DOI:10.3969/j.issn.1674-7135.2022.04.005

负电子亲和半导体的二次电子发射

刘亦凡,谢爱根,董洪杰

(南京信息工程大学 物理与光电工程学院 ,南京 210044)

摘　要:根据 0.8 keV≤E_{pomax}≤5 keV 的负电子亲和(negative electron affinity,NEA)半导体二次电子发射(secondary electron emission,SEE)的特性,初级电子产额 R,现有的次级电子产额 δ 的通用公式和实验数据,分别推导并实验证明了 NEA 金刚石的 δ 在 0.5 E_{pomax}≤E_{po}≤10 E_{pomax}, GaN 在 2 keV ≤E_{pomax}≤5 keV, NEA 金刚石的 δ 在 0.8 keV≤E_{po}≤3 keV, GaN 在 0.8 keV≤E_{pomax}≤2 keV 的特殊公式;其中E_{pomax}为 δ 达到最大值时的E_{po}, E_{po}为初级电子入射能。推导出了 0.8 keV≤E_{pomax}≤5 keV 时 NEA 半导体的内部二次电子到达发射极表面后逃逸到真空中的概率 B。还提出了计算 0.8 keV ≤E_{pomax}≤5 keV NEA 半导体 $1/\alpha$ 的方法;其中 $1/\alpha$ 为二次电子的平均逃逸深度。分析结果表明,B 和 $1/\alpha$ 的理论研究有助于研究不同样品制备方法对 NEA 半导体中 SEE 的定量影响,从而生产出理想的 NEA 发射体,如 NEA 金刚石。

关键词:负电子亲和力;二次电子产额;概率;二次电子的平均逃逸深度;半导体

中图分类号:V443;O462　　**文献标志码**:A　　**文章编号**:1674-7135(2022)04-0030-20

Secondary electron emission from negative electron affinity semiconductors

LIU Yifan, XIE Aigen, DONG Hongjie

(School of Physics and Optoelectronic Engineering, Nanjing University of Information Science and Technology, Nanjing 210044, China)

Abstract: According to the characteristics of secondary electron emission (SEE) from negative electron affinity (NEA) semiconductors with 0.8 keV≤E_{pomax}≤5 keV, R, existing universal formulas for δ of NEA semiconductors and experimental data, special formulas for δ at 0.5 E_{pomax}≤E_{po}≤10 E_{pomax} of NEA diamond and GaN with 2 keV≤E_{pomax}≤5 keV and δ at 0.8 keV≤E_{po}≤3 keV of NEA diamond and GaN with 0.8 keV ≤ E_{pomax} ≤ 2 keV were deduced and experimentally proved, respectively; where R is a primary range, δ is secondary electron yield, E_{pomax} is the E_{po} at which δ reaches maximum δ, E_{po} is incident energy of the primary electron. It can be concluded that the formula for B of NEA semiconductors with 0.8 keV ≤ E_{pomax} ≤ 5 keV was deduced and could be used to calculate B, and that the method presented in this study of calculating the $1/\alpha$ of NEA semiconductors with 0.8 keV≤E_{pomax}≤5 keV is correct; where B is the probability that an internal secondary electron escapes into vacuum upon reaching the surface of the emitter, and $1/\alpha$ is mean escape depth of secondary electrons. The results are analyzed, and it concludes that the theoretical of B and $1/\alpha$ help to research quantitative influences of different sample preparations on SEE from NEA semiconductors and produce desirable NEA emitters such as NEA diamond.

Key words: negative electron affinity; secondary electron yield; the probability; mean escape depth of secondary electrons; semiconductor

---

收稿日期:2022-05-05;　**修回日期**:2022-05-30

基金项目:国家自然科学基金(编号:11704194 ;11873013)

引用格式:刘亦凡,谢爱根,董洪杰.负电子亲和半导体的二次电子发射[J].空间电子技术,2022,19(4):30-49. LIU Y F, XIE A G, DONG H J. Secondary electron emission from negative electron affinity semiconductors[J]. Space Electronic Technology, 2022,19(4):30-49.

0 Introduction

A negative electron affinity (NEA) semiconductor means that the vacuum level of the semiconductor exists below conduction band minimum at the surface, which is a very rare property. Under NEA, internal secondary electrons in the conduction band can easily emit from the surface as there is no barrier at the semiconductor surface[1]. The secondary electron yield (SEY) δ of NEA semiconductors such as Si and GaAs in general far exceed those of positive electron affinity emitters because NEA semiconductors have much larger mean escape depth of secondary electron $1/\alpha$[2]. Thus, NEA semiconductors are outstanding secondary electron emitters and are applied in current amplifiers, vacuum tube applications, electronic information technology, etc[1, 3-4]. Therefore, NEA semiconductor is a very important topic[5-8].

Due to different bulk properties such as dopant type and doping concentration and surface terminations such as the type of adsorbate, the extent of the adsorbate coverage and the presence of coad-sorbed molecules, some NEA semiconductors such as NEA diamond[4] and GaAs[9] exhibit very high, but widely varying, δ and maximum SEY δ_m. Thus, bulk properties and surface terminations of a given NEA semiconductor decide δ and δ_m. According to the expressions of δ_m[10-11] and the fact that the δ of given emitter and incident energy of primary electron E_{po} is proportional to its δ_m, it is known that the B and $1/\alpha$ of a given kind of semiconductor almost decide the values of δ at given E_{po} and δ_m, B is the probability that an internal secondary electron escapes into vacuum upon reaching the surface of emitter. Thus, from the fact that sample preparations decide bulk properties and surface terminations of a given NEA semiconductor[4], it is known that sample preparations of a given NEA semiconductor decide the δ at given E_{po}, δ_m, B and $1/\alpha$. The B is inaccessible to measurement, and it is very difficult to measure $1/\alpha$. Therefore, from the fact that the B and $1/\alpha$ of a given kind of semiconductor almost decide the value of δ_m and the δ at given E_{po}, it concludes that the theoretical researches of B and $1/\alpha$ are necessary and help to research quantitative influences of different sample preparations on parameters of SEE such as δ at given E_{po}, δ_m, B and $1/\alpha$. Hence, from the relationships among δ_m, δ, B and $1/\alpha$ and quantitative influences of different sample preparations on parameters of SEE obtained by the theoretical researches of B and $1/\alpha$, we can change the sample preparations and produce desirable NEA emitter such as NEA diamond. In other words, the theoretical researches of B and $1/\alpha$ help to produce desirable NEA emitters such as NEA diamond and GaAs those exhibit very high, but widely varying, δ and δ_m because of different sample preparations.

According to the characteristics of SEE from NEA semiconductors with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$, R, existing universal formulas for δ of NEA semiconductors[12] and experimental data[4,13-14], special formulas for δ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of NEA diamond and GaN with $2\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$ and δ at $0.8\,\text{keV} \leqslant E_{po} \leqslant 3\,\text{keV}$ of NEA diamond and GaN with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 2\,\text{keV}$ were deduced and experimentally proved, respectively; where R is primary range, E_{pomax} is the E_{po} at which δ reaches δ_m. The formula for B of NEA semiconductors with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$ deduced in this study could be used to calculate B, and the method presented here of calculating the $1/\alpha$ of NEA semiconductors with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$ is correct. Thus, according to the fact that the theoretical researches of B and $1/\alpha$ help to research quantitative influences of different sample preparations on parameters of SEE and produce the desirable NEA emitters, it concludes that this study's research on B and $1/\alpha$ help to research quantitative influences of different sample preparations on SEE from NEA semiconductors and produce desirable NEA emitters such as NEA diamond.

High δ NEA diamond is very valuable for electron multiplication in devices such as crossed-field amplifiers and electron multipliers[4]. Thus, NEA diamond is an important topic [8, 15-18]. Therefore, this study focuses on NEA diamond. Of course, the method presented here of researching δ, B and $1/\alpha$ of NEA diamond and GaN can be used to research δ, B and $1/\alpha$ of NEA semiconductor with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$.

1 Universal formulas for R and secondary electron yield

1.1 Primary range

According to the R-E_{po} relationship deduced from the power potential law, the relation among R, the energy exponent Q and E_{po} is expressed as[19]: where Q is a constant in the same E_{po} range[19], and A depends on the atomic weight A_α, material density ρ and atomic number Z in the same E_{po} range[19]. When primary electrons at $0.8\,\text{keV} \leqslant E_{po} \leqslant 2\,\text{keV}$ enter a secondary electron emitter, the R at $0.8\,\text{keV} \leqslant E_{po} \leqslant 2\,\text{keV}$ can be expressed as[19]

$$R_{0.8-2\ \text{kev}} = \frac{3.06\times10^{-2}A_\alpha {E_{po}}^{4/3}}{\rho Z^{7/9}} \tag{1}$$

When primary electrons at $2\,\text{keV} \leqslant E_{po} \leqslant 10\,\text{keV}$ enter a secondary electron emitter, the R at $2\,\text{keV} \leqslant E_{po} \leqslant 10\,\text{keV}$ can be expressed in terms of ρ, Z, A_α, E_{po}[19]

$$R_{2-10\ \text{kev}} = \frac{1.03\times10^{-2}A_\alpha {E_{po}}^{3/2}}{\rho Z^{5/6}} \tag{2}$$

When primary electrons at $10\,\text{keV} \leqslant E_{po} \leqslant 100\,\text{keV}$ enter a secondary electron emitter, the R at $10\,\text{keV} \leqslant E_{po} \leqslant 100\,\text{keV}$ can be expressed in terms of ρ, Z, A_α, E_{po}[19]

$$R_{10-100\ \text{kev}} = \frac{3.02\times10^{-3}A_\alpha {E_{po}}^{5/3}}{\rho Z^{8/9}} \tag{3}$$

1.2 Universal formula for δ

The universal formula for δ at $0.1\,\text{keV} \leqslant E_{po} \leqslant 10\,\text{keV}$ of NEA semiconductors can be expressed as[12]:

$$\delta_{0.1-10\ \text{keV}} = \frac{\left[1+2r\left(\frac{E_{po}}{10\ \text{keV}}\right)^{1.2}\right]K(E_{po},\rho,Z)BE_{po}}{\varepsilon\alpha R_{0.1-10\ \text{keV}}}\cdot \left(1-e^{-\alpha R_{0.1-10\ \text{keV}}}\right) \tag{4}$$

where ε is the average energy required to produce an internal secondary electron in a semiconductor, α is the absorption coefficient, $R_{0.1-10\ \text{keV}}$ is R at $0.1\,\text{keV} \leqslant E_{po} \leqslant 10\,\text{keV}$, the factor $K(E_{po}, \rho, Z)$ of given NEA semiconductor and E_{po} is approximately equal to a constant and less than 1, r is the high energy back-scattering coefficient which is nearly independent of E_{po} and can be approximately expressed by[20]

$$r = -0.0254 + 0.016Z - 1.86\times10^{-4}Z^2 + 8.3\times10^{-7}Z^3 \tag{5}$$

The universal formula for δ at $10\,\text{keV} \leqslant E_p \leqslant 100\,\text{keV}$ of NEA semiconductors can be expressed as[12]:

$$\delta_{10-100\ \text{keV}} = \frac{(1+2r)K(E_{po},\rho,Z)BE_{po}}{\varepsilon\alpha R_{10-100\ \text{keV}}}\left(1-e^{-\alpha R_{10-100\ \text{keV}}}\right) \tag{6}$$

2 SEE from NEA GaN with $E_{pomax} = 3.0\,\text{keV}$

The ratio of $R_{E_{pomax}}$ in the NEA semiconductors to the corresponding $1/\alpha$ can be expressed as[12]:

$$\frac{1}{\alpha} = \frac{R_{E_{pomax}}}{n} \tag{7}$$

where n is α constant for α given NEA semiconductor, $R_{E_{pomax}}$ is R at E_{pomax}.

Seen from Fig. 1, it is known that the E_{pomax} of NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ is $3.0\,\text{keV}$[13]. $R_{3.0\ \text{keV}}$ calculated with Eq. (2) and parameters of GaN[13, 21] ($\rho = 6.1\,\text{g/cm}^3$, $A_\alpha = 42$, $Z = 19$, $E_{po} = 3.0\,\text{keV}$) is equal to 1 001.972 Å. Therefore, from Eq. (7), the $(1/\alpha)$ of NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ can be expressed as:

$$\frac{1}{\alpha} = \frac{1\,001.972}{n} \tag{8}$$

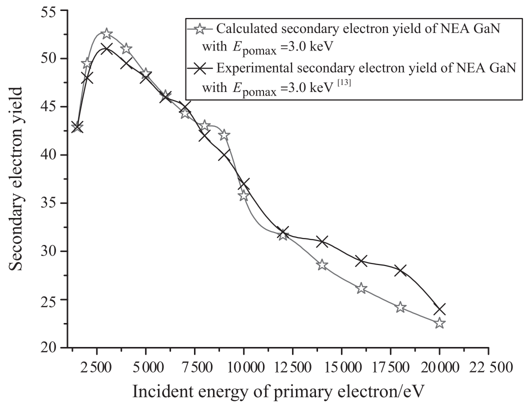

Fig. 1 Comparison between experimental δ of NEA GaN[13] with $E_{pomax} = 3.0\,\text{keV}$ and corresponding calculated ones

The r of GaN calculated with Eq. (5) and $Z = 19$ is equal to 0.206. As seen from Fig. 1, it is known that the E_{pomax} of NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ is in the range of $2\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$. According to characteristics of SEE, the course of deducing Eq. (10) of former study[12] and the conclusion that $K(E_{po}, \rho, Z)$ decreases with increasing E_{po} in the range of $E_{po} \geqslant 100$ eV[12], we assumed that $K(E_{po}, \rho, Z)$ of the NEA semiconductors with $2\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$ decreases slowly with increasing E_{po} in the range of $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$, and that $K(E_{po}, \rho, Z)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA semiconductors with $2\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$ can be approximately looked on as a constant $K(E_{po}, \rho, Z)_{C2-5}$[12]. Thus, from the assumption that $K(E_{po}, \rho, Z)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA semiconductors with $2\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$ can be approximately looked on as a constant $K(E_{po}, \rho, Z)_{C2-5}$, we take the $K(E_{po}, \rho, Z=19)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ to be a constant $K(E_{po}, \rho, Z=19)_{C3}$; and the ratio of B to ε is independent of E_{po}[22-24]. Therefore, from parameters of NEA GaN[13,21] ($\rho = 6.1\,\text{g/cm}^3$, $A_\alpha = 42$, $Z = 19$, $r = 0.206$, $E_{pomax} = 3.0\,\text{keV}$), the assumption that $K(E_{po}, \rho, Z=19)$ at $0.5E_{pmax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ equals $K(E_{po}, \rho, Z=19)_{C3}$ and Eqs. (2), (4) and (8), the δ at $2\,\text{keV} \leqslant E_{po} \leqslant 10\,\text{keV}$ of the NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ can be expressed as follows:

$$\delta_{2-10\,\text{keV}} = \left[1 + 0.412\left(\frac{E_{po}}{10\ \text{keV}}\right)^{1.2}\right]\left(\frac{1.643\,385 \times 10^5}{nE_{po}^{0.5}}\right) \cdot \left[\frac{BK(E_{po},\rho,Z=19)_{C3}}{\varepsilon}\right]\left(1 - e^{-6.085 \times 10^{-6} n (E_{po})^{1.5}}\right) \quad (9)$$

Eq. (9), the result that n of Eq. (9) approximately equals 2.2649 is obtained. Therefore, the $(1/\alpha)$ of NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ calculated with Eq. (8) and $n = 2.2649$ is equal to 442.39 Å. Based on the relation between experimental $\delta_{3.0\,\text{keV}}$ of the NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ equaling 51[13] and the $\delta_{3.0\,\text{keV}}$ calculated with Eq. (9), $E_{po} = 3.0\,\text{keV}$ and $n = 2.2649$ equaling $1.3024 \times 10^3\,[BK(E_{po}, \rho, Z=19)_{C3}]/\varepsilon$, $[BK(E_{po}, \rho, Z=19)_{C3}]/\varepsilon$ equaling 3.916×10^{-2} is obtained; according to the relation between the experimental $\delta_{5.0\,\text{keV}}$ of the NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ equaling 49[13] and the $\delta_{5.0\,\text{keV}}$ calculated with Eq. (9), $E_{po} = 5.0\,\text{keV}$ and $n = 2.2649$ equaling $1.2 \times 10^3\,[BK(E_{po}, \rho, Z=19)_{C3}]/\varepsilon$, $[BK(E_{po}, \rho, Z=19)_{C3}]/\varepsilon$ equaling 4.083×10^{-2} is obtained; on the basis of the relation between the experimental $\delta_{7.0\,\text{keV}}$ of the NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ equaling 45[13] and the calculated $\delta_{7.0\,\text{keV}}$ calculated with Eq. (9), $E_{po} = 7.0\,\text{keV}$ and $n = 2.2649$ equaling $1.097\,561 \times 10^3\,[BK(E_{po}, \rho, Z=19)_{C3}]/\varepsilon$, $[BK(E_{po}, \rho, Z=19)_{C3}]/\varepsilon$ equaling 4.1×10^{-2} is obtained. Thus, the average value of $[BK(E_{po}, \rho, Z=19)_{C3}]/\varepsilon$ equaling 4.033×10^{-2} is obtained.

From the assumption that $K(E_{po}, \rho, Z=19)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of NEA GaN equals $K(E_{po}, \rho, Z=19)_{C3}$, parameters[13, 21] ($\rho = 6.1\,\text{g/cm}^3$, $A_\alpha = 42$, $Z = 19$, $1/\alpha = 442.39$ Å, $r = 0.206$, $K(E_{po}, \rho, Z=19)_{C3}(B/\varepsilon) = 4.033 \times 10^{-2}$, $E_{pomax} = 3.0\,\text{keV}$) and Eqs. (3) and (6), the δ at $10\,\text{keV} \leqslant E_{po} \leqslant 30\,\text{keV}$ of NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ can be expressed as:

$$\delta_{10-30\,\text{keV}} = \frac{1.66 \times 10^4}{E_{po}^{2/3}}\left(1 - e^{-3.430\,84 \times 10^{-6} E_{po}^{5/3}}\right) \quad (10)$$

According to the parameters of NEA GaN with $E_{pomax} = 3.0\,\text{keV}$[13] ($n = 2.2649$, $K(E_{po}, \rho, Z=19)_{C3}(B/\varepsilon) = 4.033 \times 10^{-2}$) and Eq. (9), the δ at $2\,\text{keV} \leqslant E_{po} \leqslant 10\,\text{keV}$ of NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ can be expressed as:

$$\delta_{2-10\,\text{keV}} = \left[1 + 0.412\left(\frac{E_{po}}{10\ \text{keV}}\right)^{1.2}\right] \cdot \left(\frac{2.9262 \times 10^3}{E_{po}^{0.5}}\right)\left(1 - e^{-1.378\,235\,33 \times 10^{-5} E_{po}^{1.5}}\right) \quad (11)$$

From the assumption that $K(E_{po}, \rho, Z=19)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of NEA GaN equals $K(E_{po}, \rho, Z=19)_{C3}$, parameters[13, 21] ($\rho = 6.1\,\text{g/cm}^3$, $A_\alpha = 42$, $Z = 19$, $1/\alpha = 442.39$ Å, $r = 0.206$, $K(E_{po}, \rho, Z=19)_{C3}(B/\varepsilon) = 4.033 \times 10^{-2}$, $E_{pomax} = 3.0\,\text{keV}$) and Eqs. (1) and (4), the δ at $1.5\,\text{keV} \leqslant E_{po} \leqslant 2\,\text{keV}$ of NEA GaN with $E_{pomax} = 3.0\,\text{keV}$ can be expressed as:

$$\delta_{1.5-2\,\text{keV}} = \left[1 + 0.412\left(\frac{E_{po}}{10\ \text{keV}}\right)^{1.2}\right] \cdot \left(\frac{836.33}{E_{po}^{1/3}}\right)\left(1 - e^{-4.822\,25 \times 10^{-5} E_{po}^{4/3}}\right) \quad (12)$$

3 SEE from NEA diamond with $E_{pomax}=2.75$ keV

Seen from Fig. 2, it is known that the E_{pomax} of NEA diamond with $E_{pomax}=2.75$ keV is 2.75 keV[4]. $R_{2.75\text{ keV}}$ calculated with Eq. (2) and parameters of diamond[4, 21] ($\rho=3.52$ g/cm^3, $A_\alpha=12$, $Z=6$, $E_{po}=2.75$ keV) is equal to 1 137.68 Å. Therefore, from Eq. (7), the ($1/\alpha$) of NEA diamond with $E_{pomax}=2.75$ keV can be expressed as:

$$\frac{1}{\alpha}=\frac{1\,137.68}{n} \tag{13}$$

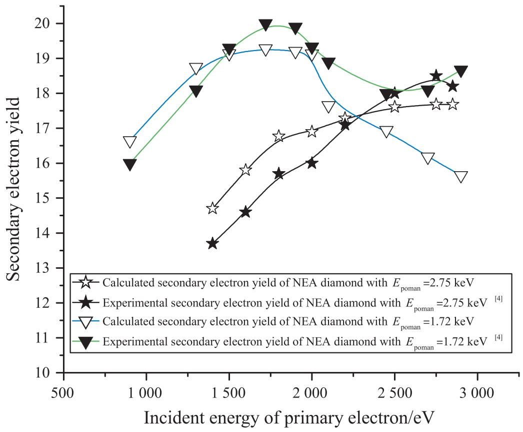

Fig. 2 Comparison between experimental δ of NEA diamond with $E_{pomax}=2.75$ keV and diamond with $E_{pomax}=1.72$ keV[4] and corresponding calculated ones

The $2r$ of diamond calculated with Eq. (5) and $Z=6$ is equal to 0.128. Seen from Fig. 2, it is known that the E_{pomax} of NEA diamond with $E_{pomax}=2.75$ keV[4] is in the range of 2 keV $\leqslant E_{pomax}\leqslant$ 5 keV. Thus, from the assumption that $K(E_{po},\rho,Z)$ at $0.5\,E_{pomax}\leqslant E_{po}\leqslant 10\,E_{pomax}$ of the NEA semiconductors with 2 keV $\leqslant E_{pomax}\leqslant$ 5 keV can be approximately looked on as a constant $K(E_{po},\rho,Z)_{C2-5}$, we take the $K(E_{po},\rho,Z=6)$ at $0.5\,E_{pomax}\leqslant E_{po}\leqslant 10\,E_{pomax}$ of the NEA diamond with $E_{pomax}=2.75$ keV to be a constant $K(E_{po},\rho,Z=6)_{C2.75}$; and the ratio of B to ε is independent of E_{po}[22-24]. Therefore, from parameters of NEA diamond with $E_{pomax}=2.75$ keV[4, 21] ($\rho=3.52$ g/cm^3, $A_\alpha=12$, $Z=6$, $2r=0.128$, $E_{pomax}=2.75$ keV), the assumption that $K(E_{po},\rho,Z=6)$ at $0.5\,E_{pomax}\leqslant E_{po}\leqslant 10\,E_{pomax}$ of the NEA diamond with $E_{pomax}=2.75$ keV equals $K(E_{po},\rho,Z=6)_{C2.75}$ and Eqs. (2), (4) and (13), the δ at 2.0 keV $\leqslant E_{po}\leqslant$ 10 keV of the NEA diamond with $E_{pomax}=2.75$ keV can be expressed as follows:

$$\delta_{2-10\text{ keV}}=\left[1+0.128\left(\frac{E_{po}}{10\text{ keV}}\right)^{1.2}\right]\left[\frac{1.4421\times10^{5}K(E_{po},\rho,Z=6)_{C2.75}B}{n\times(E_{po})^{0.5}\varepsilon}\right]\cdot\left(1-e^{-6.9343\times10^{-6}nE_{po}^{1.5}}\right) \tag{14}$$

The δ at 2.5 keV $\leqslant E_{po}\leqslant$ 10 keV of the NEA diamond with $E_{pomax}=2.75$ keV reaches δ_m at $E_{po}=2.75$ keV. Thus, from Eq. (14), the result that the n of Eq. (14) approximately equals 2.004 3 is obtained. Therefore, the $1/\alpha$ of NEA diamond with $E_{pomax}=2.75$ keV calculated with Eq. (13) and $n=2.0043$ is equal to 567.62 Å. Based on the relation between the experimental $\delta_{2.75\text{ keV}}$ of the NEA diamond with $E_{pomax}=2.75$ keV equaling 18.5[4] and the $\delta_{2.75\text{ keV}}$ calculated with Eq. (14), $E_{po}=2.75$ keV and $n=2.0043$ equaling $1.219357\times10^{3}[BK(E_{po},\rho,Z=6)_{C2.75}]/\varepsilon$, $[BK(E_{po},\rho,Z=6)_{C2.75}]/\varepsilon$ equaling 1.517×10^{-2} is obtained; on the basis of the relation between the experimental $\delta_{2\text{ keV}}$ of the NEA diamond with $E_{pomax}=2.75$ keV equaling 16[4] and the $\delta_{2\text{ keV}}$ calculated with Eq. (14), $E_{po}=2$ keV and $n=2.0043$ equaling $1.16588268\times10^{3}[BK(E_{po},\rho,Z=6)_{C2.75}]/\varepsilon$, $[BK(E_{po},\rho,Z=6)_{C2.75}]/\varepsilon$ equaling 1.372×10^{-2} is obtained; according to the relation between the experimental $\delta_{2.85\text{ keV}}$ of the NEA diamond with $E_{pomax}=2.75$ keV equaling 18.2[4] and the $\delta_{2.85\text{ keV}}$ calculated with Eq. (14), $E_{po}=2.85$ keV and $n=2.0043$ equaling $1.219\times10^{3}[BK(E_{po},\rho,Z=6)_{C2.75}]/\varepsilon$, $[BK(E_{po},\rho,Z=6)_{C2.75}]/\varepsilon$ equaling 1.493×10^{-2} is obtained; according to the relation between the experimental $\delta_{2.2\text{ keV}}$ of the NEA diamond with $E_{pomax}=2.75$ keV equaling 17.1[4] and the $\delta_{2.2\text{ keV}}$ calculated with Eq. (14), $E_{po}=2.2$ keV and $n=2.0043$ equaling $1.1926579\times10^{3}[BK(E_{po},\rho,Z=6)_{C2.75}]/\varepsilon$, $[BK(E_{po},\rho,Z=6)_{C2.75}]/\varepsilon$ equaling 1.434×10^{-2} is obtained. Thus, the average value of $[BK(E_{po},\rho,Z=6)_{C2.75}]/\varepsilon$ equaling 1.45×10^{-2} is obtained.

According to the parameters of NEA diamond with $E_{pomax}=2.75$ keV ($n=2.0043$, $[BK(E_{po},\rho,Z=$

$6)_{C2.75}]/\varepsilon = 1.45 \times 10^{-2}$) and Eq. (14), the δ at $2\,\text{keV} \leqslant E_{po} \leqslant 10\,\text{keV}$ of NEA diamond with $E_{pomax} = 2.75\,\text{keV}$ can be expressed as:

$$\delta_{2-10\,\text{keV}} = \left[1 + 0.128\left(\frac{E_{po}}{10\ \text{keV}}\right)^{1.2}\right] \cdot \left(\frac{1.043 \times 10^3}{E_{po}{}^{0.5}}\right)\left(1 - e^{-1.3898 \times 10^{-5} E_{po}{}^{1.5}}\right) \tag{15}$$

From the assumption that $K(E_{po}, \rho, Z = 6)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of NEA diamond with $E_{pomax} = 2.75\,\text{keV}$ equals $K(E_{po}, \rho, Z = 6)_{C2.75}$, parameters[4, 21] ($\rho = 3.52\,\text{g/cm}^3$, $A_\alpha = 12$, $Z = 6$, $1/\alpha = 567.62$ Å, $2r = 0.128$), $[BK(E_{po}, \rho, Z = 6)_{C2.75}]/\varepsilon = 1.45 \times 10^{-2}$, $E_{pomax} = 2.75\,\text{keV}$ and Eqs. (1) and (4), the δ at $1.375\,\text{keV} \leqslant E_{po} \leqslant 2\,\text{keV}$ of NEA diamond with $E_{pomax} = 2.75\,\text{keV}$ can be expressed as:

$$\delta_{1.375-2\,\text{keV}} = \left[1 + 0.128\left(\frac{E_{po}}{10\ \text{keV}}\right)^{1.2}\right] \cdot \left(\frac{317.9}{E_{po}{}^{1/3}}\right)\left(\left[1 - e^{-4.5612 \times 10^{-5} E_{po}{}^{4/3}}\right)\right. \tag{16}$$

4 SEE from NEA diamond with $E_{pomax} = 2.64\,\text{keV}$

Seen from Fig. 3, it is known that the E_{pomax} of NEA diamond with $E_{pomax} = 2.64\,\text{keV}$ is $2.64\,\text{keV}$[4]. $R_{2.64\,\text{keV}}$ calculated with Eq. (2) and parameters of diamond[4, 21] ($\rho = 3.52\,\text{g/cm}^3$, $A_\alpha = 12$, $Z = 6$, $E_{po} = 2.64\,\text{keV}$) is equal to 1070.1 Å. Therefore, from Eq. (7), the $(1/\alpha)$ of NEA diamond with $E_{pomax} = 2.64\,\text{keV}$ can be expressed as:

$$\frac{1}{\alpha} = \frac{1070.1}{n} \tag{17}$$

Seen from Fig. 3, it is known that the E_{pomax} of NEA diamond with $E_{pomax} = 2.64\,\text{keV}$ is in the range of $2\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$. Thus, from the assumption that $K(E_{po}, \rho, Z)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA semiconductors with $2\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$ can be approximately looked on as a constant $K(E_{po}, \rho, Z)_{C2-5}$, we take the $K(E_{po}, \rho, Z = 6)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA diamond with $E_{pomax} = 2.64\,\text{keV}$ to be a constant $K(E_{po}, \rho, Z = 6)_{C2.64}$; and the ratio of B to ε is independent of E_{po}[22-24]. Therefore, from parameters of NEA diamond with $E_{pomax} = 2.64\,\text{keV}$[4, 21] ($\rho = 3.52\,\text{g/cm}^3$, $A_\alpha = 12$, $Z = 6$, $2r = 0.128$, $E_{pomax} = 2.64\,\text{keV}$), the assumption that $K(E_{po}, \rho, Z = 6)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA diamond with $E_{pomax} = 2.64\,\text{keV}$ equals $K(E_{po}, \rho, Z = 6)_{C2.64}$ and Eqs. (2), (4) and (17), the δ at $2.0\,\text{keV} \leqslant E_{po} \leqslant 10\,\text{keV}$ of the NEA diamond with $E_{pomax} = 2.64\,\text{keV}$ can be expressed as follows:

$$\delta_{2-10\,\text{keV}} = \left[1 + 0.128\left(\frac{E_{po}}{10\ \text{keV}}\right)^{1.2}\right] \cdot \left[\frac{6.7842 \times 10^4 K(E_{po}, \rho, Z = 6)_{C2.64} B}{n \times E_{po}{}^{0.5}\varepsilon}\right] \cdot \left(1 - e^{-1.474 \times 10^{-5} n E_{po}{}^{1.5}}\right) \tag{18}$$

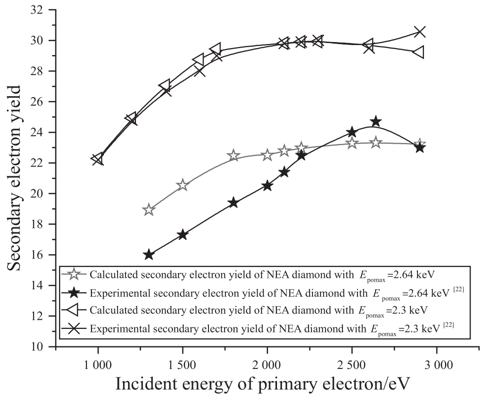

Fig. 3 Comparison between experimental δ of NEA diamond with $E_{pomax} = 2.64\,\text{keV}$ and diamond with $E_{pomax} = 2.3\,\text{keV}$[4] and corresponding calculated ones

The δ at $2\,\text{keV} \leqslant E_{po} \leqslant 10\,\text{keV}$ of the NEA diamond with $E_{pomax} = 2.64\,\text{keV}$ reaches δ_m at $E_{po} = 2.64\,\text{keV}$. Thus, from Eq. (18), the result that the n of Eq. (18) approximately equals 1.9994 is obtained. Therefore, the $(1/\alpha)$ of NEA diamond with $E_{pomax} = 2.64\,\text{keV}$ calculated with Eq. (17) and $n = 1.9994$ is equal to 535.21 Å. Based on the relation between the experimental $\delta_{2.64\,\text{keV}}$ of the NEA diamond with $E_{pomax} = 2.64\,\text{keV}$ equaling 24.7[4] and the $\delta_{2.64\,\text{keV}}$ calculated with Eq. (18), $E_{po} = 2.64\,\text{keV}$ and $n = 1.9994$ equaling $1.1711 \times 10^3 [BK(E_{po}, \rho, Z = 6)_{C2.64}]/\varepsilon$, $[BK(E_{po}, \rho, Z = 6)_{C2.64}]/\varepsilon$ equaling 2.109×10^{-2} is obtained; on the basis of the relation between the experimental $\delta_{2.9\,\text{keV}}$ of the NEA diamond with $E_{pomax} = 2.64\,\text{keV}$ equaling 23[4] and the $\delta_{2.9\,\text{keV}}$ calculated with Eq. (18), $E_{po} = 2.9\,\text{keV}$ and $n = 1.9994$ equaling $1.166656 \times 10^3 [BK(E_{po}, \rho, Z = 6)_{C2.64}]/\varepsilon$, $[BK(E_{po}, \rho, Z = 6)_{C2.64}]/\varepsilon$ equaling 1.9716×10^{-2} is obtained; according to the relation between the experimental $\delta_{2.5\,keV}$ of the NEA diamond with E_{pomax} = 2.64 keV equaling 24[4] and the $\delta_{2.5\,keV}$ calculated with Eq. (18), E_{po} = 2.5 keV and n = 1.9994 equaling $1.1695385\times10^3[BK(E_{po},\rho,Z=6)_{C2.64}]/\varepsilon$, $[BK(E_{po},\rho,Z=6)_{C2.64}]/\varepsilon$ equaling 2.0521×10^{-2} is obtained; according to the relation between the experimental $\delta_{2.2\,keV}$ of the NEA diamond with E_{pomax} = 2.64 keV equaling 22.5[4] and the $\delta_{2.2\,keV}$ calculated with Eq. (18), E_{po} = 2.2 keV and n = 1.9994 equaling $1.15383\times10^3[BK(E_{po},\rho,Z=6)_{C2.64}]/\varepsilon$, $[BK(E_{po},\rho,Z=6)_{C2.64}]/\varepsilon$ equaling 1.495×10^{-2} is obtained; on the basis of the relation between the experimental $\delta_{2.1\,keV}$ of the NEA diamond with E_{pomax} = 2.64 keV equaling 21.4[4] and the $\delta_{2.1\,keV}$ calculated with Eq. (18), E_{po} = 2.1 keV and n = 1.9994 equaling $1.144\times10^3[BK(E_{po},\rho,Z=6)_{C2.64}]/\varepsilon$, $[BK(E_{po},\rho,Z=6)_{C2.64}]/\varepsilon$ equaling 1.87×10^{-2} is obtained. Thus, the average value of $[BK(E_{po},\rho,Z=6)_{C2.64}]/\varepsilon$ equaling 1.991×10^{-2} is obtained.

According to the parameters of NEA diamond with E_{pomax} = 2.64 keV (n = 1.9994, $[BK(E_{po},\rho,Z=6)_{C2.64}]/\varepsilon = 1.991\times10^{-2}$) and Eq. (18), the δ at 2 keV $\leqslant E_{po}\leqslant$ 10 keV of NEA diamond with E_{pomax} = 2.64 keV can be expressed as:

$$\delta_{2-10\,keV}=\left[1+0.128\left(\frac{E_{po}}{10\ keV}\right)^{1.2}\right]\cdot\left(\frac{1.35\times10^3}{E_{po}^{\ 0.5}}\right)\left(1-e^{-1.474\times10^{-5}E_{po}^{\ 1.5}}\right)\qquad(19)$$

From the assumption that $K(E_{po},\rho,Z=6)$ at $0.5\,E_{pomax}\leqslant E_{po}\leqslant 10\,E_{pomax}$ of NEA diamond with E_{pomax} = 2.64 keV equals $K(E_{po},\rho,Z=6)_{C2.64}$, parameters[4, 21] ($\rho$ = 3.52 g/cm^3, A_α = 12, Z = 6, $1/\alpha$ = 535.21 Å, $2r$ = 0.128), $[BK(E_{po},\rho,Z=6)_{C2.64}]/\varepsilon = 1.991\times10^{-2}$, E_{pomax} = 2.64 keV and Eqs. (1) and (4), the δ at 1.32 keV $\leqslant E_{po}\leqslant$ 2 keV of NEA diamond with E_{pomax} = 2.64 keV can be expressed as:

$$\delta_{1.32-2\,keV}=\left[1+0.128\left(\frac{E_{po}}{10\ keV}\right)^{1.2}\right]\cdot\left(\frac{411.59}{E_{po}^{\ 1/3}}\right)\left(1-e^{-4.83734\times10^{-5}E_{po}^{\ 4/3}}\right)\qquad(20)$$

5 SEE from NEA diamond with E_{pomax} = 2.3 keV

Seen from Fig. 3, it is known that the E_{pomax} of NEA diamond with E_{pomax} = 2.3 keV is 2.3 keV[4]. $R_{2.3\,keV}$ calculated with Eq. (2) and parameters of diamond[4, 21] (ρ = 3.52 g/cm^3, A_α = 12, Z = 6, E_{po} = 2.3 keV) is equal to 870.18 Å. Therefore, from Eq. (7), the ($1/\alpha$) of NEA diamond with E_{pomax} = 2.3 keV can be expressed as:

$$\frac{1}{\alpha}=\frac{870.18}{n}\qquad(21)$$

Seen from Fig. 3, it is known that the E_{pomax} of NEA diamond with E_{pomax} = 2.3 keV is in the range of 2 keV $\leqslant E_{pomax}\leqslant$ 5 keV. Thus, from the assumption that $K(E_{po},\rho,Z)$ at $0.5\,E_{pomax}\leqslant E_{po}\leqslant 10\,E_{pomax}$ of the NEA semiconductors with 2 keV $\leqslant E_{pomax}\leqslant$ 5 keV can be approximately looked on as a constant $K(E_{po},\rho,Z)_{C2-5}$, we take the $K(E_{po},\rho,Z=6)$ at $0.5\,E_{pomax}\leqslant E_{po}\leqslant 10\,E_{pomax}$ of the NEA diamond with E_{pomax} = 2.3 keV to be a constant $K(E_{po},\rho,Z=6)_{C2.3}$; and the ratio of B to ε is independent of E_{po}[22-24]. Therefore, from parameters of NEA diamond with E_{pomax} = 2.3 keV[4, 21] (ρ = 3.52 g/cm^3, A_α = 12, Z = 6, $2r$ = 0.128, E_{pomax} = 2.3 keV), the assumption that $K(E_{po},\rho,Z=6)$ at $0.5\,E_{pomax}\leqslant E_{po}\leqslant 10\,E_{pomax}$ of the NEA diamond with E_{pomax} = 2.3 keV equals $K(E_{po},\rho,Z=6)_{C2.3}$ and Eqs. (2), (4) and (21), the δ at 2.0 keV $\leqslant E_{po}\leqslant$ 10 keV of the NEA diamond with E_{pomax} = 2.3 keV can be expressed as follows:

$$\delta_{2-10\,keV}=\left[1+0.128\left(\frac{E_{po}}{10\ keV}\right)^{1.2}\right]\cdot\left[\frac{1.10304\times10^5K(E_{po},\rho,Z=6)_{C2.3}B}{n\times E_{po}^{\ 0.5}\varepsilon}\right]\cdot\left(1-e^{-9.065844\times10^{-6}nE_{po}^{\ 1.5}}\right)\qquad(22)$$

The δ at 2 keV $\leqslant E_{po}\leqslant$ 10 keV of the NEA diamond with E_{pomax} = 2.3 keV reaches δ_m at E_{po} = 2.3 keV. Thus, from Eq. (22), the result that the n of Eq. (22) approximately equals 1.9849 is obtained. Therefore, the ($1/\alpha$) of NEA diamond with E_{pomax} = 2.3 keV calculated with Eq. (21) and n = 1.9849 is equal to 438.4 Å. Based on the relation between the experimental $\delta_{2.3\ \mathrm{keV}}$ of the NEA diamond with E_{pomax} = 2.3 keV equaling 30[4] and the $\delta_{2.3\ \mathrm{keV}}$ calculated with Eq. (22), E_{po} = 2.3 keV and n = 1.9849 equaling $1.02146\times10^{3}\,[BK(E_{\mathrm{po}},\ \rho,\ Z=6)_{\mathrm{C2.3}}]/\varepsilon$, $[BK(E_{\mathrm{po}},\ \rho,\ Z=6)_{\mathrm{C2.3}}]/\varepsilon$ equaling 2.937×10^{-2} is obtained; on the basis of relation between the experimental $\delta_{2.2\ \mathrm{keV}}$ of the NEA diamond with E_{pomax} = 2.3 keV equaling 29.9[4] and the $\delta_{2.2\ \mathrm{keV}}$ calculated with Eq. (22), E_{po} = 2.2 keV and n = 1.9849 equaling $1.0205\times10^{3}[BK(E_{\mathrm{po}},\ \rho,\ Z=6)_{\mathrm{C2.3}}]/\varepsilon$, $[BK(E_{\mathrm{po}},\ \rho,\ Z=6)_{\mathrm{C2.3}}]/\varepsilon$ equaling 2.93×10^{-2} is obtained; on the basis of the relation between the experimental $\delta_{2.1\ \mathrm{keV}}$ of the NEA diamond with E_{pomax} = 2.3 keV equaling 29.8[4] and the $\delta_{2.1\ \mathrm{keV}}$ calculated with Eq. (22), E_{po} = 2.1 keV and n = 1.9849 equaling $1.017619\times10^{3}[BK(E_{\mathrm{po}},\ \rho,\ Z=6)_{\mathrm{C2.3}}]/\varepsilon$, $[BK(E_{\mathrm{po}},\ \rho,\ Z=6)_{\mathrm{C2.3}}]/\varepsilon$ equaling 2.928×10^{-2} is obtained. Thus, the average value of $[BK(E_{\mathrm{po}},\ \rho,\ Z=6)_{\mathrm{C2.3}}]/\varepsilon$ equaling 2.93×10^{-2} is obtained.

According to the parameters of NEA diamond with E_{pomax} = 2.3 keV (n = 1.9849, $[BK(E_{\mathrm{po}},\ \rho,\ Z=6)_{\mathrm{C2.3}}]/\varepsilon = 2.93\times10^{-2}$) and Eq. (22), the δ at 2 keV ≤ E_{po} ≤ 10 keV of NEA diamond with E_{pomax} = 2.3 keV can be expressed as:

$$\delta_{2-10\ \mathrm{keV}} = \left[1+0.128\left(\frac{E_{\mathrm{po}}}{10\ \mathrm{keV}}\right)^{1.2}\right]\cdot\left(\frac{1.628\times10^{3}}{E_{\mathrm{po}}{}^{0.5}}\right)\left(1-\mathrm{e}^{-1.7995\times10^{-5}E_{\mathrm{po}}{}^{1.5}}\right) \tag{23}$$

From the assumption that $K(E_{\mathrm{po}},\ \rho,\ Z=6)$ at 0.5 E_{pomax} ≤ E_{po} ≤ 10 E_{pomax} of NEA diamond with E_{pomax} = 2.3 keV equals $K(E_{\mathrm{po}},\ \rho,\ Z=6)_{\mathrm{C2.3}}$, parameters[4, 21] ($\rho$ = 3.52 g/cm^3, A_α = 12, Z = 6, $1/\alpha$ = 438.4 Å, $2r$ = 0.128), $[BK(E_{\mathrm{po}},\ \rho,\ Z=6)_{\mathrm{C2.3}}]/\varepsilon = 2.93\times10^{-2}$, E_{pomax} = 2.3 keV) and Eqs. (1) and (4), the δ at 1.15 keV ≤ E_{po} ≤ 2 keV of NEA diamond with E_{pomax} = 2.3 keV can be expressed as:

$$\delta_{1.15-2\ \mathrm{keV}} = \left[1+0.128\left(\frac{E_{\mathrm{po}}}{10\ \mathrm{keV}}\right)^{1.2}\right]\cdot\left(\frac{496.14}{E_{\mathrm{po}}{}^{1/3}}\right)\left(1-\mathrm{e}^{-5.9056\times10^{-5}E_{\mathrm{po}}{}^{4/3}}\right) \tag{24}$$

6 SEE from NEA GaN with E_{pomax} = 1.0 keV

Seen from Fig. 4, it is known that the E_{pomax} of NEA GaN with E_{pomax} = 1.0 keV is 1.0 keV[14]. $R_{1.0\ \mathrm{keV}}$ calculated with Eq. (1) and parameters of GaN[14, 21] (ρ = 6.1 g/cm^3, A_α = 42, Z = 19, E_{po} = 1.0 keV) is equal to 213.3343 Å. Therefore, from Eq. (7), the $(1/\alpha)$ of NEA GaN with E_{pomax} = 1.0 keV can be expressed as:

$$\frac{1}{\alpha} = \frac{213.3343}{n} \tag{25}$$

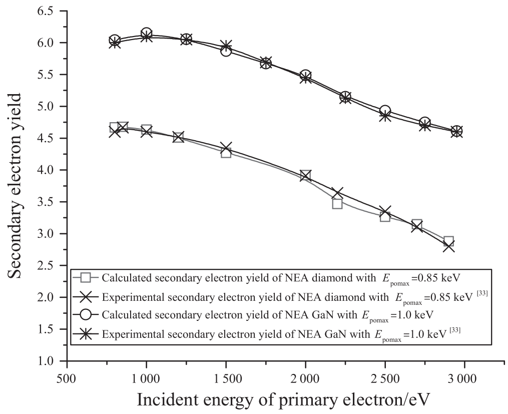

Fig. 4 Comparison between experimental δ of NEA diamond with E_{pomax} = 0.85 keV[4] and GaN with E_{pomax} = 1.0 keV[14] and corresponding calculated ones

Seen from Fig. 4, it is known that the E_{pomax} of NEA GaN with E_{pomax} = 1.0 keV is in the range of 0.8 keV ≤ E_{pomax} ≤ 2 keV. According to the conclusion that $K(E_{\mathrm{po}},\ \rho,\ Z)$ decreases with increasing E_{po} in the range of E_{po} ≥ 100 eV, we assumed that $K(E_{\mathrm{po}},\ \rho,\ Z)$ of the NEA semiconductors with 0.8 keV ≤ E_{pomax} ≤ 2 keV decreases slowly with increasing E_{po} in the range of 0.8 keV ≤ E_{po} ≤ 3 keV, and that $K(E_{\mathrm{po}},\ \rho,\ Z)$ at 0.8 keV ≤ E_{po} ≤ 3 keV of the NEA semiconductors with 0.8 keV ≤ E_{pomax} ≤ 2 keV can be approximately looked on as a constant $K(E_{\mathrm{po}},\ \rho,\ Z)_{\mathrm{C0.8-2}}$. Thus, from the assumption that $K(E_{\mathrm{po}},\ \rho,\ Z)$ at 0.8 keV ≤ E_{po} ≤ 3 keV of the NEA semiconductors with 0.8 keV ≤ E_{pomax} ≤ 2 keV can be approximately looked on as a constant $K(E_{\mathrm{po}},\ \rho,\ Z)_{\mathrm{C0.8-2}}$, we take the $K(E_{\mathrm{po}},\ \rho,\ Z=19)$ at 0.8 keV ≤ E_{po} ≤ 3 keV of the NEA GaN with E_{pomax} = 1.0 keV to be a constant $K(E_{\mathrm{po}},\ \rho,\ Z=19)_{\mathrm{C1}}$; and the ratio of B to ε is independent of E_{po}[22-24]. Therefore, from parameters of NEA GaN[14, 21] ($\rho = 6.1\,\mathrm{g/cm^3}$, $A_\alpha = 42$, $Z = 19$, $r = 0.206$, $E_{pomax} = 1.0\,\mathrm{keV}$), the assumption that $K(E_{po}, \rho, Z = 19)$ at $0.8\,\mathrm{keV} \leqslant E_{po} \leqslant 3\,\mathrm{keV}$ of the NEA GaN with $E_{pomax} = 1.0\,\mathrm{keV}$ equals $K(E_{po}, \rho, Z = 19)_{C1}$ and Eqs. (1), (4) and (25), the δ at $0.8\,\mathrm{keV} \leqslant E_{po} \leqslant 2\,\mathrm{keV}$ of the NEA GaN with $E_{pomax} = 1.0\,\mathrm{keV}$ can be expressed as follows:

$$\delta_{0.8-2\,\mathrm{keV}} = \left[1 + 0.412\left(\frac{E_{po}}{10\ \mathrm{keV}}\right)^{1.2}\right]\left(\frac{1.0 \times 10^4}{nE_{po}^{1/3}}\right) \cdot \left[\frac{BK(E_{po}, \rho, Z = 19)_{C1}}{\varepsilon}\right]\left(1 - \mathrm{e}^{-1.0 \times 10^{-4} nE_{po}^{4/3}}\right) \quad (26)$$

The δ at $0.8\,\mathrm{keV} \leqslant E_{po} \leqslant 2\,\mathrm{keV}$ of the NEA GaN reaches its δ_m at $E_{po} = 1.0\,\mathrm{keV}$. Thus, from Eq. (26), the result that n of Eq. (26) approximately equals 2.4766 is obtained. Therefore, the $(1/\alpha)$ of NEA GaN with $E_{pomax} = 1.0\,\mathrm{keV}$ calculated with Eq. (25) and $n = 2.4766$ is equal to 86.14 Å. Based on the relation between experimental $\delta_{1.0\,\mathrm{keV}}$ of the NEA GaN with $E_{pomax} = 1.0\,\mathrm{keV}$ equaling 6.1[14] and the $\delta_{1.0\,\mathrm{keV}}$ calculated with Eq. (26), $E_{po} = 1.0\,\mathrm{keV}$ and $n = 2.4766$ equaling $3.7946 \times 10^2\,[BK(E_{po}, \rho, Z = 19)_{C1}]/\varepsilon$, $[BK(E_{po}, \rho, Z = 19)_{C1}]/\varepsilon$ equaling 1.6076×10^{-2} is obtained; according to the relation between the experimental $\delta_{0.8\,\mathrm{keV}}$ of the NEA GaN with $E_{pomax} = 1.0\,\mathrm{keV}$ equaling 6.0[14] and the $\delta_{0.8\,\mathrm{keV}}$ calculated with Eq. (26), $E_{po} = 0.8\,\mathrm{keV}$ and $n = 2.4766$ equaling $3.731 \times 10^2\,[BK(E_{po}, \rho, Z = 19)_{C1}]/\varepsilon$, $[BK(E_{po}, \rho, Z = 19)_{C1}]/\varepsilon$ equaling 1.6082×10^{-2} is obtained; on the basis of the relation between the experimental $\delta_{1.5\,\mathrm{keV}}$ of the NEA GaN with $E_{pomax} = 1.0\,\mathrm{keV}$ equaling 5.95[14] and the calculated $\delta_{1.5\,\mathrm{keV}}$ calculated with Eq. (26), $E_{po} = 1.5\,\mathrm{keV}$ and $n = 2.4766$ equaling $3.6242 \times 10^2\,[BK(E_{po}, \rho, Z = 19)_{C1}]/\varepsilon$, $[BK(E_{po}, \rho, Z = 19)_{C1}]/\varepsilon$ equaling 1.6417×10^{-2} is obtained; according to the relation between the experimental $\delta_{1.75\,\mathrm{keV}}$ of the NEA GaN with $E_{pomax} = 1.0\,\mathrm{keV}$ equaling 5.69[14] and the $\delta_{1.75\,\mathrm{keV}}$ calculated with Eq. (26), $E_{po} = 1.75\,\mathrm{keV}$ and $n = 2.4766$ equaling $3.50256 \times 10^2\,[BK(E_{po}, \rho, Z = 19)_{C1}]/\varepsilon$, $[BK(E_{po}, \rho, Z = 19)_{C1}]/\varepsilon$ equaling 1.6245×10^{-2} is obtained. Thus, the average value of $[BK(E_{po}, \rho, Z = 19)_{C1}]/\varepsilon$ equaling 1.62×10^{-2} is obtained.

According to the parameters of NEA GaN with $E_{pomax} = 1.0\,\mathrm{keV}$ ($n = 2.4766$, $K(E_{po}, \rho, Z = 19)_{C1}(B/\varepsilon) = 1.62 \times 10^{-2}$) and Eq. (26), the δ at $0.8\,\mathrm{keV} \leqslant E_{po} \leqslant 2\,\mathrm{keV}$ of NEA GaN with $E_{pomax} = 1.0\,\mathrm{keV}$ can be expressed as:

$$\delta_{0.8-2\,\mathrm{keV}} = \left[1 + 0.412\left(\frac{E_{po}}{10\ \mathrm{keV}}\right)^{1.2}\right] \cdot \left(\frac{65.412}{E_{po}^{1/3}}\right)\left(1 - \mathrm{e}^{-2.4766 \times 10^{-4} E_{po}^{4/3}}\right) \quad (27)$$

From the assumption that $K(E_{po}, \rho, Z = 19)$ at $0.8\,\mathrm{keV} \leqslant E_{po} \leqslant 3\,\mathrm{keV}$ of NEA GaN equals $K(E_{po}, \rho, Z = 19)_{C1}$, parameters[14, 21] ($\rho = 6.1\,\mathrm{g/cm^3}$, $A_\alpha = 42$, $Z = 19$, $1/\alpha = 86.14$ Å, $r = 0.206$, $K(E_{po}, \rho, Z = 19)_{C1}(B/\varepsilon) = 1.62 \times 10^{-2}$, $E_{pomax} = 1.0\,\mathrm{keV}$) and Eqs. (2) and (4), the δ at $2\,\mathrm{keV} \leqslant E_{po} \leqslant 3\,\mathrm{keV}$ of NEA GaN with $E_{pomax} = 1.0\,\mathrm{keV}$ can be expressed as:

$$\delta_{0.8-2\,\mathrm{keV}} = \left[1 + 0.412\left(\frac{E_{po}}{10\ \mathrm{keV}}\right)^{1.2}\right] \cdot \left(\frac{228.868}{E_{po}^{0.5}}\right)\left(1 - \mathrm{e}^{-7.0783 \times 10^{-5} E_{po}^{1.5}}\right) \quad (28)$$

7 SEE from NEA GaN with E_{pomax} = 1.25 keV

Seen from Fig. 5, it is known that the E_{pomax} of NEA GaN with $E_{pomax} = 1.25\,\mathrm{keV}$ is 1.25 keV[14]. $R_{1.25\,\mathrm{keV}}$ calculated with Eq. (1) and parameters of GaN[14, 21] ($\rho = 6.1\,\mathrm{g/cm^3}$, $A_\alpha = 42$, $Z = 19$, $E_{po} = 1.25\,\mathrm{keV}$) is equal to 287.2614 Å. Therefore, from Eq. (7), the $(1/\alpha)$ of NEA GaN with $E_{pomax} = 1.25\,\mathrm{keV}$ can be expressed as:

$$\frac{1}{\alpha} = \frac{287.2614}{n} \quad (29)$$

Seen from Fig. 5, it is known that the E_{pomax} of NEA GaN with $E_{pomax} = 1.25\,\mathrm{keV}$ is in the range of $0.8\,\mathrm{keV} \leqslant E_{pomax} \leqslant 2\,\mathrm{keV}$. Thus, from the assumption that $K(E_{po}, \rho, Z)$ at $0.8\,\mathrm{keV} \leqslant E_{po} \leqslant 3\,\mathrm{keV}$ of the NEA semiconductors with $0.8\,\mathrm{keV} \leqslant E_{pomax} \leqslant 2\,\mathrm{keV}$ can be approximately looked on as a constant $K(E_{po}, \rho, Z)_{C0.8-2}$, we take the $K(E_{po}, \rho, Z = 19)$ at $0.8\,\mathrm{keV} \leqslant E_{po} \leqslant 3\,\mathrm{keV}$ of the NEA GaN with $E_{pomax} = 1.25\,\mathrm{keV}$ to be a constant $K(E_{po}, \rho, Z = 19)_{C1.25}$; and the ratio of B to ε is independent of E_{po}[22-24]. Therefore, from parameters of NEA GaN[14, 21] ($\rho = 6.1\,\mathrm{g/cm^3}$, A_α =

42, $Z=19$, $r=0.206$, $E_{pomax}=1.25\,\mathrm{keV}$), the assumption that $K(E_{po}, \rho, Z=19)$ at $0.8\,\mathrm{keV}\leqslant E_{po}\leqslant 3\,\mathrm{keV}$ of the NEA GaN with $E_{pomax}=1.25\,\mathrm{keV}$ equals $K(E_{po}, \rho, Z=19)_{C1.25}$ and Eqs. (1), (4) and (29), the δ at $0.8\,\mathrm{keV}\leqslant E_{po}\leqslant 2\,\mathrm{keV}$ of the NEA GaN with $E_{pomax}=1.25\,\mathrm{keV}$ can be expressed as follows:

$$\delta_{0.8-2\,\mathrm{keV}}=\left[1+0.412\left(\frac{E_{po}}{10\ \mathrm{keV}}\right)^{1.2}\right]\left[\frac{1.3465\times10^{4}}{nE_{po}^{1/3}}\right]\cdot\left[\frac{BK(E_{po},\rho,Z=19)_{C1.25}}{\varepsilon}\right]\left(1-\mathrm{e}^{-7.42654\times10^{-5}nE_{po}^{4/3}}\right)\tag{30}$$

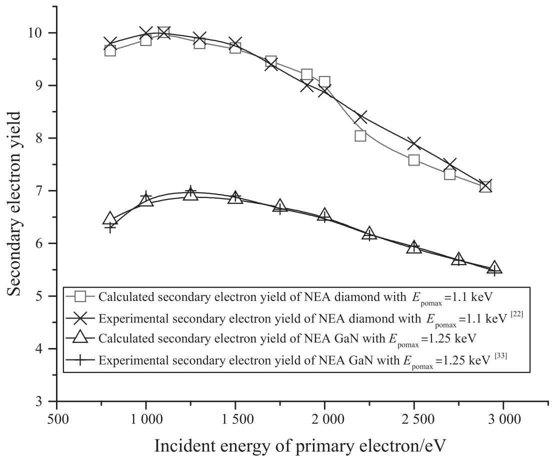

Fig. 5　Comparison between experimental δ of NEA diamond with $E_{pomax}=1.1\,\mathrm{keV}$[4] and GaN with $E_{pomax}=1.25\,\mathrm{keV}$[14] and corresponding calculated ones

The δ at $0.8\,\mathrm{keV}\leqslant E_{po}\leqslant 2\,\mathrm{keV}$ of the NEA GaN reaches its δ_m at $E_{po}=1.25\,\mathrm{keV}$. Thus, from Eq. (30), the result that n of Eq. (30) approximately equals 2.5205 is obtained. Therefore, the $(1/\alpha)$ of NEA GaN with $E_{pomax}=1.25\,\mathrm{keV}$ calculated with Eq. (29) and $n=2.5205$ is equal to 113.97 Å. Based on the relation between experimental $\delta_{1.25\,\mathrm{keV}}$ of the NEA GaN with $E_{pomax}=1.25\,\mathrm{keV}$ equaling 7.0[14] and the $\delta_{1.25\,\mathrm{keV}}$ calculated with Eq. (30), $E_{po}=1.25\,\mathrm{keV}$ and $n=2.5205$ equaling $4.7154\times10^{2}[BK(E_{po}, \rho, Z=19)_{C1.25}]/\varepsilon$, $[BK(E_{po}, \rho, Z=19)_{C1.25}]/\varepsilon$ equaling 1.4845×10^{-2} is obtained; according to the relation between the experimental $\delta_{0.8\,\mathrm{keV}}$ of the NEA GaN with $E_{pomax}=1.25\,\mathrm{keV}$ equaling 6.3[14] and the $\delta_{0.8\,\mathrm{keV}}$ calculated with Eq. (30), $E_{po}=0.8\,\mathrm{keV}$ and $n=2.5205$ equaling $4.40734\times10^{2}[BK(E_{po}, \rho, Z=19)_{C1.25}]/\varepsilon$, $[BK(E_{po}, \rho, Z=19)_{C1.25}]/\varepsilon$ equaling 1.4294×10^{-2} is obtained; on the basis of the relation between the experimental $\delta_{1\,\mathrm{keV}}$ of the NEA GaN with $E_{pomax}=1.25\,\mathrm{keV}$ equaling 6.9[14] and the calculated $\delta_{1\,\mathrm{keV}}$ calculated with Eq. (30), $E_{po}=1\,\mathrm{keV}$ and $n=2.5205$ equaling $4.637765\times10^{2}[BK(E_{po}, \rho, Z=19)_{C1.25}]/\varepsilon$, $[BK(E_{po}, \rho, Z=19)_{C1.25}]/\varepsilon$ equaling 1.4878×10^{-2} is obtained; according to the relation between the experimental $\delta_{1.75\,\mathrm{keV}}$ of the NEA GaN with $E_{pomax}=1.25\,\mathrm{keV}$ equaling 6.65[14] and the $\delta_{1.75\,\mathrm{keV}}$ calculated with Eq. (30), $E_{po}=1.75\,\mathrm{keV}$ and $n=2.5205$ equaling $4.5692\times10^{2}[BK(E_{po}, \rho, Z=19)_{C1.25}]/\varepsilon$, $[BK(E_{po}, \rho, Z=19)_{C1.25}]/\varepsilon$ equaling 1.4554×10^{-2} is obtained. Thus, the average value of $[BK(E_{po}, \rho, Z=19)_{C1.25}]/\varepsilon$ equaling 1.4643×10^{-2} is obtained.

According to the parameters of NEA GaN with $E_{pomax}=1.25\,\mathrm{keV}$ ($n=2.5205$, $K(E_{po}, \rho, Z=19)_{C1.25}(B/\varepsilon)=1.4643\times10^{-2}$) and Eq. (30), the δ at $0.8\,\mathrm{keV}\leqslant E_{po}\leqslant 2\,\mathrm{keV}$ of NEA GaN with $E_{pomax}=1.25\,\mathrm{keV}$ can be expressed as:

$$\delta_{0.8-2\,\mathrm{keV}}=\left[1+0.412\left(\frac{E_{po}}{10\ \mathrm{keV}}\right)^{1.2}\right]\cdot\left(\frac{78.2258}{E_{po}^{1/3}}\right)\left(1-\mathrm{e}^{-1.87186\times10^{-4}E_{po}^{4/3}}\right)\tag{31}$$

From the assumption that $K(E_{po}, \rho, Z=19)$ at $0.8\,\mathrm{keV}\leqslant E_{po}\leqslant 3\,\mathrm{keV}$ of NEA GaN equals $K(E_{po}, \rho, Z=19)_{C1.25}$, parameters[14, 21] ($\rho=6.1\,\mathrm{g/cm^3}$, $A_\alpha=42$, $Z=19$, $1/\alpha=113.97$ Å, $r=0.206$, $K(E_{po}, \rho, Z=19)_{C1.25}(B/\varepsilon)=1.4643\times10^{-2}$, $E_{pomax}=1.25\,\mathrm{keV}$) and Eqs. (2) and (4), the δ at $2\,\mathrm{keV}\leqslant E_{po}\leqslant 3\,\mathrm{keV}$ of NEA GaN with $E_{pomax}=1.25\,\mathrm{keV}$ can be expressed as:

$$\delta_{2-3\,\mathrm{keV}}=\left[1+0.412\left(\frac{E_{po}}{10\ \mathrm{keV}}\right)^{1.2}\right]\cdot\left(\frac{273.701}{E_{po}^{0.5}}\right)\left(1-\mathrm{e}^{-5.35\times10^{-5}E_{po}^{1.5}}\right)\tag{32}$$

8　SEE from NEA diamond with $E_{pomax}=0.85\,\mathrm{keV}$

Seen from Fig. 4, it is known that the E_{pomax} of NEA diamond with $E_{pomax}=0.85\,\mathrm{keV}$ is 0.85 keV[4]. $R_{0.85\,\mathrm{keV}}$ calculated with Eq. (1) and parameters of diamond[4, 21] ($\rho = 3.52\,g/cm^3$, $A_\alpha = 12$, $Z = 6$, $E_{po} = 0.85\,keV$) is equal to 208.4663 Å. Therefore, from Eq. (7), the $(1/\alpha)$ of NEA diamond with $E_{pomax} = 0.85\,keV$ can be expressed as:

$$\frac{1}{\alpha} = \frac{208.4663}{n} \tag{33}$$

Seen from Fig. 4, it is known that the E_{pomax} of NEA diamond with $E_{pomax} = 0.85\,keV$ is in the range of $0.8\,keV \leqslant E_{pomax} \leqslant 2\,keV$. Thus, from the assumption that $K(E_{po}, \rho, Z)$ at $0.8\,keV \leqslant E_{po} \leqslant 3\,keV$ of the NEA semiconductors with $0.8\,keV \leqslant E_{pomax} \leqslant 2\,keV$ can be approximately looked on as a constant $K(E_{po}, \rho, Z)_{C0.8-2.5}$, we take the $K(E_{po}, \rho, Z=6)$ at $0.8\,keV \leqslant E_{po} \leqslant 3\,keV$ of the NEA diamond with $E_{pomax} = 0.85\,keV$ to be a constant $K(E_{po}, \rho, Z=6)_{C0.85}$; and the ratio of B to ε is independent of E_{po}[22-24]. Therefore, from parameters of NEA diamond[4, 21] ($\rho = 3.52\,g/cm^3$, $A_\alpha = 12$, $Z = 6$, $r = 0.064$, $E_{pomax} = 0.85\,keV$), the assumption that $K(E_{po}, \rho, Z=6)$ at $0.8\,keV \leqslant E_{po} \leqslant 3\,keV$ of the NEA diamond with $E_{pomax} = 0.85\,keV$ equals $K(E_{po}, \rho, Z=6)_{C0.85}$ and Eqs. (1), (4) and (33), the δ at $0.8\,keV \leqslant E_{po} \leqslant 2\,keV$ of the NEA diamond with $E_{pomax} = 0.85\,keV$ can be expressed as follows:

$$\delta_{0.8-2\,keV} = \left[1 + 0.128\left(\frac{E_{po}}{10\ keV}\right)^{1.2}\right]\left(\frac{8.05178 \times 10^3}{nE_{po}^{1/3}}\right) \cdot \left[\frac{BK(E_{po}, \rho, Z=6)_{C0.85}}{\varepsilon}\right]\left(1 - e^{-1.242 \times 10^{-4} nE_{po}^{4/3}}\right) \tag{34}$$

The δ at $0.8\,keV \leqslant E_{po} \leqslant 2\,keV$ of the NEA diamond reaches its δ_m at $E_{po} = 0.85\,keV$. Thus, from Eq. (34), the result that n of Eq. (34) approximately equals 2.3719 is obtained. Therefore, the $(1/\alpha)$ of NEA diamond with $E_{pomax} = 0.85\,keV$ calculated with Eq. (33) and $n = 2.3719$ is equal to 87.89 Å. Based on the relation between experimental $\delta_{0.85\,keV}$ of the NEA diamond with $E_{pomax} = 0.85\,keV$ equaling 4.667[4] and the $\delta_{0.85\,keV}$ calculated with Eq. (34), $E_{po} = 0.85\,keV$ and $n = 2.3719$ equaling $3.27081 \times 10^2 [BK(E_{po}, \rho, Z=6)_{C0.85}]/\varepsilon$, $[BK(E_{po}, \rho, Z=6)_{C0.85}]/\varepsilon$ equaling 1.42686×10^{-2} is obtained; according to the relation between the experimental $\delta_{1.8\,keV}$ of the NEA diamond with $E_{pomax} = 0.85\,keV$ equaling 4.05[4] and the $\delta_{1.8\,keV}$ calculated with Eq. (34), $E_{po} = 1.8\,keV$ and $n = 2.3719$ equaling $2.8317864 \times 10^2 [BK(E_{po}, \rho, Z=6)_{C0.85}]/\varepsilon$, $[BK(E_{po}, \rho, Z=6)_{C0.85}]/\varepsilon$ equaling 1.43×10^{-2} is obtained; on the basis of the relation between the experimental $\delta_{1\,keV}$ of the NEA diamond with $E_{pomax} = 0.85\,keV$ equaling 4.6[4] and the calculated $\delta_{1\,keV}$ calculated with Eq. (34), $E_{po} = 1\,keV$ and $n = 2.3719$ equaling $3.2421825 \times 10^2 [BK(E_{po}, \rho, Z=6)_{C0.85}]/\varepsilon$, $[BK(E_{po}, \rho, Z=6)_{C0.85}]/\varepsilon$ equaling 1.4188×10^{-2} is obtained; according to the relation between the experimental $\delta_{1.5\,keV}$ of the NEA diamond with $E_{pomax} = 0.85\,keV$ equaling 4.35[4] and the $\delta_{1.5\,keV}$ calculated with Eq. (34), $E_{po} = 1.5\,keV$ and $n = 2.3719$ equaling $2.9853632 \times 10^2 [BK(E_{po}, \rho, Z=6)_{C0.85}]/\varepsilon$, $[BK(E_{po}, \rho, Z=6)_{C0.85}]/\varepsilon$ equaling 1.457×10^{-2} is obtained. Thus, the average value of $[BK(E_{po}, \rho, Z=6)_{C0.85}]/\varepsilon$ equaling 1.43×10^{-2} is obtained.

According to the parameters of NEA diamond with $E_{pomax} = 0.85\,keV$ ($n = 2.3719$, $K(E_{po}, \rho, Z=6)_{C0.85}(B/\varepsilon) = 1.43 \times 10^{-2}$) and Eq. (34), the δ at $0.8\,keV \leqslant E_{po} \leqslant 2\,keV$ of NEA diamond with $E_{pomax} = 0.85\,keV$ can be expressed as:

$$\delta_{0.8-2\,keV} = \left[1 + 0.128\left(\frac{E_{po}}{10\ keV}\right)^{1.2}\right] \cdot \left(\frac{48.5435}{E_{po}^{1/3}}\right)\left(1 - e^{-2.946 \times 10^{-4} E_{po}^{4/3}}\right) \tag{35}$$

From the assumption that $K(E_{po}, \rho, Z=6)$ at $0.8\,keV \leqslant E_{po} \leqslant 3\,keV$ of NEA diamond equals $K(E_{po}, \rho, Z=6)_{C0.85}$, parameters[4, 21] ($\rho = 3.52\,g/cm^3$, $A_\alpha = 12$, $Z = 6$, $1/\alpha = 87.89$ Å, $r = 0.064$, $K(E_{po}, \rho, Z=6)_{C0.85}(B/\varepsilon) = 1.43 \times 10^{-2}$, $E_{pomax} = 0.85\,keV$) and Eqs. (2) and (4), the δ at $2\,keV \leqslant E_{po} \leqslant 3\,keV$ of NEA diamond with $E_{pomax} = 0.85\,keV$ can be expressed as:

$$\delta_{2-3\,keV} = \left[1 + 0.128\left(\frac{E_{po}}{10\ keV}\right)^{1.2}\right] \cdot \left(\frac{159.312}{E_{po}^{0.5}}\right)\left(1 - e^{-8.9761 \times 10^{-5} E_{po}^{1.5}}\right) \tag{36}$$

9 SEE from NEA diamond with E_{pomax} = 1.1 keV

Seen from Fig. 5, it is known that the E_{pomax} of NEA diamond with E_{pomax} = 1.1 keV is 1.1 keV[4]. $R_{1.1}$keV calculated with Eq. (1) and parameters of diamond[4, 21] ($\rho = 3.52\ g/cm^3$, $A_\alpha = 12$, $Z = 6$, E_{po} = 1.1 keV) is equal to 293.9866 Å. Therefore, from Eq. (7), the $(1/\alpha)$ of NEA diamond with E_{pomax} = 1.1 keV can be expressed as:

$$\frac{1}{\alpha} = \frac{293.9866}{n} \tag{37}$$

Seen from Fig. 5, it is known that the E_{pomax} of NEA diamond with E_{pomax} = 1.1 keV is in the range of 0.8 keV ≤ E_{pomax} ≤ 2 keV. Thus, from the assumption that $K(E_{po}, \rho, Z)$ at 0.8 keV ≤ E_{po} ≤ 3 keV of the NEA semiconductors with 0.8 keV ≤ E_{pomax} ≤ 2 keV can be approximately looked on as a constant $K(E_{po}, \rho, Z)_{C0.8-2}$, we take the $K(E_{po}, \rho, Z=6)$ at 0.8 keV ≤ E_{po} ≤ 3 keV of the NEA diamond with E_{pomax} = 1.1 keV to be a constant $K(E_{po}, \rho, Z=6)_{C1.1}$; and the ratio of B to ε is independent of E_{po}[22-24]. Therefore, from parameters of NEA diamond[4, 21] ($\rho = 3.52\ g/cm^3$, A_α = 12, $Z = 6$, $r = 0.064$, E_{pomax} = 1.1 keV), the assumption that $K(E_{po}, \rho, Z=6)$ at 0.8 keV ≤ E_{po} ≤ 3 keV of the NEA diamond with E_{pomax} = 1.1 keV equals $K(E_{po}, \rho, Z=6)_{C1.1}$ and Eqs. (1), (4) and (37), the δ at 0.8 keV ≤ E_{po} ≤ 2 keV of the NEA diamond with E_{pomax} = 1.1 keV can be expressed as follows:

$$\delta_{0.8-2\ keV} = \left[1 + 0.128\left(\frac{E_{po}}{10\ keV}\right)^{1.2}\right]\left(\frac{1.135508 \times 10^4}{nE_{po}^{1/3}}\right) \cdot \left[\frac{BK(E_{po}, \rho, Z=6)_{C1.1}}{\varepsilon}\right](1 - e^{-8.8066 \times 10^{-5} nE_{po}^{4/3}}) \tag{38}$$

The δ at 0.8 keV ≤ E_{po} ≤ 2 keV of the NEA diamond reaches its δ_m at E_{po} = 1.1 keV. Thus, from Eq. (38), the result that n of Eq. (38) approximately equals 2.3849 is obtained. Therefore, the $(1/\alpha)$ of NEA diamond with E_{pomax} = 1.1 keV calculated with Eq. (37) and n = 2.3849 is equal to 123.27 Å. Based onthe relation between experimental $\delta_{1.1\ keV}$ of the NEA diamond with E_{pomax} = 1.1 keV equaling 10[4] and the $\delta_{1.1\ keV}$ calculated with Eq. (38), E_{po} = 1.1 keV and n = 2.3849 equaling 4.225143×10^2 [$BK(E_{po}, \rho, Z=6)_{C1.1}$]/$\varepsilon$, [$BK(E_{po}, \rho, Z=6)_{C1.1}$]/$\varepsilon$ equaling 2.36678×10^{-2} is obtained; according to the relation between the experimental $\delta_{1.9\ keV}$ of the NEA diamond with E_{pomax} = 1.1 keV equaling 9[4] and the $\delta_{1.9\ keV}$ calculated with Eq. (38), E_{po} = 1.9 keV and n = 2.3849 equaling 3.8833×10^2 [$BK(E_{po}, \rho, Z=6)_{C1.1}$]/$\varepsilon$, [$BK(E_{po}, \rho, Z=6)_{C1.1}$]/$\varepsilon$ equaling 2.314×10^{-2} is obtained; on the basis of the relation between the experimental $\delta_{0.8\ keV}$ of the NEA diamond with E_{pomax} = 1.1 keV equaling 9.8[4] and the $\delta_{0.8\ keV}$ calculated with Eq. (38), E_{po} = 0.8 keV and n = 2.3849 equaling 4.07572×10^2 [$BK(E_{po}, \rho, Z=6)_{C1.1}$]/$\varepsilon$, [$BK(E_{po}, \rho, Z=6)_{C1.1}$]/$\varepsilon$ equaling 2.404×10^{-2} is obtained; according to the relation between the experimental $\delta_{1.5\ keV}$ of the NEA diamond with E_{pomax} = 1.1 keV equaling 9.8[4] and the $\delta_{1.5\ keV}$ calculated with Eq. (38), E_{po} = 1.5 keV and n = 2.3849 equaling 4.0994766×10^2 [$BK(E_{po}, \rho, Z=6)_{C1.1}$]/$\varepsilon$, [$BK(E_{po}, \rho, Z=6)_{C1.1}$]/$\varepsilon$ equaling 2.39×10^{-2} is obtained. Thus, the average value of [$BK(E_{po}, \rho, Z=6)_{C1.1}$]/$\varepsilon$ equaling 2.3687×10^{-2} is obtained.

According to the parameters of NEA diamond with E_{pomax} = 1.1 keV (n = 2.3849, $K(E_{po}, \rho, Z=6)_{C1.1}$ (B/ε) = 2.3687×10^{-2}) and Eq. (38), the δ at 0.8 keV ≤ E_{po} ≤ 2 keV of NEA diamond with E_{pomax} = 1.1 keV can be expressed as:

$$\delta_{0.8-2\ keV} = \left[1 + 0.128\left(\frac{E_{po}}{10\ keV}\right)^{1.2}\right] \cdot \left(\frac{112.7795}{E_{po}^{1/3}}\right)(1 - e^{-2.1 \times 10^{-4} E_{po}^{4/3}}) \tag{39}$$

From the assumption that $K(E_{po}, \rho, Z=6)$ at 0.8 keV ≤ E_{po} ≤ 3 keV of NEA diamond equals $K(E_{po}, \rho, Z=6)_{C1.1}$, parameters[4, 21] ($\rho = 3.52\ g/cm^3$, A_α = 12, $Z = 6$, $1/\alpha$ = 123.27 Å, r = 0.064, $K(E_{po}, \rho, Z=6)_{C1.1}(B/\varepsilon)$ = 2.3687×10^{-2}, E_{pomax} = 1.1 keV) and Eqs. (2) and (4), the δ at 2 keV ≤ E_{po} ≤ 3 keV of NEA diamond with E_{pomax} = 1.1 keV can be expressed as:

$$\delta_{2-3\ keV} = \left[1 + 0.128\left(\frac{E_{po}}{10\ keV}\right)^{1.2}\right] \cdot$$

$$\left(\frac{370.124}{E_{po}{}^{0.5}}\right)(1-e^{-6.39975\times10^{-5}E_{po}{}^{1.5}}) \qquad (40)$$

10 SEE from NEA diamond with $E_{pomax}=1.72\,keV$

Seen from Fig. 2, it is known that the E_{pomax} of NEA diamond with $E_{pomax}=1.72\,keV$ is $1.72\,keV$[4]. $R_{1.72\,keV}$ calculated with Eq. (1) and parameters of diamond[4, 21] ($\rho=3.52\,g/cm^3$, $A_\alpha=12$, $Z=6$, $E_{po}=1.72\,keV$) is equal to 533.548 Å. Therefore, from Eq. (7), the $(1/\alpha)$ of NEA diamond with $E_{pomax}=1.72\,keV$ can be expressed as:

$$\frac{1}{\alpha}=\frac{533.548}{n} \qquad (41)$$

Seen from Fig. 2, it is known that the E_{pomax} of NEA diamond with $E_{pomax}=1.72\,keV$ is in the e range of $0.8\,keV\leqslant E_{pomax}\leqslant 2\,keV$. Thus, from the assumption that $K(E_{po},\rho,Z)$ at $0.8\,keV\leqslant E_{po}\leqslant 3\,keV$ of the NEA semiconductors with $0.8\,keV\leqslant E_{pomax}\leqslant 2\,keV$ can be approximately looked on as a constant $K(E_{po},\rho,Z)_{C0.8-2}$, we take the $K(E_{po},\rho,Z=6)$ at $0.8\,keV\leqslant E_{po}\leqslant 3\,keV$ of the NEA diamond with $E_{pomax}=1.72\,keV$ to be a constant $K(E_{po},\rho,Z=6)_{C1.72}$; and the ratio of B to ε is independent of E_{po}[22-24]. Therefore, from parameters of NEA diamond[4, 21] ($\rho=3.52\,g/cm^3$, $A_\alpha=12$, $Z=6$, $r=0.064$, $E_{pomax}=1.72\,keV$), the assumption that $K(E_{po},\rho,Z=6)$ at $0.8\,keV\leqslant E_{po}\leqslant 3\,keV$ of the NEA diamond with $E_{pomax}=1.72\,keV$ equals $K(E_{po},\rho,Z=6)_{C1.72}$ and Eqs. (1), (4) and (41), the δ at $0.8\,keV\leqslant E_{po}\leqslant 2\,keV$ of the NEA diamond with $E_{pomax}=1.72\,keV$ can be expressed as follows:

$$\delta_{0.8-2\,keV}=\left[1+0.128\left(\frac{E_{po}}{10\ keV}\right)^{1.2}\right]\left[\frac{2.06081\times10^4}{nE_{po}{}^{1/3}}\right]\cdot \left(\frac{BK(E_{po},\rho,Z=6)_{C1.72}}{\varepsilon}\right)(1-e^{-4.85246\times10^{-5}nE_{po}{}^{4/3}}) \qquad (42)$$

The δ at $0.8\,keV\leqslant E_{po}\leqslant 2\,keV$ of the NEA diamond reaches its δ_m at $E_{po}=1.72\,keV$. Thus, from Eq. (42), the result that n of Eq. (42) approximately equals 2.4195 is obtained. Therefore, the $(1/\alpha)$ of NEA diamond with $E_{pomax}=1.72\,keV$ calculated with Eq. (41) and $n=2.4195$ is equal to 220.52 Å. Based onthe relation between experimental $\delta_{1.72\,keV}$ of the NEA diamond with $E_{pomax}=1.72\,keV$ equaling 20[4] and the $\delta_{1.72\,keV}$ calculated with Eq. (42), $E_{po}=1.72\,keV$ and $n=2.4195$ equaling $6.57654\times10^2[BK(E_{po},\rho,Z=6)_{C1.72}]/\varepsilon$, $[BK(E_{po},\rho,Z=6)_{C1.72}]/\varepsilon$ equaling 3.04×10^{-2} is obtained; according to the relation between the experimental $\delta_{1.9\,keV}$ of the NEA diamond with $E_{pomax}=1.72\,keV$ equaling 19.9[4] and the $\delta_{1.9\,keV}$ calculated with Eq. (42), $E_{po}=1.9\,keV$ and $n=2.4195$ equaling $6.555147\times10^2[BK(E_{po},\rho,Z=6)_{C1.72}]/\varepsilon$, $[BK(E_{po},\rho,Z=6)_{C1.72}]/\varepsilon$ equaling 3.036×10^{-2} is obtained; on the basis of the relation between the experimental $\delta_{0.9\,keV}$ of the NEA diamond with $E_{pomax}=1.72\,keV$ equaling 16[4] and the $\delta_{0.9\,keV}$ calculated with Eq. (42), $E_{po}=0.9\,keV$ and $n=2.4195$ equaling $5.68106\times10^2[BK(E_{po},\rho,Z=6)_{C1.72}]/\varepsilon$, $[BK(E_{po},\rho,Z=6)_{C1.72}]/\varepsilon$ equaling 2.816×10^{-2} is obtained; according to the relation between the experimental $\delta_{1.3\,keV}$ of the NEA diamond with $E_{pomax}=1.72\,keV$ equaling 18.1[4] and the $\delta_{1.3\,keV}$ calculated with Eq. (42), $E_{po}=1.3\,keV$ and $n=2.4195$ equaling $6.3985\times10^2[BK(E_{po},\rho,Z=6)_{C1.72}]/\varepsilon$, $[BK(E_{po},\rho,Z=6)_{C1.72}]/\varepsilon$ equaling 2.829×10^{-2} is obtained. Thus, the average value of $[BK(E_{po},\rho,Z=6)_{C1.72}]/\varepsilon$ equaling 2.93×10^{-2} is obtained.

According to the parameters of NEA diamond with $E_{pomax}=1.72\,keV$ ($n=2.4195$, $K(E_{po},\rho,Z=6)_{C1.72}(B/\varepsilon)=2.93\times10^{-2}$) and Eq. (42), the δ at $0.8\,keV\leqslant E_{po}\leqslant 2\,keV$ of NEA diamond with $E_{pomax}=1.72\,keV$ can be expressed as:

$$\delta_{0.8-2\,keV}=\left[1+0.128\left(\frac{E_{po}}{10\ keV}\right)^{1.2}\right]\cdot \left(\frac{249.56}{E_{po}{}^{1/3}}\right)(1-e^{-1.174\times10^{-4}E_{po}{}^{4/3}}) \qquad (43)$$

From the assumption that $K(E_{po},\rho,Z=6)$ at $0.8\,keV\leqslant E_{po}\leqslant 3\,keV$ of NEA diamond equals $K(E_{po},\rho,Z=6)_{C1.72}$, parameters[4, 21] ($\rho=3.52\,g/cm^3$, $A_\alpha=12$, $Z=6$, $1/\alpha=220.52$ Å, $r=0.064$, $K(E_{po},\rho,Z=6)_{C1.72}(B/\varepsilon)=2.93\times10^{-2}$, $E_{pomax}=$

1.72 keV) and Eqs. (2) and (4), the δ at $2\,\text{keV} \leqslant E_{po} \leqslant 3\,\text{keV}$ of NEA diamond with $E_{pomax} = 1.72\,\text{keV}$ can be expressed as:

$$\delta_{2-3\text{ keV}} = \left[1 + 0.128\left(\frac{E_{po}}{10\text{ keV}}\right)^{1.2}\right] \cdot \left(\frac{819.024}{E_{po}^{0.5}}\right)\left(1 - e^{-3.5774\times10^{-5}E_{po}^{1.5}}\right) \tag{44}$$

11 Formula for *B*

The δ at 10 keV of NEA semiconductors can be expressed as[12]:

$$\delta_{10\text{ keV}} = -\frac{B(1+2r)}{\varepsilon}\int_0^R \frac{dE_{px}}{dx} e^{-\alpha x} dx \tag{45}$$

where x is the distance from the position to the surface of semiconductor, and E_{px} is primary energy at a given x.

Based on Eq. (3), the average energy loss of primary electron per unit path length dE_{px}/dx at 10 keV can be expressed as:

$$\frac{dE_{px}}{dx} = -\frac{0.6\rho Z^{8/9}}{3.02\times10^{-3}A_\alpha E_{px}^{2/3}} \tag{46}$$

For NEA semiconductors with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 2$ keV, the R at 10 keV is much larger than the maximum escape depth of secondary electrons T, and T is approximately equal to $5/\alpha$[25]. For example, from Section. 8, it is known that $1/\alpha$ of NEA diamond with $E_{pomax} = 0.85$ keV equals 87.89 Å, and that T of NEA diamond with $E_{pomax} = 0.85$ keV is 439.45 Å. The R at 10 keV in NEA diamond with $E_{pomax} = 0.85$ keV calculated with Eq. (3) and parameters of diamond[21] ($\rho = 3.52\,\text{g/cm}^3$, $A_\alpha = 12$, $Z = 6$, $E_{po} = 10\,\text{keV}$) is equal to 9718.79 Å. Thus, most of primary energy is dissipated outside T, and the primary energy changes little inside T. Then, from Eq. (46), the dE_{px}/dx at 10 keV inside T of NEA semiconductors with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 2$ keV can be approximately written as:

$$\frac{dE_{px}}{dx} = -\frac{0.6\rho Z^{8/9}}{3.02\times10^{-11}A_\alpha E_{po}^{2/3}} \tag{47}$$

The R at 10 keV is much larger than $5/\alpha$ of NEA semiconductors with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 2\,\text{keV}$, the internal secondary electrons excited outside $5/\alpha$ can not be emitted into vacuum[25]. Thus, the definite integral $[0, R]$ of Eq. (45) can be replaced with $[0, 5/\alpha]$ when primary electron at 10 keV enter NEA semiconductors with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 2\,\text{keV}$. So δ at 10 keV of NEA semiconductors with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 2\,\text{keV}$ can be obtained by combining Eqs. (45) and (47):

$$\begin{aligned}\delta_{10\text{ keV}} &= \frac{B(1+2r)}{\varepsilon}\int_0^{\frac{5}{\alpha}} \frac{0.6\rho Z^{8/9}}{3.02\times10^{-3}A_\alpha E_{po}^{2/3}} e^{-\alpha x} dx \\ &= \frac{0.6B\rho Z^{8/9}(1+2r)}{3.02\times10^{-3}\alpha A_\alpha \varepsilon E_{po}^{2/3}}(1-e^{-5}) \\ &= \frac{0.6B\rho Z^{8/9}(1+2r)}{3.02\times10^{-3}\alpha A_\alpha \varepsilon E_{po}^{2/3}}\end{aligned} \tag{48}$$

Based on the fact that the R at 10 keV is much larger than corresponding $1/\alpha$ and Eqs. (3) and (6), the δ at 10 keV of NEA semiconductors with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 2$ keV can be approximately written as:

$$\begin{aligned}\delta_{10\text{ keV}} &= \frac{(1+2r)K(E_{po} = 10\text{ keV}, \rho, Z)BE_{po}}{\varepsilon\alpha R} \\ &= \frac{K(E_{po} = 10\text{ keV}, \rho, Z)B\rho Z^{8/9}(1+2r)}{3.02\times10^{-3}\alpha A_\alpha E_{po}^{2/3}}\end{aligned} \tag{49}$$

From Sections 2 – 10, $[BK(E_{po}, \rho, Z)]/\varepsilon$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of NEA semiconductors with $2\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$ and that at $0.8\,\text{keV} \leqslant E_{po} \leqslant 3\,\text{keV}$ of NEA semiconductors with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 5$ keV can be expressed as follows:

$$\frac{K(E_{po}, \rho, Z))B}{\varepsilon} = C_{NEA}(E_{pomax}, \rho, Z) \tag{50}$$

From Sections 2 – 10, $C_{NEA}(E_{pomax}, \rho, Z)$ of a given NEA semiconductor with $0.8\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$ is a constant.

According to the assumption that $K(E_{po}, \rho, Z)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA semiconductors with $2\,\text{keV} \leqslant E_{pomax} \leqslant 5\,\text{keV}$ can be approximately looked on as a constant $K(E_{po}, \rho, Z)_{C2-5}$, it can be concluded that that $K(E_{po}, \rho, Z)$ of the NEA semiconductors decreases extremely slowly with increasing E_{po} in the range of $2\,\text{keV} \leqslant E_{po} \leqslant 20\,\text{keV}$. According to the fact that Eq. (48) equals Eq. (49), it is known that the $[BK(E_{po}, \rho, Z)]/\varepsilon$ at $E_{po} = 10$ keV of NEA semiconductors with $0.8\,\mathrm{keV} \leqslant E_{pomax} \leqslant 2\,\mathrm{keV}$ equals 0.6. Thus, from assumption that $K(E_{po}, \rho, Z)$ at $0.8\,\mathrm{keV} \leqslant E_{po} \leqslant 3\,\mathrm{keV}$ of NEA semiconductors with $0.8\,\mathrm{keV} \leqslant E_{pomax} \leqslant 2\,\mathrm{keV}$ approximately equals constant and conclusion that $K(E_{po}, \rho, Z)$ at $2\,\mathrm{keV} \leqslant E_{po} \leqslant 20\,\mathrm{keV}$ decreases extremely slowly with increasing E_{po}, it can be concluded that the $[BK(E_{po}, \rho, Z)]/\varepsilon$ at $0.8\,\mathrm{keV} \leqslant E_{po} \leqslant 3\,\mathrm{keV}$ of NEA semiconductors with $0.8\,\mathrm{keV} \leqslant E_{pomax} \leqslant 2\,\mathrm{keV}$ approximately equal 0.6. Therefore, from Eq. (50) and the conclusion that the $[BK(E_{po}, \rho, Z)]/\varepsilon$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA semiconductors with $2\,\mathrm{keV} \leqslant E_{pomax} \leqslant 5\,\mathrm{keV}$ also equals 0.6[12], $[BK(E_{po}, \rho, Z)]/\varepsilon$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of NEA semiconductors with $2\,\mathrm{keV} \leqslant E_{pomax} \leqslant 5\,\mathrm{keV}$ and that at $0.8\,\mathrm{keV} \leqslant E_{po} \leqslant 3\,\mathrm{keV}$ of NEA semiconductors with $0.8\,\mathrm{keV} \leqslant E_{pomax} \leqslant 5\,\mathrm{keV}$ can be expressed as follows:

$$B = 1.6667\varepsilon C_{NEA}(E_{pomax}, \rho, Z) \qquad (51)$$

Where ε can be expressed as[26]:

$$\varepsilon = \frac{E_g\left[\chi + E_g + 30\left(\frac{2}{E_g}\right)^{0.2}\right]}{\chi + 30\left(\frac{2}{E_g}\right)^{0.2}} \ln\left[\frac{\chi + E_g + 30\left(\frac{2}{E_g}\right)^{0.2}}{E_g}\right] \qquad (52)$$

where E_g and χ are the width of forbidden band and the efficient electron affinity, respectively. The χ of NEA semiconductors can considered as 0, and the ε of NEA diamond calculated with $\chi = 0$, $E_g = 5.47\,\mathrm{eV}$[27] and Eq. (52) is shown in Table. 1, the ε of NEA GaN calculated with $\chi = 0$, $E_g = 3.2\,\mathrm{eV}$[11] and Eq. (52) is also shown in Table. 1.

The formula for δ of NEA semiconductors which is used by some authors to analyze B of NEA semiconductors is written as [22]:

$$\delta = \frac{BE_{po}}{\varepsilon\alpha R}(1 - e^{-\alpha R}) \qquad (53)$$

Tab. 1 Parameters of NEA diamond and GaN with $0.8\,\mathrm{keV} \leqslant E_{pomax} \leqslant 5\,\mathrm{keV}$

NEA semiconductors/keV	Calculated ε/eV	$C_{NEA}(E_{pomax}, \rho, Z)/10^{-2}$ (Obtained from Sections 2 – 10)	Calculated B	Calculated $(1/\alpha)$/Å (Obtained from Sections 2 – 10)	Experimental δ_m [4, 13, 14]
NEA diamond with $E_{pomax} = 0.85$	11.386	1.43	0.2714	87.89	4.667
NEA diamond with $E_{pomax} = 1.1$	11.386	2.368 7	0.449 5	123.27	10
NEA diamond with $E_{pomax} = 1.72$	11.386	2.93	0.556	220.52	20
NEA diamond with $E_{pomax} = 2.3$	11.386	2.93	0.556	438.4	30
NEA diamond with $E_{pomax} = 2.64$	11.386	1.991	0.377 8	535.21	24.7
NEA diamond with $E_{pomax} = 2.75$	11.386	1.45	0.275	567.62	18.5
NEA GaN with $E_{pomax} = 1$	8.061	1.62	0.217 65	86.14	6.1
NEA GaN with $E_{pomax} = 1.25$	8.061	1.464 3	0.1967	113.97	7.0
NEA GaN with $E_{pomax} = 3$	8.061	4.033	0.5415	442.39	51

12 Results and discussion

The δ of NEA GaN and three diamond with $2\,\mathrm{keV} \leqslant E_{pomax} \leqslant 5\,\mathrm{keV}$ calculated with corresponding E_{po} and Eqs. (10), (11), (12), (15), (16), (19), (20), (23) and (24) are shown in Figs. 1-3 [4, 13]. Seen from Figs. 1 and 3 [4, 13], it is known that the calculated δ of NEA GaN with $E_{pomax} = 3.0\,\mathrm{keV}$ and diamond with $E_{pomax} = 2.3\,\mathrm{keV}$ agree very well with corresponding experimental ones [4, 13]. Seen from Figs. 2 and 3[4], as a whole, it is known that the calculated δ of NEA diamond with $E_{pomax} = 2.75\,\mathrm{keV}$ and diamond with $E_{pomax} = 2.64\,\mathrm{keV}$ agree with corresponding experimental ones[4]. But there are some differences between some calculated δ of NEA diamond with $E_{pomax} = 2.75\,\mathrm{keV}$ and diamond with $E_{pomax} = 2.64\,\mathrm{keV}$ and corresponding experimental ones. We assume that four factors may lead to this result. First, primary electron impingement modified the surface termination and thus altered the δ

during the course of measuring δ. The larger primary current was used during the measurement of the δ of NEA diamond with $E_{pomax} = 2.75\,keV$ and diamond with $E_{pomax} = 2.64\,keV$[4]. Second, there are larger experimental errors in the experimental δ of NEA diamond with $E_{pomax} = 2.75\,keV$ and diamond with $E_{pomax} = 2.64\,keV$. Third, from the course of deducing Eqs. (15), (26), (19), (20), (23) and (24), it is known that the larger experimental errors in the E_{po} and δ of the NEA diamond which are used to calculate $[BK(E_{po}, \rho, Z=23)_C]/\varepsilon$ can lead to some difference between real δ and calculated ones. Fourth, there is an approximation that $K(E_{po}, \rho, Z=23)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of NEA diamond with $2\,keV \leqslant E_{pomax} \leqslant 5\,keV \approx K(E_{po}, \rho, Z=23)_{C2-5}$ made in the course of deducing the Eqs. (15), (26), (19), (20), (23) and (24). Thus, it can be concluded that Eqs. (10), (11) and (12) can be used to calculate the δ at $1.5\,keV \leqslant E_{po} \leqslant 30\,keV$ of NEA GaN with $E_{pomax} = 3.0\,keV$, and that (15), (16), (19), (20), (23) and (24) can be approximately used to calculate the δ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 3\,keV$ of corresponding NEA diamond. Therefore, the method of deducing the formulas for δ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of NEA semiconductors with $2\,keV \leqslant E_{pomax} \leqslant 5\,keV$, which has been proved to be correct in our former study[12], has been further proved to be correct.

There is only one assumption that $K(E_{po}, \rho, Z)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA semiconductors with $2\,keV \leqslant E_{pomax} \leqslant 5\,keV \approx K(E_{po}, \rho, Z)_{C2-5}$ made in the course of deducing Eqs. (10), (11), (12), (15), (16), (19), (20), (23) and (24). So the assumption that $K(E_{po}, \rho, Z)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA semiconductors with $2\,keV \leqslant E_{pomax} \leqslant 5\,keV \approx K(E_{po}, \rho, Z)_{C2-5}$, which has been proved to be correct in our former study[12], has been further proved to be correct.

The δ at $0.8\,keV \leqslant E_{po} \leqslant 3\,keV$ of two NEA GaN and three NEA diamond with $0.8\,keV \leqslant E_{pomax} \leqslant 2\,keV$ calculated with corresponding E_{po} and Eqs. (27), (28), (31), (32), (35), (36), (39), (40), (43) and (44) are shown in Figs. 2, 4 and 5[4, 14]. Seen from Figs. 2, 4 and 5[4, 14], as a whole, it is known that the calculated δ of the two NEA GaN and three NEA diamond with $0.8\,keV \leqslant E_{pomax} \leqslant 2\,keV$ agree well with corresponding experimental ones[4, 14]. But there are some differences between the experimental δ at $2.45\,keV \leqslant E_{po} \leqslant 2.9\,keV$ of the NEA diamond with $E_{pomax} = 1.72\,keV$[4] and corresponding calculated ones. According to the shape of δ and the fact that experimental δ of the NEA diamond with $E_{pomax} = 1.72\,keV$ reaches δ_m at $1.72\,keV$, the δ at $2.45\,keV \leqslant E_{po} \leqslant 2.9\,keV$ of the NEA diamond with $E_{pomax} = 1.72\,keV$ should decrease with increasing E_{po}. But the experimental δ at $2.45\,keV \leqslant E_{po} \leqslant 2.9\,keV$ of the NEA diamond with $E_{pomax} = 1.72\,keV$ increase with increasing E_{po}. So we assume two factors may mainly lead to this result. First, there are larger experimental errors in δ at $2.45\,keV \leqslant E_{po} \leqslant 2.9\,keV$ of the NEA diamond with $E_{pomax} = 1.72\,keV$. Second, primary electron impingement modified the surface termination and thus altered the δ at $2450\,eV \leqslant E_{po} \leqslant 2.9\,keV$ during the course of measuring δ of the NEA diamond with $E_{pomax} = 1.72\,keV$. Thus, it can be concluded that Eqs. (27), (28), (31), (32), (35), (36), (39), (40), (43) and (44) can be used to calculate the δ at $0.8\,keV \leqslant E_{po} \leqslant 3\,keV$ of corresponding NEA semiconductors with $0.8\,keV \leqslant E_{pomax} \leqslant 2\,keV$, and that the method of deducing the formulas for δ at $0.8\,keV \leqslant E_{po} \leqslant 3\,keV$ of NEA semiconductors with $0.8\,keV \leqslant E_{pomax} \leqslant 2\,keV$ is correct.

There is only one assumption that $K(E_{po}, \rho, Z)$ at $0.8\,keV \leqslant E_{po} \leqslant 3\,keV$ of the NEA semiconductors with $0.8\,keV \leqslant E_{pomax} \leqslant 2\,keV \approx K(E_{po}, \rho, Z)_{C0.8-2}$ made in the course of deducing Eqs. (27), (28), (31), (32), (35), (36), (39), (40), (43) and (44). Thus, the assumption that $K(E_{po}, \rho, Z)$ at $0.8\,keV \leqslant E_{po} \leqslant 3\,keV$ of the NEA semiconductors with $0.8\,keV \leqslant E_{pomax} \leqslant 2\,keV$ can be approximately looked on as $K(E_{po}, \rho, Z)_{C0.8-2}$ is correct. Therefore, from the fact that the assumption that $K(E_{po}, \rho, Z)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA semiconductors with $2\,keV \leqslant E_{pomax} \leqslant 5\,keV$ approximately equal $K(E_{po}, \rho, Z)_{C2-5}$, it can be concluded that Eq. (51) deduced from some existed formulas and the two assumptions is correct. The B of NEA diamond and GaN with $0.8\,\mathrm{keV} \leqslant E_{pomax} \leqslant 5\,\mathrm{keV}$ calculated with Eq. (51), corresponding CNEA(E_{pomax}, ρ, Z) and ε shown in Table. 1 are still shown in Table. 1.

Up to now, none have deduced formulas for B of NEA emitters. Some authors obtained the B of NEA semiconductorsby fitting Eq. (53) to the experimental data[13, 28], and the B of NEA GaN with $E_{pomax} = 3.0\,\mathrm{keV}$ and that of NEA GaP with $E_{pomax} = 5.0\,\mathrm{keV}$ obtained by the authors are 0.36 and 0.33, respectively. The B of NEA GaN with $E_{pomax} = 3.0\,\mathrm{keV}$ calculated with parameters shown in Table. 1 and Eq. (51) is 0.5418, and the B of NEA GaP with $E_{pomax} = 5.0\,\mathrm{keV}$ calculated with parameters ($\varepsilon = 6.3552\,\mathrm{eV}$, C_{NEA} (E_{pomax}, ρ, Z) $= 6.44 \times 10^{-2}$) shown in Table. 1of our former study[12] and Eq. (51) is 0.68226. Seen from comparison between the B of NEA GaN with $E_{pomax} = 3.0\,\mathrm{keV}$ and NEA GaP with $E_{pomax} = 5.0\,\mathrm{keV}$ obtained by the authors[13, 28] and corresponding B calculated by us, it is known that the B calculated by us are about 1.6667 times of corresponding B obtained by the authors[13, 28]. Seen from Eqs. (4), (6) and (51) and the courses of deducing Eqs. (4), (6) and (51), it is known that the important factor that $\mathrm{d}E_{px}/\mathrm{d}x$ increases with increasing x[12] or parameter $K(E_{po}, \rho, Z)$ was taken into account in the course of deducing Eqs. (4), (6) and (51), and that this important factor was not taken into account in the course of deducing Eq. (53)[13, 22, 28]. According to the physical mechanism of SEE, the parameter $K(E_{po}, \rho, Z)$ must be taken into account in the course of deducing formula for δ[12, 23, 29-31]. From the courses of deducing Eqs. (4), (6) and (51) and calculating B with Eq. (51), it is known that the B of NEA GaN with $E_{pomax} = 3.0\,\mathrm{keV}$ and NEA GaPwith $E_{pomax} = 5.0\,\mathrm{keV}$ calculated by us approximately equal corresponding B obtained by the authors if parameter $K(E_{po}, \rho, Z)$ is not taken into account or taken to be 1. Thus, from above analysis, it concludes that the B of NEA semiconductors calculated with Eq. (51) deduced from Eqs. (4), (6) and some existed formulas are more reasonable than the B obtained by the authors by fitting Eq. (53) to the experimental data, and that Eq. (51) can be used to calculate the B of NEA semiconductors with $0.8\,\mathrm{keV} \leqslant E_{pomax} \leqslant 5\,\mathrm{keV}$.

Up to now, none of formulas for $1/\alpha$ of NEA semiconductors was deduced, and the $1/\alpha$ of NEA semiconductors were not measured experimentally. The expression of R is important for authors to obtain the $1/\alpha$ of NEA semiconductors by fitting Eq. (53) to the experimental data. For example, when some authors obtained $1/\alpha$ of NEA GaN with $E_{pomax} = 3.0\,\mathrm{keV}$ by using the expression of R [$R = 0.01(E_{po})^2$ (μm), E_{po} in keV] and fitting Eq. (53) to the experimental data, the obtained $1/\alpha$ of NEA GaN with $E_{pomax} = 3\,\mathrm{keV}$ is 300 Å[13]; when some authors obtained $1/\alpha$ of NEA GaN with $E_{pomax} = 3.0\,\mathrm{keV}$ by using the expression of R [$R = 0.027(E_{po})^2$ (μm), E_{po} in keV] and fitting Eq. (53) to the experimental data, the obtained $1/\alpha$ of NEA GaN with $E_{pomax} = 3.0\,\mathrm{keV}$ is 820 Å [13]. Finally, the authors assumed that the $1/\alpha$ of NEA GaN with $E_{pomax} = 3.0\,\mathrm{keV}$ was estimated to be between 300 and 800 Å[13]. The expression of R is also important for us to obtain the $1/\alpha$ of NEA semiconductors with $0.8\,\mathrm{keV} \leqslant E_{pomax} \leqslant 5\,\mathrm{keV}$. A problem arises, are Eqs. (1), (2) and (3) suitable to diamond and GaN According to the total stopping powers calculated with ESTAR program[32] and Eqs. (1), (2) and (3), we found that Eqs. (1), (2) and (3) are suitable to diamond, GaN, GaP, GaAs, etc. For example, based on Eq. (3), the $\mathrm{d}E_{px}/\mathrm{d}x$ at $10\,\mathrm{keV} \leqslant E_{po} \leqslant 100\,\mathrm{keV}$ can be expressed as Eq. (47), and the $\mathrm{d}E_{px}/\mathrm{d}x$ in diamond at 20 keV calculated with Eq. (47) and corresponding parameters is equal to 0.3915 eV/Å; the total stopping power (i. e., $\mathrm{d}E_{px}/\mathrm{d}x$) in diamond at 20 keV calculated with ESTAR program is equal to 11.69 MeV · cm^2/g, ρ of diamond is equal to 3.52 g/cm^3. Thus, the $\mathrm{d}E_{px}/\mathrm{d}x$ in diamond at 20 keV calculated with ESTAR program is equal to (11.69 MeV · cm^2/g) (3.52g/cm^3), that is, the $\mathrm{d}E_{px}/\mathrm{d}x$ in diamond at 20 keV calculated with ESTAR program is equal to 0.4115 eV/Å. Therefore, the $\mathrm{d}E_{px}/\mathrm{d}x$ in diamond at 20 keV calculated with Eq. (47) approximately equals that calculated with ESTAR program. We found that dE_{px}/dx in diamond at $10\,keV \leqslant E_{po} \leqslant 100\,keV$ calculated with Eq. (47) approximately equal corresponding those calculated with ESTAR program by similar method. Hence, it can be concluded that Eq. (3) is suitable to diamond. Therefore, from the fact that Eqs. (1), (2) and (3) are suitable to diamond, GaN, GaP, GaAs, etc, it can be concluded that the method presented here of calculating the $1/\alpha$ of NEA semiconductors with $0.8\,keV \leqslant E_{pomax} \leqslant 5\,keV$ is correct, and that the $1/\alpha$ of NEA semiconductors with $0.8\,keV \leqslant E_{pomax} \leqslant 5\,keV$ are correct.

Electron beam impingement can modify the surface termination of NEA diamond and thus alter the δ, B and $1/\alpha$ of NEA diamond[4]. The NEA diamond with $E_{pomax}=1.1\,keV$ is boron (B)-doped and hydrogen (H) terminated NEA diamond[4]; the NEA diamond with $E_{pomax}=2.64\,keV$ is B-doped and H terminated NEA diamond after 880 s of electron beam impingement at $J=4.9\times10^{-4}A/cm^2$[4]. In other words, the NEA diamond with $E_{pomax}=2.64\,keV$ studied in this study is the NEA diamond with $E_{pomax}=1.1\,keV$ studied in this study after 880 s of electron beam impingement at $J=4.9\times10^{-4}A/cm^2$[4]. The NEA diamond with $E_{pomax}=2.75\,keV$ is the NEA diamond with $E_{pomax}=2.64\,keV$ after further electron beam impingement[4]. Considering the B and $1/\alpha$ of NEA diamond shown in Table. 1, it is known that the $1/\alpha$ of NEA diamond with $E_{pomax}=2.75\,keV$ is larger than that of NEA diamond with $E_{pomax}=2.64\,keV$ which is also larger than that of NEA diamond with $E_{pomax}=1.1\,keV$, and that the B of NEA diamond with $E_{pomax}=2.75\,keV$ is less than that of NEA diamond with $E_{pomax}=2.64\,keV$ which is also less than that of NEA diamond with $E_{pomax}=1.1\,keV$. Thus, according to the relationships among the NEA diamond with $E_{pomax}=2.75\,keV$, NEA diamond with $E_{pomax}=2.64\,keV$ and NEA diamond with $E_{pomax}=1.1\,keV$, it can be concluded that the electron beam impingement can increases the $1/\alpha$ of B-doped and H terminated NEA diamond by modifying the surface termination, and that the electron beam impingement can decreases the B of B-doped and H terminated NEA diamond by modifying the surface termination. If we have more experimental δ_m and E_{pomax} and the information of sample preparations of NEA emitters, we can obtain more quantitative influences of sample preparations on B and $1/\alpha$ of NEA semiconductors by above method. Thus, from the fact that sample preparations of a given NEA semiconductor decide the δ at given E_{po}, δ_m, B and $1/\alpha$ and the fact that the B and $1/\alpha$ of a given kind of semiconductor almost decide the value of δ_m and the δ at given E_{po}, it concludes that the theoretical research of B and $1/\alpha$ help to research quantitative influences of sample preparation on SEE from NEA semiconductors with $0.8\,keV \leqslant E_{pomax} \leqslant 5\,keV$ and produce desirable NEA emitters such as NEA diamond.

13 Conclusions

According to the characteristics of SEE from NEA semiconductors with $0.8\,keV \leqslant E_{pomax} \leqslant 5\,keV$, R, existing universal formulas for δ of NEA semiconductors[12] and experimental data[4, 13, 14], special formulas for δ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of NEA diamond and GaN with $2\,keV \leqslant E_{pomax} \leqslant 5\,keV$ and δ at $0.8\,keV \leqslant E_{po} \leqslant 3\,keV$ of NEA diamond and GaN with $0.8\,keV \leqslant E_{pomax} \leqslant 2\,keV$ were deduced and experimentally proved, respectively. There is only one assumption that $K(E_{po}, \rho, Z)$ at $0.8\,keV \leqslant E_{po} \leqslant 3\,keV$ of NEA semiconductors with $0.8\,keV \leqslant E_{pomax} \leqslant 2\,keV \approx K(E_{po}, \rho, Z)_{C0.8-2}$ made in the course of deducing Eqs. (27), (28), (31), (32), (35), (36), (39), (40), (43) and (44). Thus, the assumption that $K(E_{po}, \rho, Z)$ at $0.8\,keV \leqslant E_{po} \leqslant 3\,keV$ of NEA semiconductors with $0.8\,keV \leqslant E_{pomax} \leqslant 2\,keV$ can be approximately looked on as $K(E_{po}, \rho, Z)_{C0.8-2}$ is correct. Therefore, from the fact that the assumption that $K(E_{po}, \rho, Z)$ at $0.5\,E_{pomax} \leqslant E_{po} \leqslant 10\,E_{pomax}$ of the NEA semiconductors with $2\,keV \leqslant E_{pomax} \leqslant 5\,keV$ approximately equal $K(E_{po}, \rho, Z)_{C2-5}$, it can be concluded that Eq. (51) for B of NEA semiconductors with $0.8\,keV \leqslant E_{pomax} \leqslant 5\,keV$ deduced from some existed formulas and the two assumptions is correct.

According to the fact that Eqs. (1)-(3) are suitable to diamond, GaN, GaP, GaAs, the courses of calculating $1/\alpha$ in Sections 2 - 10 and the comparison between the $1/\alpha$ calculated in Sections 2 - 10 and the $1/\alpha$ determined by other authors[13], it can be concluded that the method presented here of calculating the $1/\alpha$ of NEA semiconductors with $0.8\,\mathrm{keV} \leqslant E_{pomax} \leqslant 5\,\mathrm{keV}$ is correct, and that the obtained $1/\alpha$ of NEA diamond and GaN with $0.8\,\mathrm{keV} \leqslant E_{pomax} \leqslant 5\,\mathrm{keV}$ are correct. From the conclusion that the theoretical research of B and $1/\alpha$ in this study are correct, the relationships among δ_m, δ, B and $1/\alpha$ and the fact that sample preparations of a given NEA emitter decide the B and $1/\alpha$, it concludes that the theoretical research of B and $1/\alpha$ in this study help to research quantitative influences of different sample preparations on SEE from NEA semiconductors and produce desirable NEA emitters such as NEA diamond.

参考文献:

[1] YAMADA T, MASUZAWA T, MIMURA H, et al. Electron emission from conduction band of heavily phosphorus doped diamond negative electron affinity surface[J]. Journal of Physics D: Applied Physics, 2016, 49(4): 045102.

[2] O'DONNELL K M, EDMONDS M T, RISTEIN J, et al. Direct observation of phonon emission from hot electrons: Spectral features in diamond secondary electron emission [J]. Journal of Physics Condensed Matter: an Institute of Physics Journal, 2014, 26(39): 395008.

[3] YATER J E, SHIH A. Secondary electron emission characteristics of single-crystal and polycrystalline diamond[J]. Journal of Applied Physics, 2000, 87(11): 8103-8112.

[4] SHIH A, YATER J, PEHRSSON P, et al. Secondary electron emission from diamond surfaces[J]. Journal of Applied Physics, 1997, 82(4): 1860-1867.

[5] 陈炽,陈伟伟,王程,等. 基于连续模 FV 类的 VHF 频段放大器设计[J]. 空间电子技术, 2020, 17(2): 5-9 + 82.

[6] WANG X H, WANG M B, LIAO Y L, et al. Negative electron affinity of the GaN photocathode: A review on the basic theory, structure design, fabrication, and performance characterization[J]. Journal of Materials Chemistry C, 2021, 9(38): 13013-13040.

[7] 夏磊,汤清伦,韦炜. 纤维基柔性可拉伸电子器件的研究进展[J]. 棉纺织技术, 2022, 50(4): 73-77.

[8] MORISHITA H, OHSHIMA T, OTSUGA K, et al. Brightness evaluation of pulsed electron gun using negative electron affinity photocathode developed for time-resolved measurement using scanning electron microscope[J]. Ultramicroscopy, 2021, 230: 113386.

[9] GUTIERREZ W A, POMMERRENIG H D, HOLT S L. Secondary electron emission from GaAs[J]. Applied Physics Letters, 1972, 21(6): 249-250.

[10] XIE A G, YU Y, SONG C N, et al. Study of secondary electron emission from semiconductors induced by electrons from 20 eV to 800 eV and surface state of semiconductors [J]. Results in Physics, 2019, 15: 102724.

[11] XIE A G, YU Y, SONG C N, et al. Study of secondary electron emission from semiconductors induced by electrons from 20 eV to 800 eV and surface state of semiconductors [J]. Results in Physics, 2019, 15: 102724.

[12] XIE A G, YU Y, CHEN Y Y, et al. Theoretical research of secondary electron emission from negative electron affinity semiconductors[J]. Surface Review and Letters, 2019, 26 (4): 1850181.

[13] MARTINELLI R U, PANKOVE J I. Secondary electron emission from the GaN: Cs-O surface[J]. Applied Physics Letters, 1974, 25(10): 549-551.

[14] YATER J E, SHIH A, KATZER D S. Secondary electron emission studies of diamond and GaN materials[J]. MRS Online Proceedings Library, 1999, 558(1): 551-562.

[15] WEI K T, LI J, LIU B Y, et al. Effect of hydrogen plasma treatment on secondary electron emission properties of polycrystalline diamond films [J]. Vacuum, 2020, 172: 109046.

[16] TAFEL A, MEIER S, RISTEIN J, et al. Femtosecond laser-induced electron emission from nanodiamond-coated tungsten needle tips[J]. Physical Review Letters, 2019, 123 (14): 146802.

[17] BEATTIE J M A, GOSS J P, RAYSON M J, et al. Electron-affinity and surface-stability of aluminium-oxide terminated diamond surfaces[J]. Diamond and Related Materials, 2019, 94: 137-145.

[18] BARKL J, ZANIEWSKI A M, KOECK F, et al. Diamond photochemistry with visible light[J]. Diamond and Related Materials, 2019, 96: 195-197.

[19] KANAYA K, KAWAKATSU H. Secondary electron emission due to primary and backscattered electrons[J]. Journal of Physics D: Applied Physics, 1972, 5 (9): 1727-1742.

[20] REUTER W. Proceedings of the six international conference on x-ray optics and microanalysis[M]. Tokyo: Uin-

versity of Tokyo Press Tokyo, 1972: 45-45.

[21] 氮化镓[EB/OL].[2021-5-19]. https://baike.baidu.com/item/%E6%B0%AE%E5%8C%96%E9%95%93

[22] SEILER H. Secondary electron emission in the scanning electron microscope[J]. Journal of Applied Physics,1983,54(11):R1-R18.

[23] XIE A G,LAI M,CHEN Y L,et al. Formulae for secondary electron yield from insulators and semiconductors[J]. Nuclear Science and Techniques,2017,28(10):141.

[24] NAPCHAN E. MC-SET-Monte Carlo simulation of electron trajectories[J]. Computer Software,2008,17(2):85-89

[25] SEILER H. Einige aktuelle probleme der sekundarelektron-emission[J]. Z Angew Phys,1967,22(1): 249-263.

[26] XIE A G,LI Q F,CHEN Y Y,et al. The formulae for parameters of the secondary electron yield of insulators from 10 kev to 30 kev[J]. Modern Physics Letters B,2013,27(32):1350238.

[27] 禁带宽度[EB/OL].[2021-5-19]. https://baike.baidu.com/item/%E7%A6%81%E5%B8%A6%E5%AE%BD%E5%BA%A6/9150459? fr=aladdin.

[28] MARTINELLI R U. Secondary emission and photoemission from negative electron affinity GaP:Cs[J]. Journal of Applied Physics,1974,45(7):3203-3204.

[29] REIMER L,DRESCHER H. Secondary electron emission of 10-100 keV electrons from transparent films of Al and Au[J]. Journal of Physics D:Applied Physics,1977,10(5):805-815.

[30] XIE A G,XIA Y Q,WANG X,et al. Formulae for maximum yield and Mean escape depth of secondary electrons emitted from metals[J]. Modern Physics Letters B,2017,31(26):1750239.

[31] XIE A,ZHON K,ZHAO D,et al. Formulae for low-energy secondary electron yield from different kinds of emitters as a function of measurable variables[J]. Modern Physics Letters B,2017,31(10):1750105.

[32] NIST. The ESTAR database[EB/OL].[2021-5-19]. https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html.

作者简介:刘亦凡(1999-),江苏南通人,硕士研究生。主要研究方向为二次电子发射、光电发射。E-mail:lyf1466160581@outlook.com

通迅作者:谢爱根(1971-),安徽芜湖人,博士、副教授、硕士生导师,以第一作者且为通讯作者发表二次电子发射方面学术论文40余篇,其中30余篇被SCI和SCIE收录。主要研究方向为二次电子发射理论及航天器充电(空间天气学)研究。E-mail:xagth@126.com