Secondary electron emission and photoemission from a negative electron affinity semiconductor with large mean escape depth of excited electrons

Ai-Gen Xie(谢爱根)[1,2,3,†], Hong-Jie Dong(董红杰)[1], and Yi-Fan Liu(刘亦凡)[1]

[1] *School of Physics and Optoelectronic Engineering, Nanjing University of Information Science and Technology, Nanjing* 210044, *China*
[2] *Jiangsu Key Laboratory for Optoelectronic Detection of Atmosphere and Ocean, Nanjing University of Information Science & Technology, Nanjing* 210044, *China*
[3] *Jiangsu international Joint Laboratory on Meteorological Photonics and Optoelectronic Detection, Nanjing University of Information Science & Technology, Nanjing* 210044, *China*

(Received 9 April 2022; revised manuscript received 30 June 2022; accepted manuscript online 2 July 2022)

The formulae for parameters of a negative electron affinity semiconductor (NEAS) with large mean escape depth of secondary electrons λ (NEASLD) are deduced. The methods for obtaining parameters such as λ, B, $E_{\rm pom}$ and the maximum δ and δ at 100.0 keV $\geq E_{\rm po} \geq$ 1.0 keV of a NEASLD with the deduced formulae are presented (B is the probability that an internal secondary electron escapes into the vacuum upon reaching the emission surface of the emitter, δ is the secondary electron yield, $E_{\rm po}$ is the incident energy of primary electrons and $E_{\rm pom}$ is the $E_{\rm po}$ corresponding to the maximum δ). The parameters obtained here are analyzed, and it can be concluded that several parameters of NEASLDs obtained by the methods presented here agree with those obtained by other authors. The relation between the secondary electron emission and photoemission from a NEAS with large mean escape depth of excited electrons is investigated, and it is concluded that the presented method of obtaining λ is more accurate than that of obtaining the corresponding parameter for a NEAS with large $\lambda_{\rm ph}$ ($\lambda_{\rm ph}$ being the mean escape depth of photoelectrons), and that the presented method of calculating B at $E_{\rm po} > 10.0$ keV is more widely applicable for obtaining the corresponding parameters for a NEAS with large $\lambda_{\rm ph}$.

Keywords: negative electron affinity semiconductor, secondary electron emission, photoemission, the probability, secondary electron yield, large mean escape depth of excited electrons

PACS: 81.90.+c, 79.20.Hx, 79.20.Ap, 29.20.–c **DOI:** 10.1088/1674-1056/ac7dbd

1. Introduction

Secondary electron emission (SEE) and the suppression of SEE are applied in various areas such as particle accelerators, plasma physics and information technology.[1,2] The excited electrons in the conduction band of a negative electron affinity semiconductor (NEAS) can be easily emitted from the surface due to the lack of a surface barrier. The mean escape depth (in the μm range) of the excited electrons at the bottom of the conduction band of a NEAS (i.e., thermalized electrons) is much larger than that (in the nm range) of hot electrons. Thus, quantum efficiency Y, secondary electron yield δ and maximum secondary electron yield $\delta_{\rm m}$ from a NEAS in general far exceed the corresponding parameters for a positive electron affinity semiconductor. Therefore, NEASs have more applications in current amplifiers, photo-injectors (such as RF photocathode guns in accelerators) and x-ray sources.[3–6] Therefore, NEASs are an important topic.[7–11]

A NEAS with high $E_{\rm pom}$ (> 20.0 keV) and large λ ($> 1.0\times10^4$ Å) is called a NEAS with large λ (NEASLD), where λ is mean escape depth of secondary electrons and $E_{\rm pom}$ is the incident energy of primary electrons $E_{\rm po}$ corresponding to $\delta_{\rm m}$. A NEASLD has several outstanding SEE parameters, such as a large $\delta_{\rm m}$ (≥ 100). Note that $\delta_{20.0-100.0}$ is applied in an increasing number of fields;[12] in this study, the subscript (written in Arabic numerals) of a parameter denotes that parameter at an $E_{\rm po}$ equal to the subscript in keV. For example, $\delta_{20.0-100.0}$ denotes δ in the range $E_{\rm po} = 20.0$ keV–100.0 keV. Due to the technical difficulty of measuring δ at $E_{\rm po} > 20.0$ keV, there are almost no measured values of δ at $E_{\rm po} > 20.0$ keV, λ, $E_{\rm pom}$, and $\delta_{\rm m}$ for NEASLDs[13] in the literature; furthermore, nobody has successfully investigated δ, λ, $E_{\rm pom}$, and $\delta_{\rm m}$ of NEASLDs in theory. So systematic investigations of these parameters are necessary.

In this paper we study a new SEE model for λ, $E_{\rm pom}$, m, $\delta_{\rm m}$, B at $E_{\rm po} > 10.0$ keV and $\delta_{1.0-100.0}$ of a NEASLD, which was developed from the theories of SEE and the fact that $\lambda_{\rm b}(Z,E_{\rm po})$ at $E_{\rm po} < 50.0$ keV is less than the λ value of a NEASLD, where m is the parameter denoting the ratio of $R(E_{\rm pom})$ to λ, $R(E_{\rm pom})$ is the primary range of R at $E_{\rm pom}$, B is the probability that an internal secondary electron escapes into the vacuum upon reaching the emission surface of emitter and $\lambda_{\rm b}(Z,E_{\rm po})$ denotes the mean diffusion depth of backscattered electrons from materials with an average atomic number Z at $E_{\rm po}$. The parameters obtained here were analyzed or compared with those obtained by other authors,[14–17] and we conclude

†Corresponding author. E-mail: xagth@126.com

© 2023 Chinese Physical Society and IOP Publishing Ltd

that λ, m, B at $E_{po} > 10.0$ keV and $\delta_{1.0-100.0}$ of a NEASLD obtained by the method presented here agree with those obtained by other authors, and that the methods presented here for calculating E_{pom} and δ_m of a NEASLD are correct.

From the analysis of common mechanisms of SEE from NEASLDs and photoemission from NEASs with large λ_{ph} (NEASLPs),[18,19] it can be concluded that λ of a NEASLD is equal to λ_{phl} of a NEASLP, but that λ of a NEASLD is $> \lambda_{phlow}$ of a NEASLP. Thus, the method of obtaining λ_{phl} of a NEASLP by obtaining λ of a NEASLD is presented. Here λ_{ph} is the mean escape depth of photoelectrons, λ_{phl} is the mean escape depth of photoelectrons excited by photons with $h\gamma > (h\gamma_0 + 2.4 \times 10^{-20}$ J), where h is the Plank constant, γ is the photon frequency, $h\gamma$ is the photon energy, γ_0 is the threshold γ and λ_{phlow} is λ_{ph} in the γ range $[\gamma_0, (h\gamma_0 + 2.4 \times 10^{-20}$ J$)/h]$. Relative errors in λ obtained here are much less than those in λ_{phl} of a NEASLP obtained by analyzing parameters of photoemission.[16,20,21] Thus, it can be concluded that the presented method of obtaining λ_{phl} from λ is a more accurate method than existing ones.

Based on the analysis of experimental Y values in the γ range $[(h\gamma_0 + 2.4 \times 10^{-20}$ J$)/h$, $\gamma_{h\text{-flat}}]$,[14,16] the existing formula for Y of a NEASLP and the photoelectric characteristics of NEASLPs, we assume that f_{th} at $\gamma > [(h\gamma_0 + 2.4 \times 10^{-20}$ J$)/h]$ in a NEASLP is independent of $E_{obtainp}$ when $E_{obtainp} > (h\gamma_0 + 2.4 \times 10^{-20}$ J). Here $[(h\gamma_0 + 2.4 \times 10^{-20}$ J$)/h$, $\gamma_{h\text{-flat}}]$ is the γ range corresponding to the flat portion of the spectral response curve of the NEASLP, $\gamma_{h\text{-flat}}$is the maximum γ of the flat portion of the spectral response curve, $E_{obtainp}$ is the energy obtained by a thermalized electron absorbing one photon and f_{th} is the energy distribution of thermalized electrons. Thus, from this assumption, the fact that E_{po} is much larger than $E_{obtainp}$ and the common mechanisms of SEE from NEASLDs and photoemission from NEASLPs, we state that f_{th} in a NEASLD is the same as that in a NEASLP produced by photons with $h\gamma > (h\gamma_0 + 2.4 \times 10^{-20}$ J), and that B at $E_{po} > 10$ keV of a NEASLD is equal to B_{ph} in the γ range of $[(h\gamma_0 + 2.4 \times 10^{-20}$ J$)/h$, $\gamma_{h\text{-flat}}]B_{phflat}$, where B_{ph} is the probability that an internal photoexcited electron absorbing a photon escapes into the vacuum upon reaching the emission surface of the NEASLP. The statement that B at $E_{po} > 10$ keV of a NEASLD equals B_{phflat} is proved to be true by the comparison between B at $E_{po} > 10$ keV of a NEASLD and B_{phflat} obtained here. Thus, because there is only one assumption made in the course of making the statement that B at $E_{po} > 10$ keV of a NEASLD equals B_{phflat}, we can conclude that above assumption is correct. Therefore, from the fact that there is also only one assumption made in the course of making the statement that f_{th} in a NEASLD is the same as that in a NEASLP produced by photons with $h\gamma > (h\gamma_0 + 2.4 \times 10^{-20}$ J), this statement is also correct. B_{phflat} can be calculated from the formula for reflection mode Y and several parameters such as Y in the γ range $[(h\gamma_0 + 2.4 \times 10^{-20}$ J$)/h$, $\gamma_{h\text{-flat}}]$.[16] However, the spectral response curves of some NEASLPs have no flat portions,[16,22] which are necessary to calculate B_{phflat} with the formula for reflection mode Y. Thus, the B_{phflat} of these NEASLPs cannot be calculated by the formula for reflection mode Y. The B_{phflat} of these NEASLPs can be obtained by estimation, but the estimated B_{phflat} have larger relative errors ($\pm 10\%$ relative errors).[16,22] Therefore, because the method presented here of calculating accurate B_{phflat} by calculating B at $E_{po} > 10$ is suitable for all NEASLPs, it can be concluded that the presented method is more widely applicable for calculating B_{phflat} than the current methods.

The λ_{phl} and B_{phflat} are important parameters of Y, which is the most important parameter for characterizing the properties of a NEASLP.[23,24] Thus, the two improved methods presented here of obtaining λ_{phl} and B_{phflat} help to improve the design of and investigations into NEASLPs. Therefore, because NEASLPs such as NEA GaAs and diamond are being applied in more and more fields[25,26] it can be concluded that the presentation two improved methods for obtaining λ_{phl} and B_{phflat} is significant. Note that the unit of R, λ_{phl}, λ_{phlow}, λ_{ph}, $\lambda_b(Z, E_{po})$, and λ is Å and that both λ_{ph} and λ in this study are mean escape depths of excited electrons.

2. SEE model

2.1. Parameters of *R*

The ESTAR program[27] can be used to calculate R, and the R–E_{po} relation can also be obtained from the ESTAR program.[27] The obtained relations between R, the energy exponent n and E_{po} can be written as[28,29]

$$R = AE_{po}^{n}. \tag{1}$$

For a given kind of material, the parameters A and n both slowly change with E_{po} and can be approximately treated as constant in the same E_{po} range;[8] A depends on atomic weight, material density ρ and Z.

Suppose that the E_{po} is $E_{poH} = H$ keV and $E_{poh} = h$ keV ($h < H$), and that E_{poH} and E_{poh} are in the same E_{po} range; H and h are Arabic numerals. Thus, from Eq. (1), and the fact that both A and n can be approximately treated as constant in the same E_{po} range, R_{h-H} can be approximately written as[8]

$$R_{h-H} = A_{h-H}(E_{po})^{n_{h-H}}, \tag{2}$$

where n_{h-H} can be written as[8]

$$n_{h-H} = \ln(L_h/L_H)/\ln(E_{poH}/E_{poh}) + 1, \tag{3}$$

and A_{h-H} can be approximately written as[8]

$$A_{h-H} = \left[L_{h-H} n_{h-H} E_{po}^{(n_{h-H}-1)}\right]^{-1}. \tag{4}$$

The energy loss of primary electrons per unit path length L in the range $E_{po} = 1.0 \times 10^{-3}$ MeV–1.0×10^{4} MeV can be obtained from the ESTAR website.[27] Thus, n_{h-H} and A_{h-H} can be calculated from E_{poH}, E_{poh}, ρ, L_h, L_{h-H}, L_H, n_{h-H}, E_{po} and Eqs. (3) and (4) if E_{poH} and E_{poh} are in the range $E_{po} = 1.0 \times 10^{-3}$–$1.0 \times 10^{4}$ MeV.[8,27]

The following values are given for Si on the ESTAR website: $L_{1.0} = 7.478 \times 10^{7}$ eV·cm^2·g^{-1}, $L_{1.2} = 6.831 \times 10^{7}$ eV·cm^2·g^{-1}, and $L_{1.3} = 6.548 \times 10^{7}$ eV·cm^2·g^{-1}.[27] Thus, from the definition of L and the fact that ρ[30] of Si equals 2.35 g·cm^{-3}, $L_{1.0} = (7.478 \times 10^{7}$ eV·cm^2·g$^{-1}) \times (2.35$ g·cm$^{-3}) = 1.75733$ eV·Å^{-1}, $L_{1.2} = 1.605285$ eV·Å^{-1} and $L_{1.3} = 1.53878$ eV·Å^{-1} are calculated for Si. We can take E_{po} in the range 1.0 keV–1.3 keV and for the same E_{po} range $n_{1.0-1.3} = 1.506$ can be calculated for Si from Eq. (3), $E_{po} = 1.0$ keV, $E_{po} = 1.3$ keV, $L_{1.0}$, and $L_{1.3}$. Thus, $A_{1.0-1.3} = 1.144 \times 10^{-2}$ Å·(eV)$^{-1.506}$ can be calculated for Si from Eq. (4), $E_{po} = 1.2$ keV, $n_{1.0-1.3}$, and $L_{1.2}$.

The R parameters of Si, GaAs, $Al_{0.1}Ga_{0.9}As$, $Al_{0.2}Ga_{0.8}As$, and $Al_{0.3}Ga_{0.7}As$ calculated with the above method are shown in Tables 1–3. Note that AlGaAs at three different AlAs concentrations (10%, 20%, and 30%) is expressed as $Al_{0.1}Ga_{0.9}As$, $Al_{0.2}Ga_{0.8}As$ and $Al_{0.3}Ga_{0.7}As$, respectively.

Table 1. The calculated n values for various NEA materials.

Material	$n_{1.0-1.3}$	$n_{1.3-1.7}$	$n_{1.7-2.5}$	$n_{2.5-4.0}$	$n_{4.0-6.0}$	$n_{6.0-10.0}$	$n_{10.0-15.0}$	$n_{15.0-20.0}$	$n_{20.0-30.0}$	$n_{20.0-60.0}$
Si	1.506	1.562	1.614	1.644	1.70	1.726	1.74	1.743	1.741	
GaAs	1.1875	1.329	1.447	1.547	1.6158	1.661	1.6894	1.70		1.689
$Al_{0.1}Ga_{0.9}As$	1.196	1.336	1.450	1.550	1.618	1.662	1.691	1.702		1.690
$Al_{0.2}Ga_{0.8}As$	1.205	1.3415	1.456	1.550	1.620	1.664	1.692	1.703		1.690
$Al_{0}.3Ga_{0}.7As$	1.215	1.349	1.460	1.555	1.622	1.666	1.690	1.703		1.692

Table 2. The calculated A values for various NEA materials.

Material	$A_{1.0-1.3}$	$A_{1.3-1.7}$	$A_{1.7-2.5}$	$A_{2.5-4.0}$	$A_{4.0-6.0}$
Si	1.144×10^{-2} Å·(eV)$^{-1.506}$	7.384×10^{-3} Å·(eV)$^{-1.562}$	4.849×10^{-3} Å·(eV)$^{-1.614}$	3.18×10^{-3} Å·(eV)$^{-1.664}$	2.313×10^{-3} Å·(eV)$^{-1.70}$
GaAs	1.109×10^{-1} Å·(eV)$^{-1.1875}$	3.6×10^{-2} Å·(eV)$^{-1.329}$	1.37×10^{-2} Å·(eV)$^{-1.447}$	5.865×10^{-3} Å·(eV)$^{-1.547}$	3.81×10^{-3} Å·(eV)$^{-1.6158}$
$Al_{0.1}Ga_{0.9}As$	1.04×10^{-1} Å·(eV)$^{-1.196}$	3.519×10^{-2} Å·(eV)$^{-1.336}$	1.386×10^{-2} Å·(eV)$^{-1.45}$	5.935×10^{-3} Å·(eV)$^{-1.55}$	3.242×10^{-3} Å·(eV)$^{-1.618}$
$Al_{0.2}Ga_{0.8}As$	1.02×10^{-1} Å·(eV)$^{-1.205}$	3.446×10^{-2} Å·(eV)$^{-1.3415}$	1.353×10^{-2} Å·(eV)$^{-1.456}$	6.1×10^{-3} Å·(eV)$^{-1.55}$	3.27×10^{-3} Å·(eV)$^{-1.62}$
$Al_{0.3}Ga_{0.7}As$	9.64×10^{-2} Å·(eV)$^{-1.215}$	3.324×10^{-2} Å·(eV)$^{-1.349}$	1.343×10^{-2} Å·(eV)$^{-1.46}$	6.0×10^{-3} Å·(eV)$^{-1.555}$	3.307×10^{-3} Å·(eV)$^{-1.622}$

Table 3. Further calculated A values for various NEA materials.

Material	$A_{6.0-10.0}$	$A_{10.0-15.0}$	$A_{15.0-20.0}$	$A_{20.0-30.0}$	$A_{20.0-60.0}$
Si	1.817×10^{-3} Å·(eV)$^{-1.726}$	1.586×10^{-3} Å·(eV)$^{-1.74}$	1.54×10^{-3} Å·(eV)$^{-1.743}$	1.572×10^{-3} Å·(eV)$^{-1.741}$	
GaAs	2.0887×10^{-3} Å·(eV)$^{-1.661}$	1.583×10^{-3} Å·(eV)$^{-1.6894}$	1.423×10^{-3} Å·(eV)$^{-1.7}$		1.608×10^{-3} Å·(eV)$^{-1.689}$
$Al_{0.1}Ga_{0.9}As$	2.1525×10^{-3} Å·(eV)$^{-1.662}$	1.623×10^{-3} Å·(eV)$^{-1.691}$	1.451×10^{-3} Å·(eV)$^{-1.702}$		1.6566×10^{-3} Å·(eV)$^{-1.69}$
$Al_{0.2}Ga_{0.8}As$	2.17×10^{-3} Å·(eV)$^{-1.664}$	1.654×10^{-3} Å·(eV)$^{-1.692}$	1.479×10^{-3} Å·(eV)$^{-1.703}$		1.708×10^{-3} Å·(eV)$^{-1.69}$
$Al_{0.3}Ga_{0.7}As$	2.2×10^{-3} Å·(eV)$^{-1.666}$	1.74×10^{-3} Å·(eV)$^{-1.69}$	1.527×10^{-3} Å·(eV)$^{-1.703}$		1.72×10^{-3} Å·(eV)$^{-1.692}$

2.2. New SEE model for δ

When primary electrons impact materials perpendicularly, $[100(1-\eta)]\%$ primary electrons are scattered through small angles and come to rest by gradual deceleration, and $(100\eta)\%$ primary electrons are scattered through large angles and become backscattered electrons with energy > 50 eV.[31] The backscattering coefficient η is defined as the ratio of the number of backscattered electrons to that of primary electrons; for some experimental η,[8,11,13,33] η can be expressed as[8,11,32]

$$\eta = \begin{cases} r(Z), & E_{po} \geq 10.0 \text{ keV}, \\ r(Z)(E_{po}/10.0 \text{ keV})^{1.2}, & 1.0 \text{ keV} \leq E_{po} \leq 10.0 \text{ keV}, \end{cases} \tag{5}$$

where $r(Z)$ is η at $E_{po} \geq 10.0$ keV and $r(Z)$ can be approximately written as[33]

$$r(Z) = -0.0254 + 0.016Z - 1.86 \times 10^{-4}Z^2 + 8.3 \times 10^{-7}Z^3. \tag{6}$$

When primary electrons at $E_{po} \geq 1.0$ keV impact insulators and NEASs with an energy of 1.0 keV $\leq E_{pom} \leq 10.0$ keV, the yield per primary electron can be expressed as[8]

$$\delta_p = \frac{K(E_{po}, \rho, Z)\lambda B E_{po}}{\varepsilon R}(1 - e^{-R/\lambda}). \tag{7}$$

The value of the parameter $K(E_{po}, \rho, Z)$ depends on E_{po} and E_{pom}, and $K(E_{po}, \rho, Z)$ of insulators and NEASs with 1.0 keV $\leq E_{pom} \leq 10.0$ keV can be expressed as[8]

$$K(E_{po}, \rho, Z) = \begin{cases} [n(E_{po})]^{-1}, & E_{po} \geq 10.0 E_{pom}, \\ [n(E_{po})]^{-Q}, & 1.0 \text{ keV} \leq E_{po} < 10.0 E_{pom}, \end{cases} \tag{8}$$

where $n(E_{po})$ denotes n at E_{po}. The parameter Q in Eq. (8) can be expressed as

$$Q=\frac{0.55[3.051(E_{\rm po}/E_{\rm pom})^3-17.21(E_{\rm po}/E_{\rm pom})^2+150.3(E_{\rm po}/E_{\rm pom})+45.38]}{(E_{\rm po}/E_{\rm pom})^3-4.215(E_{\rm po}/E_{\rm pom})^2+90.88(E_{\rm po}/E_{\rm pom})+95.01}. \tag{9}$$

The energy band structures and surface states of a NEAS with 1.0 keV $\leq E_{\rm pom} \leq$ 10.0 keV are very similar to those of a NEASLD, and $E_{\rm pom}$ of both a NEAS with 1.0 keV $\leq E_{\rm pom} \leq$ 10.0 keV and of a NEASLD are high. Thus, the characteristics of SEE of a NEASLD and those of a NEAS with 1.0 keV $\leq E_{\rm pom} \leq$ 10.0 keV are similar. Therefore, equations (8) and (9) are fairly suitable for a NEASLD.

The average energy required to produce an internal secondary electron in semiconductors or insulators, ε, can be written as[34]

$$\varepsilon=\frac{E_{\rm g}[\chi+E_{\rm g}+30(2/E_{\rm g})^{0.2}]}{\chi+30(2/E_{\rm g})^{0.2}}\ln\left\{\frac{[\chi+E_{\rm g}+(2/E_{\rm g})^{0.2}]}{E_{\rm g}}\right\}, \tag{10}$$

where χ and $E_{\rm g}$ are the original electron affinity and the width of the forbidden band, respectively. The χ of a NEAS can be treated as 0 in Eq. (10).[11]

Based on Eq. (7) and the fact that $[100(1-\eta)]\%$ primary electrons enter materials and come to rest by gradual deceleration,[31] the yield due to the primary electrons which enter a NEASLD and come to rest can be expressed as

$$\delta_{\rm prest}=(1-\eta)\delta_{\rm p}. \tag{11}$$

According to Eq. (1) and the definitions of L and R, L can be obtained by deriving Eq. (1) with respect to $E_{{\rm p}x}$. The obtained L can be expressed as

$$L={\rm d}E_{{\rm p}x}/{\rm d}x=-\left[nAE_{{\rm p}x}^{(n-1)}\right]^{-1}, \tag{12}$$

where $E_{{\rm p}x}$ is the primary energy at a given x, x being the distance from the incident surface to the point reached by the primary electrons or backscattered electrons.

From Eqs. (1) and (12) and the fact that most of the backscattered electrons lose hardly any energy during the course of moving in the material, the average energy loss of backscattered electrons per unit path length can be approximately expressed as[31]

$${\rm d}E_{{\rm b}x}/{\rm d}x=-\left[nAE_{\rm po}^{(n-1)}\right]^{-1}=-E_{\rm po}/(nR), \tag{13}$$

where $E_{{\rm b}x}$ is the energy of the backscattered electrons at a given x.

Therefore, $(100\eta)\%$ primary electrons enter the material, then diffuse back from the material at different x and become backscattered electrons.[35,36] Thus, from the two stages of movement of the $(100\eta)\%$ primary electrons, it is known that they are still treated as primary electrons during the first stage of their entry into the material and that they are treated as backscattered electrons during the second stage of their diffusing back from the material. Therefore, the number of backscattered electrons is equal to that of the $(100\eta)\%$ primary electrons. Based on Kanter's theory,[37,38] the backscattered electrons that diffuse from the interior of a material obey a cosine distribution. Thus, from these characteristics and the three processes of SEE and the fact that $(100\eta)\%$ primary electrons and most of the backscattered electrons lose hardly any energy during the course of moving in a material,[31,35,36] it is known that the ratio of the number of internal secondary electrons excited by backscattered electrons to that of internal secondary electrons excited by the $(100\eta)\%$ primary electrons is equal to 2.0.[37,38] In other words, the total number of internal secondary electrons excited by backscattered electrons and the $(100\eta)\%$ primary electrons equals three times the number of internal secondary electrons excited by the $(100\eta)\%$ primary electrons. Therefore, from these characteristics and the three processes of SEE, Eq. (13) and the investigations of backscattered electrons,[35,36] it can be assumed that the yield due to backscattered electrons and the $(100\eta)\%$ primary electrons can be expressed as follows:

$$\begin{aligned}\delta_{b+100\eta\%} &= 3\eta\int_0^{2\lambda_{\rm b}(Z,E_{\rm po})}\frac{{\rm d}E_{{\rm b}x}}{{\rm d}x}\frac{B}{\varepsilon}{\rm e}^{-x/\lambda}\,{\rm d}x\\ &= 3\eta\int_0^{2\lambda_{\rm b}(Z,E_{\rm po})}-\frac{E_{\rm po}B}{nR\varepsilon}{\rm e}^{-x/\lambda}\,{\rm d}x\\ &= \frac{3\eta E_{\rm po}B\lambda}{nR\varepsilon}\left(1-{\rm e}^{-2\lambda_{\rm b}(Z,E_{\rm po})/\lambda}\right),\end{aligned} \tag{14}$$

where x denotes the distance from the incident surface to the point where internal secondary electrons are excited and $\lambda_{\rm b}(Z,E_{\rm po})$ in Eq. (14) can be expressed as[36]

$$\lambda_{\rm b}(Z,E_{\rm po})=[5.29\times10^2(E_{\rm po})^{1.7}]/[Z({\rm keV})^{1.7}]. \tag{15}$$

In this new SEE model, δ, which comprises $\delta_{\rm prest}$ and $\delta_{b+100\eta\%}$, is written as

$$\delta=\delta_{b+100\eta\%}+\delta_{\rm prest}. \tag{16}$$

Thus, according to Eqs. (5), (7), (11), and (14), the formulae for $\delta_{1.0-10.0}$ and $\delta_{10.0-100.0}$ of a NEASLD can be written as follows:

$$\begin{aligned}\delta_{1.0-10.0}=&\left\{\left[1-r(Z)\left(\frac{E_{\rm po}}{10.0\,{\rm keV}}\right)^{1.2}\right]K(E_{\rm po},\rho,Z)\right.\\ &\times\left(1-{\rm e}^{-\frac{R_{1.0-10.0}}{\lambda}}\right)+\left(\frac{E_{\rm po}}{10.0\,{\rm keV}}\right)^{1.2}\frac{3r(Z)}{n_{1.0-10.0}}\\ &\left.\times\left(1-{\rm e}^{-\frac{2\lambda_{\rm b}(Z,E_{\rm po})}{\lambda}}\right)\right\}\frac{\lambda BE_{\rm po}}{\varepsilon R_{1.0-10.0}},\end{aligned} \tag{17}$$

$$\delta_{10.0-100.0}=\left\{[1-r(Z)]K(E_{\rm po},\rho,Z)\left(1-{\rm e}^{-\frac{R_{10.0-100.0}}{\lambda}}\right)+\frac{3r(Z)}{n_{10.0-100.0}}\left(1-{\rm e}^{-\frac{2\lambda_{\rm b}(Z,E_{\rm po})}{\lambda}}\right)\right\}\times\frac{E_{\rm po}\lambda B}{\varepsilon R_{10.0-100.0}}. \tag{18}$$

The relation between $R(E_{\rm pom})$, m, and λ can be written as[39]

$$\lambda=R(E_{\rm pom})/m. \tag{19}$$

From Eq. (19) and the fact that $E_{\rm pom}$ of a NEASLD is $>$ 20.0 keV,[14–17] $\delta_{\rm m}$ of a NEASLD can be written as

$$\delta_{\rm m}=\left[(1-r(Z))K(E_{\rm pom},\rho,Z)(1-{\rm e}^{-m})+\frac{3r(Z)}{n(E_{\rm pom})}\left(1-{\rm e}^{-\frac{2\lambda_{\rm b}(Z,E_{\rm pom})}{\lambda}}\right)\right]\frac{E_{\rm pom}\lambda B}{\varepsilon R(E_{\rm pom})}, \tag{20}$$

where $K(E_{\rm pom},\rho,Z)$[8] is equal to $[n(E_{\rm pom})]^{-0.55}$, $n(E_{\rm pom})$ is n at $E_{\rm pom}$ and $\lambda_{\rm b}(Z,E_{\rm pom})$ is $\lambda_{\rm b}(Z,E_{\rm po})$ at $E_{\rm pom}$.

Based on Eqs. (17) and (20), the new SEE model for $\delta_{1.0-10.0}$ of a NEASLD can also be written as

$$\delta_{1.0-10.0}=\frac{\left[1-r(Z)\left(\frac{E_{\rm po}}{10.0\ {\rm keV}}\right)^{1.2}\right]K(E_{\rm po},\rho,Z)\left(1-{\rm e}^{-\frac{R_{1.0-10.0}}{\lambda}}\right)+\left(\frac{E_{\rm po}}{10.0\ {\rm keV}}\right)^{1.2}\frac{3r(Z)}{n_{1.0-10.0}}\left(1-{\rm e}^{-\frac{2\lambda_{\rm b}(Z,E_{\rm po})}{\lambda}}\right)}{\left[(1-r(Z))K(E_{\rm pom},\rho,Z)(1-{\rm e}^{-m})+\frac{3r(Z)}{n(E_{\rm pom})}\left(1-{\rm e}^{-\frac{2\lambda_{\rm b}(Z,E_{\rm pom})}{\lambda}}\right)\right]\frac{E_{\rm pom}R_{1.0-10.0}}{\delta_{\rm m}E_{\rm po}R(E_{\rm pom})}}. \tag{21}$$

From Eqs. (18) and (20), the new SEE model for $\delta_{10.0-100.0}$ of a NEASLD can also be written as

$$\delta_{10.0-100.0}=\frac{[1-r(Z)]K(E_{\rm po},\rho,Z)\left(1-{\rm e}^{-\frac{R_{10.0-100.0}}{\lambda}}\right)+\frac{3r(Z)}{n_{10.0-100.0}}\left(1-{\rm e}^{-\frac{2\lambda_{\rm b}(Z,E_{\rm po})}{\lambda}}\right)}{\left[(1-r(Z))K(E_{\rm pom},\rho,Z)(1-{\rm e}^{-m})+\frac{3r(Z)}{n(E_{\rm pom})}\left(1-{\rm e}^{-\frac{2\lambda_{\rm b}(Z,E_{\rm pom})}{\lambda}}\right)\right]\frac{E_{\rm pom}R_{10.0-100.0}}{\delta_{\rm m}E_{\rm po}R(E_{\rm pom})}}. \tag{22}$$

2.3. Old SEE model for δ

According to the methods for deducing the formula for $\delta_{1.0-10.0}$ of a NEAS in our previous studies[8,11] and the relation $\delta_{1.0-10.0}=[1+2r(Z)(E_{\rm po}/10.0\ {\rm keV})^{1.2}]\delta_{\rm p}$[8,11,32] deduced in the old SEE model, the formula for $\delta_{1.0-10.0}$ of a NEASLD can be expressed as[8,11]

$$\delta_{1.0-10.0}=\frac{\left[1+2r(Z)(E_{\rm po}/10.0\ {\rm keV})^{1.2}\right]K(E_{\rm po},\rho,Z)B\lambda E_{\rm po}}{\varepsilon R_{1.0-10.0}}\times(1-{\rm e}^{-R_{1.0-10.0}/\lambda}). \tag{23}$$

From the methods for deducing the formula for $\delta_{10.0-100.0}$ of NEAS in our previous studies[8,11] and the relation $\delta_{10.0-100.0}=[1+2r(Z)]\delta_{\rm p}$[8,11,33] deduced in the old SEE model, the formula for $\delta_{10.0-100.0}$ of a NEASLD can be written as[8,11]

$$\delta_{10.0-100.0}=\frac{[1+2r(Z)]K(E_{\rm po},\rho,Z)\lambda BE_{\rm po}}{\varepsilon R_{10.0-100.0}}\times(1-{\rm e}^{-R_{10.0-100.0}/\lambda}). \tag{24}$$

Based on the fact that $E_{\rm pom}$ of a NEASLD is >20.0 keV[14–17] and Eqs. (19) and (24), $\delta_{\rm m}$ of a NEASLD can be written as

$$\delta_{\rm m}=\frac{(1+2r(Z))K(E_{\rm pom},\rho,Z)BE_{\rm pom}}{\varepsilon m}(1-{\rm e}^{-m}). \tag{25}$$

The formula for $\delta_{1.0-10.0}$ of a NEASLD can be obtained by combining Eqs. (19), (23), and (25). Thus, the old SEE model for $\delta_{1.0-10.0}$ of a NEASLD can also be written as

$$\delta_{1.0-10.0}=\frac{\left[1+2r(Z)(E_{\rm po}/10.0\ {\rm keV})^{1.2}\right]K(E_{\rm po},\rho,Z)E_{\rm po}R(E_{\rm pom})(1-{\rm e}^{-R_{1.0-10.0}/\lambda})\delta_{\rm m}}{(1+2r(Z))K(E_{\rm pom},\rho,Z)R_{1.0-10.0}E_{\rm pom}(1-{\rm e}^{-m})}. \tag{26}$$

The formula for $\delta_{10.0-100.0}$ of a NEASLD can be obtained by combining Eqs. (19), (24), and (25). Thus, the old SEE model for $\delta_{10.0-100.0}$ of a NEASLD can also be written as

$$\delta_{10.0-100.0}=\frac{K(E_{\rm po},\rho,Z)E_{\rm po}R(E_{\rm pom})(1-{\rm e}^{-R_{10.0-100.0}/\lambda})\delta_{\rm m}}{K(E_{\rm pom},\rho,Z)R_{10.0-100.0}E_{\rm pom}(1-{\rm e}^{-m})}. \tag{27}$$

Note that Eqs. (26) and (27) are deduced here on the basis of the old SEE model and the fact that $E_{\rm pom}$ of a NEASLD is >20.0 keV.

2.4. Relations among parameters

According to Eqs. (8) and (9), given that $E_{\rm pom}$ of a NEASLD is >20.0 keV and that n at $E_{\rm po}\geq 10.0$ keV changes extremely slowly with $E_{\rm po}$,[8] we know that $K(E_{\rm po},\rho,Z)$ at $H\geq E_{\rm po}\geq h$ keV (with, in this section, $h\geq 10.0$ keV)

for a NEASLD decreases extremely slowly with increasing E_{po} and can be approximately treated as a constant, $K(E_{po}, \rho, Z)_{ChH}$. From Eqs. (2), (6), (8), (9), (15), and (18), the fact that λ of a NEASLD is $> 1.0 \times 10^4$ Å,[14–17] the parameter R calculated in Subsection 2.1 and the fact that Z of a NEASLD is in the range (14, 32), we know that $\{(3r(Z)/n_{10.0-100.0})[1 - \exp(-2\lambda_b(Z,E_{po})/\lambda)]\}$ of Eq. (18) is much less than $\{[1 - r(Z)]K(E_{po},\rho,Z)[1 - \exp(-R_{10.0-100.0}/\lambda)]\}$. Thus, in an approximation, $\{(3r(Z)/n_{10.0-100.0})[1-\exp(-2\lambda_b(Z,E_{po})/\lambda)]\}$ can be omitted. Based on Eqs. (6) and (15), the fact that λ of a NEASLD is $> 1.0 \times 10^4$ Å,[14–17] that Z of NEASLD is in the range (14, 32) and the $n_{10.0-100.0}$ calculated in Subsection 2.1, we know that $\{(3r(Z)/n_{10.0-100.0})[1 - \exp(-2\lambda_b(Z,E_{po})/\lambda)]\}$ increases with E_{po}. Thus, the approximation that $\{(3r(Z)/n_{10.0-100.0})[1-\exp(-2\lambda_b(Z,E_{po})/\lambda)]\}$ of Eq. (18) can be omitted can partly compensate for the approximation that $K(E_{po}, \rho, Z)_{h-H}$ slowly decreasing with increasing E_{po} is treated as a constant. Therefore, from Eq. (18) and the above two approximations, δ_{h-H} of a NEASLD can be approximately expressed as

$$\delta_{h-H} = K(Z,h,H)(1-r(Z))K(E_{po},\rho,Z)_{ChH} \times \left(1 - e^{-\frac{R_{h-H}}{\lambda}}\right)\frac{E_{po}\lambda B}{\varepsilon R_{h-H}}. \quad (28)$$

Because $\{(3r(Z)/n_{10.0-100.0})[1 - \exp(-2\lambda_b(Z,E_{po})/\lambda)]\}$ in Eq. (18) is omitted in the course of obtaining Eq. (28), for a given NEASLD the parameter $K(Z,h,H)$ of Eq. (28) is a constant a little larger than 1.

Therefore, since λ, B, and ε are independent of E_{po} [39–41] and from Eqs. (2), (6), and (28), the ratio of δ_H to δ_h relative to a NEASLD can be expressed as

$$\delta_H/\delta_h = \left[(h/H)^{(n-1)}\left(1 - e^{-R_H/\lambda}\right)\right] / \left(1 - e^{-R_h/\lambda}\right). \quad (29)$$

From Eqs. (2), (6), and (28), the fact that λ, B, and ε are independent of E_{po} [39–41] and that $K(E_{po}, \rho, Z)$ at $H \geq E_{po} \geq h$ keV of a NEASLD can be approximated as a constant $K(E_{po}, \rho, Z)_{ChH}$, we can derive Eq. (28) with respect to E_{po} and obtain the relationships among parameters of a NEASLD

$$\frac{d\delta_{h-H}}{dE_{po}} = \frac{(n-1)K(Z,h,H)(1-r(Z))K(E_{po},\rho,Z)_{ChH}\lambda B}{\varepsilon R_{h-H}} \times \left[e^{-R_{h-H}/\lambda} + \frac{n}{\lambda(n-1)}R_{h-H}e^{-R_{h-H}/\lambda} - 1\right]. \quad (30)$$

Based on Eq. (30), the fact that h and H are in the same E_{po} range, that the n of Eq. (30) is n_{h-H} (i.e., n_{h-H} of Eq. (30) is a constant) and the relations among δ_m, E_{pom}, $n(E_{pom})$ and $R(E_{pom})$,[39,42] we know that in the case that δ_{h-H} reaches δ_m, Eq. (30), R_{h-H} and n of Eq. (30) become 0, $R(E_{pom})$ and $n(E_{pom})$, respectively. Thus, from Eq. (30), the facts that both $n(E_{pom})$ and $K(Z, h, H)$ are > 1.0 and that both $r(Z)$ and $K(E_{po}, \rho, Z)_{ChH}$ are positive and < 1.0, when δ_{h-H} of a NEASLD reaches δ_m the relationships among $R(E_{pom})$, $n(E_{pom})$, and λ of NEASLD can be obtained and expressed as

$$e^{-R(E_{pom})/\lambda} + \left[n(E_{pom})/(n(E_{pom})-1)\right] \times \left[R(E_{pom})/\lambda\right] e^{-R(E_{pom})/\lambda} - 1 = 0. \quad (31)$$

According to Eqs. (19) and (31), we obtain

$$1 + \left[n(E_{pom})/(n(E_{pom})-1)\right] m = e^m. \quad (32)$$

From Eq. (29), the facts that h and H are in the same E_{po} range, that the n of Eq. (29) is n_{h-H} (i.e., n_{h-H} of Eq. (29) is a constant) and the relations among δ_m, E_{pom}, $n(E_{pom})$, and $R(E_{pom})$,[39–42] we know that when we take δ_H in Eq. (29) to be δ_m, the H, n, and R_H of Eq. (29) become E_{pom}, $n(E_{pom})$, and $R(E_{pom})$, respectively. Thus, from Eqs. (19) and (29), if we take δ_H of Eq. (29) to be δ_m the formula for δ_m from a NEASLD can be obtained and written as

$$\delta_m = \frac{\delta_h(h/E_{pom})^{(n(E_{pom})-1)}(1 - e^{-R(E_{pom})/\lambda})}{1 - e^{-R_h/\lambda}} = \frac{\delta_h(h/E_{pom})^{(n(E_{pom})-1)}(1 - e^{-m})}{1 - e^{-R_h/\lambda}}. \quad (33)$$

2.5. Calculation of the parameters of a NEASLD

We may obtain an undesirable λ if we use an unsuitable experimental $\delta_{10.0-20.0}$ to obtain λ. In order to obtain a desirable λ, we should choose a suitable experimental $\delta_{10.0-20.0}$ by following three steps (this method of obtaining λ is called the calculating method). First, we should choose an experimental $\delta_{10.0-20.0}$ that lies on the fitting curves of δ–E_{po} in the original literature as a suitable experimental δ.[14–17] Second, there is an approximation that $K(E_{po}, \rho, Z)$ at $H \geq E_{po} \geq h$ keV of a NEASLD is treated as a constant in deducing Eq. (29). However, $K(E_{po}, \rho, Z)$ decreases slowly with increasing E_{po}. Thus, we should use different pairs of the nearest two experimental δ values to obtain λ. Which two experimental δ should be chosen as a pair of two near experimental δ values? For example, among the chosen experimental $\delta_{10.0}$, $\delta_{12.0}$ and $\delta_{14.0}$ lying on the fitting curves of δ–E_{po} [15] of a NEA GaAs with $\delta_{18.0} = 510$, and $\delta_{20.0} = 528.57$, experimental $\delta_{10.0}$ and $\delta_{12.0}$ values can be chosen as one pair of two experimental δ, and experimental $\delta_{12.0}$ and $\delta_{14.0}$ values can be chosen as another; however, experimental $\delta_{10.0}$ and $\delta_{14.0}$ values cannot be chosen (we have chosen some experimental δ of eight NEASLDs shown in Table 4[14–17] as suitable experimental $\delta_{10.0-20.0}$ values using the above two steps). Third, we use Eq. (29) and different pairs of nearest experimental $\delta_{10.0-20.0}$ values to obtain a desirable λ. This step is described in detail in the following paragraphs.

Table 4. The Z values and chosen suitable experimental $\delta_{10.0-20.0}$ for various NEASLDs.[14–17]

NEASLD	$\delta_{10.0}$	$\delta_{12.0}$	$\delta_{14.0}$	$\delta_{16.0}$	$\delta_{18.0}$	$\delta_{20.0}$	Z
GaAs with $\delta_{18.0}=510$ and $\delta_{20.0}=528.57$[15]	287.93	340	389.63				32
Si[14]	661	745.8	830.5	874.6	922	950	14
GaAs with $\delta_{16.0}=441$ and $\delta_{18.0}=472$[16]	309.36	362.85					32
GaAs with $\delta_{18.0}=400$ and $\delta_{20.0}=404.7$[17]		340.8	366.7	389	400	404.7	32
GaAs with $\delta_{18.0}=143.74$ and $\delta_{20.0}=145.43$[17]		124.14	134	139.4	143.74	145.43	32
$Al_{0.1}Ga_{0.9}As$[16]			350	392			31.1
$Al_{0.2}Ga_{0.8}As$[16]			279.1	320	359		30.2
$Al_{0.3}Ga_{0.7}As$[16]					122.73	132.98	29.3

Table 5. The obtained parameters for various NEASLDs.

NEASLD	m	E_{pom} (eV)	$n(E_{pom})$	R (E_{pom}) (10^4 Å)	$K(E_{pom},\rho,Z)$	λ (10^4 Å)	δ_m
Si	1.52	25781.8	1.741	7.522	0.73716	4.9485	986.2
GaAs with $\delta_{16.0}=441$ and $\delta_{18.0}=472$	1.588	43800	1.689	11.116	0.7496	7.0	722.14
GaAs with $\delta_{18.0}=400$ and $\delta_{20.0}=404.7$	1.588	20868	1.689	3.176	0.7496	2.0	407.9
GaAs with $\delta_{18.0}=143.74$ and $\delta_{20.0}=145.43$	1.588	20868	1.689	3.176	0.7496	2.0	146.45
$Al_{0.1}Ga_{0.9}As$	1.587	52800	1.69	15.87	0.7493	10.0	726.41
$Al_{0.2}Ga_{0.8}As$	1.587	51860	1.69	15.87	0.7493	10.0	656.11
$Al_{0.3}Ga_{0.7}As$	1.584	50900	1.692	15.84	0.7488	10.0	201.02

According to Eq. (2) and the R parameters calculated in Subsection 2.1, the formulae for $R_{10.0-15.0}$, $R_{15.0-20.0}$, and $R_{20.0-60.0}$ in GaAs can be expressed as follows:

$$R_{10.0-15.0}=1.583\times10^{-3}(E_{po})^{1.6894}\ (\text{eV})^{-1.6894}\ \text{Å}, \quad (34)$$

$$R_{15.0-20.0}=1.423\times10^{-3}(E_{po})^{1.7}\ (\text{eV})^{-1.7}\ \text{Å}, \quad (35)$$

$$R_{20.0-60.0}=1.608\times10^{-3}(E_{po})^{1.689}\ (\text{eV})^{-1.689}\ \text{Å}. \quad (36)$$

Based on $n_{10.0-15.0}=1.6894$, experimental values of $\delta_{10.0}=287.93$ and $\delta_{12.0}=340$[15] for NEA GaAs with $\delta_{18.0}=510$, $\delta_{20.0}=528.57$ and a large λ, we take h, H, and $n_{10.0-15.0}$ to be 10.0 keV, 12.0 keV, and 1.6894, respectively. Thus, $\lambda=1.0\times10^5$ Å can be obtained from the adopted values of h, H and $n_{10.0-15.0}$, the experimental values $\delta_{10.0}=287.93$ and $\delta_{12.0}=340$ and Eqs. (29) and (34). From $n_{10.0-15.0}=1.6894$, the experimental values $\delta_{12.0}=340$ and $\delta_{14.0}=389.63$[15] for NEA GaAs and Eqs. (29) and (34), $\lambda=1.0\times10^5$ Å can be also obtained. Therefore, from the two obtained λ, the average $\lambda=1.0\times10^5$ Å of NEA GaAs with $\delta_{18.0}=510$, $\delta_{20.0}=528.57$ and large λ can be calculated.

According to the shape of the experimental curves of δ–E_{po},[15] we can estimate that the E_{pom} of NEA GaAs with $\delta_{18.0}=510$, $\delta_{20.0}=528.57$, and large λ lies in the energy range 20.0 keV–60.0 keV. Thus, from Eq. (36), it is known that $n_{20.0-60.0}$ equals 1.689, and $n(E_{pom})$ of NEA GaAs with $\delta_{18.0}=510$, $\delta_{20.0}=528.57$ and large λ equals 1.689. Therefore, from Eq. (32), an m value of 1.588 can be obtained for NEA GaAs. Then, from Eq. (19), the relationship between $R(E_{pom})$ and λ of NEA GaAs with $\delta_{18.0}=510$, $\delta_{20.0}=528.57$ and large λ can be expressed as

$$R(E_{pom})=1.588\lambda. \quad (37)$$

The $R(E_{pom})$ value calculated with Eq. (37) and $\lambda=1.0\times10^5$ Å equals 1.588×10^5 Å. Because the average λ equals 1.0×10^5 Å and using Eqs. (36) and (37), an E_{pom} value of 54114 eV can be calculated for NEA GaAs with $\delta_{18.0}=510$, $\delta_{20.0}=528.57$ and large λ. Thus, since $n(E_{pom})=1.689$ and from the relation $K(E_{pom},\rho,Z)=n(E_{pom})^{-0.55}$ we calculate $K(E_{pom},\rho,Z)=0.7496$. Because the experimental $\delta_{20.0}$ value is 528.57,[15] we take h to be 20.0 keV. Thus, from $h=20.0$ keV, $E_{pom}=54114$ eV, $\lambda=1.0\times10^5$ Å, $\delta_h=\delta_{20.0}=528.57$,[15] $n(E_{pom})=1.689$, $m=1.588$ and Eqs. (33), (35), and (37), we can calculate δ_m of NEA GaAs as 827.75. From $h=18.0$ keV, $E_{pom}=54114$ eV, $\lambda=1.0\times10^5$ Å, $\delta_h=\delta_{18.0}=510$,[15] $n(E_{pom})=1.689$, $m=1.588$ and Eqs. (33), (35), and (37), δ_m of NEA GaAs can also be calculated as 878.37. Therefore, from the two calculated δ_m, an average δ_m of NEA GaAs with $\delta_{18.0}=510$, $\delta_{20.0}=528.57$ and large λ can be calculated as $\delta_m=853.58$. The $\delta_{1.0-20.0}$ values for NEA GaAs are calculated using Eqs. (2), (6), (8), (9), (15), (21), and (22), $Z=32$, the E_{po}, parameters of R calculated in Subsection 2.1 and the obtained parameters m, E_{pom}, $n(E_{pom})$, $R(E_{pom})$, $K(E_{pom},\rho,Z)$, λ and δ_m. The calculated $\delta_{2.0-20.0}$ from NEA GaAs with $\delta_{18.0}=510$, $\delta_{20.0}=528.57$ and large λ shown in Fig. 1 are compared with the experimental values.

The parameters m, E_{pom}, $n(E_{pom})$, $R(E_{pom})$, $K(E_{pom},\rho,Z)$, λ and δ_m of eight NEASLDs shown in Table 5 were obtained by the above method. Finally, $\delta_{1.0-20.0}$ of the NEASLDs were calculated with Eqs. (2), (6), (8), (9), (15), (21), and (22), Z, E_{po}, the parameters of R calculated in Subsection 2.1 and the corresponding parameters shown in Table 5. The calculated $\delta_{1.0-20.0}$ for NEASLDs shown in Figs. 1–4 were compared with the corresponding experimental

values.

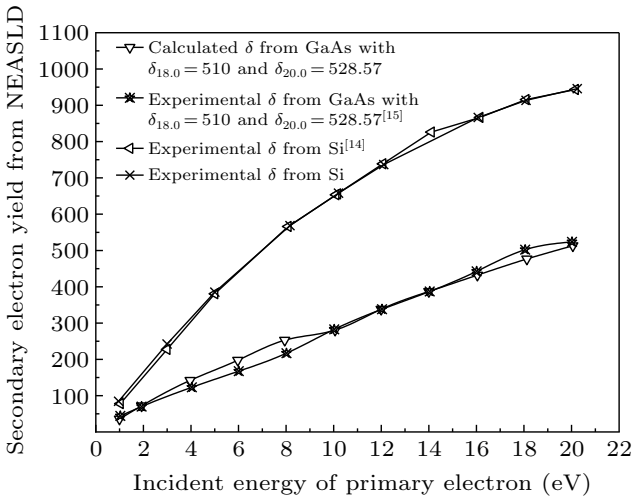


Fig. 1. Comparison between the experimental δ of NEA Si and NEA GaAs with $\delta_{18.0} = 510$ and $\delta_{20.0} = 528.57$ and the corresponding values calculated with Eqs. (21) and (22).

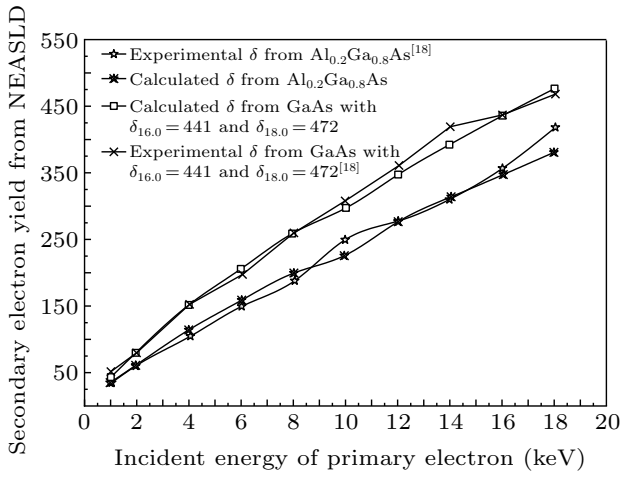


Fig. 2. Comparison between the experimental δ of NEA GaAs with $\delta_{16.0} = 441$ and $\delta_{18.0} = 472$ and NEA $Al_{0.2}Ga_{0.8}As$ and the corresponding values calculated with Eqs. (21) and (22).

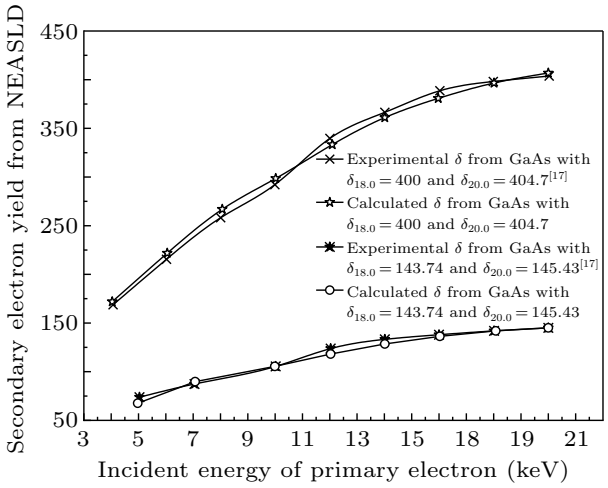


Fig. 3. Comparison between the experimental δ of NEA GaAs with $\delta_{18.0} = 400$ and $\delta_{20.0} = 404.7$ and NEA GaAs with $\delta_{18.0} = 143.74$ and $\delta_{20.0} = 145.43$ and the corresponding values calculated with Eqs. (21) and (22).

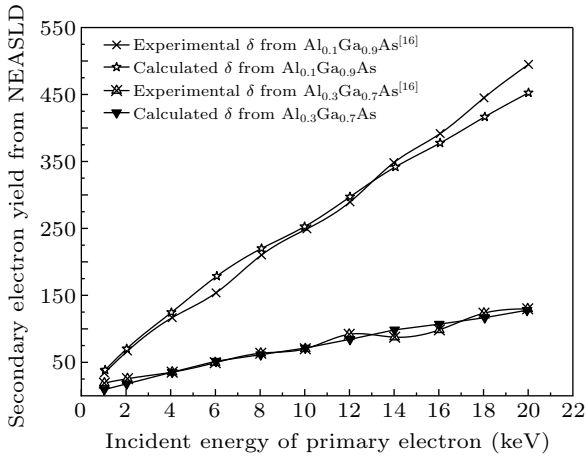


Fig. 4. Comparison between the experimental δ of NEA $Al_{0.1}Ga_{0.9}As$ and NEA $Al_{0.3}Ga_{0.7}As$ and the corresponding values calculated with Eqs. (21) and (22).

During the course of obtaining the parameters m, $E_{\rm pom}$, $n(E_{\rm pom})$, $R(E_{\rm pom})$, $K(E_{\rm pom}, \rho, Z)$, λ, and $\delta_{\rm m}$ we found that the obtained λ is the most important factor in determining the agreement between $\delta_{1.0-20.0}$ of NEASLDs calculated here and the experimental values, and that the obtained λ is sensitive to the values of the nearest two chosen experimental δ. If the obtained λ is somewhat less than the desirable one, the $\delta_{2.0-8.0}$ calculated with Eqs. (21) and (22) and the obtained parameters m, $E_{\rm pom}$, $n(E_{\rm pom})$, $R(E_{\rm pom})$, $K(E_{\rm pom}, \rho, Z)$, λ, and $\delta_{\rm m}$ are somewhat larger than the corresponding experimental ones, and vice versa. If we cannot obtain a desirable λ by calculation, we can use a fitting method described in detail in the next paragraph to obtain a desirable λ.

First, according to the shape of the experimental curves of δ–$E_{\rm po}$, Eqs. (2), (6), (8), (9), (15), (21), and (22), Z and the calculated R parameters, we estimate the desirable value of λ by fitting. That is, we obtain the estimated λ by fitting. Second, we obtain the parameters m, $E_{\rm pom}$, $n(E_{\rm pom})$, $R(E_{\rm pom})$, $K(E_{\rm pom}, \rho, Z)$, and $\delta_{\rm m}$. From above methods of obtaining m, $E_{\rm pom}$, $n(E_{\rm pom})$, $R(E_{\rm pom})$, $K(E_{\rm pom}, \rho, Z)$, $\delta_{\rm m}$ of NEA GaAs with $\delta_{18.0} = 510$ and $\delta_{20.0} = 528.57$, we know that if the estimated λ and calculated R parameters are given, the parameters m, $E_{\rm pom}$, $n(E_{\rm pom})$, $R(E_{\rm pom})$, $K(E_{\rm pom}, \rho, Z)$, and $\delta_{\rm m}$ can be obtained from the ESTAR program, experimental $\delta_{10.0-20.0}$ and Eqs. (8), (9), (19), (32), and (33). Third, the δ from NEASLDs are calculated with Eqs. (2), (6), (8), (9), (15), (21), and (22), Z, calculated R parameters, estimated λ and the obtained parameters. If these calculated δ are in good agreement with experimental ones the estimated λ is a desirable one, otherwise the estimated λ is an undesirable one. Ordinarily, the above steps are repeated many times; in the end we can obtain a desirable λ.

3. SEE and photoemission

The mean escape depth of hot electrons $\lambda_{\rm hot}$ of a NEASLP is of the order of 100 Å,[43] hot electrons in NEASLPs become

thermalized electrons after propagating about 100 Å,[26,43] and the mean escape depth of thermalized electrons $\lambda_{\rm th}$ of a NEASLP is of the order of 10^4 Å.[14–17,43] Thus, most of the excited electrons (including hot electrons and thermalized electrons) in a NEASLP which can become photoelectrons are thermalized electrons. Therefore, we can conclude that the value of $\lambda_{\rm hot}$ has almost no influence on the value of $\lambda_{\rm ph}$ in a NEASLP, and that $\lambda_{\rm ph}$ of a NEASLP is approximately equal to its $\lambda_{\rm th}$. The reflection mode quantum efficiency $Y_{\rm R}(\lambda_{\rm wave})$ can be expressed as[16,44]

$$Y_{\rm R}(\lambda_{\rm wave}) = \frac{[(1-r(\lambda_{\rm wave}))B_{\rm ph}\alpha(\lambda_{\rm wave})\lambda_{\rm ph}]}{(1+\alpha(\lambda_{\rm wave})\lambda_{\rm ph})}, \tag{38}$$

where $\lambda_{\rm wave}$ is the wavelength of incident light, $r(\lambda_{\rm wave})$ is the $\lambda_{\rm wave}$-dependent reflection coefficient of incident light and $\alpha(\lambda_{\rm wave})$ is the $\lambda_{\rm wave}$-dependent optical absorption constant.

Beyond the threshold region of the spectral response curve of a NEASLP, $[\alpha(\lambda_{\rm wave})\lambda_{\rm ph}]$ is much larger than 1. Thus, in this region $Y_{\rm R}(\lambda_{\rm wave})$ of a NEASLP can be approximately expressed as[16,44,45]

$$Y_{\rm R}(\lambda_{\rm wave}) = [1-r(\lambda_{\rm wave})]B_{\rm ph}. \tag{39}$$

The γ range $[(h\gamma_0 + 0.15\ {\rm eV})/h,\ \gamma_{\text{h-flat}}]$ (i.e., $[(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h,\ \gamma_{\text{h-flat}}]$) of a NEASLP is beyond the threshold region of the spectral response curve.[16,22,45] Thus, equation (39) is suitable for a NEASLP in the range $[(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h,\ \gamma_{\text{h-flat}}]$. Therefore, from Eq. (39), the fact that $Y_{\rm R}(\lambda_{\rm wave})$ in the range $[(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h,\ \gamma_{\text{h-flat}}]$ of a NEASLP is a constant[16,45] and that $r(\lambda_{\rm wave})$ in the range $[(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h,\ \gamma_{\text{h-flat}}]$ is approximately constant,[16] it can be concluded that $B_{\rm phflat}$ is also a constant. Because $\lambda_{\rm phl}$ of a NEASLP is constant,[14,16,45] we can conclude that $\lambda_{\rm ph}$ of a NEASLP is equal to $\lambda_{\rm th}$ of a NEASLP and from the definitions of $\lambda_{\rm phl}$ and $\lambda_{\rm ph}$ we can state that $\lambda_{\rm th}$ at $\gamma > [(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h]$ $\lambda_{\rm thl}$ of a NEASLP is constant and equal to $\lambda_{\rm phl}$, and that $\lambda_{\rm thflat}$ of a NEASLP is constant, where $\lambda_{\rm thflat}$ is $\lambda_{\rm th}$ in the range $[(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h,\ \gamma_{\text{h-flat}}]$. Thus, because both $\lambda_{\rm th}$ and $B_{\rm ph}$ are proportional to the energy of thermalized electrons[46,47] and $\lambda_{\rm thflat}$ and $B_{\rm thflat}$ of a NEASLP are independent of γ in the range $[(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h,\ \gamma_{\text{h-flat}}]$, we conclude that thermalized electrons in a NEASLP produced by photons in the range $[(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h,\ \gamma_{\text{h-flat}}]$ have the same $f_{\rm th}$. That is, the $f_{\rm th}$ of a NEASLP excited by photons in the range $[(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h,\ \gamma_{\text{h-flat}}]$ is independent of $E_{\rm obtainp}$ when $E_{\rm obtainp}$ is in the range $[(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h,\ \gamma_{\text{h-flat}}]$ (note that $E_{\rm obtainp}$ equals $h\gamma$). Therefore, since $f_{\rm th}$ decides $\lambda_{\rm th}$[46,47] and $\lambda_{\rm thl}$ of a NEASLP is a constant, we assume that $f_{\rm th}$ at $\gamma > [(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h]$ of a NEASLP is independent of γ. That is, we assume that $f_{\rm th}$ at $\gamma > [(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h]$ of a NEASLP is independent of $E_{\rm obtainp}$ when $E_{\rm obtainp} > (h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})$.

Because λ of an insulator is of the order of 100 Å,[8,34,42] i.e., $\lambda_{\rm hot}$ of an insulator due to primary electrons is of the order of 100 Å, the hot electrons excited by primary electrons in an insulator mainly lose energy by electron–electron interaction as those in a NEASLD do, and χ of an insulator is very low or equal to 0.[48] Thus, $\lambda_{\rm hot}$ of a NEASLD due to primary electrons is also of the order of 100 Å. Therefore, since SEE and photoemission have a common transport mechanism[18,19] and hot electrons excited by photons in a NEASLP become thermalized after propagating for about 100 Å,[26,43] we know that hot electrons excited by primary electrons in a NEASLD also become thermalized after propagating for about 100 Å. Because $\lambda_{\rm th}$ in a NEASLD is also of the order of 10^4 Å[14–17] and the $\lambda_{\rm hot}$ of a NEASLD due to primary electrons is of the order of 100 Å, we know that most of the excited electrons in a NEASLD which can become secondary electrons are thermalized electrons. Thus, we can conclude that $\lambda_{\rm hot}$ of a NEASLD has hardly any influence on the value of λ, and that λ of a NEASLD is equals to its $\lambda_{\rm th}$ value. Note that for a given NEAS, a NEASLP is also a NEASLD.[14,16] $E_{\rm po}$ is much larger than $(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})$. Thus, from the excitation process of internal secondary electrons in semiconductors,[34] it is known that the energy of thermalized electrons obtained from primary electrons can also be greatrer than $(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})$. Therefore, from the assumption that $f_{\rm th}$ in a NEASLP is independent of $E_{\rm obtainp}$ when $E_{\rm obtainp} > (h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})$ (i.e., thermalized electrons produced by photons at $\gamma > [(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h]$ have the same $f_{\rm th}$) and that a NEASLP is also a NEASLD,[14,16] it can be stated that $f_{\rm th}$ in a NEASLD is the same as that in a NEASLP produced by photons with $h\gamma > (h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})$. Then, since $\lambda_{\rm thl}$ of a NEASLP is equal to its $\lambda_{\rm phl}$ and λ of a NEASLD equals its $\lambda_{\rm th}$, λ of a NEASLD equals $\lambda_{\rm phl}$ of a NEASLP.

Base on the calculated R values it is known that R at $E_{\rm po} > 10$ keV is of the order of micrometers. Thus, since $\lambda_{\rm hot}$ of a NEASLD due to primary electrons is of the order of 100 Å and λ of a NEASLD is of the order of micrometers,[14–17] we conclude that when the primary electrons at $E_{\rm po} > 10$ keV enter a NEASLD almost all the internal secondary electrons which can become secondary electrons are thermalized electrons, and that B at $E_{\rm po} > 10$ keV of a NEASLD is approximately equal to $B_{\rm seth}$, where $B_{\rm seth}$ is the probability that a thermalized electron escapes into the vacuum upon reaching the emission surface of the NEASLD. From the definition of $B_{\rm phflat}$, it seems that $B_{\rm phflat}$ is only the probability that a thermalized electron produced by photons with $h\gamma$ in the range $[(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J}),\ h\gamma_{\text{h-flat}}]$ escapes into the vacuum upon reaching the emission surface of the NEASLP. But based on the definition of $B_{\rm phflat}$ and the assumption that $f_{\rm th}$ at $\gamma > [(h\gamma_0 + 2.4\times 10^{-20}\ {\rm J})/h]$ of a NEASLP is independent of

E_{obtainp} in the case that $E_{\text{obtainp}} > (h\gamma_0 + 2.4 \times 10^{-20}\ \text{J})$, it is known that B_{phflat} is in fact the probability that a thermalized electron produced by photons with $h\gamma > (h\gamma_0 + 2.4 \times 10^{-20}\ \text{J})$ escapes into the vacuum upon reaching the emission surface of a NEASLP. Therefore, from the statement that f_{th} produced by photons with $h\gamma > (h\gamma_0 + 2.4 \times 10^{-20}\ \text{J})$ is the same as that produced by primary electrons and the fact that SEE and photoemission have common mechanisms of escape and transport,[18,19] we can state that B_{seth} equals B_{phflat}. Then, from the conclusion that B of a NEASLD at $E_{\text{po}} > 10$ keV approximately equals B_{seth}, the B at $E_{\text{po}} > 10$ keV of a NEASLD equals B_{phflat}.

The B_{phflat} of NEA GaAs with $\delta_{16.0} = 441$, $\delta_{18.0} = 472$ and large λ_{ph} is calculated from Eq. (39) and parameters in the range of $[(h\gamma_0 + 2.4 \times 10^{-20}\ \text{J})/h,\ \gamma_{\text{h-flat}}]$, $r(\lambda_{\text{wave}}) \approx 0.33$[49–51] and $Y_{\text{R}}(\lambda_{\text{wave}}) = 0.15625$;[16] the calculated $B_{\text{phflat}} = 0.233$ is shown in Table 6. B_{phflat} of NEA $Al_{0.2}Ga_{0.8}As$ is calculated from Eq. (39) and parameters in the range $[(h\gamma_0 + 2.4 \times 10^{-20}\ \text{J})/h,\ \gamma_{\text{h-flat}}]$, $r(\lambda_{\text{wave}}) \approx 0.33$[52,53] and $Y_{\text{R}}(\lambda_{\text{wave}}) = 0.1275$;[16] the calculated $B_{\text{phflat}} = 0.1932$ is also shown in Table 6. The average Z of $Al_{0.1}Ga_{0.9}As$, $Al_{0.2}Ga_{0.8}As$, and $Al_{0.3}Ga_{0.7}As$ are calculated from $Z = 31$ for Ga, $Z = 33$ for As, and $Z = 13$ for Al and the corresponding s, respectively. The calculated average Z of $Al_{0.1}Ga_{0.9}As$, $Al_{0.2}Ga_{0.8}As$, and $Al_{0.3}Ga_{0.7}As$ are 31.1, 30.2, and 29.3, respectively. The ε value for NEA GaAs calculated with Eq. (10), $E_{\text{g}} = 1.424$ eV and $\chi = 0$ is 4.79 eV. The ε values of NEA $Al_{0.1}Ga_{0.9}As$, $Al_{0.2}Ga_{0.8}As$, and $Al_{0.3}Ga_{0.7}As$ are calculated with Eq. (10), s, $\chi = 0$ and the relation for E_{g} of $Al_sGa_{(1-s)}As = 1.424\ \text{eV} + 1.247s$ eV,[54] respectively. The calculated ε of NEA $Al_{0.1}Ga_{0.9}As$, $Al_{0.2}Ga_{0.8}As$, and $Al_{0.3}Ga_{0.7}As$ are 5.0 eV, 5.245 eV, and 5.5 eV, respectively. B values at 20.0 keV $\geq E_{\text{po}} \geq$ 12.0 keV for the four NEASLDs are calculated from Eqs. (2), (6), (8), (9), (15), (18), Z, ε, E_{po}, experimental δ and parameters obtained in Subsections 2.1 and 2.5. These calculated B values are shown in Table 6. From Table 6, we can see that the average B of NEA GaAs with $\delta_{16.0} = 441$ and $\delta_{18.0} = 472$ and NEA $Al_{0.2}Ga_{0.8}As$ are approximately equal and correspond to B_{phflat}.

Table 6. Calculated B values at 20.0 keV $\geq E_{\text{po}} \geq$ 12.0 keV for various NEASs and calculated B_{ph} flat for NEA GaAs and $Al_{0.2}Ga_{0.8}As$.

NEAS	$B_{12.0}$	$B_{14.0}$	$B_{16.0}$	$B_{18.0}$	$B_{20.0}$	Average B	B_{phflat}
GaAs with $\delta_{16.0} = 441$ and $\delta_{18.0} = 472$	0.238	0.243	0.2314	0.226		0.2346	0.233
$Al_{0.1}Ga_{0.9}As$	0.194	0.2038	0.2052	0.2121	0.2174	0.2065	
$Al_{0.2}Ga_{0.8}As$	0.1916	0.188	0.1943	0.2074		0.1953	0.1932
$Al_{0.3}Ga_{0.7}As$	0.0662	0.0575	0.058	0.0643	0.0644	0.06208	

Thermalized electrons have an energy E which is less than several $K_{\text{B}}T$, where K_{B} is the Boltzmann constant, T is the temperature in kelvin and E is measured from the bottom of the conduction band of the semiconductor.[43] Thus, from the relation $h\gamma_0 = E_{\text{g}}$ of a NEASLP, the law of energy conservation and the conclusion that thermalized electrons of a NEASLP produced by photons in the range $[(h\gamma_0 + 2.4 \times 10^{-20}\ \text{J})/h,\ \gamma_{\text{h-flat}}]$ have the same f_{th}, we know that thermalized electrons in a NEASLP at room temperature have an energy $E < 2.4 \times 10^{-20}$ J [i.e., $5.77K_{\text{B}}T$; note that $K_{\text{B}}T = 0.026\ \text{eV} = 4.16 \times 10^{-21}\ \text{J}$ ($T = 300$ K)], and that the upper limit of energy of thermalized electrons in a NEASLP at room temperature is 2.4×10^{-20} J or 0.15 eV. From the transportation theories of thermalized electrons[46,47] we know that thermalized electrons with less energy have a shorter escape depth. Thus, from the law of energy conservation, the fact that the upper limit of the energy of thermalized electrons is 2.4×10^{-20} J and the relation $h\gamma_0 = E_{\text{g}}$ for a NEASLP, we know that the average energy of thermalized electrons produced by photons at $\gamma_0 < \gamma < [(h\gamma_0 + 2.4 \times 10^{-20}\ \text{J})/h]$ is less than that of thermalized electrons produced by photons at $\gamma > (h\gamma_0 + 2.4 \times 10^{-20}\ \text{J})/h$, and that λ_{phlow} is $< \lambda_{\text{phl}}$. Therefore, because λ of a NEASLD equals λ_{phl} of a NEASLP, we can conclude that λ of a NEASLD is $> \lambda_{\text{phlow}}$. Some authors[14,16,45] only presumed that λ of a NEASLD equals λ_{ph} of a NEASLP without analyzing the relation between λ of a NEASLD and λ_{ph} of a NEASLP in different γ ranges, and did not conclude that λ of a NEASLD is $> \lambda_{\text{phlow}}$. Thus, we have improved comprehension of the relation between λ of a NEASLD and λ_{ph} of a NEASLP.

4. Results and discussion

As shown in Figs. 1–4, the calculated δ of NEASLDs, apart from $\delta_{1.0}$ and $\delta_{2.0}$ of NEA $Al_{0.3}Ga_{0.7}As$, agree well with experimental values,[14–17] and the average value of calculated $\delta_{1.0}$ is a little less than that of the experimental $\delta_{1.0}$. The three factors may lead to these results. First, according to the shape of the empirical δ–E_{po} curve,[13] it is known that the real $\delta_{1.0}$ and $\delta_{2.0}$ of NEA $Al_{0.3}Ga_{0.7}As$ should be less than the experimental vales.[16] Thus, the fact that the experimental $\delta_{1.0}$ and $\delta_{2.0}$ of NEA $Al_{0.3}Ga_{0.7}As$ are greater than the actual values leads to some differences between the calculated $\delta_{1.0}$ and $\delta_{2.0}$ of NEA $Al_{0.3}Ga_{0.7}As$ and the experimental vales. Second, during the course of obtaining λ, E_{pom}, and δ_{m} in Subsection 2.5, it is known that some experimental errors in

$\delta_{10.0-20.0}$, which is used to obtain λ and δ_m, can lead to some differences between the real λ, E_{pom}, and δ_m and the experimental values. From the process of calculating δ, it is known that some differences between the real λ, E_{pom}, and δ_m and obtained values can lead to some differences between calculated δ and experimental values. Thus, the experimental errors in $\delta_{10.0-20.0}$ can lead to some differences between calculated δ and experimental ones. Third, the method for calculating δ at $E_{po} < 2$ keV presented here is approximate. From Section 3, it is known that in the case when primary electrons at $E_{po} > 10$ keV enter a NEASLD the internal secondary electrons which become secondary electrons are almost thermalized, and that B at $E_{po} > 10$ keV is approximately equal to B_{seth}. However, primary electrons at $E_{po} < 2$ keV excite a relatively increasing number of hot electrons close to the surface of the NEASLD with decreasing E_{po}, and these hot electrons escape into the vacuum with probabilities larger than B at $E_{po} > 10$ keV. Thus, it can be concluded that B at $E_{po} < 2$ keV is a little larger than B at $E_{po} > 10$ keV, and that the approximation in this study that $B_{1.0-100.0}$ is a constant mainly leads to the result that the average value of $\delta_{1.0}$ calculated from the eight NEASLDs is a little less than the experimental value. So far, B in every existing formulae for SEE from a given emitter has been treated as a constant.[8,29,34,55,56] From the above analysis, and the fact that all the experimental δ values for NEASLDs which we can find agree well with corresponding values calculated by the method presented here, we can conclude that δ of NEASLDs calculated using Eqs. (21) and (22) agree well with the experimental results.

The m obtained here decrease with increasing $n(E_{pom})$. From our former study[8], it is known that the m of insulators and NEASs, which also decrease with increasing $n(E_{pom})$, are in the range 1.69–3.02, and that the corresponding $n(E_{pom})$ are in the range of 1.2778–1.6324. Thus, because the m of NEASLDs obtained here are in the range 1.52–1.588 and the corresponding $n(E_{pom})$ are in the range 1.689–1.741, it can be concluded that the m of NEASLDs obtained here are consistent with those in our previous study.

The values $\lambda = 4.9485 \times 10^4$ Å of NEA Si and $\lambda = 7.0 \times 10^4$ Å of NEA GaAs with $\delta_{16.0} = 441$ and $\delta_{18.0} = 472$ obtained here agree well with $\lambda = 5.5 \times 10^4$ Å for the corresponding NEA Si and $\lambda = 8.0 \times 10^4$ Å for the corresponding NEA GaAs obtained from data analysis.[14,16] In addition $\lambda = 2.0 \times 10^4$ Å of NEA GaAs with $\delta_{18.0} = 400$ and $\delta_{20.0} = 404.7$, and $\lambda = 2.0 \times 10^4$ Å of NEA GaAs with $\delta_{18.0} = 143.74$ and $\delta_{20.0} = 145.43$ obtained here are equal to λ for a corresponding NEA GaAs obtained by estimation.[17] Thus, it can be concluded that the λ values for NEALDs obtained here agree well with those obtained by other authors.

The relative errors in the λ_{phl} of a NEASLP obtained by analyzing the parameters of photoemission are estimated to be $\pm 20\%$,[16,22] and those for λ of a NEASLD obtained here are estimated to be $\pm 10\%$. Thus, because λ of a NEASLD is equal to λ_{phl}, we can conclude that the method presented here for obtaining λ_{phl} of a NEASLP from λ of a NEASLD is more accurate.

From Eq. (19), the obtained formula for $R(E_{pom})$,[8,39] the procedures for obtaining E_{pom} and our conclusions that the methods of obtaining m and λ for a NEASLD are correct, we can state that the method presented here for calculating E_{pom} of a NEASLD is correct. For a given secondary electron emitter, δ is proportional to its δ_m,[8,13,46] and all the $\delta_{1.0-20.0}$ for NEASLDs calculated with δ_m obtained here agree well with experimental results. Thus, because no loose approximation was made in the course of deducing Eq. (33) and the facts that $n(E_{pom})$, m, E_{pom}, λ, and the formulae for R obtained here are correct,[8] it can be concluded that the method presented here for calculating δ_m of a NEASLD is correct.

According to the conclusion that the methods presented here for obtaining $n(E_{pom})$, $R(E_{pom})$, m, λ, E_{pom}, and δ_m of a NEASLD and calculating δ of a NEASLD with Eqs. (21) and (22) are correct, it follows that Eqs. (21) and (22) are correct. From the course of deducing Eqs. (21) and (22) we know that Eqs. (21) and (22) are derived from Eqs. (17) and (18). Thus, it can be concluded that Eqs. (17) and (18) are correct. Therefore, from the fact that only one assumption was made in the course of deducing Eqs. (17), (18), (21), and (22), it can be concluded that the only assumption, i.e., that $\delta_{b+100\eta\%}$ can be expressed as Eq. (14), is correct.

Based on the conclusion that Eq. (18) is correct and that the parameters apart from B in Eq. (18) are calculable, equation (18) can be used to calculate B and the calculated $B_{12.0-20.0}$ for four NEASLDs shown in Table 6 are correct. Thus, since the average calculated B of NEA GaAs with $\delta_{16.0} = 441$ and $\delta_{18.0} = 472$ and NEA $Al_{0.2}Ga_{0.8}As$ are approximately equal and correspond to B_{phflat}, the statement that B at $E_{po} > 10$ keV of a NEASLD equals B_{phflat} is proved to be true, and the method presented here for calculating B_{phflat} by calculating B of a NEASLD at $E_{po} > 10$ keV is correct. Therefore, because only one assumption was made in stating that B at $E_{po} > 10$ keV of a NEASLD equals B_{phflat}, we can conclude that the assumption that f_{th} in a NEASLP is independent of $E_{obtainp}$ when $E_{obtainp} > (h\gamma_0 + 2.4 \times 10^{-20}$ J) is correct. Since only one assumption made in the course of stating that f_{th} produced by photons with energy greater than $(h\gamma_0 + 2.4 \times 10^{-20}$ J) is the same as that produced by primary electrons, the statement that f_{th} produced by photons with energy greater than $(h\gamma_0 + 2.4 \times 10^{-20}$ J) is the same as that produced by primary electrons must be correct. Therefore, because the conclusion that λ of a NEASLD equals λ_{phl} of a

NEASLP is made on the basis of this statement and that λ_{thl} of a NEASLP equals its λ_{phl} and λ of a NEASLD equals its λ_{th}, the conclusion that λ of a NEASLD equals λ_{phl} of a NEASLP must be correct.

The spectral response curves of some NEASLPs such as NEA $Al_{0.1}Ga_{0.9}As$ and $Al_{0.3}Ga_{0.7}As$ have no flat portion.[16,22] Moreover, the absorption constants for these NEASLPs are not accurately known. Thus, B_{phflat} of these NEASLPs cannot be calculated using Eq. (39).[16,22] From Section 3 it is known that the method presented here can be used to calculate B at $E_{po} > 10$ keV for all NEASLDs. Therefore, since B at $E_{po} > 10$ keV equals B_{phflat}, the method presented here for calculating B_{phflat} by calculating B of a NEASLD is a more widely applicable method of calculating B_{phflat}.

From Eqs. (8) and (9) and the fact that n at $E_{po} \geq 10.0$ keV changes extremely slowly with E_{po},[8] we know that $K(E_{po}, \rho, Z)$ of a NEASLD at $E_{po} \geq 10.0$ keV decreases extremely slowly with increasing E_{po} and that $K(E_{po}, \rho, Z)$ at $E_{po} \geq 10.0$ keV and in the same E_{po} range is approximately constant. Thus, since λ, B, and ε are independent of E_{po}[39–41] and Eqs. (2), (6), and (24), equation (29) can also be deduced from Eqs. (2), (6), and (24). Similar to the course of deducing Eqs. (32) and (33) in Subection 2.4, equations (32) and (33) can also be derived from Eqs. (2), (6), and (24). Since Eqs. (2) and (6) have been proved correct,[8,33] precisely speaking Eqs. (29), (32), and (33) can be derived from Eq. (24). Therefore, because Eqs. (26) and (27) are derived from Eq. (24), it is known that δ of NEA Si and GaAs can be calculated from Eqs. (26) and (27) and the corresponding parameters (m, λ, δ_m) obtained using Eqs. (29), (32), and (33) in Subsection 2.5. Then, $\delta_{1.0-20.0}$ of NEA Si can be calculated with Eqs. (2), (6), (8), (9), (26), and (27), $Z = 14$, E_{po}, the calculated R parameters and parameters m, E_{pom}, $R(E_{pom})$, $K(E_{pom}, \rho, Z)$, λ, and δ_m obtained in Subsection 2.5. These calculated $\delta_{1.0-20.0}$ for NEA Si shown in Fig. 5 are compared with experimental δ values.[14] The $\delta_{1.0-20.0}$ for NEA GaAs are calculated with Eqs. (2), (6), (8), (9), (26), and (27), $Z = 32$, E_{po}, the calculated R parameters and parameters m, E_{pom}, $R(E_{pom})$, $K(E_{pom}, \rho, Z)$, λ, and δ_m obtained in Subsection 2.5. These calculated $\delta_{1.0-20.0}$ for NEA GaAs with $\delta_{18.0} = 510$ and $\delta_{20.0} = 528.57$ are shown in Fig. 5 are compared with experimental δ values.[15] Figures 1 and 5 show that $\delta_{1.0-20.0}$ for NEA Si and GaAs calculated with Eqs. (21) and (22) agree better with the experimental values than those calculated with Eqs. (26) and (27), and the $\delta_{1.0-20.0}$ for NEA Si and GaAs calculated with Eqs. (26) and (27) increase at a slightly larger rate with E_{po} than the experimental δ. Figure 5 also shows that the calculated δ for NEA Si and GaAs are a little lower than the experimental values at lower E_{po} but a little larger than the experimental values at higher E_{po}.

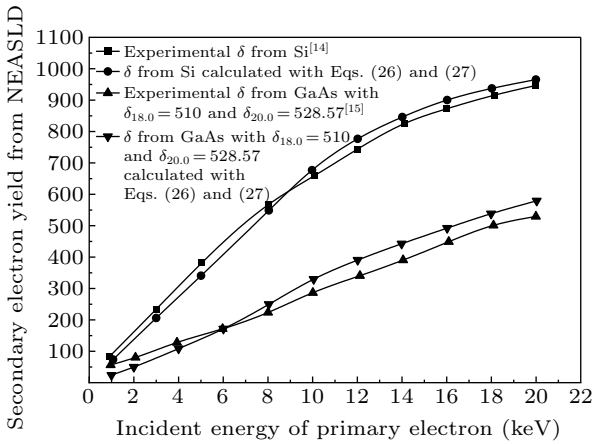


Fig. 5. Comparison between the experimental δ of NEA Si and NEA GaAs with $\delta_{18.0} = 510$ and $\delta_{20.0} = 528.57$ and the corresponding values calculated with Eqs. (26) and (27).

Some papers, including our previous papers,[8,11,32] have presented the formulae for $\delta_{1.0-100.0}$ on the basis of the relation $\delta_{1.0-100.0} = (1+2\eta)\delta_p$, and the δ calculated with these formulae agree well with experimental values. But the δ from NEASLDs calculated with Eqs. (26) and (27) deduced here on the basis of the relation $\delta_{1.0-100.0} = (1+2\eta)\delta_p$ do not agree well with experimental values. What is the new physics behind this? Based on the R calculated with Eq. (2), the ESTAR program and $\lambda_b(Z, E_{po})$ calculated with Eq. (15), it is known that R is greater than the corresponding $\lambda_b(Z, E_{po})$. Several works have investigated secondary electron emitters[8,11,32] with a shorter $\lambda (< 1.0 \times 10^3$ Å), but this paper investigates NEASLDs. The value of $\lambda_b(Z, E_{po})$ at $E_{po} < 50.0$ keV is less than λ of a NEASLD, but for secondary electron emitters with a shorter λ, λ is less than or much less than $\lambda_b(Z, E_{po})$ at $E_{po} > 12.0$ keV. Thus, from the process of SEE and the fact that $R > \lambda_b(Z, E_{po})$, it is known that relative contribution of backscattered electrons of a NEASLD to δ is less than that of emitters with a shorter λ. That is, the relative contribution of backscattered electrons of a NEASLD to δ in the new SEE model for Eqs. (21) and (22) is less than that of emitters with a shorter λ in the old SEE model for Eqs. (26) and (27). Therefore, it is not difficult to comprehend that the formulae for $\delta_{1.0-100.0}$ in a NEASLD can be accurately expressed as Eqs. (21) and (22) but cannot be accurately expressed as Eqs. (26) and (27).

From the above, we find three peculiar surface characteristics of SEE from a NEASLD. First, $\lambda_b(Z, E_{po})$ at $E_{po} <$ 50.0 keV is less than λ of a NEASLD. Thus, more accurate formulae for $\delta_{1.0-100.0}$ of a NEASLD should be deduced from the new SEE model but cannot be deduced from the old SEE model. Second, according to the analysis in the first paragraph of Section 4, we can conclude that B of a NEASLD at $E_{po} < 2$ keV is a little larger than B of a NEASLD at $E_{po} >$

10.0 keV. From the peculiar characteristics of NEASLDs and the fact that the relative number of hot electrons close to the surface of a NEASLD and excited by the primary electrons at $E_{po} < 2$ keV increases with decreasing E_{po}, we can conclude that B of a NEASLD at $E_{po} < 2$ keV slowly increases with decreasing E_{po}, but that B of a given NEASLD at $E_{po} > 2$ keV can still be looked upon as constant. Third, λ and B of a NEASLD at $E_{po} > 10.0$ keV equal λ_{phl} and B_{phflat} of a NEASLP, respectively.

Diamond materials with hydrogen adsorption surfaces, which are also NEA semiconductors and may be NEASLDs, have been extensively studied experimentally over the past few decades, especially with regard to secondary electron spectra and δ.[57–59] From Subsection 2.5 we know that when the values for δ at $E_{po} \geq 10.0$ keV of a given NEASLD are not known we cannot obtain its parameters such as λ, m, and E_{pom} by the new SEE model developed here. So far, nobody has measured or calculated δ at $E_{po} \geq 10.0$ keV of NEA diamond with large λ, so we cannot research NEA diamond in this work. If δ of NEA diamond at $E_{po} \geq 10.0$ keV with large λ is measured or calculated in the future, the new SEE model developed here can be used to research NEA diamond with large λ.

5. Conclusion

Based on the R parameters calculated by the ESTAR program, the fact that $\lambda_b(Z, E_{po})$ at $E_{po} < 50.0$ keV is less than λ of a NEASLD, experimental δ values and existing and deduced formulae for SEE and backscattered electrons, methods for obtaining m and λ and calculating δ_m, E_{pom}, B at $E_{po} > 10.0$ keV and $\delta_{1.0-100.0}$ of a NEASLD are presented. According to the comparison between the calculated $\delta_{1.0-20.0}$ of NEA Si, $Al_sGa_{1-s}As$ and GaAs and experimental ones, it can be concluded that $\delta_{1.0-100.0}$ of NEASLDs calculated with the method presented here agree well with experimental values.

Comparing the values of m and $n(E_{pom})$ for NEASLDs obtained here and those of insulators and NEASs obtained by other authors, we can be conclude that m values obtained here for NEASLDs are consistent with those in our former study. From the course of obtaining desirable λ values in this study and the fact that the λ obtained here agree well with those obtained by other authors, we can conclude that the method presented here for obtaining λ of NEASLDs is correct. Thus, because λ of a NEASLD is equal to λ_{phl} and the relative errors in λ of NEASLDs obtained here are less than those in λ_{phl} of NEASLPs obtained by data analysis, we conclude that the method presented here for obtaining λ_{phl} of a NEASLP from λ of a NEASLD is a more accurate method.

Because the methods of obtaining m and λ of NEASLDs are concluded to be correct, the facts that $n(E_{pom})$ and formula for R obtained here are correct and the calculations for E_{pom} and δ_m, the methods presented here for calculating E_{pom} and δ_m must be correct. Thus, since only one assumption is made in the course of deducing Eqs. (21) and (22) and the conclusions that the methods for obtaining m and λ and calculating δ with Eqs. (21) and (22) are correct, the only assumption, i.e., that $\delta_{b+100\eta\%}$ can be written as Eq. (14), must be correct.

Since it is concluded that Eq. (18) is correct and all parameters excluding B in Eq. (18) are calculable, B of NEASLDs can be calculated with Eq. (18). Thus, since the average values of B calculated for NEA GaAs and $Al_{0.2}Ga_{0.8}As$ are approximately equal and correspond to B_{phflat}, the statement that B of a NEASLD at $E_{po} > 10$ keV is equal to B_{phflat} has been proven correct, and the method presented in this work for calculating B of a NEASLD can be used to calculate B_{phflat}. Therefore, since the method of calculating B can be used to calculate B_{phflat} of all NEASLPs, we can conclude that the method presented here for calculating B_{phflat} by calculating B is a more widely applicable method.

Three peculiar surface characteristics of SEE from NEASLD were found. First, $\lambda_b(Z, E_{po})$ at $E_{po} < 50.0$ keV is less than λ of the NEASLD. So more accurate formulae for $\delta_{1.0-100.0}$ of a NEASLD should be deduced from the new SEE model but cannot be deduced from old SEE model. Second, B of a NEASLD at $E_{po} < 2$ keV slowly increases with decreasing E_{po}, but B at $E_{po} > 2$ keV still can be looked on as a constant. Third, λ and B of a NEASLD at $E_{po} > 10.0$ keV are equal to λ_{phl} and B_{phflat} of a NEASLP, respectively.

Because only one assumption was made when stating that B of a NEASLD at $E_{po} > 10$ keV equals B_{phflat}, which has been proved to be true, the assumption that f_{th} at $\gamma > [(h\gamma_0 + 2.4 \times 10^{-20}\ \text{J})/h]$ of a NEASLP is independent of $E_{obtainp}$ for the case $E_{obtainp} > (h\gamma_0 + 2.4 \times 10^{-20}\ \text{J})$ must also be correct. Therefore, because only one assumption was also made when stating that f_{th} in a NEASLD is the same as that in a NEASLP produced by photons with $h\gamma > (h\gamma_0 + 2.4 \times 10^{-20}\ \text{J})$, we can conclude that the statement that f_{th} in a NEASLD is the same as f_{th} at $\gamma > [(h\gamma_0 + 2.4 \times 10^{-20}\ \text{J})/h]$ of a NEASLP is also correct.

Acknowledgment

Project supported by the National Natural Science Foundation of China (Grant No. 11873013).

References

[1] Jin X L, Ji P U, Zhuge L J, *et al.* 2022 *Chin. Phys. B* **31** 027901
[2] Wang D, He Y N, Guo J J, *et al.* 2021 *J. Appl. Phys.* **129** 093304
[3] Yater J E and Shih A 2000 *J. Appl. Phys.* **87** 8103
[4] Ghale P and Johnson H 2019 *Phys. Rev. B* **99** 155405
[5] Carson M, Woods W, Reynolds S, *et al.* 2021 *IEEE. T. Nucl. Sci.* **68** 292

[6] Yang Q, Shen J, Jiang H, *et al.* 2021 *ACS Photonics* **8** 1027
[7] Alperovich V L, Kazantsev D M, Zhuravlev A G, *et al.* 2021 *Appl. Surf. Sci.* **561** 149987
[8] Xie A G, Pan Z, Dong H J, *et al.* 2021 *Results. Phys.* **20** 103745
[9] Morishita H, Ohshima T, Kuwahara M, *et al.* 2020 *J. Appl. Phys.* **127** 164902
[10] Joshi M and Ghanty T K 2020 *Phys. Chem. Chem. Phys.* **22** 13368
[11] Xie A G, Yu Y, Chen Y Y, *et al.* 2019 *Surf. Rev. Lett.* **26** 1850181
[12] Liao L 2015 *Research and design of microwave micro-pulse electron gun* (Shanghai: Shanghai Institute of Applied Physics, Chinese Academy of Science) pp. 1–134 (in Chinese)
[13] http://www.mc-set.com
[14] Martinelli R U 1970 *Appl. Phys. Lett.* **17** 313
[15] Martinelli R U and Schultz M L 1972 *J. Appl. Phys.* **43** 4803
[16] Martinelli R U and Ettenberg M 1974 *J. Appl. Phys.* **45** 3896
[17] Gutierrez W A, Pommerrenig H D and Holt S L 1972 *Appl. Phys. Lett.* **21** 249
[18] Cazaux J 2001 *J. Appl. Phys.* **89** 8265
[19] Cazaux J 2001 *Polym. Int.* **50** 748
[20] Yang Z, Chang B K, Zou J J, *et al.* 2007 *Appl. Optics.* **46** 7035
[21] Andre J P, Guittard P, Hallais J, *et al.* 1981 *J. Cryst. Growth.* **55** 235
[22] Du X Q, Chang B K and Wang G H 2002 *Adv. Mater and Dev for Sens and Imaging.* **4919** 83
[23] Konishi K, Akimoto I, Isberg J, *et al.* 2020 *Phys. Rev. B* **102** 195204
[24] Zeiske S, Kaiser C, Meredith P, *et al.* 2020 *ACS. Photonics.* **7** 256
[25] Zhuravlev A G, Khoroshilov V S and Alperovich V L 2017 *JETP. Letters.* **105** 686
[26] Zhuravle A G, Khoroshilov V S and Alperovich V L 2019 *Appl. Surf. Sci.* **483** 895
[27] https://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html
[28] Ono S and Kanaya K 1979 *J. Phys. D: Appl. Phys.* **12** 619
[29] Kanaya K and Kawakatsu H 1972 *J. Phys. D: Appl. Phys.* **5** 1727
[30] https://www.baidu.com
[31] Xie A G, Zhang C Y and Zhong K 2014 *Mod. Phys. Lett. B* **28** 1450046
[32] Xie A G, Dong H J and Pan Z 2021 *Results. Phys.* **28** 104554
[33] Reuter W 1972 *Proceedings of the Six International Conference on X-ray Optics and Microanalysis* (Tokyo: Uinversity of Tokyo Press) pp. 121–130
[34] Xie A G, Li Q F, Chen Y Y, *et al.* 2013 *Mod. Phys. Lett. B* **27** 1350238
[35] Reimer L and Drescher H 1977 *J. Phys. D: Appl. Phys.* **10** 805
[36] Xie A G, Liu H Y, Yu Y, *et al.* 2018 *Surf. Rev. Lett.* **25** 1850047
[37] Kanter H 1961 *Phys. Rev.* **121** 461
[38] Xie A G, Zhao H F, Wang T B 2010 *Nucl. Instrum. Methods. Phys. Res. B* **268** 687
[39] Seiler H 1983 *J. Appl. Phys.* **54** R1
[40] Bai C J, Hu T C, He Y, *et al.* 2021 *Chin. Phys. B* **30** 17901
[41] Hu X C, Zhang X W, Zhang R, *et al.* 2020 *Results. Phys.* **19** 103475
[42] Xie A G, Yu Y, Song C N, *et al.* 2019 *Results. Phys.* **15** 102724
[43] Ling Z L and Wang X J 2013 *Cathode Electronics*, 1th edition (National defense industry Press) p. 192
[44] Fisher D G, Enstrom R E, Escher J S, *et al.* 1972 *J. Appl. Phys.* **43** 3815
[45] Martinelli R U 1970 *Appl. Phys. Lett.* **16** 261
[46] Xie A G, Pan Z and Chen Y Y 2020 *Results. Phys.* **18** 103120
[47] Llacer J and Garwin E L 1969 *J. Appl. Phys.* **40** 2766
[48] Alig R C and Bloom S 1978 *J. Appl. Phys.* **49** 3476
[49] Adachi S 1989 *J. Appl. Phys.* **66** 6030
[50] Rakić A D and Majewski M L 1996 *J. Appl. Phys.* **80** 5909
[51] Ozaki S and Adachi S 1995 *J. Appl. Phys.* **78** 3380
[52] Aspnes D E, Kelso S M, Logan R A, *et al.* 1986 *J. Appl. Phys.* **60** 754
[53] Papatryfonos K, Angelova T, Brimont A, *et al.* 2021 *AIP Adv.* **11** 025327
[54] Zhang Y J, Niu J, Zhao J, *et al.* 2010 *J. Appl. Phys.* **108** 093108
[55] Zhang W L, Wang Y G, Wang S H, *et al.* 2021 *Appl. Surf. Sci.* **564** 150419
[56] Bercx M, Partoens B and Lamoen D 2019 *Phys. Rev. B* **99** 085413
[57] Ullah S, Wan G, Kouzios C, *et al.* 2021 *Appl. Surf. Sci.* **559** 149962
[58] Yater J E and Shih A 2000 *J. Appl. Phys.* **87** 8103
[59] Shih A, Yater J, Pehrsson P, *et al.* 1997 *J. Appl. Phys.* **82** 1860