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Resolution characteristics of graded band-gap reflection-mode AlGaAs/GaAs photocathodes

Wenjuan Deng [a,b], Daoli Zhang [a], Jijun Zou [b,*], Xincun Peng [b], Weilu Wang [b], Yijun Zhang [c], Benkang Chang [c]

[a] School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Engineering Research Center of New Energy Technology and Equipment of Jiangxi Province, East China Institute of Technology, Nanchang 330013, China
[c] School of Electronic and Optical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

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ABSTRACT

The modulation transfer function (MTF) of graded band-gap AlGaAs/GaAs reflection-mode photocathodes was determined using two-dimensional Poisson and continuity equations through numerical method. Based on the MTF model, we calculated the theoretical MTF of graded and uniform band-gap reflection-mode photocathodes. We then analyzed the effects of Al composition, wavelength of incident photon, and thicknesses of AlGaAs and GaAs layer on the resolution. Calculation results show that graded band-gap structures can increase the resolution of reflection-mode photocathodes. When the spatial frequency is 800 lp/mm and wavelength is 600 nm, the resolution of graded band-gap photocathodes generally increases by 15.4–29.6%. The resolution improvement of graded band-gap photocathodes is attributed to the fact that the built-in electric field in graded band-gap photocathodes reduces the lateral diffusion distance of photoelectrons.

1. Introduction

Most imaging intensifiers use transmission-mode (t-mode) photocathodes because the optical path in imaging intensifiers can be easily obtained [1–6]. However, compared with t-mode photocathodes, reflection-mode (r-mode) photocathodes have a higher quantum efficiency and are easier to fabricate. These properties have motivated research on possible approaches to apply r-mode photocathodes into imaging devices [7]. Previous studies have reported on the application of r-mode photocathodes in imaging detectors [8,9]. For a photocathode, quantum efficiency and resolution are the primary performance parameters. Over the last several decades, the quantum efficiency of photocathodes has been widely investigated [10–15]; however, the resolution characteristics of photocathodes are rarely reported, especially for r-mode photocathodes. The resolution of photocathodes is usually neglected in the calculation of system resolution despite its significant effects on the performance of systems using photocathodes.

Many factors affect photocathode resolution, but the most significant is the influence of an electric field along the opposite direction of photoelectron transport toward the surface of negative electron affinity (NEA). Experiments have verified that photocathodes with a constant built-in electric field have higher quantum efficiencies [16–18]. Materials with a graded Al composition also have a graded band-gap. The built-in electric field of graded band-gap photocathodes is generally greater than that of exponential-doping photocathodes [11,19]. Fig. 1 shows the effect of the built-in electric field on resolution. For graded band-gap AlGaAs/GaAs photocathodes, the diameter of the dispersion circle is smaller than that of uniform band-gap cathodes. The electric field facilitates photoelectron movement toward the cathode surface and decreases the lateral diffusion of photoelectrons, thereby increasing resolution. Furthermore, the dependence of resolution on the AlGaAs/GaAs photocathode structure, Al composition, active layer thickness, and wavelength of incident light needs to be discussed. Accordingly, we established a model to calculate and analyze the resolution of r-mode graded band-gap photocathodes.

2. Resolution model

The schematic and band structure of r-mode graded band-gap AlGaAs/GaAs photocathodes are shown in Fig. 2. A band-bending region, as shown in Fig. 2(b), is formed because of the Fermi-level leveling effect in the graded band-gap AlGaAs layer. This region induces a built-in electric field that facilitates the movement of photo-excited electrons toward the surface. Light is incident on the

* Corresponding author.
E-mail address: jjzou@ecit.cn (J. Zou).

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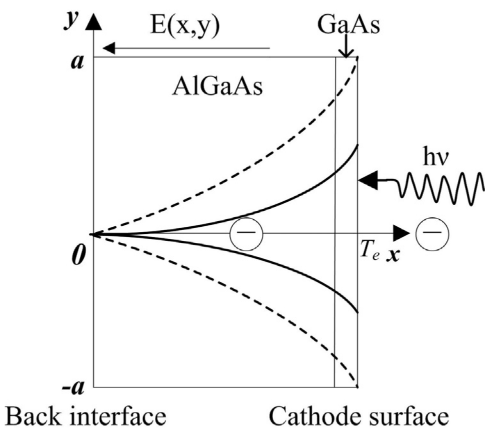

Fig. 1. Schematic of electron transport in the active layer of an AlGaAs/GaAs photocathode. Solid lines represent electron transport with a built-in electric field. Dashed lines represent electron transport without built-in electric field.

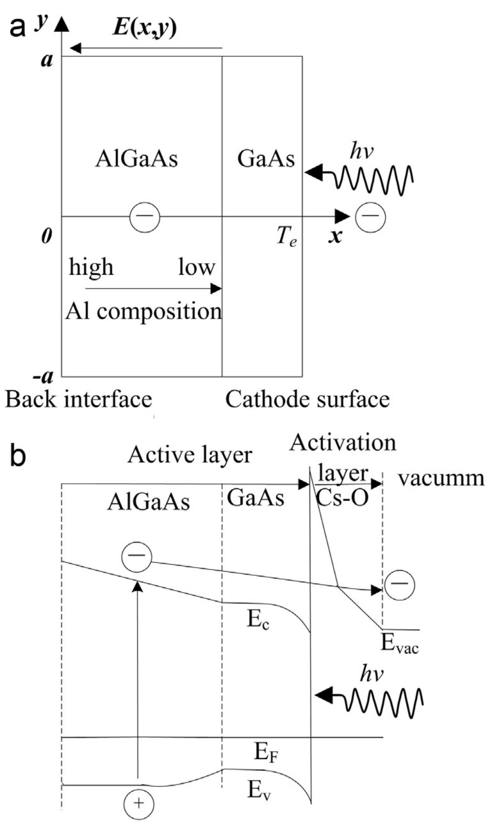

Fig. 2. (a) Schematic and (b) band structure of graded band-gap AlGaAs/GaAs photocathodes, E_c is the conduction band minimum, E_v is the valence band peak level, E_{vac} is the vaccum level, E_F is the Fermi level, and T_e is the thickness of the active layer.

cathode surface in r-mode cathodes. Based on the drift-diffusion model in semiconductors, the two-dimensional Poisson and continuity equations in r-mode AlGaAs/GaAs photocathodes, as shown in Fig. 2(a), can be obtained as

$$\begin{cases} \nabla\cdot\varepsilon\nabla\psi = -q(p-n-N_a) \\ \nabla\cdot(\mu_n\dfrac{k_bT}{q}\nabla n+\mu_n nE_n)-U+G=0 \\ \nabla\cdot(\mu_p\dfrac{k_bT}{q}\nabla p-\mu_p pE_p)-U+G=0 \end{cases} \tag{1}$$

where n and p are the electron and hole concentrations, respectively; N_a is the acceptor density, E_n and E_p are the intensities of the built-in electric field accelerating electrons and holes, respectively; μ_n and μ_p are the electron and hole mobilities, respectively; G is the photoelectron generation function, and U is the carrier recombination rate. The nonequilibrium electrons and holes recombine throughout the entire active layer at a rate of U through three basic recombination mechanisms, namely, radiative, Shockley–Read–Hall (SRH), and Auger recombination.

The modulation transfer function (MTF) is a general measure of the resolution for an image intensifier system. In this work, coupled Poisson and continuity equations are solved numerically, and the theoretical model is established using a finite volume method. Based on the theoretical model, the MTF of cathodes can be calculated [20,21].

3. Simulation and discussion

In this simulation, the p-type doping concentration in the AlGaAs/GaAs cathodes is $1\times10^{19}\,\text{cm}^{-3}$, and the other material parameters chosen for the simulation [22–25] are as follows: intrinsic electron mobility $\mu_n=2000\,\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$, intrinsic hole mobility $\mu_p=150\,\text{cm}^2\,\text{V}^{-1}\,\text{s}^{-1}$, intrinsic carrier life-times $\tau_n=10$ ns (electron), and $\tau_p=30$ ns (hole). The Al mole fraction is designed to linearly decrease from the back interface to the cathode surface in graded band-gap cathodes and is zero in uniform band-gap cathodes (GaAs cathodes).

Based on the resolution model, we simulate the MTFs curves as a function of Al composition, AlGaAs or GaAs layer thickness, and incident light wavelength. We then compare the resolution of graded band-gap cathodes to that of uniform band-gap cathodes. These MTF curves are shown in Fig. 3.

In Fig. 3(a), the Al mole fraction linearly decreases from 0.4 to 0 and from 0.2 to 0. In Fig. 3(b)–(d), the Al mole fraction linearly decreases from 0.4 to 0. The most obvious feature in all MTF curves is that the resolution decreases with increased spatial frequency, which is directly related to the lateral diffusion of photoelectrons. Another interesting feature is that the graded band-gap structure can dramatically increase the resolution of photocathodes because of the built-in electric fields induced by a graded composition. This structure helps facilitate the movement of photo-excited electrons toward the surface through diffusion and directional drift under the built-in electric fields. In Fig. 3(a), at a spatial frequency $f=800$ lp/mm, the MTFs of Al composition 0.4 cathode and Al composition 0.2 cathode are 0.66 and 0.59, respectively, which are 29.6% and 15.4% greater than those of the uniform band-gap photocathode. A high Al composition in graded band-gap photocathodes indicates a high MTF of cathodes. However, the band gap of the AlGaAs layer increases with increased Al composition, and some long wave-length photons cannot be absorbed in the high Al composition region. Thus, a high Al composition affects the quantum efficiency of long wavelength photons.

Fig. 3(b) shows the effect of the incident light wavelength λ on the MTFs of both graded and uniform band-gap AlGaAs/GaAs photocathodes. The intensities of these curves increase with decreased λ, and the uniform band-gap structure becomes more pronounced. For instance, at $f=800$ lp/mm, the MTF of graded band-gap photocathodes increases by 56.7% with decreased λ from 700 nm to 450 nm, whereas that of uniform band-gap cathode increases by 109.1%. Given that the absorption coefficient of short wavelength photons is larger, the majority of photoelectrons are excited near the surface, and the extent of lateral diffusion is minimized.

Fig. 3(c) shows that the photocathode resolution improves with decreased AlGaAs layer thickness T_{AlGaAs}. The effect on the graded band-gap photocathode is more pronounced. The lateral diffusion distance of electrons decreases with decreased T_{AlGaAs}. The built-in