Comparative research on resolution characteristics between transmission-mode exponential-doping and uniform-doping GaAs photocathodes

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Using the modulation transfer function obtained by establishing and solving the two-dimensional continuity equation, we have calculated and comparatively analysed the resolution characteristics of transmission-mode exponential-doping and uniform-doping GaAs photocathodes. The calculated results show that, compared with the uniform-doping GaAs photocathode, the exponential-doping structure can upgrade significantly not only the resolution but also the quantum efficiency of a negative electron affinity GaAs photocathode. This improvement differs from the method for high resolution by reducing the emission layer T_e and the electron diffusion length L_d or by increasing the recombination velocity of back-interface S_V, which leads to a low quantum efficiency. Moreover, the improvement of resolution and quantum efficiency for transmission-mode exponential-doping GaAs photocathode is the result of facilitating the electron transport and restraining the lateral diffusion by the built-in electric field.

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Keywords: GaAs photocathode, Resolution, Exponential-doping, Modulation transfer function

1. Introduction

Negative electron affinity (NEA) GaAs photocathodes have several important applications in image intensifiers and polarized electron sources [1-4]. In the past decades, we have witnessed intensive research activity in the quantum efficiency and the energy distribution of GaAs photocathodes [5-10], whereas relatively little attention has been paid to the resolution.

The resolution characteristics of a photocathode is an important indicator in imaging applications [11]. Not only must the photocathode detect the incident light, but also it must reliably convert the optical image into a photoelectron image. Unfortunately, during the conversion of the light signal into an electronic signal, the resolution is degraded within the photocathode mainly because of the lateral diffusion of photoelectrons. Some propitious work [12-14] has shown that the degradation of the resolution may be offset to a certain extent, if there is an electric field along the opposite direction of photoelectrons transport towards the surface of a NEA photocathode. As shown in Figs. 1 and 2, the exponential -doping structure forms the bent-band region which linearly slopes downwards and then generates a constant built-in electric field [15]. Interestingly, an exponential-doping photocathode with this constant built-in electric field properly satisfies the demand of offsetting the degradation of the resolution. At the same time, it can achieve higher quantum efficiency, which has been experimentally verified [16,17]. Particularly, Fig. 3 shows that the size of the dispersion circle generated by lateral diffusion of photoelectrons at exponential-doping GaAs photocathode surface is smaller than that at uniform-doping GaAs photocathode surface, since the latter cannot generate the above built-in electric field. Therefore, the resolution of a NEA photocathode would be improved by electron drift motion resulting from this electric field. In a bid to further study the dependence of resolution on the parameters of GaAs photocathode, we have obtained a group of curves describing the relationship among variables through the modulation transfer function (MTF). Calculations and comparative analysis of the resolution characteristics and corresponding values of the quantum efficiency for transmission-mode exponential-doping and uniform-doping GaAs photocathodes are given in this paper.

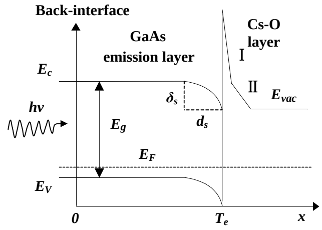

Fig. 1. Band structure diagram of the transmission-mode uniform-doping GaAs photocathode. E_c is the conduction-band minimum; E_V is the valence-band maximum; E_g is the band gap; E_F is the Fermi level; δ_s and d_s are the height and width of the surface bent-band region, respectively; and E_{vac} is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

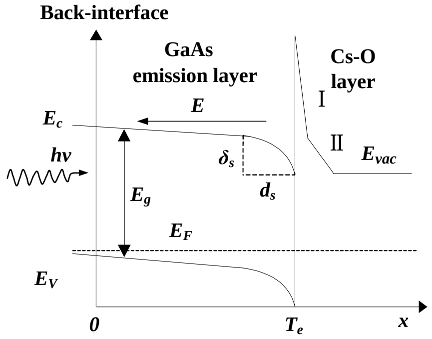

Fig. 2. Band structure diagram of the transmission-mode exponential-doping GaAs photocathode. E is the strength of built-in electric field

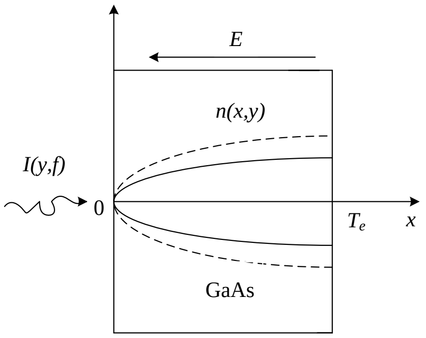

Fig. 3. Schematic diagram of electron transport within a GaAs photocathode. Solid lines denote electron transport with constant built-in electric field; Dashed lines denote electron transport without this electric field

2. Derivation of an MTF expression

As a standard measure of the resolution characteristics of an imaging system, in this case, MTF characterizes transfer of input pattern and contrast reduction (such as sinusoidal wave) by the photocathode [11]. In this section, through establishing and then solving two-dimensional equation, the expression of MTF for transmission-mode exponential-doping GaAs photocathode has been obtained. The derivation of MTF expression is given as follows.

In Fig. 3, assuming that there is a beam of the incident light which is normal to the substrate of the transmission-mode exponential-doping GaAs photocathode, and its intensity $I(y,f)$ takes the form of

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

where ϕ is the flux of incident light, and f is the spatial frequency. For a uniform-doping GaAs photocathode, the model used for the generation of internal photoelectrons and their subsequent diffusion to the surface is given by [18]

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

where x represents the distance between a point within the emission layer and the surface of GaAs photocathode; $n(x,y)$ is the density of photoelectron, L_d is the diffusion length of electron, D_n is the diffusion coefficient of electron in GaAs photocathode, and T_e is the thickness of emission layer within GaAs photocathode. Moreover, $G(x,y)$ is the photoelectron-generating function varying spatially, and it is in 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 for GaAs photocathode. However, for an exponential-doping GaAs photocathode, since the constant built-in electric field is formed, the model should be modified as

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

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 denotes the recombination velocity of back -interface.

To obtain the solution for Eq.(5) that is a complex second-order partial differential equation, it is necessary to implement Fourier transform of this equation with regard to y. Assuming that Fourier transform of $n(x,y)$ is expressed as $F[n(x,y)]=\tilde{n}(x,\lambda)$, this ordinary differential equation on x is given by

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

and its boundary condition is given by

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

After solving Eq.(6) for $\tilde{n}(x,y)$, the expression of photocurrent density of transmission-mode exponential-doping GaAs photocathode is obtained by the inverse Fourier transform, and is shown as

$$\begin{aligned} J_T(y,f) &= -PD_n \left.\frac{\partial n(x,y)}{\partial x}\right|_{x=T_{e1}} \\ &= \frac{\phi}{2}\left[Y_{T0} + Y_{T\omega}\cos(2\pi fy)\right] \end{aligned} \tag{8}$$

where P is the surface escape probability of photoelectrons, Y_{T0} and $Y_{T\omega}$ are the quantum efficiency of photocathode pertaining to uniform and cosine distribution of incident light, respectively. Furthermore, both expressions are given by

$$Y_{T0} = \frac{P(1-R)\alpha L_d}{\alpha^2 L_d{}^2 + \alpha L_0 - 1}\cdot \left\{ \frac{N_0(S+\alpha D_n)\exp\left(\frac{L_0 T_e}{2L_d{}^2}\right) - Q_0\exp(-\alpha T_e)}{M_0} - \alpha L_d \exp(-\alpha T_e) \right\} \tag{9}$$

$$Y_{T\omega} = \frac{P(1-R)\alpha L_d{}'}{\alpha^2 L_d{}'^2 + \alpha L_\omega - 1}\cdot \left\{ \frac{N_\omega(S+\alpha D_n)\exp\left(\frac{L_\omega T_e}{2L_d{}'^2}\right) - Q_\omega\exp(-\alpha T_e)}{M_\omega} - \alpha L_d{}' \exp(-\alpha T_e) \right\} \tag{10}$$

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

$$M_0 = \frac{N_0 D_n}{L_d}\cosh\left(\frac{N_0 T_e}{2L_d{}^2}\right) + \left(2SL_d - \frac{L_0 D_n}{L_d}\right)\sinh\left(\frac{N_0 T_e}{2L_d{}^2}\right),$$

$$Q_0 = SN_0\cosh\left(\frac{N_0 T_e}{2L_d{}^2}\right) + \left(SL_0 + 2D_n\right)\sinh\left(\frac{N_0 T_e}{2L_d{}^2}\right),$$

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

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

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

In reality, 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 is the contrast of image plane, and C_0 is the contrast of objective plane. For a GaAs photocathode, C_ω is actually the contrast of photoemission current density. Thus, the MTF expression for transmission-mode exponential-doping GaAs photocathode is in the form of

$$MTF(f) = \frac{C_\omega}{C_0} = \frac{Y_{T\omega}/Y_{T0}}{1} = \frac{Y_{T\omega}}{Y_{T0}} \tag{11}$$

Concretely,

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

Additionally, by modifying the expression (12) appropriately, we can obtain the MTF expression for transmission-mode uniform-doping GaAs photocathode 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 GaAs photocathodes. At the same time, the dependence of resolution characteristics on L_d, T_e, α, and S_V has been investigated in detail. Furthermore, to evaluate the overall performance of both GaAs photocathodes, we have given the corresponding values of quantum efficiency Y_T. The conditions for calculations are assumed that the matching amount of bent-band is 0.06eV when doping concentration varies exponentially in the range of $1\times10^{18}cm^{-3}$ to $1\times10^{19}cm^{-3}$, P =0.5, R =0.31, and $D_n = 120cm^2/s$ at room temperature [19,20]. By varying L_d, T_e, α, and S_V individually, a group of MTF curves for transmission-mode exponential-doping and uniform-doping GaAs photocathodes are obtained. Specifically, these MTF curves for each set of parameter values along with the corresponding values of Y_T as the spatial frequencies f ranges from 0 to 800 lp/mm are shown in Figs. 4-7.

The most striking feature in all four figures is that each MTF curve drops off as f increases. This decrease is mainly caused by the lateral diffusion of photoelectrons. Even if for a given f, the changes in MTF curves with several parameters for a GaAs photocathode can be interpreted in accordance with the effect of lateral diffusion. More importantly, the exponential-doping structure is capable of improving the resolution characteristics of GaAs 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 presented in more detail.

Fig. 4 shows that both MTF for exponential-doping and uniform-doping GaAs photocathodes increases with decreasing the electron diffusion L_d , and the latter improves more obviously. Its reason has two fold: for a short L_d, the electrons cannot reach the back-interface, and thus they are not 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. Simultaneously, as the distance of lateral diffusion of electrons shortens, the role of electric field is gradually weakened. Nevertheless, it should be noted that the price for high resolution obtained with a short diffusion length L_d is paid in the loss of quantum efficiency Y_T for both GaAs photocathodes.

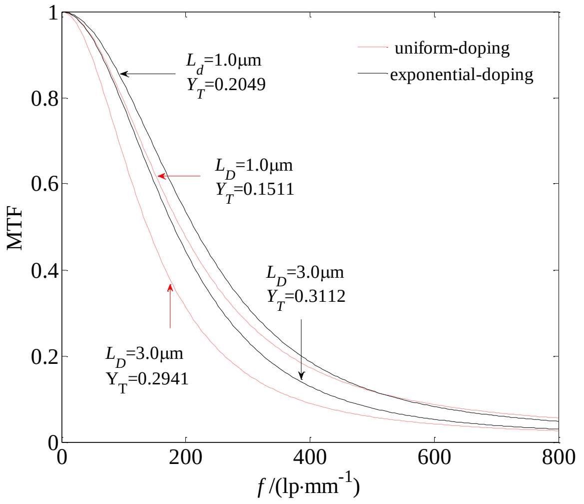

Fig. 4. MTF of exponential-doping and uniform-doping GaAs phoctocathodes for $L_d = 1.0\mu m$ *and* $3.0\mu m$ *, and corresponding values of* Y_T *assuming* $T_e = 1.6\mu m$, $\alpha = 2\times10^4 cm^{-1}$, *and* $S_V = 0$

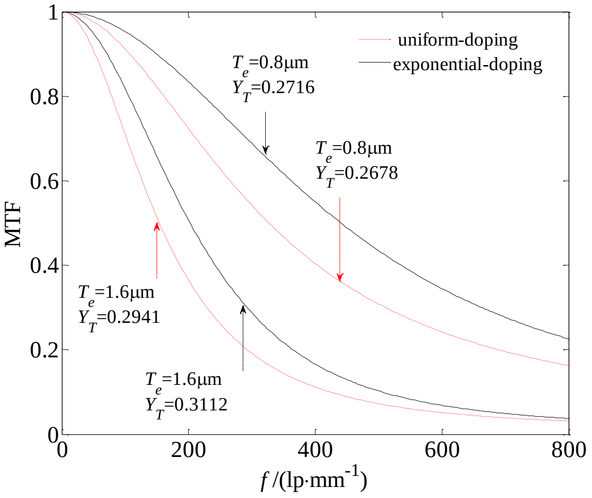

Fig. 5. MTF of exponential-doping and uniform-doping GaAs phoctocathodes for $T_e = 0.8\mu m$ *and* $1.6\mu m$ *, and corresponding values of* Y_T *assuming* $L_d = 3.0\mu m$, $\alpha = 2\times10^4 cm^{-1}$, *and* $S_V = 0$

Fig. 5 shows that the MTF for both GaAs photocathodes upgrade significantly as the thickness of emission layer T_e shortens, and the MTF for exponential-doping GaAs photocathode increases more evidently. The main reason of this effect is the reduced lateral diffusion distance of electrons and the facilitated electron transport by a stronger built-in E for a shorter T_e. However, it should be emphasized that a shorter T_e would lead to a lower quantum efficiency at short-wavelength. In addition, for a given transmission-mode GaAs photocathode, the influence of the variation of T_e on the quantum efficiency at varying wavelengths is different. With a shorter T_e, the response at short-wavelength increases, whereas the one at long wave-length decreases obviously. Conversely, for a longer T_e, the quantum efficiency at full-wavelength range decreases and the built-in electric field generated by exponential-doping structure is weak. Therefore, there is an optimal thickness of T_e (T_{em}) for the transmission-mode GaAs photocathode.

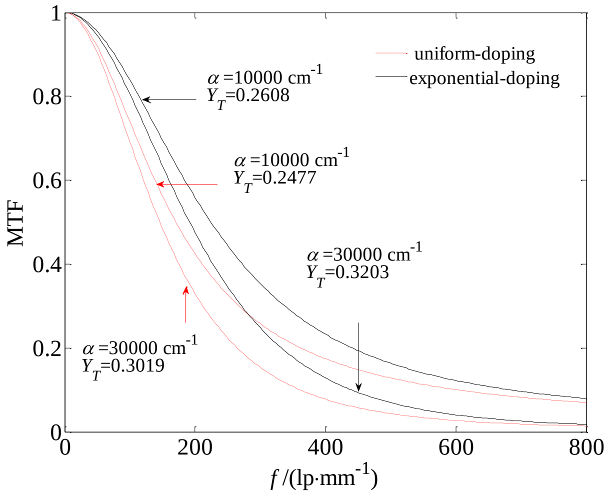

Fig. 6. MTF of exponential-doping and uniform-doping GaAs phoctocathodes for $\alpha = 10000 cm^{-1}$ *and* $30000 cm^{-1}$, *and corresponding values of* Y_T *, assuming* $T_e = 1.6\mu m$, $L_d = 3.0\mu m$, *and* $S_V = 0$

As shown in Fig. 6, as the optical absorption coefficient α increases for both transmission-mode GaAs photocathodes, their MTF drops off. This degradation occurs mainly because a greater fraction of the electrons is generated near the cathode back-interface with increasing α. For a larger α, the electrons generally have a longer distance to transport towards the NEA surface, and hence diffuse farther laterally. Meanwhile, for the case of $T_e \le T_{em}$, the quantum efficiency Y_T increases with increasing α, owing to the increased number of photoexcited electrons, most of which can escape. For $T_e > T_{em}$, Y_T decreases with increasing α. The latter effect may be explained by two aspects. On one hand, for a small α, light absorption is approximately uniform throughout GaAs 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, when α is small, there are multiple internal reflections, increasing the number of electrons generated near the emission surface. As α increases, this enhancement decreases.

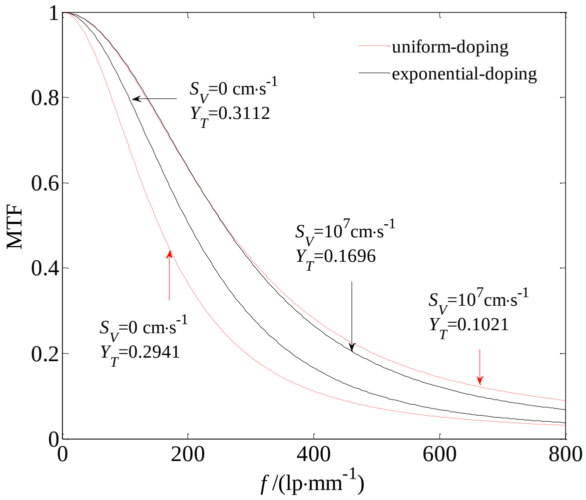

Fig. 7. MTF of exponential-doping and uniform-doping GaAs phoctocathodes for $S_V = 0$ *and* $10^7 cm \cdot s^{-1}$ *,and corresponding values of* Y_T *assuming* $T_e = 1.6 \mu m$, $L_d = 3.0 \mu m$, *and* $\alpha = 2 \times 10^4 cm^{-1}$

Fig. 7 shows that the MTF for both GaAs photocathodes upgrade with increasing the recombination velocity of back-interface S_V , whereas the uniform-doping GaAs photocathode upgrades more obviously. When $S_V = 10^7 cm \cdot s^{-1}$ both MTF have almost identical characteristics, i.e., 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 thus a large fraction of emitted electrons diffuse further laterally because of a longer diffusion distance, which can be reduced by the built-in electric field for exponential-doping GaAs photocathode. Accordingly, the resolution of exponential-doping GaAs photocathode is much higher than that of uniform-doping counterpart for a small S_V .

For a large S_V ($10^7 cm \cdot s^{-1}$ or larger), most electrons reaching the back-interface are lost, which means that the role of the built-in electric field E can be neglected. This condition upgrades the MTF by increasing S_V , but, it should be noted that along with high resolution, the quantum efficiency degrades. Those emitted electrons that degrade the quantum efficiency are just the ones that upgrade the MTF. In addition, the value of S_V would be influenced by the cathode/substrate lattice match and the energy band profile at the back-interface. Furthermore, the better lattice match in real films can decrease S_V and enable more electrons to reach the NEA surface, and hence films can be optimized.

As discussed above, except for a very large value of S_V , the exponential-doping structure can significantly improve the resolution characteristics of a transmission-mode GaAs photocathode. This improvement is the result of the facilitated electron transport towards the NEA surface and their reduced lateral diffusion. More importantly, it can be found that the method employing the exponential-doping structure by which a high MTF is obtained differs from the approach of reducing T_e , L_D or increasing S_V which leads to a high MTF but a low quantum efficiency. Besides, the selection of values of the above parameters is by no means arbitrary. For example, the optical absorption coefficient α pertaining to the wavelength of incident light is basically fixed for a given GaAs photocathode. Consequently, maximum resolution and high quantum efficiency with varying these parameters are contradictory requirements, and a compromise must be made in practice.

4. Conclusions

In summary, the resolution characteristics of transmission-mode exponential -doping and uniform-doping GaAs photocathodes have been calculated and comparatively analysed with the MTF expression obtained by solving the established two-dimensional continuity equation. The calculated results show that the exponential-doping structure can upgrade significantly the resolution and the quantum efficiency of GaAs photocathode. This improvement differs from the method for high resolution by reducing T_e , L_D or increasing S_V which lead to a low quantum efficiency. Thus, the transmission-mode exponential-doping NEA GaAs photocathode has a potential advantage in image intensifiers.

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