Indian Journal of Pure & Applied Physics
Vol. 53, May 2015, pp. 298-303

Formulae for secondary electron yield and the ratio of the average number of secondary electrons generated by a single backscattered electron to that generated by a single primary electron

Ai-Gen Xie[1,2]*, Min Lai[1], Yu-Lin Chen[1], Yi-Jun Yao[1] & Hong-Yan Wu[1]

[1]School of Physics and Optoelectronic Engineering, Nanjing University of Information Science and Technology, 210044, Nanjing, China

[2]Department of Electrical and Biological Physics, Kwangwoon University, 20 Kwangwoon-gil, Nowon-gu, Seoul 139-701, Republic of Korea

*E-mail: xagth@126.com(Ai-Gen Xie)

Received 8 May 2013; revised 13 February 2015; accepted 12 March 2015

On the basis of the characteristic of secondary electron emission, the number of secondary electrons ($\delta_{PE\theta}$) released per primary electron entering metals in the incident energy (W_{p0}) range 10-102 keV and the incident angle (θ) range 0-89° was deduced. In addition, the number of secondary electrons released per primary electron entering metals at θ=0 (δ_{PE0}) was obtained. Based on the deduced $\delta_{PE\theta}$, the characteristic of the emission angle distribution of the backscattered electrons and the definition of β_θ, the relationships among β_θ, cosθ and the parameter x were given, where β_θ is the ratio of the average number of secondary electrons generated by a single backscattered electron to that generated by a single primary electron entering the emitter at θ. Considering the relationship between $\delta_{PE\theta}$ and δ_{PE0} and the relationship between the secondary electron yields at W_{p0}=10-102 keV and θ=0-89° (δ_θ) and the secondary electron yields at θ=0(δ_0), a universal formula for expressing δ_θ through δ_0, the backscattered coefficient at θ (η_θ), the backscattered coefficient at θ=0(η_0), cosθ and the parameter x were deduced. Further, the parameters x related to beryllium, uranium, aluminium and copper were computed with the deduced formula and experimental results; then, the formulae for expressing δ_θ from the four metals through δ_0, η_θ, η_0 and cosθ were obtained; and the relationships between β_θ of the four metals and cosθ were found. The δ_θ calculated with the formulae and the yields measured experimentally were compared. Finally, it is concluded that the formulae for δ_θ and β_θ from the four metals at W_{p0}=10-102 keV and θ=0-89° have been established, respectively.

Keywords: Secondary electron yield, Emission angle distribution, Backscattered electron, Incident angle

1 Introduction

Secondary electron yield parameters of secondary electron yields and formulae for secondary electron yield has been studied by many researchers[1-8]. Many researchers have studied secondary electron yield δ_θ (the subscript θ means the primary electron is incident at θ and θ is given with respect to surface normal in the present paper[9-12]) and given the simple angle-yield relationship of $\delta_\theta=\delta_0$ $(\cos\theta)^m$, where δ_0 is the secondary electron yield at θ=0 and m depends on the atomic number (z) of the material. The increase of the backscattered coefficient η_θ with θ was not taken into account in the present relationship, thus, these formulae can only give an estimate in practical applications of secondary electrons[9-12] at θ=0-60°. The universal formula has been deduced for expressing δ_θ through δ_0, η_θ, backscattered coefficient at θ=0 (η_0), and θ in our former work[13]. The increase of η_θ with θ has been taken into account in the formula deduced in our former work as a whole, this universal formula is suitable in the incident energy (W_{p0}) range 10-102 keV and the incident angle range 0-80°.The fact that the β_θ decreases with z of metals was not taken into account in our former work[13], where β_θ is the ratio of the average number of secondary electrons generated by a single backscattered electron to that generated by a single primary electron entering the emitter at θ. Thus, for θ=70° and 80°, the values of δ_θ from beryllium and aluminium calculated by the formula deduced in our former work do not agree well with experimental ones[13].

The fact that the value of β_θ decreases with z of metals was taken into account in the present study. Based on the characteristic of the emission angle

Project supported by National Natural Science Foundation of China (Grant No.11473049). The present Research has been conducted by the Research Grant of Kwangwoon University in 2015

distribution of the backscattered electrons, some relationships between the parameters of secondary electron yield, the definition of β_θ, and experimental results, the formulae for expressing δ_θ from beryllium, uranium, aluminium and copper at W_{p0}=10-102 keV and θ=0-89° through δ_0, η_θ, η_0 and cosθ have been deduced in the present study; and the relationships between β_θ of beryllium, uranium, aluminium and copper and cosθ have been obtained. The secondary electron yield calculated with these formulae and the yields measured experimentally from beryllium, uranium, aluminium and copper have been compared and the results indicate that the proposed formulae may be used to estimate secondary electron yields at W_{p0}=10-102 keV and θ=0-89°.

2 Ratio and Backscattered Coefficient

When primary electrons at W_{p0}=10–102 keV and θ=0–80^0 enter metal, the number of secondary electrons released per primary electron $\delta_{PE\theta}$ can be written[13] as follows :

$$\delta_{PE0} = \frac{C}{W_{p0}^{n-1}\cos\theta} \quad \ldots(1)$$

For a metal, C is a constant[9].

Eq. (1) was deduced on the condition that the range of primary electron(R) is significantly larger than 1/(αcosθ) (θ<80°), where 1/α is the mean escape depth of secondary electron from the metal[13]. 1/α is on the order[11] of 1/α=0.5-1.5 nm. Namely, 28.65 nm≦1/ (αcos89°)≦85.95 nm; thus, R is still significantly larger than 1/(αcosθ)(θ≦89°). For example, when W_{p0} is equal to 25.2 keV, the range of aluminium[13] is 5740.7 nm. Therefore, when primary electrons at W_{p0}=10-102 keV and θ=0-89° enter metal, $\delta_{PE\theta}$ still can be written as Eq. (1).

Using Eq.(1), δ_{PE0} can be written[13] as follows:

$$\delta_{PE0} = \frac{C}{W_{p0}^{n-1}} \quad \ldots(2)$$

when primary electrons at W_{p0}=10-102 keV enter metal perpendicularly, some primary electrons are scattered through small angles as they interact with atoms. In addition to the small-angle scattering, the scattered electrons diffuse back from different distance from the surface of metal at different directions, the emission angle Φ(Φ) is given with respect to surface normal) distribution of the backscattered electrons follow (cosΦ)^p(p>1) distribution, the number of secondary electron released per backscattered electron at W_{p0}≥10 keV and θ=0 can be written approximately[14] as follows:

$$\delta_{RE0} = \frac{2C}{W_{p0}^{n-1}} \quad \ldots(3)$$

β_0 is the ratio of the mean secondary electron generation of one backscattered electron to one primary electron hitting on emitter at θ=0, several researchers have shown that several metals[15,16] possess β_0 of 2 at W_{p0} >10 keV. We divide Eq. (3) by Eq.(1), we obtain:

$$\beta_{\theta 0} = 2\cos\theta \approx \beta_0 \cos\theta \quad \ldots(4)$$

The average emission angle of the backscattered electrons at W_{p0}=10-102 keV and θ=0–89° is larger than the average emission angle of the backscattered electrons[12] at W_{p0}=10-102 keV and θ=0. Thus, based on the process of deducing Eq. (3), the number of secondary electron released per backscattered electron at W_{p0}=10-102 keV and θ=0–89° $\delta_{RE\theta}$ is larger than Eq. (3). Based on the definition of β_θ, β_θ is $\delta_{RE\theta}/\delta_{PE\theta}$. Thus, β_θ is larger than Eq. (4). Therefore, we assume that β_θ can be written as follows:

$$\beta_\theta = 2(\cos\theta)^x \approx \beta_0(\cos\theta)^x (0 < x < 1) \quad \ldots(5)$$

According to the characteristic of the emission angle distribution of the backscattered electrons from beryllium, aluminium, copper and gold[12], we found that the average emission angle of the backscattered electrons at the same W_{p0} and θ decreases with z of metals. From the process of deducing Eq. (3), it can be concluded that the number of secondary electron released per backscattered electron at W_{p0}=10-102 keV and θ=0-89° increases with the average emission angle of the backscattered electrons, based on the process of deducing β_θ and the characteristic of the emission angle distribution of the backscattered electrons from beryllium, aluminium, copper and gold[12,14], it is concluded that β_θ increases with the average emission angle of the backscattered electrons at the same W_{p0} and θ, so β_θ decreases with z of metals, therefore, x related to different metals monotonically increases with z of metals.

When primary electrons at W_{p0}=10-102 keV and θ=0-89° enter metal[17], η_θ is given by:

$$\eta_\theta = \eta_0 e^{A_\eta(1-\cos\theta)} \quad \ldots(6)$$

$$A_\eta = 7.37 z^{-0.56875} \quad \ldots(7)$$

3 Universal Formula

When primary electrons at W_{p0}=10-102 keV and θ=0-89° enter metal, δ_θ can be written[11] as follows:

$$\delta_\theta = \delta_{PE\theta}(1+\beta_\theta \eta_\theta) \quad \ldots(8)$$

Using Eq. (8), δ_0 can be written[11] as follows :

$$\delta_0 = \delta_{PE0}(1+\beta_0 \eta_0) = \delta_{PE0}(1+2\eta_0) \quad \ldots(9)$$

Based on Eqs (1), (2), (8) and (9), δ_θ at W_{p0}=10-102 keV and θ=0–89° can be written as:

$$\delta_\theta = \frac{\delta_0[1+2\eta_\theta(\cos\theta)^x]}{(1+2\eta_0)\cos\theta} \quad \ldots(10)$$

In our former work, δ_θ at W_{p0}=10–102 keV and θ=0-80° was written[13] as:

$$\delta_\theta = \frac{\delta_0[1+2\eta_\theta(\cos\theta)^{0.88}]}{(1+2\eta_0)\cos\theta} \quad \ldots(11)$$

4 Computation of *x* and the Formulae

Using x as a fit parameter, x related to Be x_{Be} is extracted by adapting Eqs.(6), (7) and (10) in order to fit at best experimental η_0, cosθ, z, δ_0 and δ_θ from beryllium[12,16] and x_{Be} is shown in Table 1. Using the same method, x_U, x_{Al} and x_{Cu} are extracted by adapting Eqs (6), (7) and (10) in order to fit at best experimental η_0, cosθ, z, δ_0 and δ_θ from uranium[12,18] aluminium[12]and copper[12], respectively; and the values of x_U, x_{Al} and x_{Cu} are presented in Table 1.

According to the conclusion that x related to different metals monotonically increases with z of metals, Eq. (10), x_{Be}=0.371 and x_{Al}=0.454, the formula for the δ_θ at W_{p0}=10–102 keV and θ=0-89° from lower z metals (4<z<13) can be approximately written as follows:

$$\delta_{lower\theta} = \frac{\delta_0[1+2\eta_\theta(\cos\theta)^{x_{lower}}]}{(1+2\eta_0)\cos\theta} \quad \ldots(12)$$

where 0.371< x_{lower} < 0.454.

Table 1 — Fit parameter x related to four metals

Metal	Be	U	Al	Cu
z	4	92	13	29
x	0.371	0.930	0.454	0.915

From Eq. (5), the formula for β_θ of lower z metals (4<z<13) can be approximately written as follows:

$$\beta_{lower\theta} = 2(\cos\theta)^{x_{lower}} \quad \ldots(13)$$

According to the conclusion that x related to different metals monotonically increases with z of metals, Eq. (10), x_{Cu}=0.915 and x_U=0.93, the formula for the δ_θ at W_{p0}=10-102 keV and θ=0-89° from medium and higher z metals (29<z<92) can be approximately written as follows:

$$\delta_{mh\theta} = \frac{\delta_0[1+2\eta_\theta(\cos\theta)^{x_{mh}}]}{(1+2\eta_0)\cos\theta} \quad \ldots(14)$$

where 0.915< x_{mh} < 0.93.

From Eq. (5), the formula for β_θ of medium and higher z metals (29<z<92) can be approximately written as follows:

$$\beta_{mh\theta} = 2(\cos\theta)^{x_{mh}} \quad \ldots(15)$$

5 Results and Discussion

Some researchers measured δ_θ from beryllium and uranium[12] at W_{p0}= 9-100 keV, they found that the relationship between δ_θ from beryllium and uranium at W_{p0}= 9-100 keV and θ does not have dependence on W_{p0}, what they found agree with Eq. (10) deduced in the present study. They normalized δ_0 from beryllium and uranium[12] at W_{p0}= 9-100 keV and their experimental δ_θ are presented in Table 2.

Using x_{Be}=0.371 presented in Table.1 and Eqs (6), (7) and (10), some values of δ_θ from beryllium have been computed with experimental[12] δ_0, cosθ,η_0 9 (Ref. 16)and z, as presented in Table. 2; using x_U=0.930 presented in Table 1 and Eqs (6), (7) and (10), some values of δ_θ from uranium have been computed with experimental δ_0 (Ref.12), cosθ, η_0 (Ref. 18) and z, as presented in Table. 2. Using Eqs (6), (7) and (11), some values of δ_θ from beryllium and uranium have been computed with experimental δ_0, cosθ, η_0 and z (Refs 12,16,18), respectively, as presented in Table 2. Some values of δ_θ from beryllium and uranium have been computed by Monte Carlo method[12] respectively, as presented in Table 2. From Table 2, as a whole, it can be seen that there is good agreement between experimental values[12]at W_{p0}= 11-102 keV and θ=0-80° and the values calculated with the x as presented in Table 1 and

Table 2 — Comparison between calculated δ_θ and experimental [12] ones

θ(degrees)	0	10	20	30	40	50	60	65	70	75	80
Theoretical δ_θ from beryllium by Monte Carlo calculation[12]]	1.0	1.04	1.17	1.24	1.40	1.76	2.49		3.87		7.27
Experimental δ_θ from beryllium	1.0	1.04	1.1	1.2	1.4	1.827	2.71	3.17	4.0255	5.47	8.2
Theoretical δ_θ from beryllium by x_{Be} and Eqs (6), (7) and (10)	1.0	1.02	1.08	1.2	1.4	1.77	2.47	3.07	4.025	5.65	8.88
Theoretical δ_θ from beryllium by Eqs.(6), (7) and (11)	1.0	1.02	1.08	1.19	1.38	1.7	2.28	2.94	3.46	5.2	6.78
Theoretical δ_θ from uranium by Monte Carlo calculation[12]	1.0	1.06	1.02	1.09	1.13	1.23	1.41		1.80		3.05
Experimental δ_θ from uranium	1.0	1.02	1.02	1.09	1.23	1.4	1.68	1.845	2.23	2.868	4.1
Theoretical δ_θ from uranium by x_U and Eqs.(6), (7) and (10)	1.0	1.01	1.05	1.12	1.23	1.4	1.69	1.9	2.23	2.75	3.74
Theoretical δ_θ from uranium by Eqs (6), (7) and (11)	1.0	1.01	1.05	1.13	1.24	1.42	1.71	1.95	2.73	2.8	3.82

Eqs (6), (7) and (10) deduced in the present study and that the values calculated with x as presented in Table1 and Eqs (6), (7) and (10) agree better with experimental ones[12] than the values calculated with the Eqs (6), (7) and (11) do; and that the values calculated with x as presented in Table 1 and Eqs (6), (7) and (10) agree better with experimental ones[12] than the values computed by Monte Carlo method[12] do. Computational approaches based on Monte Carlo method allow us to estimate δ_θ from metals with great accuracy[12,19-22], but it is difficult for some of us to estimate δ_θ from metals by the Monte Carlo method, we can use the proposed formulae for δ_θ from metals to estimate δ_θ with greater accuracy.

Using x_{Al}=0.454 as presented in Table 1 and Eqs (6), (7) and (10), some values of δ_θ from aluminium have been computed with experimental δ_0, cosθ, η_0 and z (Ref. 12) as shown in Figs 1 and 2, respectively. From Figs 1 and 2, it can be seen that there is very good agreement between experimental values[12] and the calculated ones at W_{p0}= 11–102 keV and θ=0-80°, and that the values calculated with x_{Al}=0.454 and Eqs (6), (7) and (10) agree better with experimental ones[12] than the values[13] calculated with Eqs (6), (7) and (11) do. Using x_{Cu}=0.915 as presented in Table 1 and Eqs (6), (7) and (10), some values of δ_θ from copper are computed with experimental[12] δ_0, cosθ, η_0 and z, which are shown in Figs 3 and 4, respectively. From Figs 3 and 4, it can be seen that there is very good agreement between experimental values[12] and the calculated ones at W_{p0}= 11-102 keV and θ=0-80°, and that the values calculated with x_{Cu}=0.915 and Eqs (6), (7) and (10) agree better with

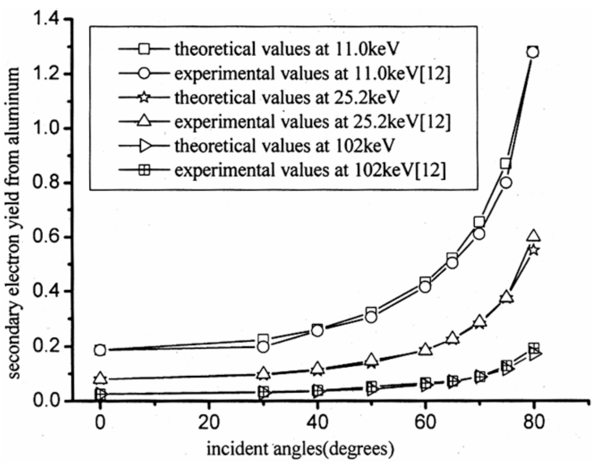

Fig. 1 — Secondary electron yield at θ from aluminium

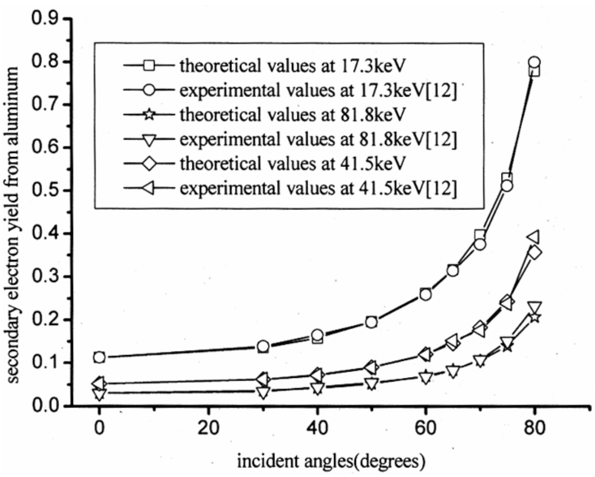

Fig. 2 — Secondary electron yield at θ from aluminium

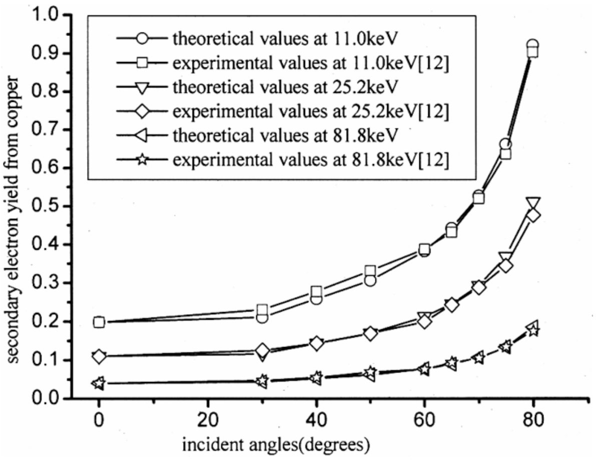

Fig. 3 — Secondary electron yield at θ from copper

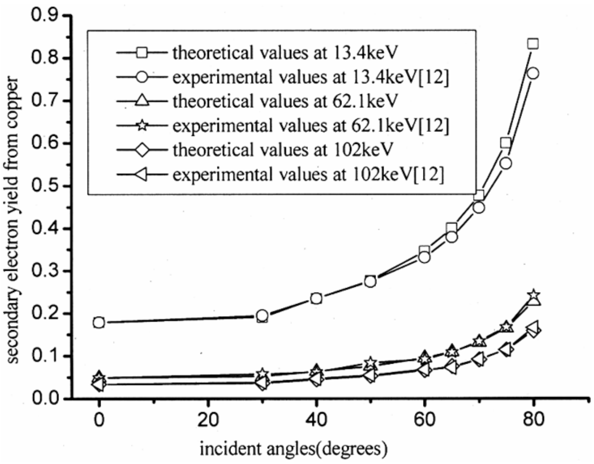

Fig. 4 — Secondary electron yield at θ from copper

experimental ones[12] than the values calculated[13] with Eqs (6), (7) and (11) do. Hence, it is concluded that it is necessary to take into account the value of β_θ decreases when z increases during the course of deducing the Eq. (10), and that the formulae composed of the x as presented in Table 1 and Eqs (6), (7) and (10) can be used to estimate the value of δ_θ beryllium, uranium, aluminium and copper at W_{p0}= 11-102 keV and θ=0-80°.

We could not find more experimental δ_θ to establish more formulae for δ_θ from other metals at W_{p0} = 11-102 keV and θ=0-89° by Eq. (10), The decision to divide the elements in "lower" and "median and higher" z is arbitrary and is only used because of lacking of more experimental data. According to the conclusion that x related to different metals monotonically increases with z, δ_θ computed with Eqs (6), (7) and (10) and x_{Be}=0.371 and δ_θ computed with Eqs (6), (7) and (10) and x_{Al}=0.454, we assume that that δ_θ from lower z metals ($4<z<13$) calculated with Eqs (6), (7) and (10) and x_{Al}=0.454 agree better with experimental ones than the values calculated with Eqs (6), (7) and (11) do; According to the conclusion that x related to different metals monotonically increases with z, δ_θ computed with Eqs (6), (7) and (10) and x_{Cu}=0.915 and δ_θ computed with Eqs (6), (7) and (10) and x_U=0.93, we assume that δ_θ from medium and higher z metals ($29<z<92$) calculated with Eqs (6), (7) and (10) and x_{Cu}=0.915 agree better with experimental ones than the values calculated with Eqs (6), (7) and (11) do.

It is a pity that we can not find experimental δ_θ at W_{p0}= 11-102 keV and θ=0-89°. Thus, the formulae composed of the x shown in Table 1 and Eqs (6), (7) and (10) can not proved to be true by the experimental δ_θ at W_{p0}= 11-102 keV and θ=0-89°. The δ_θ from beryllium, uranium, aluminum and copper at W_{p0}= 11-102 keV and θ=0-80° calculated with the x shown in Table 1 and Eqs (6), (7) and (10) agree well with experimental δ_θ, in addition, there is not a rude approximation in the course of deducing Eq. (10) and computing x shown in Table 1, we think that the formulae composed of the x shown in Table.1 and Eqs (6), (7) and (10) may be used to estimate δ_θ from beryllium, uranium, aluminum and copper at W_{p0}= 11-102 keV and θ=0-89°.

6 Conclusions

Based on the characteristic of the angle distribution of the backscattered electrons, some relationships between the parameters of secondary electron yield, the definition of β_θ and experimental results, the formulae composed of the x as presented in Table 1 and Eqs (6), (7) and (10) for expressing δ_θ from beryllium, uranium, aluminium and copper at W_{p0}= 11-102 keV and θ=0-89° through δ_0, η_θ, η_0 and $\cos\theta$ have been established, respectively. The present values calculated with the formulae are found to be in good agreement with the previous experimental data at W_{p0}= 11-102 keV and θ=0-80°. Thus, the formulae composed of the x as presented in Table1 and Eqs (6), (7) and (10) can be applied to estimate δ_θ from beryllium, uranium, aluminium and copper at W_{p0}= 11-102 keV and θ=0-80°, respectively; the formulae composed of the x as presented in Table 1 and Eqs (6), (7) and (10) may be used to estimate δ_θ from beryllium, uranium, aluminium and copper at W_{p0}= 11-102 keV and θ=0-89°, respectively.

According to the process of deducing the formula given in Eq. (10), β_θ is the only assumption part of the formula given in Eq. (10) and the formulae composed of x as presented in Table 1 and Eqs (6), (7) and (10) have been successfully established, respectively. It is concluded that the formulae composed of the x as presented in Table1 and Eq. (5) for expressing β_θ of beryllium, uranium, aluminium and copper through $\cos\theta$ were reasonable, respectively; so the formulae composed of the x as presented in Table 1 and Eq. (5) may be applied to estimate the value of β_θ of beryllium, uranium, aluminium and copper at W_{p0}= 11-102 keV and θ=0-89°, respectively.

References

1 Xie A G, Zhao H F & Wang T B, *Nucl Instrum Methods Phys Res Sec B*, 268 (2010) 687.
2 Xie A G, Li C Q & Wang T B, *Mod Phys Lett B*, 23 (2009) 2331.
3 Xie A G, Zhang J & Wang T B, *Chin Phys* Lett, 28 (2011) 097901.
4 Xie A G, Zhao H F, Song B & Pei Y J, *Nucl Instrum Methods Phys Res Sec B*, 267 (2009) 1761.
5 Reimer L & Tolkamp C, *Scanning*, 3 (1980) 35.
6 Shimizu R, *J Appl Phys*, 45 (1974) 2107.
7 Moncrieff D A & Barker P R, *Scanning*, 1 (1976) 195.
8 Czaja W, *J Appl Phys*, 37 (1966) 4236.
9 Kanaya K & Kawakatsu H, *J Phys D*, 5 (1972) 1727.
10 Bronshtein I M & Denisov S S, *Sov Phys Solid State*, 9 (1967) 731.
11 Seiler H, *J Appl Phys*, 54 (1983) 1.
12 Reimer L & Pfefferkorn G, *Berlin Springer*, 34 (1977).
13 Xie A G, Zhang J & Wang T B, *Jpn J Appl Phys*, 50 (2011) 126601.
14 Xie A G, Zhang C Y & Zhon K, *Mod Phys Lett B*, 28 (2014) 1450046.
15 Ono S & Kanaya K, *J Phys D*, 12 (1979) 619.
16 Drescher H, Reimer L & Seidel M, *Z Angew Phys*, 29 (1970) 331.
17 Laframboise J G & Kamitsuma M, *Proc Workshop on Natural Charging of Large Space Structures in Near Earth Polar Orbit* (Massachusetts Air Force Geophy Lab) Sagalyn R C, Donatelli D E & Michael I, 293 (1983).
18 Reimer L & Tolkamp C, *Scanning*, 3 (1980) 35.
19 Ganachaud J P & Mokrani A, *Surf Sci*, 334 (1995) 329.
20 Kuhr J Ch & Fitting H J, *J Electron Spectrosc Relat Phenom*, 105 (1999) 257.
21 Dapor M, *Nuc Instru & Methods in Phys Res* B, 267 (2009) 3055.
22 Lin Y & Joy D C, *Surf Interface Anal*, 37 (2005) 895.