Quantum efficiency of transmission-mode graded bandgap Al$_x$Ga$_{1-x}$As/GaAs photocathode

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Abstract. Graded bandgap Al$_x$Ga$_{1-x}$As/GaAs photocathode with enhanced quantum efficiency is analyzed in this study. We present the relevant quantum efficiency equations by solving one-dimensional continuity equations for transmission-mode graded bandgap Al$_x$Ga$_{1-x}$As/GaAs and standard AlGaAs/GaAs photocathodes. The results show that the built-in electrical field from bandgap gradation efficiently collects photogenerated electrons in the buffer layer such that quantum efficiencies in the short regions are improved in transmission-mode Al$_x$Ga$_{1-x}$As/GaAs photocathode. The results also show that a thinner buffer layer improves the short-wavelength response of transmission-mode photocathode. Increasing the active layer thickness improves long-wavelength responses but reduces short-wavelength responses. The method presented in this work may provide better estimate of performance and guide the optimum design of graded bandgap Al$_x$Ga$_{1-x}$As/GaAs photocathode.

1. Introduction

GaAs photocathodes have been widely applied in many devices. Extensive effort has been exerted to improve the photoemission performance of GaAs photocathodes, and various structures and models have been proposed [1-2]. Photocathodes with built-in electrical fields from bandgap gradation have been proposed to improve quantum efficiency. The compositional grading method has been used to create graded bandgap Al$_x$Ga$_{1-x}$As/GaAs photocathodes, which have been implemented as polarized electron emitters with increased electron emission efficiency [3-4].

A special design of Al$_x$Ga$_{1-x}$As/GaAs photocathode, wherein the compositional grade of the Al$_x$Ga$_{1-x}$As buffer layer is associated with the doping grade of the GaAs active layer, was recently reported [5]. Given the built-in electrical fields introduced by band-gap gradation, the measured quantum efficiency in the short- and long-wavelength regions is significantly enhanced in transmission- and reflection-mode photocathodes, respectively. However, the relevant analytical quantum efficiency equation was not presented in Ref. [5] and the effect of a built-in electrical field on the performance was not discussed in detail.

Zhao et al. [6] prepared an extended blue transmission-mode photocathode with a graded bandgap Al$_x$Ga$_{1-x}$As buffer layer and presented a numerical quantum efficiency equation to fit the experimental spectral response. Compared with standard photocathodes, the photocathode with graded Al components in the buffer layer demonstrates better performance in the short-wavelength range. Improvements in extended blue performance are attributed to the reduced thickness and Al component gradation of the buffer layer. In Ref. [6], the quantum efficiency equation was multiplied by the transmissivity factor of...
the buffer layer. This is equivalent to the assumption that photogenerated electrons in the buffer layer cannot enter the active layer or contribute to the emission current. When this treatment is applied to reflection-mode photocathode with a graded bandgap buffer layer, however, the enhanced quantum efficiency in the long-wavelength region cannot be explained.

The effect that the built-in electrical field arising from the bandgap gradation in the buffer layer may have on the quantum efficiency should be considered. In this work, we present a model that takes buffer layer thickness, photon absorption, and electron transport in the buffer layer into account. This model is based on the one-dimensional continuity equation. The effects of buffer layers with different structures are then analyzed and compared in detail. The model presented in this paper can be applied to improve the performance and optimum design of photocathodes with graded bandgap buffer layers.

2. Theoretical model

Schematic band diagrams of a graded bandgap AlxGa1-xAs/GaAs photocathode and a standard AlGaAs/GaAs photocathode with uniform bandgap buffer layer are shown in Figs. 1(a) and 1(b), respectively. \( S_1 \) and \( S_2 \) indicate the recombination velocities of the back surface and heterojunction interface, respectively. \( E_{g1} \) and \( E_{g2} \) indicate the bandgaps of the buffer layer at the back surface and heterojunction interface, respectively. \( E_{g3} \) is the bandgap of the active layer. Bandgap gradation in the AlxGa1-xAs layer is achieved by varying the proportion of Al from 0.63 to 0.1 in the AlxGa1-xAs layer. For a standard AlGaAs/GaAs photocathode, the proportion of Al is set to 0.63 as a point of comparison. As shown in Fig. 1, the conduction band minimum is assumed to be influenced by the gradient Al concentration while the valence band maximum is assumed to be fixed. This assumption is valid because the electron affinity in AlxGa1-xAs decreases by almost the same amount as the bandgap increases with increasing \( x \) [7]. To eliminate the influence of gradient-doping, both buffer layers and active layers are assumed to be uniformly doped to \( 1 \times 10^{19} \text{cm}^{-3} \).

When incident light illuminates the back surface of the photocathodes, higher-energy photons are absorbed in the buffer layer, whereas lower-energy photons are absorbed deep inside the photocathodes in the active layer. In the graded bandgap photocathode, electrons generated in the AlxGa1-xAs layer are accelerated by the built-in electrical field toward the heterojunction interface. Transport of photogenerated electrons in the AlGaAs layer is caused by diffusion.

The one-dimensional continuity equation for excess electrons in the graded bandgap buffer layer is given by [8]

\[
\frac{d^2 n_1}{dx^2} + \frac{\mu_{n1} E}{D_{n1}} \frac{dn_1}{dx} - \frac{n_1}{L_{n1}^2} + G_1(x) = 0
\]

where \( n_1 \) is the excess electrons concentration, \( D_{n1} \) is the electron diffusion coefficient, \( L_{n1} \) is the electron diffusion length, \( \mu_{n1} \) is the electron mobility, and \( G_1(x) \) is the photon generation function of the electrons. E is the built-in electric field induced by bandgap gradation, which is given by
where $q$ is the electron charge.

The general solution of Eq. 1 can be written as

$$n_1(x) = C_1 \exp(A_1x) + C_2 \exp(A_2x) + \frac{1}{A_1-A_2} \left[ \exp(A_1x)F_1(x) + \exp(A_2x)F_2(x) \right]$$

where $A_1 = -\frac{\mu_n E}{2D_n} + \left(\frac{\mu_n E}{2D_n} + \frac{1}{\mu_n^2} \right)^{1/2}$ and $A_2 = -\frac{\mu_n E}{2D_n} - \left(\frac{\mu_n E}{2D_n} + \frac{1}{\mu_n^2} \right)^{1/2}$.

The functions $F_1(x)$ and $F_2(x)$ are defined by

$$F_1(x) = -\frac{1}{D_n} \int_0^x \exp(-A_1x) G(x) \, dx \quad \text{and} \quad F_2(x) = \frac{1}{D_n} \int_0^x \exp(-A_2x) G(x) \, dx.$$

The constants $C_1$ and $C_2$ can be determined from the boundary conditions.

For simplicity, the absorption coefficient of the graded bandgap buffer layer is given as [9]

$$\alpha_1(x) = A^*[\nu - E_0(x)]^{1/2}$$

where $A^*$ is assumed to be a constant. The energy bandgap in the buffer layer at the abscissa ($x$) is expressed as

$$E_0(x) = E_{g1} + E'x$$

where $E'$ is the gradient of the energy gap, the magnitude of which is equal to that of the built-in electric field ($E$).

The photon generation function of the electrons is given as

$$G_1(x) = -\frac{dI_1}{dx} = \alpha_1(x)I_1(x)$$

where $I_1(x)$ is the photon flux, which is defined as

$$I_1(x) = (1 - R)I_0 \exp \left(\int_0^x -\alpha_1(x) \, dx\right)$$

Where $I_0$ is the incident photon flux, $R$ is the reflectivity of the back surface of the photocathode. The continuity equation for excess electrons in the uniform bandgap buffer layer is given by

$$\frac{d^2n_1}{dx^2} - \frac{n_1}{\mu_n^2} + \frac{G_1(x)}{\mu_n} = 0$$

where $G'_1(x)$ is the generation function of the electrons, which is calculated as

$$G'_1(x) = (1 - R)I_0 \alpha'_1 \exp \left(-\alpha'_1 x\right)$$

where $\alpha'_1$ is the absorption coefficient of the uniform buffer layer and defined as $A^*[\nu - E_{g1}]^{1/2}$.

Boundary conditions at the back surface of the graded and uniform buffer layers are given by

$$D_n \left. \frac{dn_1}{dx} \right|_{x=0} + n_1(0)\mu_n E = n_1(0)S_1$$

and

$$D_n \left. \frac{dn_1}{dx} \right|_{x=0} = n_1(0)S_1$$

respectively.

When kept in zero-bias conditions, the heterojunction interface can act as a perfect sink for conductive band electrons in the buffer layer. We assume that electrons reaching the interface ($x = d_1$) are either injected into the active layer or recombined, and that the boundary condition is

$$n_1(d_1) = 0$$

The density of the current from buffer layer to the interface is

$$J_{in} = -q D_n \left. \frac{dn_1}{dx} \right|_{x=d_1}$$

By applying Eqs. 11 and 13 to Eq. 1 and Eqs. 12 and 13 to Eq. 9, the value of $J_{in}$ in the graded buffer layer and uniform buffer layer can be respectively written as [10]

$$J_{in} = -\frac{qD_n}{2} \left\{ F_1(d_1) \exp(A_1d_1) + F_2(d_1) \exp(A_2d_1) \right\} \cdot \left[ \frac{S_1}{2D_n} \right] \left( a \cosh(f d_1) + f \sinh(f d_1) \right) - F_1(d_1) \exp(A_1d_1) + F_2(d_1) \exp(A_2d_1)$$

where $a = -\frac{\mu_n E}{2D_n} f = \left(\frac{\mu_n E}{2D_n} \right)^2 + \frac{1}{\mu_n^2} \right)^{1/2}$,
\[ J_{in} = \frac{q(1-R)\alpha'_{1}L_{n1}}{\alpha'_{1}L_{n1}^{2}-1} \left\{ \frac{\alpha'_{1}D_{n1}+S_{1}}{\frac{D_{n1}\cosh(d_{n1}/L_{n1})}{L_{n1}}+S_{1}\sinh(d_{n1}/L_{n1})} - \frac{\exp(-\alpha'_{1}d_{1})\left[ S_{1}\cosh(d_{1}/L_{n1})+\frac{D_{n1}}{L_{n1}}\sinh(d_{1}/L_{n1}) \right]}{\frac{D_{n1}\cosh(d_{1}/L_{n1})}{L_{n1}}+S_{1}\sinh(d_{1}/L_{n1})} - \alpha'_{1}L_{n1}\exp(-\alpha'_{1}d_{1}) \right\}. \]

(16)

The continuity equation for excess electrons in the active layer is

\[ \frac{d^{2}n_{2}}{dx^{2}} + \frac{n_{2}}{\mu_{n2}} + \frac{G_{2}(x)}{\mu_{n2}} = 0 \]

(17)

where \( n_{2}, D_{n2}, \) and \( L_{n2} \) respectively denote the excess electron concentration, electron diffusion coefficient, and electron diffusion length in the active layer. The photon generation function \( G_{2}(x) \) is given by

\[ G_{2}(x) = I_{2}\alpha_{2}\exp(-\alpha_{2}x) \]

(18)

where \( \alpha_{2} \) is the absorption coefficient of active layer and \( I_{2} \) is the photon flux at the interface whose value equals \( I_{1}(d_{1}) \).

At the interface, the direction of the current injected from the buffer layer into the active layer is opposite that of the recombination current. Therefore, the boundary condition of the interface is

\[ -qD_{n2} \frac{d^{2}n_{2}}{dx^{2}} \bigg|_{x=0} = K \cdot J_{in} - qn_{2}(0)S_{2} \]

(19)

where \( K \) is the ratio of the current injected into the active layer to the current from the buffer layer to the interface.

At the emissive surface, the boundary condition is given by

\[ n_{2}(d_{2}) = 0 \]

(20)

By solving the continuity equation Eq. 17 with the boundary conditions in Eqs. 19 and 20, the excess electron concentration in the active layer can be obtained. Supposing \( P \) is the surface electron escape probability, the quantum efficiency of the photocathode is given by

\[ Y = -\frac{qD_{n2} \frac{dn_{2}}{dx}}{\mu_{n2}} \bigg|_{x=d_{2}} = \frac{P_{D_{n2}}}{\mu_{n2}} \left\{ \frac{A'(\alpha_{2}D_{n2}+S_{2})}{\frac{P_{D_{n2}}}{\mu_{n2}}\cosh(d_{2}/L_{n2})+S_{2}\sinh(d_{2}/L_{n2})} - \frac{A' \exp(-\alpha_{2}d_{2})\left[ S_{2}\cosh(d_{2}/L_{n2})+\frac{P_{D_{n2}}}{\mu_{n2}}\sinh(d_{2}/L_{n2}) \right]}{\frac{P_{D_{n2}}}{\mu_{n2}}\cosh(d_{2}/L_{n2})+S_{2}\sinh(d_{2}/L_{n2})} - A' \frac{K \cdot J_{in} - qn_{2}(0)S_{2}}{P_{D_{n2}}\mu_{n2}} \right\} \]

(21)

where \( A' = \frac{(1-R)\exp(-\alpha'_{1}d_{1})\alpha_{2}L_{n2}^{2}}{D_{n2}(\alpha_{2}^{2}L_{n1}^{2}-1)} \).

3. Discussion

For simplicity, the reflection at the photocathode back surface is neglected. In the simulations, \( L_{n1}, \mu_{n}, \) and \( D_{n1} \) are assumed to be constant in the graded and uniform bandgap buffer layers. Here, \( L_{n1} = 2 \mu m, L_{n2} = 2 \mu m, D_{n1} = 120 \text{ cm}^{2}/s, D_{n2} = 120 \text{ cm}^{2}/s, \) and \( P = 0.50 \). The electron mobility in the buffer layer is set to 2000 cm/V · s and the back surface recombination velocity is set to 10^7 cm/s.

The quantum efficiency curves of the transmission-mode graded bandgap AlxGa1-xAs/GaAs and standard AlGaAs/GaAs photocathodes are shown in Fig. 2. The buffer layer thickness is 1.0 \mu m, the active layer thickness is 1.5 \mu m, and the interface recombination velocity is 10^6 cm/s. When \( K = 0 \), as in Fig. 2(a), the effect of the buffer layer on the quantum efficiency is only described by the short-wavelength threshold constraint, \( \exp(-\alpha'_{1}d_{1}) \), which is similar to the treatment in Ref. [6]. Photons with energy greater than \( E_{g1} \) will be absorbed in the buffer layer, and more photons are absorbed in the graded bandgap buffer layer than in the uniform buffer layer in the spectral region of \( E_{g1} > h\nu > E_{g2} \). Because of the assumption that photogenerated electrons in the buffer layer cannot be transported into the active layer or contribute to the emission current, the quantum efficiency in the short-wavelength range is reduced in the graded bandgap photocathode. In Ref. [6], compared with the standard photocathode, more photons are absorbed in the graded bandgap photocathode because of its increased thickness and lower average Al component. Therefore, quantum efficiency enhancement of graded bandgap photocathode in the short-wavelength range was attributed to the higher probability of surface escape and lower interface recombination rather than the effect of a built-in electrical field in the AlxGa1-xAs layer [6]. The quantum efficiency curves of the graded bandgap and standard photocathodes operating in transmission-mode when \( K = 1 \) are shown in Fig. 2(b). The built-in
electrical field generated from Al component grading drives photogenerated electrons in the AlxGa1-xAs layer toward the heterojunction interface. Subsequently, these electrons may enter the active layer and participate in the emission process. Efficient collection of photogenerated electrons in the buffer layer improves the quantum efficiency of photons in the short-wavelength range. The factor $K$ describes the probability that electrons reaching the interface enter the active layer; relevant values can be obtained by fitting the measured quantum efficiency curves.

Fig. 2. Quantum efficiency curves of transmission-mode graded bandgap Al$_x$Ga$_{1-x}$As/GaAs and standard AlGaAs/GaAs photocathodes. (a) $K=0$; (b) $K=1$.

The effects of the buffer layer and active layer thicknesses on the quantum efficiencies of the Al$_x$Ga$_{1-x}$As/GaAs and AlGaAs/GaAs photocathodes are shown in Fig. 3. In Figs. 3(a) and 3(b), the thickness of the active layer is 1.5 μm while the buffer layer thickness is varied; by contrast, the thickness of the buffer layer is 1.0 μm and the active layer thickness is varied in Figs. 3(c) and 3(d). Other parameters used in this simulation are similar to those in Fig. 2. As shown in Figs. 3(a) and 3(b), variations in buffer thickness only influence the short-wavelength responses of Al$_x$Ga$_{1-x}$As/GaAs and AlGaAs/GaAs photocathodes. Shor-t-wavelength responses increase as the buffer layer thickness decreases. In the Al$_x$Ga$_{1-x}$As/GaAs photocathode, decreasing the buffer layer thickness enhances the built-in electrical field in this layer and increases electron generation in the active layer. In the AlGaAs/GaAs photocathode, improvements in short-wavelength responses in photocathodes with thinner buffer layers are caused only by reduction of photon absorption in the buffer layer. Consequently, the quantum efficiency of the AlGaAs/GaAs photocathode is lower than that of the Al$_x$Ga$_{1-x}$As/GaAs photocathode.
The effect of active layer thickness is slightly more complicated. For a photocathode with a thinner active layer, electrons excited by high-energy photons in the buffer are more likely to encounter the emissive surface and be emitted into the vacuum. However, absorption of low energy photons in the active layer is insufficient under such circumstances. Therefore, the quantum efficiency of photons in the short-wavelength region increases as the active layer thickness decreases; by contrast, the long-wavelength response decreases under the same conditions. In the spectral region of $E_{g1} > h\nu > E_{g2}$, photons can be absorbed in the $\text{Al}_x\text{Ga}_{1-x}\text{As}$ layer. However, photons in this region cannot be absorbed in the AlGaAs layer. Therefore, the quantum efficiency in the middle-energy region decreases rapidly in AlGaAs/GaAs photocathodes with thinner active layers.

4. Conclusion

We have presented quantum efficiency equations based on one-dimensional continuity equations for transmission-mode graded bandgap $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ and standard AlGaAs/GaAs photocathodes. Performance improvements in the short-wavelength regions of transmission-mode $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ photocathode can be explained by the quantum efficiency equations. Analysis results show that the built-in electrical field induced by bandgap gradation effectively collects photogenerated electrons in the graded bandgap buffer layer. We then discuss the effect of variations in buffer and active layer thicknesses on the performance of transmission-mode photocathodes. The results show that only the short-wavelength response improves as the buffer layer thickness decreases and that increases in active layer thickness enhance long-wavelength responses but decrease short-wavelength responses. The present method allows better estimation of the performance of graded bandgap $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{GaAs}$ photocathodes as well as analysis and optimization of the effects of various parameters.
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