Resolution characteristics of transmission-mode exponential-doping GaN photocathodes

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According to the electron transport equation for the transmission-mode uniform-doping GaN photocathode, we have obtained the electron transport equation for the transmission-mode exponential-doping GaN photocathode. And then through solving this equation, the expression of modulation transfer function for an exponential-doping GaN photocathode is determined. Subsequently, the resolution characteristics of transmission-mode exponential-doping and uniform-doping GaN photocathodes are calculated and comparatively analyzed. Simultaneously, the quantum efficiencies of both GaN photocathodes are given. These calculated results show that the exponential-doping structure can upgrade remarkably not only the resolution but also the quantum efficiency of a negative electron affinity GaN photocathode, compared with the uniform-doping structure. This upgradation differs from the approach for high resolution by shortening the thickness of emission layer T_e and the diffusion length of electron L_d or by increasing the recombination velocity of back-interface S_V, which leads to a low quantum efficiency. Furthermore, the upgradation of resolution and quantum efficiency for a transmission-mode exponential-doping GaN photocathode result mainly from the facilitation of the electron transport and constraint of the lateral diffusion by the built-in electric field.

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1. Introduction

Negative electron affinity (NEA) GaN photocathodes find wide usage in ultraviolet (UV) detection for its high quantum efficiency, and become an ideal photocathode used in ultraviolet image intensifiers [1]. Concretely, the UV image intensifiers employing transmission-mode or reflection-mode GaN photocathode have been developed [2]. However, most research into a NEA GaN photocathode has focused on its quantum efficiency, preparation process and energy distribution [3-7], and relatively little attention has been paid to the resolution characteristics.

In image intensification applications, the role of the resolution characteristics of a photocathode is very important [8].This is mainly because the photocathode must not only detect the incident light but also faithfully convert the light image to a photoelectron image. Precisely during this conversion, the resolution is degraded within the photocathode mainly due to the lateral diffusion of photoelectrons. Some meaningful work [9-11] indicates that the degradation of resolution may be offset to some degree, if there is an electric field which is contrary to the direction of photoelectrons transport towards the surface of a NEA photocathode. As can be seen from Figs. 1 and 2, the exponential -doping structure shapes the bent-band region that linearly slopes downwards and then generates a constant built-in electric field [12]. Therefore, an exponential-doping GaN photocathode just meet the requirement of offsetting the degradation of resolution. Additionally, this photocathode can achieve higher quantum efficiency, which has been experimentally verified [13, 14]. Fig. 3 shows that the diameter of dispersion circle formed by the lateral diffusion of photoelectrons at an exponential-doping GaN photocathode surface is smaller than that at a uniform-doping GaN photocathode surface, since the latter cannot generate a built-in electric field. Naturally, the resolution of GaN photocathode would be upgraded by the electron drift motion which results from this electric field. It will be important in further discussions to determine the dependence of resolution on the parameters of a GaN photocathode. Besides, the quantum efficiency of a GaN photocathode, which is an another important indicator for an UV image intensifier, should also be considered. In other words, the relationship between the quantum efficiency and the resolution must be researched. To this end, using the modulation transfer function (MTF), we have obtained a family of curves that describe the above relationship among variables. Accordingly, comparative analysis of the resolution characteristics of transmission-mode exponential-doping and uniform-doping GaN photocathodes is presented, and the corresponding values of quantum efficiencies are given in this paper.

2. Derivation of an MTF Expression

MTF is a standard measure of the resolution characteristics of an imaging system, in this case, a photocathode [8]. In this section, by establishing and then solving two-dimensional electron transport equation, the expression of MTF for a transmission-mode exponential-doping GaN photocathode has been given. This derivation is as follows.

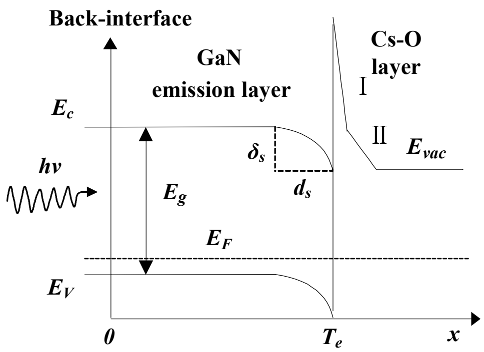

Fig. 1. Band structure diagram of a transmission-mode uniform-doping GaN photocathode E_c. is the conduction-band minimum, E_V is the valence-band maximum, E_g is the band gap, E_F is the Fermi level, δ_S and d_S are the height and width of the bent-band region, respectively, and E_{vac} is the vacuum level.

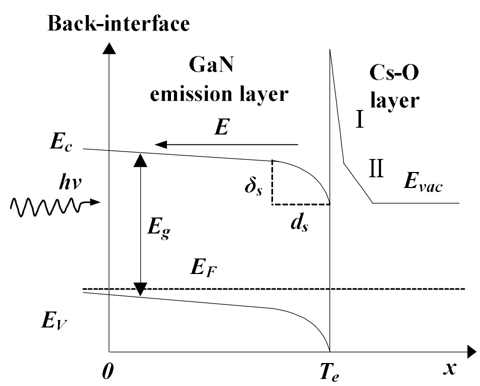

Fig. 2. Band structure diagram of a transmission-mode exponential-doping GaN photocathode. E is the strength of built-in electric field

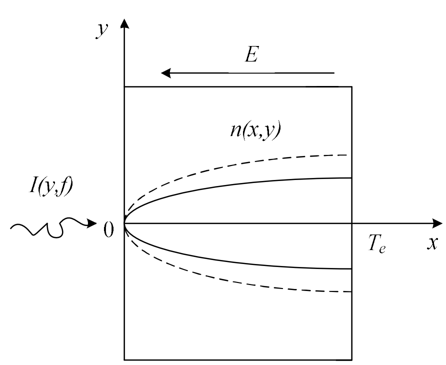

Fig.3. Schematic diagram of electron transport within a GaN photocathode. Solid lines represent electron transport with a constant built-in electric field; Dashed lines represent electron transport without this electric field

As shown in Fig. 3, we assume that there is a beam of the incident light which is normal to the substrate of a transmission-mode exponential-doping GaN photocathode, and its intensity $I(y,f)$ is defined as

$$I(y,f)=\frac{\phi}{2}[1+\cos(2\pi fy)] \tag{1}$$

where ϕ is the incident light flux, and f is the spatial frequency. For a uniform-doping GaN photocathode, the model used for the generation of photoelectrons and then their transport towards the surface is given by [15]

$$\frac{\partial^2 n(x,y)}{\partial x^2}+\frac{\partial^2 n(x,y)}{\partial y^2}-\frac{n(x,y)}{L_d{}^2}+\frac{G(x,y)}{D_n}=0 \qquad (x\in[0,T_e],\, y\in Real) \tag{2}$$

where x is the distance between a point within the emission layer and surface of GaN photocathode, $n(x,y)$ is the photoelectron density, L_d is the diffusion length of electron, D_n is the diffusion coefficient of electron, and T_e is the thickness of emission layer. In addition, $G(x,y)$ is the generation function of photoelectron that varies spatially, and it takes the form of

$$G(x,y)=\alpha(1-R)\exp(-\alpha x)I(y,f) \tag{3}$$

where α is the optical absorption coefficient, and R is the reflectivity of GaN photocathode. It should be emphasized that, for an exponential-doping GaN photocathode, since the constant built-in electric field is generated, the photoelectron transport model should be modified as

$$\frac{\partial^2 n(x,y)}{\partial x^2}+\frac{\partial^2 n(x,y)}{\partial y^2}-\frac{q|E|}{kT}-\frac{n(x,y)}{L_d{}^2}+\frac{G(x,y)}{D_n}=0 \qquad (x\in[0,T_e],\, y\in Real) \tag{4}$$

where q is the electronic charge, k is Boltzmann's constant, and T is the temperature. The boundary condition of Eq.(4) is given by

$$D_n\left[\frac{\partial n(x,y)}{\partial x}-\frac{q|E|}{kT}n(x,y)\right]_{x=0}=S_V n(x,y)\big|_{x=0}, \qquad n(x,y)\big|_{x=T_e}=0 \tag{5}$$

where S_V is the recombination velocity of back-interface.

In order to obtain the solution for Eq.(5) which is a complex second-order partial differential equation, it is necessary to implement Fourier transform of this equation about y. Suppose that the Fourier transform of $n(x,y)$ is denoted as $F[n(x,y)]=n(x,\lambda)$, the ordinary differential equation with regard to x can be obtained and given by

$$D_n\left[\frac{d^2n(x,\lambda)}{dx^2}-\frac{q|E|}{kT}\cdot\frac{dn(x,\lambda)}{dx}-\left(\lambda^2+\frac{1}{L_d^2}\right)n(x,\lambda)\right] +\alpha(1-R)\exp(-\alpha x)\cdot \left[\sqrt{2\pi}\delta(\lambda)+\sqrt{\frac{\pi}{2}}\left(\delta(\lambda+\omega)+\delta(\lambda-\omega)\right)\right]=0 \tag{6}$$

Furthermore, its boundary condition is in the form of

$$\left[D_n\frac{dn(x,\lambda)}{dx}-\frac{q|E|}{kT}n(x,\lambda)\right]\Bigg|_{x=0}=S_V n(x,\lambda)\big|_{x=0}, \quad n(x,\lambda)\big|_{x=T_e}=0 \tag{7}$$

After solving Eq.(6) for $n(x,y)$, by the inverse Fourier transform, we can obtain the expression of photocurrent density of transmission-mode exponential-doping GaN photocathode, and it is denoted as

$$J_T(y,f)=-PD_n\frac{\partial n(x,y)}{\partial x}\bigg|_{x=T_e} =\frac{\phi}{2}\left[Y_{T0}+Y_{T\omega}\cos(2\pi fy)\right] \tag{8}$$

where P is the surface escape probability of photoelectrons, Y_0 and Y_ω are the quantum efficiencies of GaN photocathode with the uniform and cosine distribution of incident light, respectively. And then both expressions are given by

$$Y_0=\frac{P(1-R)\alpha L_d}{\alpha^2L_d^2+\alpha L_0-1}\cdot \left\{\frac{N_0(S+\alpha D_n)\exp\left(\frac{L_0T_e}{2L_d^2}\right)-Q_0\exp(-\alpha T_e)}{M_0}-\alpha L_d\exp(-\alpha T_e)\right\} \tag{9}$$

$$Y_\omega=\frac{P(1-R)\alpha L_d'}{\alpha^2L_d'^2+\alpha L_\omega-1}\cdot \left\{\frac{N_\omega(S+\alpha D_n)\exp\left(\frac{L_\omega T_e}{2L_d'^2}\right)-Q_\omega\exp(-\alpha T_e)}{M_\omega}-\alpha L_d'\exp(-\alpha T_e)\right\} \tag{10}$$

where,

$$L_0=\frac{q|E|}{kT}L_d^2,\ S=S_V+\frac{q|E|}{kT}D_n,\ N_0=\sqrt{L_0^2+4L_d^2},$$

$$M_0=\frac{N_0D_n}{L_d}\cosh\left(\frac{N_0T_e}{2L_d^2}\right)+\left(2SL_d-\frac{L_0D_n}{L_d}\right)\sinh\left(\frac{N_0T_e}{2L_d^2}\right),$$

$$Q_0=SN_0\cosh\left(\frac{N_0T_e}{2L_d^2}\right)+\left(SL_0+2D_n\right)\sinh\left(\frac{N_0T_e}{2L_d^2}\right),$$

$$L_d'=\sqrt{\frac{L_d^2}{L_d^2\omega^2+1}},\ L_\omega=\frac{q|E|}{kT}L_d'^2,\ N_\omega=\sqrt{L_\omega^2+4L_d'^2},$$

$$M_\omega=\frac{N_\omega D_n}{L_d'}\cosh\left(\frac{N_\omega T_e}{2L_d'^2}\right)+\left(2SL_d'-\frac{L_\omega D_n}{L_d'}\right)\sinh\left(\frac{N_\omega T_e}{2L_d'^2}\right),$$

$$Q_\omega=SN_\omega\cosh\left(\frac{N_\omega T_e}{2L_d'^2}\right)+\left(SL_\omega+2D_n\right)\sinh\left(\frac{N_\omega T_e}{2L_d'^2}\right).$$

From a practical standpoint, the definition of MTF is the ratio of C_ω to C_0 when the image is formed by a light with cosine distribution at a certain spatial frequency, where C_ω and C_0 are the contrast of image plane and objective plane, respectively. For a GaN photocathode, C_ω is actually the contrast of photoemission current density. Therefore, the MTF expression for transmission-mode exponential-doping GaN photocathode takes the form of

$$MTF(f)=\frac{C_\omega}{C_0}=\frac{Y_\omega/Y_0}{1}=\frac{Y_\omega}{Y_0} \tag{11}$$

More concretely,

$$MTF(f)=\frac{L_d'M_0(\alpha^2L_d^2+\alpha L_0-1)}{L_dM_\omega(\alpha^2L_d'^2+\alpha L_\omega-1)} \cdot\left[\frac{N_\omega(s+\alpha D_n)\exp\left(\frac{L_\omega T_e}{2L_d'^2}\right)-Q_\omega\exp(-\alpha T_e)-M_\omega\alpha L_d'\exp(-\alpha T_e)}{N_0(s+\alpha D_n)\exp\left(\frac{L_0T_e}{2L_d^2}\right)-Q_0\exp(-\alpha T_e)-M_0\alpha L_d\exp(-\alpha T_e)}\right] \tag{12}$$

Moreover, the MTF expression for transmission-mode uniform-doping GaN photocathode can be obtained when $|E|$=0 in Eq. (4).

3. Calculations and analyses

According to the expression (12), we have calculated the MTF and comparatively analysed the resolution characteristics of transmission-mode exponential-doping and uniform-doping GaN photocathodes. Meanwhile, the dependence of resolution on L_d, T_e, α, and S_V has been researched. Furthermore, in order to evaluate the overall performance of both GaN photocathodes, the corresponding values of quantum efficiency Y are given. The calculation condition is that the amount of bent-band is 0.073eV, P =0.36, R =0.2, and $D_n=25cm^2/s$ at room temperature [11]. Varying L_d, T_e, α, and S_V individually, we can obtain a family of MTF curves for transmission-mode exponential-doping and uniform-doping GaN photocathodes. Particularly, these MTF curves for each set of parameter values along with the corresponding values of Y when the spatial frequencies f is in the range of 0 to 1200 lp/mm are shown in Figs.4-7.

From the data of all four figures, it is clear that each MTF curve drops off as f increases. This decrease is mainly caused by the lateral diffusion of electrons. Even if for a given f, the changes in MTF curves with several parameters for a GaN photocathode can be explained in terms of the effect of lateral diffusion. More importantly, the exponential-doping structure is able to upgrade the resolution of GaN photocathode definitely in most cases, compared with the uniform-doping one. And then the comparative analyses of the effect of L_d, T_e, α, and S_V on MTF are given.

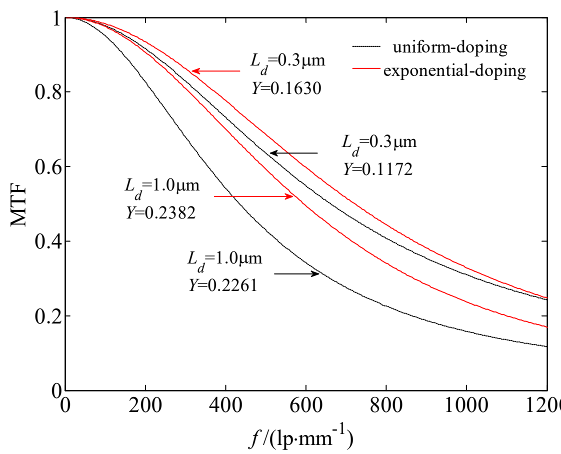

Fig. 4. MTF of the exponential-doping and uniform-doping GaN phoctocathodes for L_d=0.3 μm and 1.0μm and the corresponding values of Y when T_e = 0.6μm, α =4×10^{4}cm^{-1} and S_V=0

Fig. 4 shows that both MTF for exponential-doping and uniform-doping GaN photocathodes rise when the diffusion length of electron L_d shortens, and the latter rises more evidently. The reason has two fold: for a short L_d, the electrons do not reach the back-interface, and thus they cannot be influenced by the condition there. The lateral diffusion is minimized since the electrons escaping into vacuum mainly come from the region near the NEA surface. At the same time, with shortening the distance of lateral diffusion of electrons, the function of built-in electric field is gradually weakened. However, it is important to notice that the price for high resolution obtained with a short L_d is paid in the loss of the quantum efficiency Y for both GaN photocathodes.

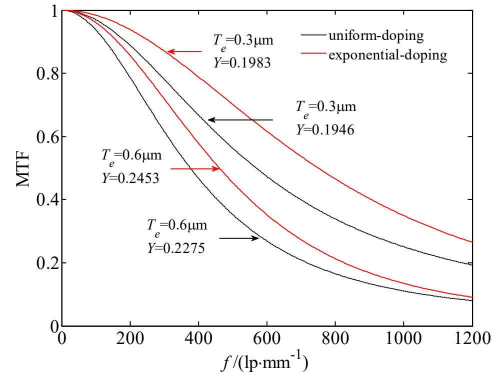

Fig. 5. MTF of the exponential-doping and uniform-doping GaN phoctocathodes for T_e = 0.3 μm and 0.3 μm and the corresponding values of Y, when L_d = 1.0 μm, α = 4 × 10^4 cm^{-1}, and S_V = 0.

Fig. 5 shows that the MTF for both GaN photocathodes rise markedly with shortening the thickness of emission layer T_e, and the MTF for exponential-doping GaN photocathode rises more obviously. This is mainly attributed to the reduced lateral diffusion distance of electrons and the facilitated electron transport by a stronger built-in electron field E for a shorter T_e. Nevertheless, it should be emphasized that a shorter T_e would result in a lower quantum efficiency at short-wavelength. Besides, for a commercial transmission-mode GaN photocathode, the effect of the variation of T_e on the quantum efficiency at various wavelengths is different. With a shorter T_e, the response at short-wavelength increases, while that at long wave-length decreases significantly. On the contrary, for a longer T_e, the quantum efficiency at full-wavelength range decreases and the strength of built-in electric field formed by the exponential-doping structure is weak. As a consequence, there is an optimal thickness of T_e (T_{em}) for a transmission -mode GaN photocathode.

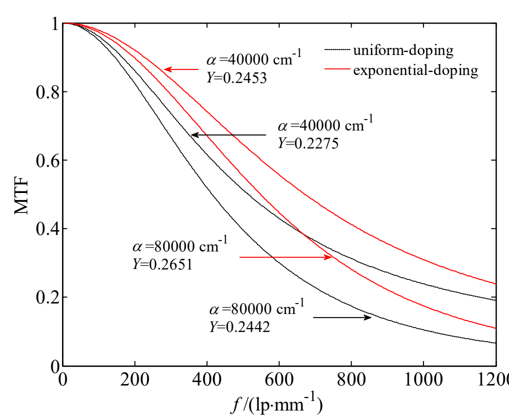

Fig. 6. MTF of the exponential-doping and uniform-doping GaN phoctocathodes for α = 40000 cm^{-1} and 80000 cm^{-1} and the corresponding values of Y, when T_e = 0.6 μm, L_d = 1.0 μm and S_V = 0

As can be seen from Fig. 6, with increasing the optical absorption coefficient α, the MTF for both GaN photocathodes drops off. This degradation is mainly due to the fact that a greater fraction of electrons is generated near the cathode back-interface as α increases. For a larger α, the electrons naturally have a longer distance to transport towards the NEA surface, and thus diffuse farther laterally. In the meantime, when $T_e \le T_{em}$, the quantum efficiency Y increases with increasing α because of the increased number of photoexcited electrons, most of which can escape into the vacuum. For $T_e > T_{em}$, Y decreases with increasing α. The latter may be interpreted by two-fold. On one hand, for a small α, the light absorption is approximately uniform throughout GaN photocathode, which means that there is an appreciable number of electrons generated within a diffusion length of the photocathode surface. As α increases, fewer electrons are generated near the surface. On the other hand, for the case when α is small, there are multiple internal reflections, increasing the number of electrons generated near the emission surface. With increasing α, this enhancement decreases.

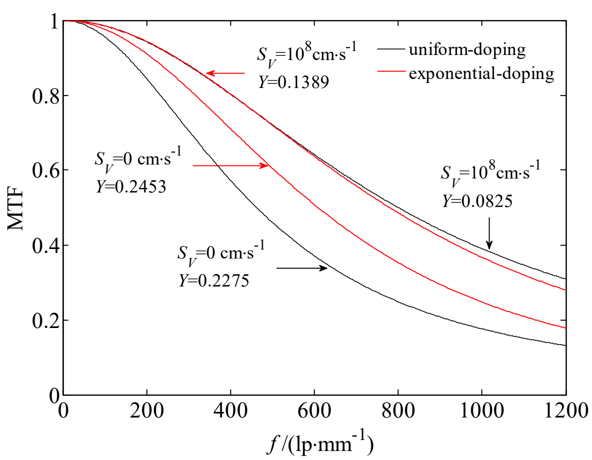

Fig. 7. MTF of the exponential-doping and uniform-doping GaN phoctocathodes for $S_V = 0$ and $10^8 cm\cdot s^{-1}$, and the corresponding values of Y, when $T_e = 0.6\mu m$, $L_d = 1.0\mu m$, and $\alpha = 4\times 10^4 cm^{-1}$

Fig. 7 shows that the MTF for both GaN photocathodes improve as the recombination velocity of back-interface S_V increases, whereas the uniform-doping GaN photocathode improves more evidently. When $S_V = 10^8 cm\cdot s^{-1}$, both MTF have almost identical properties, in other words, the exponential-doping structure has almost no effect on the resolution. When $S_V = 0$, the electrons are perfectly reflected from the back-interface, and hence a large fraction of emitted electrons diffuse further laterally owing to a longer diffusion distance, which can be reduced by the built-in electric field for an exponential-doping GaN photocathode. As a result, the resolution of exponential-doping GaN photocathode is much higher than that of uniform-doping counterpart for a small S_V.

For a large S_V ($10^8 cm\cdot s^{-1}$), most electrons reaching the back-interface are recombined, i.e., the effect of the built-in electric field E can be neglected. This condition upgrades the MTF with increasing S_V, however, it should be noted that along with high resolution, the quantum efficiency decreases. Those emitted electrons degrading the quantum efficiency are just the ones upgrading the MTF. Additionally, the value of S_V is partly governed by the cathode/substrate lattice match and the energy band profile at the back-interface. Specifically, the better lattice match in practical films can decrease S_V and enable more electrons to reach the NEA surface, and thus films can be optimized.

As described previously, with the exception of a very large value of S_V, the exponential-doping structure can significantly upgrade the resolution of a transmission-mode GaN photocathode. This improvement results mainly from the facilitated electron transport towards the NEA surface and their reduced lateral diffusion. More importantly, it can be found that the approach using the exponential-doping structure by which a high MTF is obtained differs from that of reducing T_e, L_D or increasing S_V which results in a high MTF but a low quantum efficiency. Moreover, the selection of values of these parameters is in no way arbitrary. For instance, the optical absorption coefficient α is basically fixed for a commercial GaN photocathode. Therefore, maximum resolution and high quantum efficiency obtained by varying these parameters are contradictory requirements, and a compromise must be made in application.

4. Conclusions

In conclusion, the resolution characteristics of transmission-mode exponential-doping and uniform-doping GaN photocathodes have been calculated and comparatively analysed by using the MTF expression. The calculated results show that the exponential-doping structure can upgrade significantly the resolution and the quantum efficiency of a transmission-mode GaN photocathode. It is different from the approach for high resolution by reducing T_e, L_D or increasing S_V which lead to a low quantum efficiency. And consequently, the transmission-mode exponential-doping NEA GaN photocathode has a potential advantage in UV image intensifiers.

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