Research on quantum efficiency formula for extended blue transmission–mode GaAlAs/GaAs photocathodes

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The quantum efficiency formula of the transmission-mode photocathodes is solved from the one-dimensional continuity equation, in which the photoelectrons generated in the GaAlAs layer are considered. According to the quantum efficiency formula, we analyze the impact of some relational performance parameters on the quantum efficiency, such as the interface recombination velocity, the thickness of both GaAlAs and GaAs layers and so on. Besides, we use the quantum efficiency formula to fit the experimental curve. The results show that compared with the conventional quantum efficiency formula, the solved quantum efficiency formula is more suitable to the extended blue transmission-mode photocathode with a thin GaAlAs layer.

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1. Introduction

Nowadays, III-V group GaAlAs/GaAs heterojunction has been widely used in various optoelectronic devices such as polarized electron source, solar cell, image intensifier tube and so on [1-4]. As the key part of the negative electron affinity transmission-mode GaAs photocathodes [5], the structure of GaAlAs/GaAs would directly influence the performance of the photocathodes. Quantum efficiency is the most important characteristic parameter to evaluate the performance of photocathodes. The performance parameters influencing the quantum efficiency mainly include the minority carrier diffusion length, the back interface recombination velocity and the surface electron escape probability [6-9]. The conventional quantum efficiency formula of transmission-mode GaAs photocathodes is obtained by solving the one-dimensional continuity equations with the given boundary conditions [9]. Based on the conventional uniform-doping quantum efficiency formula, Zou et al put forward the exponential-doping quantum efficiency formula [10]. Zhang et al think the GaAlAs window layer could absorb the short-wavelength photons, and revise the uniform-doping and exponential-doping quantum efficiency formulas which are suitable to the photocathodes with the thick GaAlAs layer [11]. However, no matter the quantum efficiency formulas given by Ref. [9, 10], or the formulas given by Ref. [11], they have not calculated the photoelectrons contributed by the GaAlAs layer. Actually, some photoelectrons generated in the GaAlAs layer will diffuse into the GaAs layer when the GaAlAs layer is thin enough, and affect the final quantum efficiency especially at the short-wavelength section.

In this paper, in order to fully understand the impact of the GaAlAs layer on the quantum efficiency, a quantum efficiency formula of transmission-mode photocathode considering the photoelectrons contributed by the GaAlAs layer is put forward by solving one-dimensional continuity equations with the given boundary conditions. We analyze the impact of the GaAlAs layer on the final quantum efficiency, and use the extended blue formula to well fit the experimental curve. The formula given in this paper will help to design the extended blue transmission-mode GaAlAs/GaAs photocathodes.

2. Quantum efficiency formula for extended blue photocathode

The band structure diagram of the transmission-mode GaAlAs/GaAs photocathode is shown in Fig. 1.

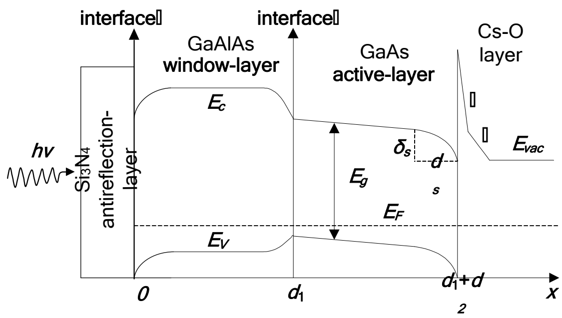

Fig. 1. Band structure diagram of the transmission-mode GaAlAs/GaAs photocathode. E_c is the conduction-band minimum, E_v is the valence band maximum, E_g is the band gap, E_F is the Fermi level, E_{vac} is the vacuum level, and δ_s and d_s are the height and width of the surface band-banding region (BBR).

When the incident light illuminates on the Si_3N_4 antireflection layer, most photons can penetrate into the GaAlAs layer while others are reflected to vacuum. Though the GaAlAs layer has a bigger bandgap in contrast with the GaAs layer, it can still absorb the high-energy photons and generate photoelectrons. Parts of photoelectrons will diffuse into the GaAs layer in the form of electron current when the GaAlAs layer is thin, and escape from the body of photocathode.

The conventional transmission-mode uniform-doping GaAs quantum efficiency formula is derived from the one-dimensional continuity equation [12]

$$D_n \frac{d^2 n(x)}{dx^2} - \frac{n(x)}{\tau} + g(x) = 0 \tag{1}$$

In Eq. (1), $n(x)$ is the density of minority carrier (electron), τ is the lifetime of minority carrier (electron), D_n is the diffusion coefficient of electron, $g(x)$ is the generation rate of photoelectrons.

By analyzing the band structure in Fig. 1, we can find the incident light firstly absorbed in the GaAlAs layer, the generation rate of photoelectrons in the GaAlAs layer is given by

$$g_1(x) = (1-R) I_0 \alpha_1 \exp(-\alpha_1 x) \qquad x \in [0, d_1] \tag{2}$$

In Eq. (2), I_0 is the intensity of incident light, α_1 is the absorption coefficient of GaAlAs, R is the reflectivity on the surface of photocathode, and d_1 is the thickness of the GaAlAs layer.

The boundary conditions are given by

$$n(x)\big|_{x=0} = 0 \tag{3}$$

$$D_n \frac{dn(x)}{dx}\bigg|_{x=d_1^-} = -S_v\, n(x)\big|_{x=d_1^-} \tag{4}$$

Eq. (4) expresses the electron current in at the interface Ⅱ in the GaAlAs layer as shown in Fig. 1. The number of the electrons at the GaAlAs/GaAs interface is obtained by solving Eq. (1), which is given by

$$n(d_1^-) = \frac{\alpha_1 I_0 (1-R) L_1^2 / D_n}{1-\alpha_1^2 L_1^2} \left\{ \frac{(\alpha_1 D_n - S_v)\exp(-\alpha_1 d_1)\sinh(d_1/L_1) - D_n/L_1}{S_v \sinh(d_1/L_1) + D_n/L_1 \cosh(d_1/L_1)} + \exp(-\alpha_1 d_1) \right\} \tag{5}$$

In Eq. (5), S_v is the electron recombination velocity at the interface Ⅱ, L_1 is the diffusion length of minority carrier (electron) in the GaAlAs layer. Eq. (5) is suitable to the condition that the photocathode with a thin GaAlAs layer, wherein the electrons generated in the GaAlAs layer can arrive at the interface Ⅱ. When the GaAlAs layer is thick, plenty of photoelectrons would be recombined in the body and few electrons could arrive at the interface Ⅱ because of the short absorption length in the GaAlAs layer.

After the incident light is fully absorbed in the GaAlAs layer, the photons are mainly absorbed in the GaAs layer. In this paper, the exponential-doping GaAs structure is considered. Differing from the conventional uniform-doping structure, the exponential-doping structure results in a built-in electric field in the GaAs layer. The drift item induced by the built-in electric field E is added to the one-dimensional continuity equation as follows [13]

$$D_n \frac{d^2 n(x)}{dx^2} - \mu |E| \frac{dn(x)}{dx} - \frac{n(x)}{\tau} + g_2(x) = 0 \tag{6}$$

The generation rate of photoelectrons in the GaAs layer is given by

$$g_2(x) = (1-R) I_0 \alpha_2 \exp(-\alpha_2 x)\exp(-\alpha_1 d_1) \qquad x \in [d_1, d_1 + d_2] \tag{7}$$

Where α_2 is the absorption coefficient of the GaAs layer, and d_2 is the thickness of the GaAs layer. The boundary conditions are given as follows

$$\left[D_n \frac{dn(x)}{dx} - \mu |E| n(x) \right]\bigg|_{x=d_1^+} = S_v \left[n(x) - n(d_1^-) \right]\big|_{x=d_1^+} \tag{8}$$

$$n(x)\big|_{x=d_1+d_2} = 0 \tag{9}$$

In Eq. (8), $n(d_1^-)$ represents the number of electrons in the GaAlAs layer, while $n(d_1^+)$ represents the number of electrons in the GaAs layer at the interface Ⅱ. In our model, the electrons are considered discontinuous at the interface Ⅱ, namely the $n(d_1^-)$ is not equal to $n(d_1^+)$.

We obtain the final quantum efficiency formula for the extended blue transmission-mode exponential-doping GaAlAs/GaAs photocathode by solving Eq. (6) and combining with $Y_T = -D_n \frac{dn(x)}{dx} \cdot P/I_0$, the quantum efficiency formula is given by

$$Y_T = \frac{P/I_0 \cdot N D_n / L_2 \cdot S_v\, n(d_1^-)\exp(L_E d_2 / 2L_2^2)}{M} + \frac{P(1-R)\alpha_2 L_2 \exp(-\alpha_1 d_1)}{\alpha_2^2 L_2^2 + \alpha_2 L_E - 1} \times \left[\frac{N(S + \alpha_2 D_n)\exp(L_E d_2 / 2L_2^2)}{M} - \frac{Q\exp(-\alpha_2 d_2)}{M} - \alpha_2 L_2 \exp(-\alpha_2 d_2) \right] \tag{10}$$

Ref. [11] gives a quantum efficiency formula for the conventional transmission-mode exponential-doping GaAs photocathode with thick GaAlAs layer. The formula is given by

$$Y_{TE} = \frac{P(1-R)\alpha_2 L_2 \exp(-\alpha_1 d_1)}{\alpha_2^2 L_2^2 + \alpha_2 L_E - 1} \times \left[\frac{N(S+\alpha_2 D_n)\exp(L_E d_2 / 2L_2^2)}{M} - \frac{Q\exp(-\alpha_2 d_2)}{M} - \alpha_2 L_2 \exp(-\alpha_2 d_2) \right] \quad (11)$$

Where

$$N = \sqrt{L_E^2 + 4L_2^2}$$

$$S = \mu|E| + S_v$$

$$L_E = \mu|E|\tau_2 = \frac{q|E|}{k_0 T} L_2^2$$

$$M = (ND_n/L_2)\cosh(Nd_2/2L_2^2) + (2SL_2 - D_n L_E/L_2)\sinh(Nd_2/2L_2^2)$$

$$Q = SN\cosh(Nd_2/2L_2^2) + (SL_E + 2D_n)\sinh(Nd_2/2L_2^2)$$

In Eq. (10), P is the surface electron escape probability, L_2 is the electron diffusion length in the GaAs layer, μ is the electron mobility, τ_2 is the minority carrier lifetime in the GaAs layer, L_E is the electron drift length under the built-in electric field E. The average distance of photoelectrons moving toward the surface in the exponential-doping GaAs layer is defined the electron diffusion and drift length L_{DE} [13]

$$L_{DE} = \frac{1}{2}\left(\sqrt{L_E^2 + 4L_2^2} + L_E\right) \quad (12)$$

If the value of E in Eq. (10) is zero, the formula is the quantum efficiency formula for the extended blue transmission-mode uniform-doping GaAlAs/GaAs photocathode.

3. Theoretical simulation

According to the Eq. (10), we did some simulations about quantum efficiency for the extended blue transmission-mode exponential-doping GaAlAs/GaAs photocathode, and analyzed the influence of different performance parameters on the quantum efficiency, which would help to design photocathodes with better performance. Changing respectively the values of the interface recombination velocity S_v, the thickness of the GaAlAs layer d_1, and the thickness of the GaAs layer d_2, and fixing other parameters, P=0.55, D_n=120cm^2/s, L_1=2.5μm, E=3.3×10^{4}V/m.

The quantum efficiency curves with various interface recombination velocity S_v are shown in Fig. 2. It is clear that quantum efficiency decreases at the middle and low-energy sections as S_v improves, especially at the middle-energy section. The middle-energy photons are absorbed nearby the interface of GaAlAs/GaAs, lots of photoelectrons generated here are recombined. In Fig. 2, we can also find the quantum efficiency at the high-energy section increases when S_v increases moderately, but decreases when S_v is very large. This phenomenon can be explained by analyzing the boundary conditions. In our quantum efficiency model of the transmission-mode GaAlAs/GaAs photocathode, the interface recombination velocity of Si_3N_4/GaAlAs is very large due to lattice mismatch, so the electron concentration satisfies the boundary condition as Eq. (3). When S_v is small, plenty of electrons will diffuse to the interface Ⅰ, few electrons diffuse into the GaAs layer. When S_v increases moderately, more electrons diffuse into interface Ⅱ, which increases the quantum efficiency at the high-energy sections. When S_v is large enough, plenty of electrons are recombined at the interface Ⅱ although lots of electrons are supplied here, so the quantum efficiency at the high-energy section decreases as S_v increases.

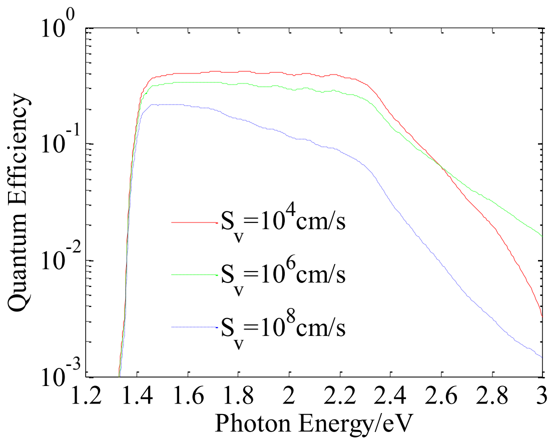

Fig. 2. The quantum efficiency of extended blue transmission - mode photocathode when S_v changes (d_1=0.5μm, d_2=1.8 μm).

The quantum efficiency curves changing with the thickness of the GaAlAs layer d_1 are shown in Fig. 3. The quantum efficiency at the high-energy section decreases as d_1 increases, while the quantum efficiency at other sections has no change. So, decreasing the thickness contributes to increasing extended blue response [14,15]. But, the theory model is not suitable to the case of no GaAlAs layer. The recombination velocity of the Si_3N_4/GaAs interface is very large due to the lattice mismatch, which will have a bad influence on the photocathode. In conclusion, the GaAlAs layer is indispensable to the transmission-mode photocathode, which serves not only as a window layer but also as an emission layer. There exists an optimal thickness of the GaAlAs layer in a certain preparation condition.

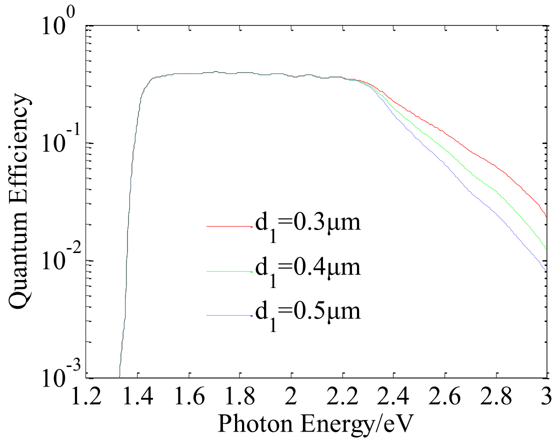

Fig. 3. The quantum efficiency of extended blue transmission - mode photocathode when d_1 changes ($S_v=2\times10^5$cm/s, d_2=1.8μm).

The quantum efficiency curves with different thickness of the GaAs layer d_2 are shown in Fig. 4. The quantum efficiency at the low-energy section increases as d_2 increases, while the quantum efficiency at the high-energy section decreases. The thicker GaAs layer could fully absorb the photons because the photons with low energy have a large absorption length. The photoelectrons generated at the GaAlAs layer and GaAs layer nearby the interface will traverse a long distance before escaping from the photocathode. In the process, lots of photoelectrons lose because of recombination, scattering and other factors, which cause the decrease of quantum efficiency at the high-energy section. Therefore, the optimal value of thickness of the GaAs layer is a compromise between the photon absorption and electron transport.

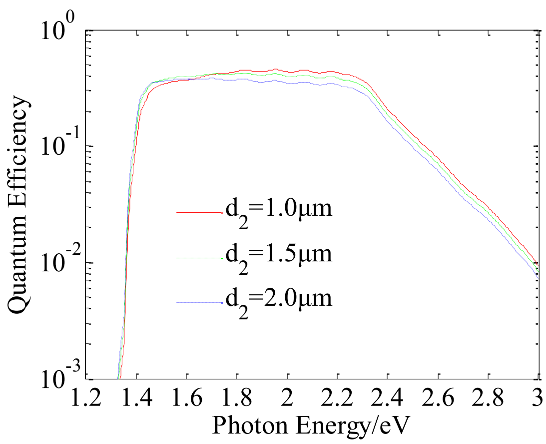

Fig. 4. The quantum efficiency of extended blue transmission - mode photocathode when d_2 changes ($S_v=2\times10^5$cm/s, d_1=0.5μm).

4. Experiment and analysis

To verify the deduced quantum efficiency formula, we designed a transmission-mode GaAlAs/GaAs photocathode sample with a thin GaAlAs layer. The sample was grown on the high-quality p-type GaAs(100)-oriented substrate by metal-organic chemical vapor deposition(MOCVD). The epitaxial layers are consisted of a GaAs buffer layer, a GaAlAs stop layer, a GaAs active layer, a GaAlAs window layer, and a GaAs cap layer. After the growth, as shown in Fig. 5, the photocathode sample was made into the photocathode module with a glass/Si_3N_4/GaAlAs/GaAs structure after selectively etching away other layers [16]. The GaAs active layer of 1.8μm in total thickness is a quasi-exponentially doped structure with the p-type zinc (Zn)-doped concentration exponentially ranging from 10^{19}cm^{-3} to 10^{18}cm^{-3}, while the Zn-doped concentration and Al mole fraction of the 0.5μm-thick GaAlAs window layer are designed as 10^{18}cm^{-3} and 0.7 respectively.

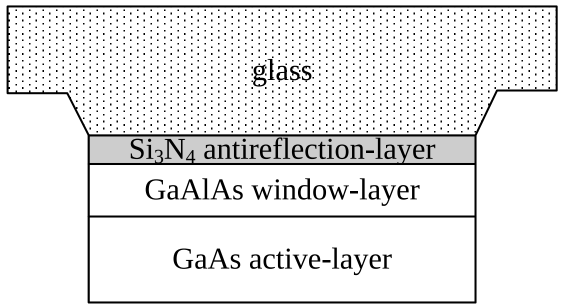

Fig. 5. Diagram of the transmission-mode GaAlAs/GaAs photocathode module.

Following chemical cleaning and heat cleaning, a two-step (Cs, O) activation for the photocathode module was performed in an ultrahigh vacuum chamber [17-19], the base vacuum pressure is better than 10^{-9}Pa. After activation, the spectral response curve of the photocathode was measured *in situ* by a spectral response measurement [20-22], as shown in Fig. 6.

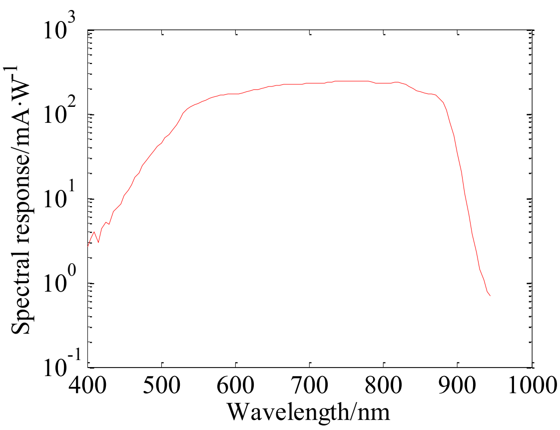

Fig. 6. Experimental spectral response curve for GaAlAs/GaAs photocathode.

The quantum efficiency curve can be obtained by transforming the spectral response curve according to the following equation

$$Y_T(h\upsilon) = 1.24 S_\lambda / \lambda \quad (13)$$

Where S_λ is the spectral response value of the corresponding wavelength λ. The fitting quantum efficiency curves are shown in Fig. 7. Compared with the conventional theoretical curve, the extended blue theoretical curve can be better fitted to the experimental curve at the high-energy section. It is clear that the photoelectrons generated in the GaAlAs layer have an obvious influence on the final quantum efficiency.

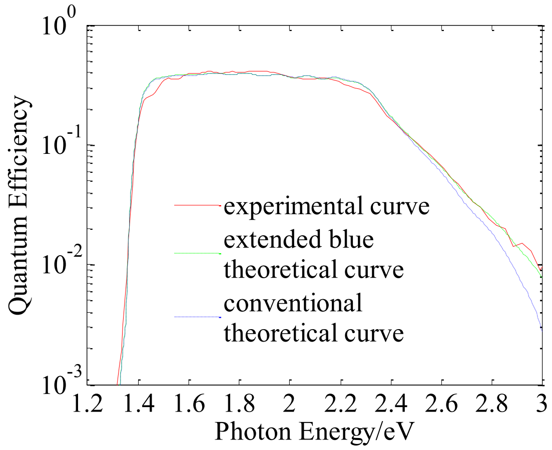

Fig. 7. Comparison of the two theoretical curves which are fitted to the experimental curve.

The fitted performance parameters are listed in Table 1 by using Eq. (10) and Eq. (11). The fitted electron escape probability *P* and the electron diffusion-drift length L_{DE} of the two theoretical curves are similar. The conventional quantum efficiency formula Eq. (11) doesn't consider the photoelectrons contributed by the GaAlAs layer, in order to fit the experimental curve, S_v would be small as much as possible. However, the performance parameters obtained by using Eq. (11) can't reflect the real parameters.

Table 1. Fitted performance parameters of two quantum efficiency formulas.

Formula	S_v(cm/s)	P	L_{DE}(μm)
Conventional	5×10^4	0.53	5.1
Extended blue	2×10^5	0.55	5.2

As is stated above, we can obtain the accurate performance parameters by using Eq. (10) to fit the experimental curve of the photocathode with the thin GaAlAs layer, namely the extended blue transmission-mode GaAlAs/GaAs photocathode, while Eq. (11) is only suitable to the photocathode with the thick GaAlAs layer.

5. Conclusion

In this paper, we have put forward the quantum efficiency formula for extended blue transmission-mode GaAlAs/GaAs photocathode by considering the photoelectrons generated in the GaAlAs layer. By using the formula, the impact of some relational performance parameters on the quantum efficiency were analyzed. Besides, we have used the extended blue quantum efficiency formula to fit the experimental curve. The results show that compared with the conventional quantum efficiency formula, the extended blue quantum efficiency formula could fit well with the experimental curve. The contribution of the photoelectrons generated in the GaAlAs layer is obvious, which increases the quantum efficiency of photocathode at the high-energy section. The extended blue quantum efficiency formula has a guiding significance for the design and preparation of extended blue transmission-mode GaAlAs/GaAs photocathodes in the future work.

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