]. To date, only we have deduced a formula for S_{2-10} [29].

On the basis of some relationship between δ for metal, $S_{0.8-10}$ as a function of S_{10-30}, $\delta_{0.8-10}$, δ_{10-30}, backscattered coefficient $\eta_{0.8-10}$, η_{10-30} and W_{p0} was deduced in this study. The deduced formula for S can give an estimate in practical applications of $S_{0.8-10}$.

2. Number of secondary electrons released per primary electron

When primary electrons from 0.8 keV to 30 keV hit a metal, with a range of R, the number of secondary electrons released per primary electron δ_{PE} can be obtained as follows [9,19]:

$$\delta_{PE} = -\int_0^R \frac{B}{\varepsilon}\frac{dW_p}{dx}e^{-\alpha x}dx, \tag{1}$$

where B is a constant <1 and takes into account the fact that only a fraction of the excited electrons migrate toward the surface and accounts for the probability of these electrons reaching the surface and passing over the surface barrier into vacuum, ε is the average energy required to produce a secondary electron, W_p is the primary energy at some given depth in the solid, x is the distance from the surface of the emitter and $1/\alpha$ is the mean escape depth.

According to several researchers [30–32], secondary electron yield reaches the maximum secondary electron yield Y_m, if R is approximately equal to $1/\alpha$ and most of the secondary electrons excited at distances greater than $1/\alpha$ cannot be emitted into vacuum [33]. For metals, δ reaches Y_m [9] when the energy range of $W_{p0} \leqq 800$eV. Therefore, when primary electrons with energies ranging from 0.8 keV to 30 keV enter the metal, the definite integral $[0, R]$ of eq. (1) can be replaced with $[0, 1/\alpha]$.

Based on the range–energy relationship deduced from the power potential law, the relation between R, the energy exponent n and W_{p0} is given by [9]

$$R = AW_{p0}^n, \tag{2}$$

where n is a constant in the same energy range and parameter A depends on the density of the metal and atomic weight of the metal in the same energy range. Based on eq. (2), we obtain the following expression:

$$\frac{dW_p}{dx} = -\frac{1}{AnW_p^{n-1}}. \tag{3}$$

When primary electrons with energy ranging from 2 keV to 30 keV hit a metal, R is much larger than $1/\alpha$. So most of the primary energy is dissipated outside this

region. The energy loss of the primary electrons per unit path length S inside $1/\alpha$ can be approximately written as

$$\frac{\mathrm{d}W_\mathrm{p}}{\mathrm{d}x} = -\frac{1}{AnW_{\mathrm{p0}}^{n-1}}. \tag{4}$$

When primary electrons with energies ranging from 0.8 keV to 2 keV hit a metal, R is not much larger than $1/\alpha$, S inside $1/\alpha$ increases faster with the decrease of W_{p0} than eq. (4) does. According to some researchers [34,35], S within the metal is approximately a constant. Therefore, we suppose that $S_{0.8-2}$ inside $1/\alpha$ is given by

$$S_{0.8-2} = \frac{\mathrm{d}W_\mathrm{p}}{\mathrm{d}x} = -\frac{\left(2\,\mathrm{keV}/W_{\mathrm{p0}}\right)^{0.15}}{AnW_{\mathrm{p0}}^{n-1}} = -\frac{(2\,\mathrm{keV})^{0.15}}{AnW_{\mathrm{p0}}^{n-1.15}}. \tag{5}$$

Therefore, on the basis of eqs (1) and (4), $\delta_{\mathrm{PE2-30}}$ can be written as follows:

$$\delta_{\mathrm{PE2-30}} = \frac{B}{\varepsilon}\int_0^{1/\alpha} -\frac{1}{AnW_{\mathrm{p0}}^{n-1}}\mathrm{e}^{-\alpha x}\mathrm{d}x = \frac{B(e-1)}{\varepsilon e\alpha AnW_{\mathrm{p0}}^{n-1}}. \tag{6}$$

Therefore, on the basis of eqs (1) and (5), $\delta_{\mathrm{PE0.8-2}}$ can be written as follows:

$$\delta_{\mathrm{PE0.8-2}} = \frac{B}{\varepsilon}\int_0^{1/\alpha} -\frac{(2\,\mathrm{keV})^{0.15}}{AnW_{\mathrm{p0}}^{n-1.15}}\mathrm{e}^{-\alpha x}\mathrm{d}x = \frac{B(e-1)(2\,\mathrm{keV})^{0.15}}{\varepsilon e\alpha AnW_{\mathrm{p0}}^{n-1.15}}. \tag{7}$$

3. Secondary electron yield

δ can be written as [11]

$$\delta = \delta_{\mathrm{PE}} + \eta\delta_{\mathrm{RE}} = \delta_{\mathrm{PE}}(1+\beta\eta), \tag{8}$$

where δ_{RE} is the number of secondary electrons released per backscattered electron and $\beta = \delta_{\mathrm{RE}}/\delta_{\mathrm{PE}}$ is the ratio of the mean secondary electron generation of one backscattered electron to that of one primary electron.

From eqs (6) and (8), we obtain a universal formula for δ_{2-10} for metals:

$$\delta_{2-10} = \frac{B(e-1)(1+\beta\eta)}{\varepsilon e\alpha nAW_{\mathrm{p0}}^{n-1}}. \tag{9}$$

Y_m for metal is given by [19]

$$Y_\mathrm{m} = \frac{B(e-1)}{\varepsilon e\alpha}\frac{\rho Z^{2/3}}{2.0\times10^{-9}A_\alpha}, \tag{10}$$

where ρ is the density of the metal, Z is the atomic number and A_α is the atomic weight.

On the basis of eqs (9) and (10), eq. (9) can be written as follows:

$$\delta_{2-10} = \frac{(1+\beta\eta)2.0\times10^{-9}A_\alpha Y_\mathrm{m}}{\rho Z^{2/3}AnW_{\mathrm{p0}}^{n-1}}. \tag{11}$$

Based on the relation between R, n, W_{p0}, $n_{2-10} = 1.5$ [9], A_{2-10} is given by [9]

$$A_{2-10} = \frac{D_{2-10}}{NZ^{5/6}}, \tag{12}$$

where D_{2-10} is an approximate constant for a given metal and N is the number of atoms per unit volume [9]. The density of the metal is given by

$$\rho = NA_\alpha. \tag{13}$$

Suppose $(Z^{1/6}4.0 \times 10^{-9})/(3D_{2-10}) = E_{2-10}(Z)$. Thus, based on eqs (11)–(13), δ_{2-10} can be written as follows:

$$\delta_{2-10} = \frac{E_{2-10}(Z)(1+\beta\eta)Y_{\mathrm{m}}}{W_{\mathrm{p0}}^{0.5}}. \tag{14}$$

From eqs (7) and (8), we obtain a universal formula for $\delta_{0.8-2}$ for metals:

$$\delta_{0.8-2} = \frac{B(e-1)(2\,\mathrm{keV})^{0.15}(1+\beta\eta)}{\varepsilon e\alpha AnW_{\mathrm{p0}}^{n-1.15}}. \tag{15}$$

Based on the relation between R, n, W_{p0}, $n_{0.8-2} = 4/3$ [9], $A_{0.8-2}$ can be written as [9]

$$A_{0.8-2} = \frac{D_{0.8-2}}{NZ^{7/9}}, \tag{16}$$

where $D_{0.8-2}$ is a constant for a given material.

Suppose $(Z^{1/9}3.0 \times 10^{-9})/(2D_{0.8-2}) = E_{0.8-2}(Z)$. Thus, on the basis of eqs (10), (13), (15) and (16), $\delta_{0.8-2}$ can be written as follows:

$$\delta_{0.8-2} = \frac{E_{0.8-2}(Z)(1+\beta\eta)Y_{\mathrm{m}}(2\,\mathrm{keV})^{0.15}}{W_{\mathrm{p0}}^{(1/3-0.15)}}. \tag{17}$$

4. Ratio and backscattered coefficient

Some researchers obtained $\beta \approx 4$ for beryllium at $W_{\mathrm{p0}} = 4$ keV [36]; some others obtained $\beta \approx 2$ for metals at $W_{\mathrm{p0}} > 10$ keV [37,38]. Based on these values, $\beta_{0.8-10}$ of metals can be approximately written as follows:

$$\beta(W_{\mathrm{p0}}) = \frac{5.69(\mathrm{keV})^{0.365}}{W_{\mathrm{p0}}^{0.365}}. \tag{18}$$

When primary electrons enter the same kind of emitter, η is given by [39]

$$\eta = G - He^{-IW_{\mathrm{p0}}}, \tag{19}$$

where G, H and I are constants for a given metal in the energy range of $W_{\mathrm{p0}} = 0.8$–10 keV. The parameters G, H and I related to seven types of metals are shown in table 1 [39,40].

From eqs (14), (18) and (19), the universal formula for δ_{2-10} for metals is given by

$$\delta_{2-10} = \frac{E_{2-10}(Z)[1+(5.69(\mathrm{keV})^{0.365}/W_{\mathrm{p0}}^{0.365})(G-He^{-IW_{\mathrm{p0}}})]Y_{\mathrm{m}}}{W_{\mathrm{p0}}^{0.5}}. \tag{20}$$

Based on eqs (17)–(19), the universal formula for $\delta_{0.8-2}$ for metals is given by

$$\delta_{0.8-2} = \frac{E_{0.8-2}(Z)(2\,\mathrm{keV})^{0.15}[1+(5.69(\mathrm{keV})^{0.365}/W_{\mathrm{p0}}^{0.365})(G-He^{-IW_{\mathrm{p0}}})]Y_{\mathrm{m}}}{W_{\mathrm{p0}}^{(1/3-0.15)}}. \tag{21}$$

5. Computation of $E(Z)$ and the formulae

When $W_{p0} = 2.0$, 3.0, 4.0,5.0, 6.0, 7.0 and 8.0 keV, the δ [41] for gold is 1.24, 0.97, 0.84, 0.78, 0.65, 0.52 and 0.47, respectively; using eq. (20) and parameters G, H, I shown in table 1 and $Y_{mAu} = 1.77$ [41], we can compute the parameters $E_{Au2.0}$, $E_{Au3.0}$, $E_{Au4.0}$, $E_{Au5.0}$, $E_{Au6.0}$, $E_{Au7.0}$ and $E_{Au8.0}$, respectively. Finally, we obtain the average parameter $E_{Au} = (E_{Au2.0} + E_{Au3.0} + E_{Au4.0} + E_{Au5.0} + E_{Au6.0} + E_{Au7.0} + E_{Au8.0})/7 = 11.51(\text{eV})^{0.5}$.

Based on eq. (20), experimental δ [41–44] shown in table 2 and the parameters shown in table 1, the average parameters $E_{2-10}(Z)$ related to four metals were computed using the same method, respectively; and the average parameters $E_{2-10}(Z)$ are shown in table 2. We only averaged the parameter $E_{2-10}(Z)$ over five metals. Sufficient data are not available regarding experimental δ, and so we cannot average over all metals.

As shown in table 2, we found that the average parameter $E_{2-10}(Z)$ of each metal in table 2 is approximately a constant. Therefore, it is concluded that the average parameter $E_{2-10}(Z)$ of metals is approximately a constant. We averaged the average parameters $E_{2-10}(Z)$ for each metal in table 2 as an average parameter related to metal: $E_{metal} = (E_{Au} + E_{Ag} + E_{Al} + E_{Mo} + E_{Cu})/5 = 11.68(\text{eV})^{0.5}$. Based on eq. (20) and E_{metal}, δ_{2-10} for metals can be written as

$$\delta_{2-10} = \frac{11.68(\text{eV})^{0.5}[1 + (5.69(\text{keV})^{0.365}/W_{p0}^{0.365})(G - He^{-IW_{p0}})]Y_m}{W_{p0}^{0.5}}. \quad (22)$$

For the same metal, δ only change with W_{p0}. Thus, the δ_2 computed with eq. (22) is equal to the δ_2 computed with eq. (21). Thus, $E_{0.8-2}(Z)$ can be computed with eqs (21)

Table 1. The parameters of gold, aluminum, silver, molybdenum, tungsten, copper and platinum [39,40].

Parameters	Au	Al	Ag	Mo	W	Cu	Pt
G	0.4802	0.1568	0.3900	0.3961	0.5370	0.3136	0.4576
H	0.3566	0.0303	0.2890	0.1898	0.2508	0.0692	0.1808
I	0.6103	0.3431	0.6320	0.3001	0.1335	0.6207	0.3137

Table 2. $E_{2-10}(Z)$ related to silver, aluminum, molybdenum and copper [41–44].

	δ_m	$\delta_{2.0}$	$\delta_{2.5}$	$\delta_{3.0}$	$\delta_{3.5}$	$\delta_{4.0}$	$\delta_{5.0}$	$\delta_{6.0}$	$\delta_{7.0}$	$\delta_{8.0}$	$\delta_{9.0}$	$\delta_{10.0}$	$E_{2-10}/(\text{eV})^{0.5}$
Ag	1.2157	0.8824		0.6863		0.5588	0.4666	0.4012	0.353	0.3137	0.2941	0.265	12.22
Al	3.179	1.32	1.06	0.959	0.854	0.752	0.679						10.51
Mo	1.6			0.891			0.592					0.376	12.72
Cu	1.034	0.771	0.702	0.61		0.498							11.45
	1.009	0.5882		0.4216		0.3255	0.2745	0.245	0.2157	0.1961	0.1804	0.1666	

and (22) and found to be $3.29(\text{eV})^{1/3}$. Therefore, based on eq. (21), $\delta_{0.8-2}$ for metals can be written as follows:

$$\delta_{0.8-2} = \frac{3.29(\text{eV})^{1/3}(2\,\text{keV})^{0.15}\,[1+(5.69(\text{keV})^{0.365}/W_{\text{p0}}^{0.365})(G-He^{-IW_{\text{p0}}})]Y_{\text{m}}}{W_{\text{p0}}^{(1/3-0.15)}}. \tag{23}$$

6. Total stopping power

According to eq. (4), S_{10-30} can be written as

$$S_{10-30} = -\frac{1}{A_{10-30}n_{10-30}W_{\text{p0}}^{n_{10-30}-1}}, \tag{24}$$

where A_{10-30} is an approximate constant for a given metal, n_{10-30} is also an approximate constant for a given metal. Therefore, S_{10-30} is a constant at a given W_{p0}. Some researchers measured $\beta \approx 2$ of metals at $W_{\text{p0}} > 10$ keV [37,38]. When primary electrons from 10 keV to 30 keV hit on a metal, η_{10-30} is an approximate constant and is given by [45]

$$\eta_{10-30} = -0.0254 + 0.016Z - 0.000186Z^2 + 8.3 \times 10^{-7}Z^3. \tag{25}$$

Therefore, according to eqs (6), (8), (24) and (25), δ_{10-30} for metals can be written as follows:

$$\delta_{10-30} = \frac{B(e-1)S_{10-30}(1+2\eta)}{\varepsilon e\alpha}. \tag{26}$$

Based on eq. (5), $S_{0.8-2}$ is a constant at a given W_{p0}. Therefore, based on eqs (5), (15), (18) and (19), $\delta_{0.8-10}$ for metals can be written as follows:

$$\delta_{0.8-10} = \frac{B(e-1)S_{0.8-10}}{\varepsilon e\alpha}\left[1+\frac{5.69(\text{keV})^{0.365}}{W_{\text{p0}}^{0.365}}(G-He^{-IW_{\text{p0}}})\right]. \tag{27}$$

On the basis of eqs (26) and (27), $S_{0.8-10}$ can be written as follows:

$$S_{0.8-10} = \frac{\delta_{0.8-10}(1+2\eta_{10-30})S_{10-30}}{\delta_{10-30}[1+(5.69(\text{keV})^{0.365}/W_{\text{p0}}^{0.365})(G-H\text{e}^{-IW_{\text{p0}}})]}. \tag{28}$$

7. Computation of several parameters

Suppose that the primary energies at the surface are $W_{\text{p0}x}$ and $W_{\text{p0}y}$, and that the ranges are R_x and R_y, respectively. From eq. (2), we obtain

$$R_x/R_y = (W_{\text{p0}x}/W_{\text{p0}y})^n, \tag{29}$$

where

$$n = \ln\left(\frac{R_x}{R_y}\right)\Big/\ln\left(\frac{W_{\text{p0}x}}{W_{\text{p0}y}}\right). \tag{30}$$

Based on eq. (30) and R in different metals computed with ESTAR program [27], the average n_{10-30} related to aluminum, gold, silver and copper are computed and are shown in table 3. Based on eq. (2), R of different metals computed with ESTAR program [27] and the calculated n_{10-30} shown in table 2, the average A_{10-30} of aluminum, gold, silver and copper are computed and are shown in table 3. η_{10-30} are calculated with eq. (25) and are also shown in table 3.

8. Results and discussion

There are several approximations made in the course of deducing eqs (22), (23) and (28); for example, when primary electrons enter the emitter, the definite integral $[0, R]$ of eq. (1) is replaced with $[0,1/\alpha]$. As $R \geq 1/\alpha$, most of the secondary electrons excited at distances greater than $1/\alpha$ cannot be emitted into vacuum [33]. As another example, $S_{0.8-2}$ inside $1/\alpha$ increases faster with the decrease of W_{p0} than eq. (4) does, and according to the opinion of some researchers [34,35], S within the metal is approximately constant. Therefore, we suppose that $S_{0.8-2}$ inside $1/\alpha$ can be approximately written as eq. (5) and so eqs (22), (23) and (28) are only approximate.

Primary electrons bombarding a metal produce secondary electrons inside the metal. These internal secondary electrons loose energy in electron–electron collisions. Classically, only electrons with a kinetic energy $E > \Phi$ are capable of escaping into vacuum [46], where Φ is the work function and E is the energy measured from Fermi level. By decreasing Φ, the minimum energy for secondary electrons to escape decreases. Thus, B increases. Then, the electrons that are formed deeper in the substrate and suffered more collisions survive with sufficient energy to escape. In other words, volume in the metal from which electrons escape increases with decreasing Φ and from this added volume only cold electrons emerge. As a result, an increase in $1/\alpha$ is expected. Therefore, B/α increases with decreasing Φ. For the same kind of secondary electron emitter, different sample preparation techniques can lead to different Φ [26]. Different sample preparation techniques can lead to different B/α. Therefore, different sample preparation techniques can lead to different Y_m and $\delta.\delta$ is extremely sensitive to the local change of Φ with crystalline orientation, contamination or submonolayer on the surface of foreign species; a small change of Φ of the metal $\Delta\Phi(\Delta\Phi = 1.0$ eV) may lead to the scattering of δ on the order of 2 : 1. For example, when Φ of gold increases from 4.5 eV up to 5.5 eV, the δ of gold decreases and the calculated δ represents the scattering of δ on the order of about 2 : 1 [47]. The measured δ of a metal in vacuum represents the scattering of δ on the order of about 2 or 3 : 1, such as δ of gold, δ of aluminum and δ of copper [19,41].

Table 3. Parameters of emitters.

Element	A_{10-30} (cm/eV^n)	n_{10-30}	Z [9]	η_{10-30}
Al	1.567×10^{-11}	1.73	13	0.153
Au	2.627×10^{-11}	1.55	79	0.487
Ag	1.449×10^{-11}	1.64	47	0.402
Cu	9.706×10^{-12}	1.68	29	0.302

Based on the above analysis and eqs (10), (22), (23), it is concluded that it is possible for the same kind of metal, when prepared by different methods, to exhibit different Y_m and $\delta_{0.8-10}$, and that Y_m and $\delta_{0.8-10}$ increase with decreasing Φ. The above analysis accounts for the scattering of $\delta_{0.8-10}$ shown in figures 1–7, which show two or three sets of Y_m corresponding to two or three sets of $\delta_{0.8-10}$. The above analysis also accounts for the scattering of $\delta_{0.8-10}$ on the order of about 2 : 1 shown in figures 1 and 4. Therefore, the

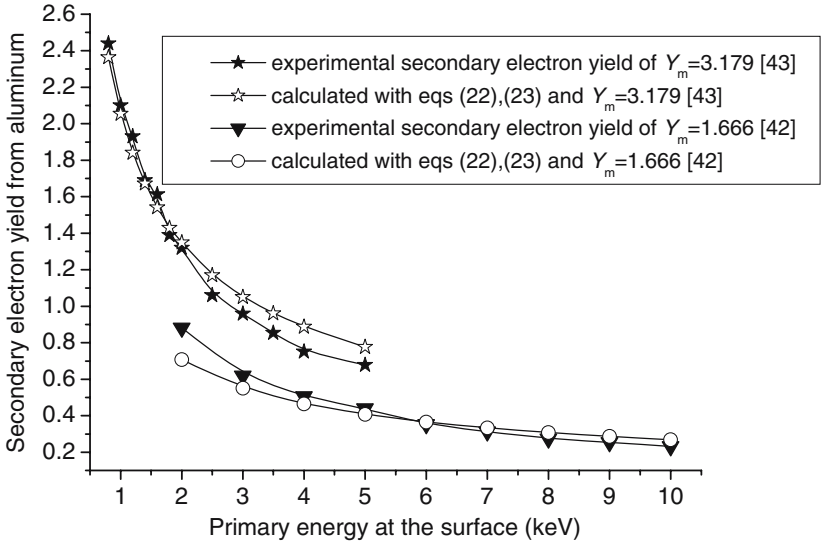

Figure 1. Secondary electron yield for aluminum.

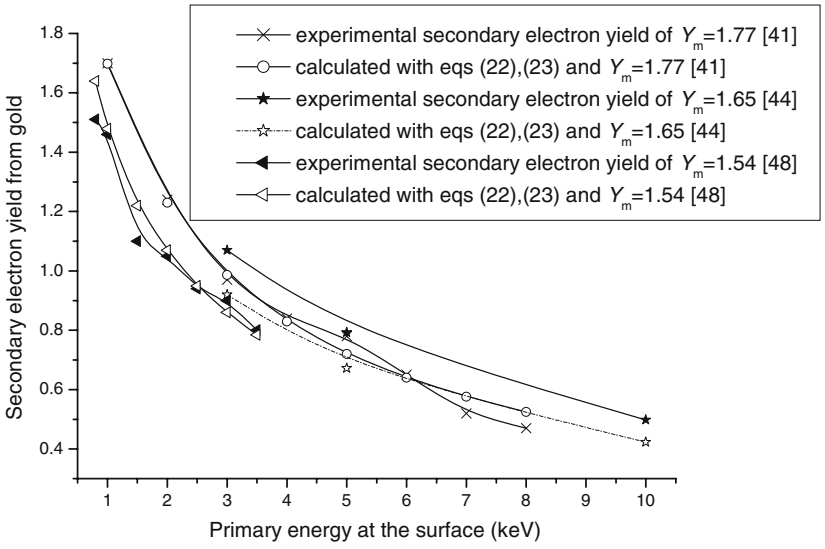

Figure 2. Secondary electron yield for gold.

formulae for $\delta_{0.8-10}$ should be functions of Y_m, and $\delta_{0.8-10}$ for a metal is only proportional to its Y_m.

We present experimental δ [41–44,48–51] for aluminum, gold, silver, copper, molybdenum, platinum and tungsten which are shown in figures 1–7, respectively. From figures 1–7, as a whole, it can be seen that there is a good agreement between the experimental $\delta_{0.8-10}$ of two or three sets of Y_m [41–44,48–51] and those calculated with eqs (22), (23),

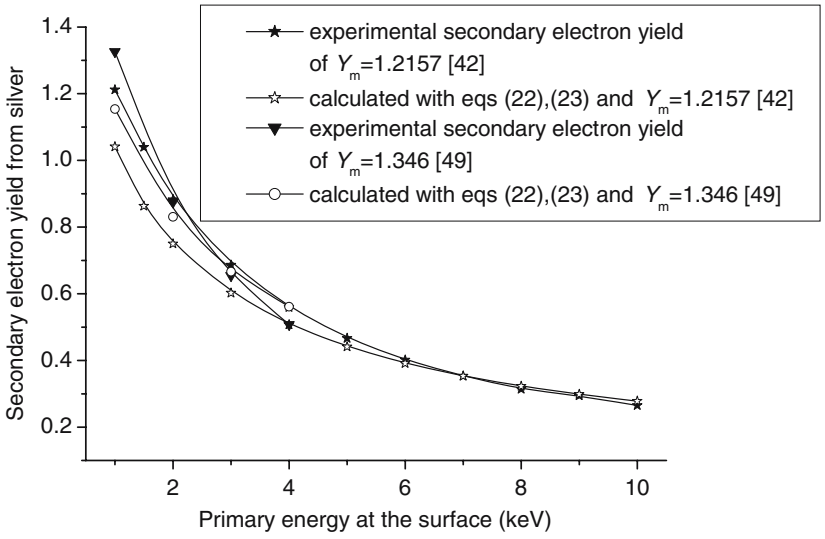

Figure 3. Secondary electron yield for silver.

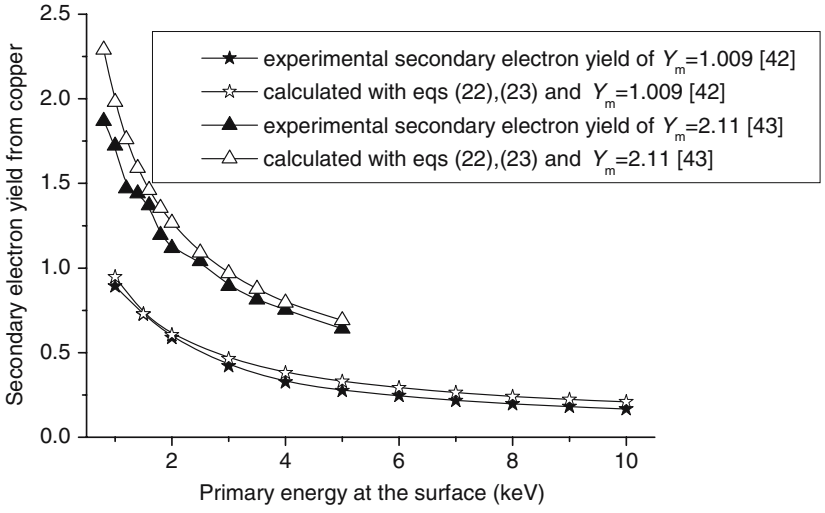

Figure 4. Secondary electron yield for copper.

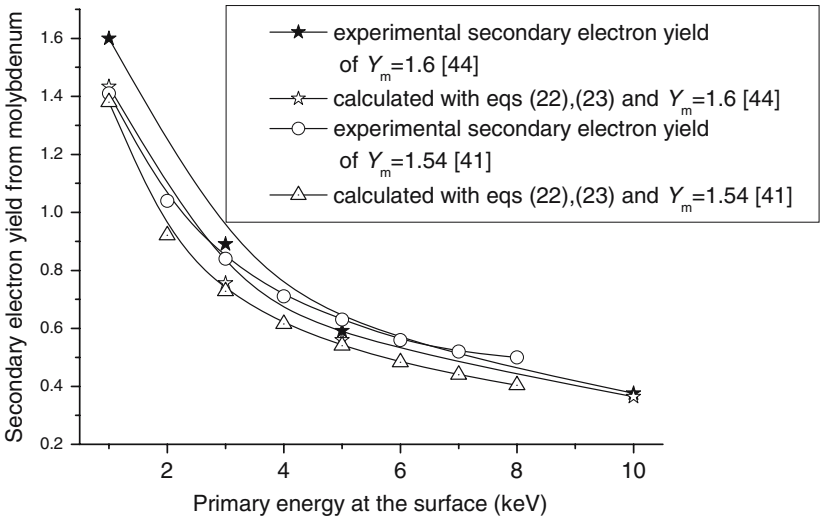

Figure 5. Secondary electron yield for molybdenum.

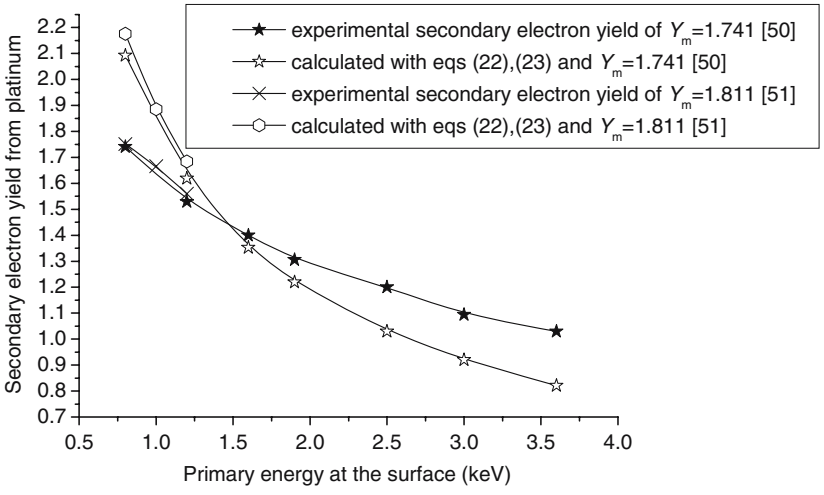

Figure 6. Secondary electron yield for platinum.

corresponding Y_m and the parameters G, H and I shown in table 1 [39,40], respectively. Therefore, eqs (22) and (23) for $\delta_{0.8-10}$ for metals were successfully deduced in this paper.

According to the analysis accounting for the scattering of $\delta_{0.8-10}$ and the former analysis accounting for the scattering of δ_{10-100} [19], when we calculate $S_{0.8-10}$ with eqs (24) and (28), the parameters shown in tables 1 and 3 and the experimental δ, the $\delta_{0.8-10}$ and δ_{10-30} must have the same Y_m.

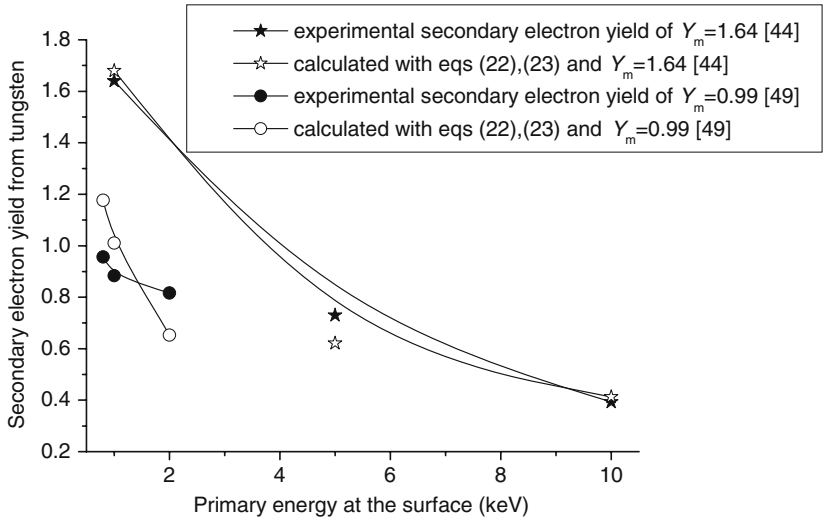

Figure 7. Secondary electron yield for tungsten.

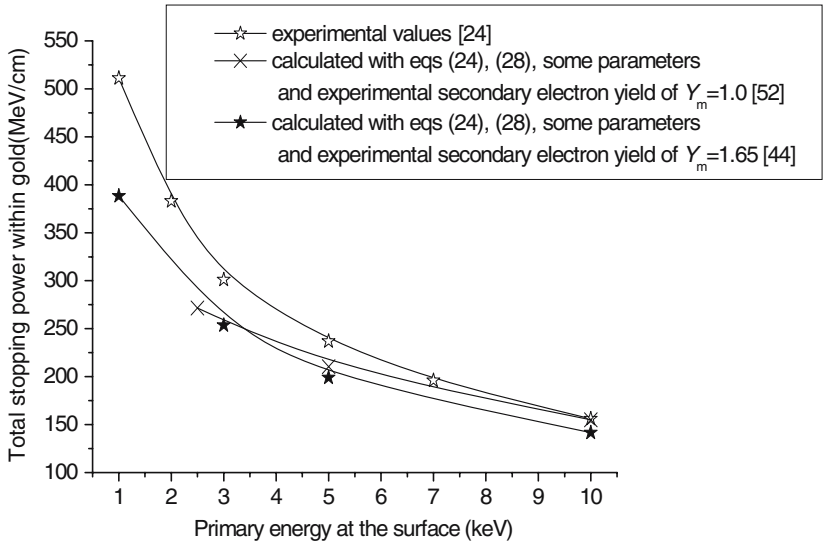

Figure 8. Total stopping power within gold.

Based on eq. (24) and the calculated parameters shown in table 3, we calculated S_{20} within gold ($S_{\mathrm{Au},20}$) to be 105.838 MeV/cm; using eq. (19) and the calculated parameters shown in table 1 [39,40], the $\eta_{1.0}$ for gold ($\eta_{\mathrm{Au},1.0}$) was calculated which was found to be 0.2865. According to eq. (28), the values of $\eta_{\mathrm{Au},1.0}$, $S_{\mathrm{Au},20}$, η_{10-30} shown in table 3, the experimental δ_{20} [44] and the experimental $\delta_{1.0}$ [44], we calculated $S_{1.0}$ within gold ($S_{\mathrm{Au},20,1.0}$) to be 362.06 MeV/cm. Based on eqs (19), (24) and (28), the parameters shown in tables 1 and 3 and the experimental δ [44], we calculated $S_{\mathrm{Au},30,1.0}$ to be 414.49

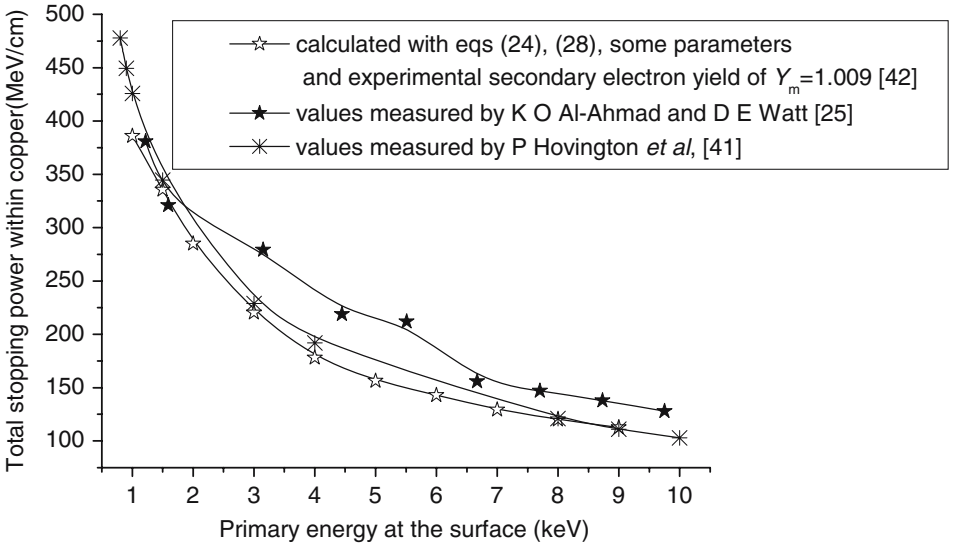

Figure 9. Total stopping power within copper.

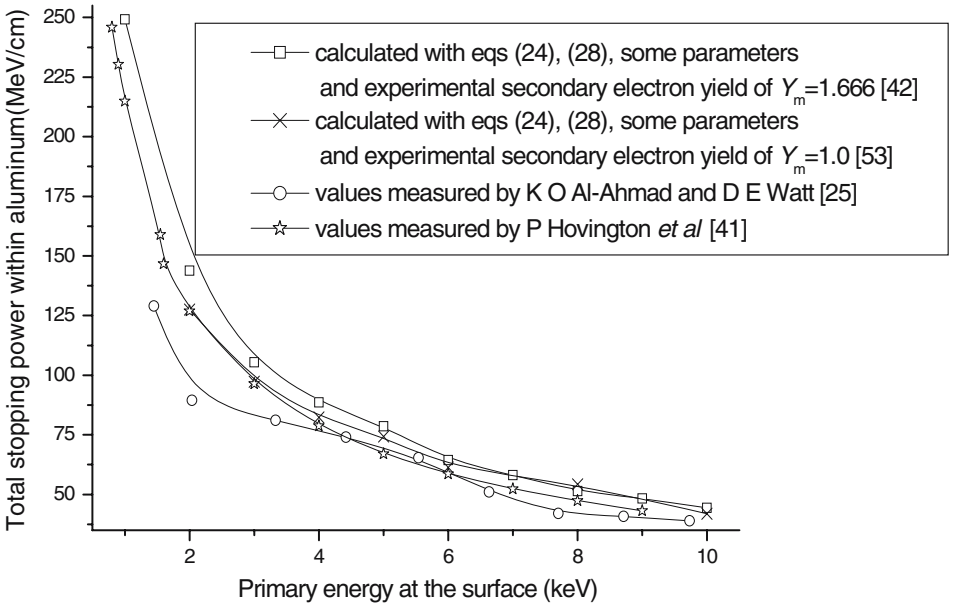

Figure 10. Total stopping power within aluminum.

MeV/cm. Thus, the average $S_{1.0}$ within gold ($S_{\mathrm{Au},1.0}$) was calculated. That is, $S_{\mathrm{Au},1.0} = (S_{\mathrm{Au},20,1.0} + S_{\mathrm{Au},30,1.0})/2)$. Therefore, $S_{\mathrm{Au},1.0} = 388.275$ MeV/cm. Finally, $S_{\mathrm{Au},3.0}$, $S_{\mathrm{Au},5.0}$ and $S_{\mathrm{Au},10.0}$ were calculated using the same method. Based on eqs (19), (24) and (28), the experimental δ and parameters shown in tables 1 and 3, we calculated the average $S_{0.8-10}$ within copper, aluminum and silver, respectively.

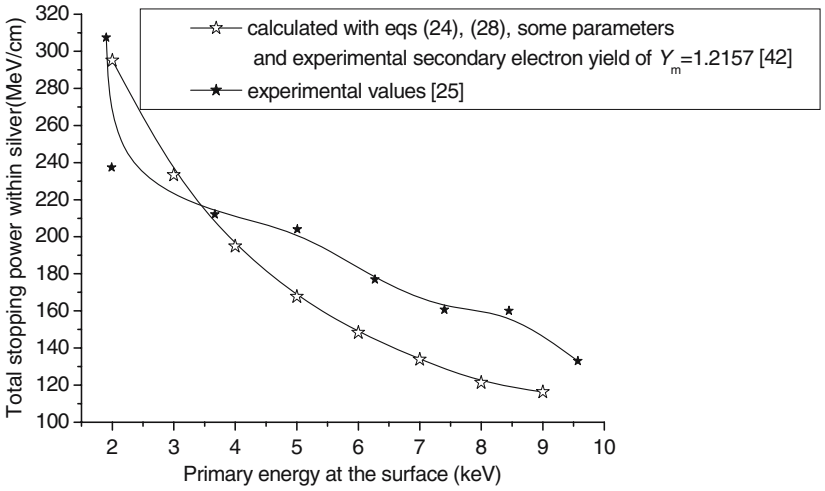

Figure 11. Total stopping power within silver.

There is a good agreement between the S calculated with eqs (24), (28), the parameters shown in tables 1 and 3 and one set of experimental δ [42,44,52,53] and the S calculated with eqs (24), (28), the parameters shown in tables 1 and 3 and another set of experimental δ [42,44,52,53] (figures 8 and 10).

According to the measurements of several authors [24,25,41], we present experimental values of $S_{0.8-10}$, which are shown in figures 8–11, respectively. As shown in figure 8, $S_{1.0}$ within gold and in figure 11, $S_{8.45}$ within silver, the difference between the experiment and theory is larger. It may be that larger experimental errors exist in the experimental $S_{1.0}$ within gold and $S_{8.45}$ within silver. In figures 8–11, as a whole, good agreement is seen between the experimental values [24,25,41] and those calculated with eqs (24), (28), as well as experimental δ [42,44,52,53] and the parameters shown in tables 1 and 3. Therefore, a universal formula (28) for $S_{0.8-10}$ for metals was successfully deduced in this paper.

9. Conclusions

Based on the range–energy relationship, the characteristics of secondary electron emission, relationship between the secondary electron yield δ and experimental results, the universal formulae (22), (23) for $\delta_{0.8-10}$ for metals were deduced in this paper. On the basis of a relationship between parameters of δ, we deduced the universal formula (28) for expressing $S_{0.8-10}$ as a function of S_{10-30}, $\delta_{0.8-10}$, δ_{10-30}, $\eta_{0.8-10}$, η_{10-30} and W_{p0}. According to eqs (26) and (27), $\delta_{0.8-10}$ for metal is proportional to $S_{0.8-10}$ inside $1/\alpha$. Based on the above analysis and the formulae (10), (22)–(23), it is concluded that it is possible for the same kind of metal, when prepared by different techniques, to exhibit different Y_m and $\delta_{0.8-10}$, and that Y_m and $\delta_{0.8-10}$ increase with decreasing Φ.

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