Modulation transfer function characteristic of uniform-doping transmission-mode GaAs/GaAlAs photocathode*

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(Received 24 November 2010; revised manuscript received 1 March 2011)

The resolution characteristic can be obtained by the modulation transfer function (MTF) of a GaAs/GaAlAs photocathode. After establishing the theoretical model of GaAs(100)-oriented atomic configuration and the formula for the ionized impurity scattering of the non-equilibrium carriers, this paper calculates the trajectories of photoelectrons in a photocathode. Thus the distribution of photoelectron spots on the emit-face is obtained, which is namely the point spread function. The MTF is obtained by Fourier transfer of the line spread function obtained from the point spread function. The MTF obtained from these calculations is shown to depend heavily on the electron diffusion length, and enhanced considerably by decreasing the electron diffusion length and increasing the doping concentration. Furthermore, the resolution is enhanced considerably by increasing the active-layer thickness, especially at high spatial frequencies. The best spatial resolution is 860 lp/mm, for the GaAs photocathode of doping concentration 1×10^{19} cm^{-3}, electron diffusion length 3.6 μm and the active-layer thickness 2 μm, under the 633-nm light irradiated. This research will contribute to the future improvement of the cathode's resolution for preparing a high performance GaAs photocathode, and improve the resolution of a low light level image intensifier.

Keywords: GaAs/GaAlAs photocathode, uniform-doping, modulation transfer function, spatial resolution

PACS: 73.61.Ey, 42.30.Lr, 73.50.–h, 79.60.–i **DOI:** 10.1088/1674-1056/20/8/087308

1. Introduction

Negative-electron-affinity (NEA) GaAs photocathodes have already found widespread applications in night vision image intensifiers and are potential sources for next-generation electron accelerators and lithography because of their high quantum efficiency, low dark emission, and narrow energy spread.[1−5] Third generation proximity focused image intensifiers consist basically of a GaAs photocathode, a microchannel plate, and a phosphor screen. Existing models of the resolution of image intensifiers still did not cover the GaAs photocathode.[6,7] The resolution of the GaAs photocathode is thought to be infinity, which leads to the experimental value of an image intensifier's resolution, which is less than the theoretical value. Thereby, insight has to be gained into the way electrons move through the cathode and the MTF of photocathodes. It has been widely accepted that photoemission from a NEA photocathode is a three-step process of optical absorption, electron transport to the surface, and escape across the surface into a vacuum.[8] This theory allows photoemission to be related to the optical absorption coefficient, electron scattering mechanism, and the height of the potential barrier at the surface.[9]

The function chosen to represent the spatial resolution is the MTF, which is defined as the ratio of the image modulation to the object modulation and varies with the spatial frequency. The MTF is often used to characterize the performance of optical systems since the MTF contains almost all of the optical information of a system. The researchers have studied the resolution of GaAs photocathodes by solving the MTF from the 2-dimensional continuity equations.[10] By another method, this article calculates the trajectories of electrons exiting in the cathode bulk, considering the reflectance and transmissivity of GaAs/GaAlAs and the absorption coefficient of GaAs photocathodes. The MTF is obtained by Fourier transfer of the line spread function (LSF) obtained from the point spread function, which is namely the distribution of light spots

*Project supported by the National Natural Science Foundation of China (Grant No. 60678043) and the Research and Innovation Plan for Graduate Students of Jiangsu Higher Education Institutions, China (Grant No. CX09B_096Z).

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on the emit-face.

2. Model

2.1. The atomic configuration of a GaAs(100)–oriented photocathode

For the beryllium (Be) doped p-type GaAs active-layer, this article establishes a simple model in which GaAs(Be) cuboid is the volume element of a NEA GaAs photocathode. Those elements composed of this GaAs active layer and one Be atom are in the centre of the GaAs(Be) cuboid, as shown in Fig. 1. The GaAs active-layer thickness (from the back interface to the emit-face) and the cathode surface are obtained by extending the GaAs(Be) cuboid in the longitudinal direction and lateral direction, respectively.

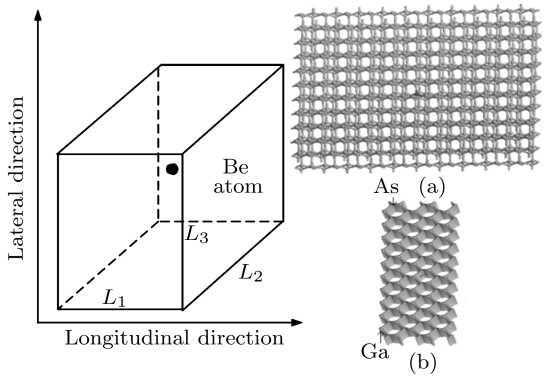


Fig. 1. The GaAs(Be) cuboid of a NEA GaAs photocathode as a volume element: surface (a) represents the arrangement of lateral direction; surface (b) represents the arrangement of longitudinal direction.

The atomic concentration of GaAs $n = 1 \times 10^{22}$ cm^{-3}, and the doping concentration of Be $n_{\rm A} = 1 \times 10^{19}$ cm^{-3}, then $n_{\rm A}/n = 1/10^3$, it is namely that there are 500 gallium (Ga) atoms and 500 arsenic (As) atoms in the GaAs(Be) cuboid and one Be atom in the centre of the GaAs(Be) cuboid. There are $10 \times 10 = 100$ As atoms on the surface (a) of the GaAs(Be) cuboid, and 5 layers of Ga atoms and 5 layers of arsenic atoms on the surface (b). Since the diameters of the Ga atom and the As atom are 2.36 Å and 2.52 Å (1 Å = 0.1 nm), respectively, this paper assumes that the distance between adjacent As atoms is 2.52 Å and the distance between adjacent Ga and As atoms is 2.44 Å. So $L_1 = 10 \times 2.44 = 24.4$ Å, $L_2 = L_3 = 10 \times 2.52 = 25.2$ Å of the GaAs(Be) cuboid, as shown in Fig. 1. If the ratio of $n_{\rm A}/n$ is not equal to $1/10^3$, then L_1, L_2, and L_3 become $2.44/(n_{\rm A}/n)^{1/3}$ Å, $2.52/(n_{\rm A}/n)^{1/3}$ Å, and $2.52/(n_{\rm A}/n)^{1/3}$ Å respectively.

The two-dimensional atomic configuration of GaAs(100)-oriented is carried out by extending the surface (b) of the GaAs(Be) cuboid, as shown in Fig. 2. The studies of the MTF of the GaAs photocathode are based on this theoretical model.

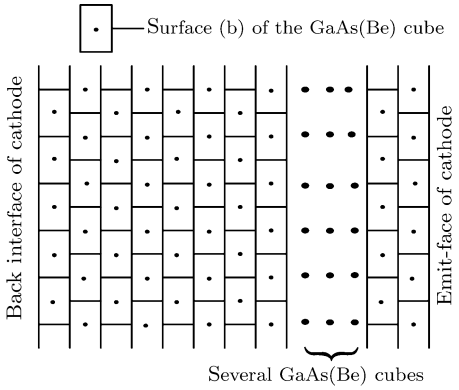


Fig. 2. The two-dimensional atomic configuration of GaAs(100)-oriented.

2.2. The formula of ionized impurity scattering

The exiting photoelectrons could be influenced by the Be ion in the process of moving to the emit-face of the photocathode; this interaction is called the ionized impurity scattering of non-equilibrium carriers, which is similar to Rutherford scattering.[11] The equation of Rutherford scattering is[12]

$$\tan\left(\frac{\varphi}{2}\right) = \frac{1}{4\pi\varepsilon\varepsilon_0}\frac{zZe^2}{mv^2b}. \tag{1}$$

The ionized impurity scattering of photoelectrons in the GaAs photocathode is simulated by the theory of Rutherford scattering. In Eq. (1), φ is the scattering angle, ε is the relative dielectric constant of GaAs, ε_0 is the dielectric constant of the vacuum, z is the charge number of the electron, Z is the charge number of the Be ion, e is the electronic charge, m is the mass of the electron, ν is the velocity of the electron relative to Be ion before the ionized impurity scattering, and b is the distance of the Be ion perpendicular to the path along which the photoelectron moves. In order to make the formula of ionized impurity scattering simple and clear, equation (1) can be written as

$$\tan\left(\frac{\varphi}{2}\right) = \frac{A}{Eb}. \tag{2}$$

In Eq. (2), the constant $A = e^2/4\pi\varepsilon\varepsilon_0$, $E = mv^2/2$ is the energy of the photoelectron before the ionized impurity scattering. The schematic figure of ionized impurity scattering is shown in Fig. 3. In this model, during the interaction between the photoelectron and

the Be ion, because the Be ion is much heavier than the photoelectron, the Be ion is static after the interaction, and the photoelectron stays away from the Be ion with the scattering angle φ. The $V(r)$ stands for the Coulomb potential that the photoelectron suffers from. The $\boldsymbol{u}$ and $\boldsymbol{u}'$ are the velocities relative to the Be ion before and after the ionized impurity scattering, respectively.

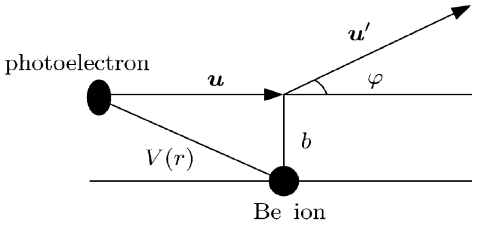


Fig. 3. Schematic figure of ionized impurity scattering.

Substituting $\varepsilon = 13.2$, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/M, and $e = 1.602 \times 10^{-19}$ C into the expression of A, we obtain the constant $A = 1.7483 \times 10^{-29}$ J·m. For 1 eV $= 1.6 \times 10^{-19}$ J, $A = 1.7483 \times 10^{-29}/(1.6 \times 10^{-19}) \times 10^9$ eV $\cdot$ nm $= 0.1093$ eV $\cdot$ nm. Finally, equation (2) becomes

$$\tan\left(\frac{\varphi}{2}\right) = \frac{0.1093}{Eb}. \tag{3}$$

In Eq. (3), the units of E and b are eV and nm, respectively.

3. Results and discussion

In order to calculate the MTF of the uniform-doping transmission-mode GaAs/GaAlAs photocathode, the trajectories of the photoelectrons exiting at initial angles must be calculated. The function $g(x)$ stands for the production function of photoelectrons exiting from one site,

$$g(x) = (1 - R - T) \times I_0 \times \exp(-\beta_{h\nu} \cdot t_w) \times \alpha_{h\nu} \times \exp(-\alpha_{h\nu} \cdot x). \tag{4}$$

In Eq. (4), R, T, and $\alpha_{h\nu}$ are the optical reflectivity, transmissivity, and optical absorption coefficient of the GaAs/GaAlAs photocathode, respectively, I_0 is the intensity of incident light, $\beta_{h\nu}$ and t_w are the optical absorption coefficient and the thickness of the GaAlAs, respectively, and x is the distance between a photoelectron excited site and the back interface of the active layer.

The distribution of the photoelectrons' initial angle is defined as

$$n(x, \theta) = g(x) \times \cos\theta. \tag{5}$$

In Eq. (5), θ is the bias angle between the velocity of the photoelectron and the longitudinal direction, and $n(x, \theta)$ stands for the number of photoelectrons exited at different angles and sites.

Considering the reflectance of GaAs/GaAlAs and the absorption coefficient, we calculated the full trajectories of photoelectrons exiting from one site in a GaAs photocathode under 633-nm light irradiation based on the above theoretical models and formulas. The photoelectrons would suffer from the photoelectron–lattice collision and the ionized impurity scattering while moving to the emit-face in the GaAs bulk. Opposite to the photoelectron–lattice collision, the ionized impurity scattering is an elastic collision without energy loss. This article assumes that the relationship between energy loss and the movement distance of the photoelectron is a linear function. Due to the limit of energy loss and the electron diffusion length, some photoelectrons would vanish and fail to reach the emit-face of the photocathode to contribute to the improvement of quantum efficiency. By tracking and calculating the trajectories of photoelectrons in the GaAs photocathode, we obtain the number of photoelectrons in different energies and different positions reaching the band bending zone, which is namely the distribution of photoelectron spots on the band bending zone. The surface barrier mainly affects the surface electron escape probability and has little effect on the distribution of photoelectron spots. The distribution of photoelectron spots on the band bending zone can be considered to be the distribution of photoelectron spots on the emit-face. Then the LSF can be obtained by means of the integral of the point spread function, which is the distribution of a light spot on the emit-face. Finally, the MTF is calculated by Fourier transform of the LSF. We let $I(y)$ represent the distribution of photoelectron spots on the emit-face and y represent the lateral position of photoelectrons reaching the band bending zone, then[13]

$$M_{\mathrm{c}} = \frac{\int_{-\infty}^{\infty} I(y) \cos(2\pi f y)\, \mathrm{d}y}{\int_{-\infty}^{\infty} I(y)\, \mathrm{d}y}, \tag{6}$$

$$M_{\mathrm{s}} = \frac{\int_{-\infty}^{\infty} I(y) \sin(2\pi f y)\, \mathrm{d}y}{\int_{-\infty}^{\infty} I(y)\, \mathrm{d}y}, \tag{7}$$

$$\mathrm{MTF} = M(f) = \left(M_C^2 + M_S^2\right)^{1/2}. \tag{8}$$

Using Eqs. (6)–(8), we calculate the theoretical MTF of uniform-doping transmission-mode GaAs photocathode. The parameters of the resolution theoretical model are shown in Table 1.

Table 1. Parametric table of resolution theoretical model.

Parameter	Numerical value
Wavelength of light/nm	633
Atomic concentration of GaAs/cm^{-3}	1×10^{22}
Energy loss every collision with lattice/meV	1.12
Distribution of initial exited angle	cosine distribution
Light absorption coefficient of GaAs active-layer/nm^{-1}	0.0674
Light absorption coefficient of GaAlAs/nm^{-1}	0.0039
Reflectivity of GaAs/GaAlAs	0.0058
Transmissivity of GaAs/GaAlAs	5×10^{-5}
Thickness of GaAlAs /μm	1
Interface recombination/cm^{-2}	∞

Changing respectively the values of the thickness of the GaAs active-layer $T_{\rm e}$, the electron diffusion length $L_{\rm D}$, and the doping concentration of the photocathode $n_{\rm A}$, and fixing other parameters, the MTFs are shown in Fig. 4. The results show that the MTF value decreases as the frequency grows. The changes in MTF depend on the lateral diffusion during the photoelectron movement towards the emit-face of the GaAs photocathode. With the same lateral diffusion length, a larger frequency would lead to a smaller fringe spacing, which is easier to overlap.

In Fig. 4(a), the MTF improves as the electron diffusion length of the GaAs photocathode decreases. It is now clear that the lateral diffusion length of the electron is shorter and the number of larger scattering angle photoelectrons reaching the band-bending zone drops by reducing the electron diffusion length $L_{\rm D}$. So the dispersion circle on the emit-face of the photocathode becomes smaller as the electron diffusion length decreases, and the resolution is improved relatively. For $L_{\rm D1} = 1$ μm and $L_{\rm D2} = 3.6$ μm, 2.4% and 11.59% photoelectrons reach the band-bending zone, respectively. Certainly, the MTF of the GaAs photocathode is improved at the expense of a reduction in quantum efficiency.

In Fig. 4(b), for the different active-layer thicknesses, the MTFs are improved when the frequency is more than 500 lp/mm, and basically remain the same when the frequency is smaller than 500 lp/mm. The less the thickness of the cathode, the lower the collision frequency of electron scattering with the Be ion and the lattice is, leading to less energy loss and a shorter electron path in the photocathode. Due to the electron diffusion length and the energy loss, the number of larger elastic scattering angle photoelectrons in the thin cathode is more than those in the thick one. For $T_{\rm e_1} = 1.8$ μm, $T_{\rm e_2} = 2$ μm, and $T_{\rm e_3} = 2.2$ μm respectively, 22.92%, 11.59%, and 5.78% photoelectrons reach the band-bending zone. We can conclude that a thinner cathode will lead to more electrons reaching the band-bending zone, but it may produce a larger dispersion circle on the emit-face, because the resolution of the cathode reduces as the thickness decreases.

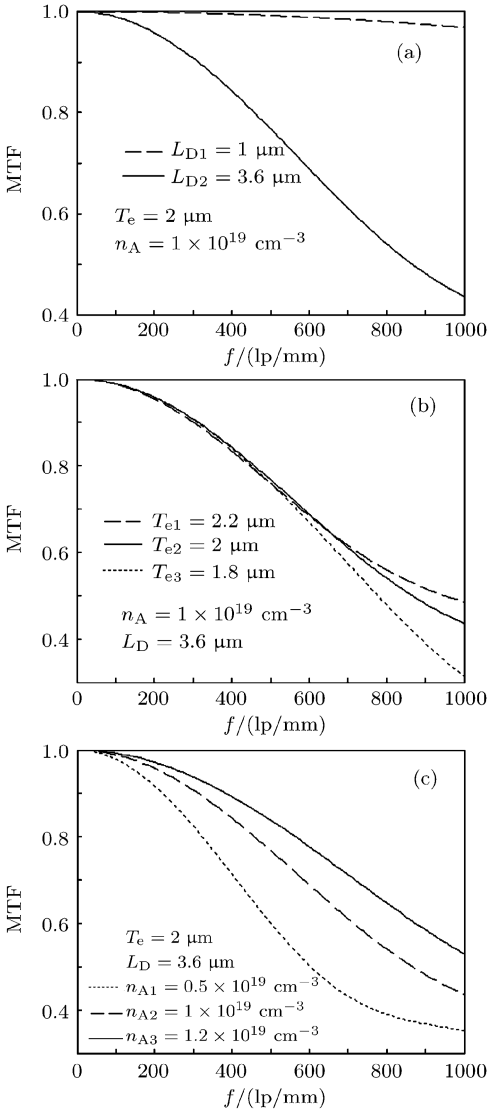


Fig. 4. The MTF of uniform-doping transmission-mode GaAs photocathode: (a) changing the value of $L_{\rm D}$, (b) changing the value of $T_{\rm e}$, and (c) changing the value of $n_{\rm A}$.

In Fig. 4(c), as the doping concentration of the Be ion increases, the MTF is improved. As $n_{\rm A}$ grows, the

collision between photoelectrons and the Be ion happens more frequently and the photoelectrons' overall transport distance increases. Due to the limit of electron diffusion length and energy loss, the larger elastic scattering angle electrons cannot reach the emit-face when $n_{\rm A}$ is relatively large, and the electron beam is concentrated at the band-bending zone. For $n_{\rm A1} = 0.5 \times 10^{19}$ cm^{-3}, $n_{\rm A2} = 1 \times 10^{19}$ cm^{-3}, and $n_{\rm A3} = 1.2 \times 10^{19}$ cm^{-3}, the percentages of photoelectrons reaching the band-bending zone are 64.2%, 11.59%, and 6.79%, respectively. The MTF values are all zero for the case where the doping concentration of the Be ion is more than the value at about 2×10^{19} cm^{-3} and the atomic concentration of the GaAs photocathode is 1×10^{22} cm^{-3}, when we calculate the resolution of the uniform-doping transmission-mode GaAs photocathode in different doping concentrations under the 633-nm light illuminated. This is because there are no photoelectrons reaching the band-bending zone.

From the above calculations, the MTF value of the photocathode is relatively higher than another part of the image intensifier. The resolution of the cathode is at least 2 orders of magnitude, and it looks as if its influence on the image intensifier could be neglected. But the parts are locked into each other of image intensifier actually, and the photocathode is at the front of the image intensifier. The influence of the cathode on the resolution must be taken into account, since the MTF value is not equal to 1, and the energy and angle distribution of the photoelectrons emitting into the vacuum seriously affect the resolution of the image intensifier.

4. Conclusion

According to the cosine distribution of the photoelectrons' initial angle, the trajectories of photoelectrons in a GaAs photocathode at different initial angles are mainly simulated. The MTF based on the photoelectron spots on the emit-face is obtained, and the relations of the resolution and parameters of the GaAs photocathode are discussed. The resolution and quantum efficiency cannot reach the maximum value, so there are optimum values for them. The calculations show that the MTF obtained from these simulations is shown to depend heavily on the electron diffusion length. The MTF is enhanced considerably by decreasing the electron diffusion length and increasing the doping concentration. Varying the doping concentration from 0.5×10^{19} cm^{-3} to 1.2×10^{19} cm^{-3} increases the MTF. Furthermore, the resolution is enhanced considerably by increasing the active-layer thickness, especially at high spatial frequencies. According to the definition of the "best spatial resolution", the image quality is very high when the MTF is equal to 0.5. So the best spatial resolution is 860 lp/mm, for the GaAs photocathode of doping concentration 1×10^{19} cm^{-3}, electron diffusion length 3.6 μm, and the active-layer thickness 2 μm, under the 633 nm light irradiated.

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