The optimal thickness of a transmission-mode GaN photocathode*

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A 150-nm-thick GaN photocathode with a Mg doping concentration of 1.6×10^{17} cm^{-3} is activated by Cs/O in an ultrahigh vacuum chamber, and a quantum efficiency (QE) curve of the negative electron affinity transmission-mode (t-mode) of the GaN photocathode is obtained. The maximum QE reaches 13.0% at 290 nm. According to the t-mode QE equation solved from the diffusion equation, the QE curve is fitted. From the fitting results, the electron escape probability is 0.32, the back-interface recombination velocity is 5×10^4 cm$\cdot$s^{-1}, and the electron diffusion length is 116 nm. Based on these parameters, the influence of GaN thickness on t-mode QE is simulated. The simulation shows that the optimal thickness of GaN is 90 nm, which is better than the 150-nm GaN.

Keywords: gallium nitride, transmission-mode, quantum efficiency, optimal thickness

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1. Introduction

The negative electron affinity (NEA) GaN photocathode has wide applications in lithographic manufacture, rocket tracking, atmospheric monitoring, fire alarms and other fields,[1−9] because of advantages such as its high quantum efficiency (QE), low dark current, and concentrative emitting electron energy distribution.[10−22] Material structure is the major factor that determines the performance of the NEA GaN photocathode, which mainly includes p-type doping concentrations and GaN thickness T_e. There is an optimal doping concentration that is able to balance the surface-electron escape probability P and the electron diffusion length L_D, which creates the maximum QE. Recently, we have shown that the optimal doping concentration for a GaN photocathode is 10^{17} cm^{-3}.[23]

For the reflection-mode (r-mode) of the NEA GaN photocathode, QE grows with the increase of T_e until the GaN becomes thicker than L_D. However, the influence of T_e on the transmission-mode (t-mode) QE is more complicated. For the t-mode photocathode, the incident light irradiates from the substrate direction, so much of the short wavelength light (high energy) will be absorbed near the back-interface completely because of the higher absorption coefficient, and the photoelectrons excited by this light are far from the GaN (0001) surface. If the thickness T_e is too large, the photoelectrons must travel a long distance before they reach the surface, and because L_D is limited, the photoelectrons that could reach the surface will be reduced, so the QE of the photocathode will decrease accordingly; if T_e is too small, the incident light will not be fully absorbed by the GaN emission layer, and much of this light is going through the emission layer ineffectually, especially the long wavelength light with a low absorption coefficient, so the QE is not high, either. Therefore, there is an optimal T_e for the t-mode NEA GaN photocathode to make

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QE reach a maximum.

In order to find the optimal t-mode $T_{\rm e}$, we activate a t-mode GaN sample on the basis of the optimal doping concentration, and obtain the QE curve. According to the QE equation of the t-mode NEA GaN photocathode, the P, $L_{\rm D}$, and back-interface recombination velocity $S_{\rm v}$ are fitted. Based on these parameters and the equation, influence of $T_{\rm e}$ on QE is simulated and the optimal $T_{\rm e}$ is obtained.

2. Experiment and model

2.1. Experimental procedure

The sample used in our experiments was a 150-nm-thick GaN film grown by metal organic chemical vapour deposition (MOCVD) on a c axis sapphire (Al_2O_3) substrate with a $Ga_{1-x}Al_xN$ buffer layer. The GaN layer was a p-type layer doped with Mg (1.6×10^{17} cm^{-3}) and has a wurtzite structure (0001).

Our experiments were performed in a demountable ultrahigh vacuum (UHV) system (base pressures $\leq 3.3\times10^{-8}$ Pa) connected to a multi-information measurement system. The GaN sample was cleaned first by a 2:2:1 solution of sulphuric acid (98%) to hydrogen peroxide (30%) to de-ionized water, and then the GaN sample was subsequently transferred into the UHV system for heat cleaning, where the GaN was annealed in a vacuum at a temperature of 710 °C for 20 min.

After the surface cleaning, an atomically clean GaN (0001) surface was achieved, and the GaN can be activated by Cs/O. The photocurrent during Cs/O activation was recorded *in situ* by the multi-information measurement system. Cesium was performed with GaN at room temperature (20 °C) until a maximum photocurrent was obtained. Cesium deposition continued under a constant Cs flux, and the oxygen was not admitted into the chamber until the photocurrent stopped increasing. When the photocurrent reached a peak, the oxygen was cutoff, and the photocurrent dropped off. The oxygen was turned on again when the photocurrent dropped to about 97% of the peak. After oxygen switching on was repeated six times, the photocurrent reached a maximum, then, oxygen and cesium were turned off, and the activation process was completed. The photocurrent curve during activation is shown in Fig. 1.

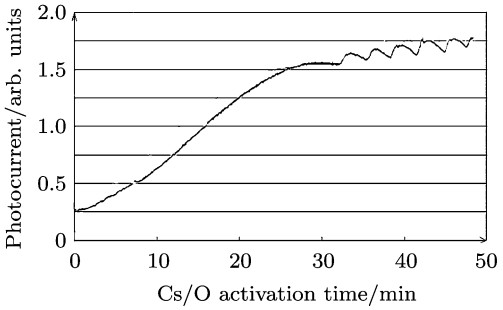


Fig. 1. Photocurrent during activation.

2.2. Model

According to the Spicer three-step model of photoemission theory,[24,25] the photoemission process of a t-mode NEA GaN photocathode can be divided into the following three consecutive steps: 1) the electron of the valence band is excited to the conduction band by incident light; 2) the photoelectrons in the conduction band transport to the GaN (0001) surface by the action of diffusion; 3) the photoelectrons that have reached the GaN (0001) surface escape to the vacuum.

Based on the Spicer three steps, the t-mode QE equation of the NEA GaN photocathode can be obtained by solving the diffusion equation of minority carrier (electrons),[26] which can be expressed as

$$Y(h\nu) = \frac{P(1-R)\exp(-\beta t)\alpha_{h\nu}L_{\rm D}}{\alpha_{h\nu}^2L_{\rm D}^2-1}\left\{\frac{\alpha_{h\nu}D_n+S_{\rm v}}{(D_n/L_{\rm D})\cosh(T_{\rm e}/L_{\rm D})+S_{\rm v}\sinh(T_{\rm e}/L_{\rm D})}\right.$$
$$\left.-\frac{\exp(-\alpha_{h\nu}T_{\rm e})\left[S_{\rm v}\cosh(T_{\rm e}/L_{\rm D})+(D_n/L_{\rm D})\sinh(T_{\rm e}/L_{\rm D})\right]}{(D_n/L_{\rm D})\cosh(T_{\rm e}/L_{\rm D})+S_{\rm v}\sinh(T_{\rm e}/L_{\rm D})}-\alpha_{h\nu}L_{\rm D}\exp(-\alpha_{h\nu}T_{\rm e})\right\}, \quad (1)$$

where R is the reflection of the photocathode, β is the absorption coefficient of the buffer layer, t is the thickness of buffer layer, α_{hv} is the absorption coefficient of GaN, and D_n is the electron diffusion coefficient.

3. Results and discussion

3.1. Experiment results

Spectral response was tested by the multi-information measurement system subsequently after the activation, and a QE curve can be drawn from the spectral response. The QE curve of the t-mode NEA GaN photocathode is shown in Fig. 2 with a solid line. It can be seen from the figure that there are high and flat quantum yields in a wavelength range between 255 nm and 355 nm. The maximum QE reaches 13.0% at 290 nm. When the wavelength of the incident light exceeds 355 nm, the QE begins to drop rapidly with the increase of the wavelength, and a distinct inflection point is at 355 nm. The QE falls to 3.5% at the threshold wavelength of 365 nm, and the QE is only 0.1% at the 385 nm, which demonstrates the excellent long wavelength cut-off property. The QE of the t-mode GaN photocathode decreases at short wavelengths less than 250 nm, which is different from the r-mode, QE reduces to about 0.6% at 240 nm while the quantum yield for the r-mode is still high. That is because the incident light illuminates the sapphire substrates in the t-mode, and the light must go through the substrate and the $Ga_{1-x}Al_xN$ buffer layer before reaching the GaN emission layer. The $Ga_{1-x}Al_xN$ buffer layer has a larger band gap than the GaN, and it has a higher absorption coefficient for the short wavelength light. Most of the short wave will be absorbed in the buffer layer and find it difficult to reach the GaN emission layer, so the QE of the t-mode NEA GaN photocathode will eventually go down at short wavelengths.

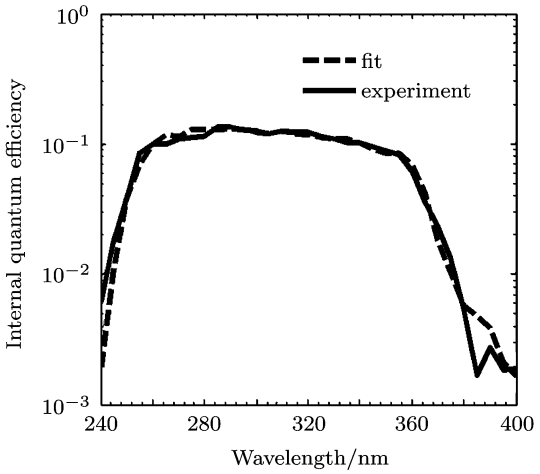


Fig. 2. Experimental and fitting curves of the t-mode NEA GaN photocathode.

3.2. Fitting of QE curve

According to Eq. (1), the QE curve was fitted. In the fitting, $T_e = 150$ nm, $t = 20$ nm, $R = 0.2$, GaN band gap $E_g = 3.4$ eV and $D_n = 25$ cm^2/s were taken. The absorption coefficients of the GaN emission layer and the $Ga_{1-x}Al_xN$ buffer layer are shown in Figs. 3(a) and 3(b), respectively.[27,28]

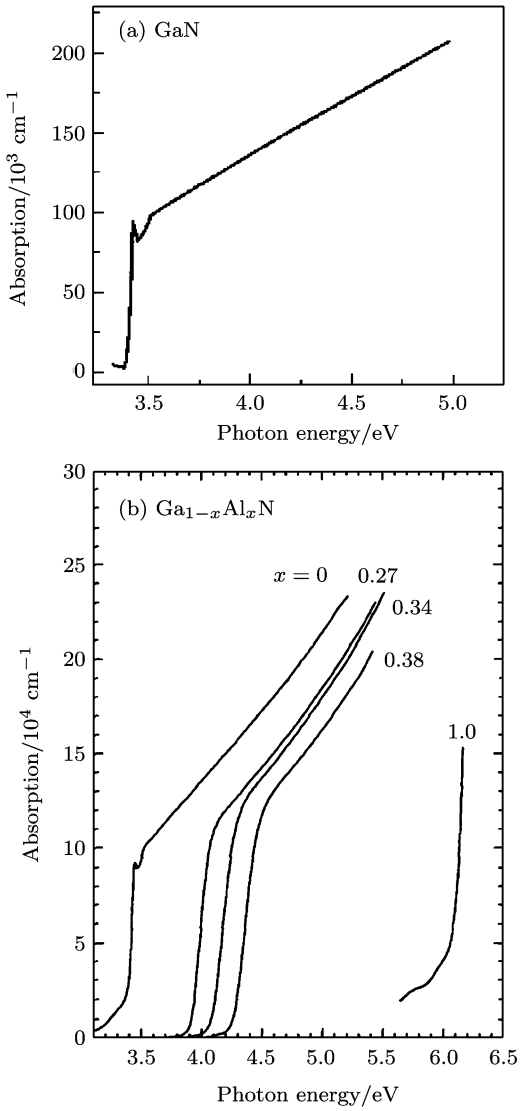


Fig. 3. Absorption coefficients of (a) GaN, and (b) $Ga_{1-x}Al_xN$.

The fitted QE curve is shown in Fig. 2 by a dotted line. From Fig. 2 it can be seen that the fitted curve is in reasonable agreement with the experimental curve in a wavelength range between 250 nm and 360 nm, including the main response wavelength band. Though a large difference between 380 nm and 400 nm is observed, this is beyond the threshold wavelength of GaN. The fitting result parameters of the photo-

cathode are listed in Table 1, including P, $L_{\rm D}$, and $S_{\rm v}$.

Table 1. Fitting results of photocathode parameters.

P	$L_{\rm D}$/nm	$S_{\rm v}$/cm · s^{-1}
0.32	116	5×10^4

3.3. Simulation of GaN thickness $T_{\rm e}$

Based on the parameters of the photocathode, the influence of $T_{\rm e}$ on QE at 290 nm is simulated according to Eq. (1). The curve of QE versus $T_{\rm e}$ at 290 nm is shown in Fig. 4. From the figure it can be seen clearly that there is an optimal $T_{\rm e}$ at which QE reaches the maximum. The simulation result shows that the maximum QE reaches 15.6% when $T_{\rm e}$ is 90 nm, and in the experiment the QE is 13.0% at 290 nm while the thickness of GaN is 150 nm, which illustrates that the sample used in this experiment may be thicker than the optimal thickness, and a thinner sample will achieve higher performance under the same experimental conditions.

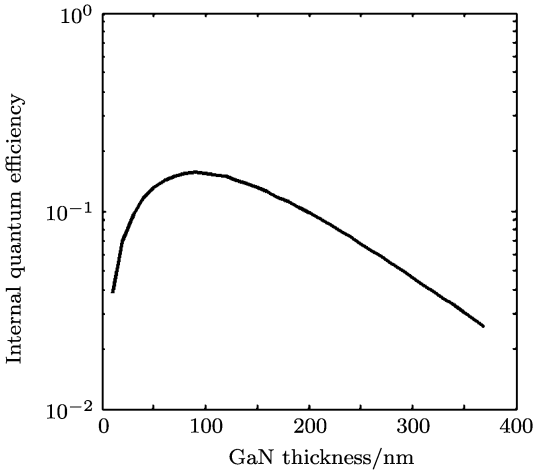


Fig. 4. QE versus $T_{\rm e}$ at 290 nm.

In order to investigate the relationship between QE and $T_{\rm e}$ in detail, three-dimensional figures are drawn for the whole wavelength range as shown in Fig. 5.

The simulation result shows that QE reaches the maximum of 15.9% at 275 nm while $T_{\rm e}$ is 90 nm. It can be found that the optimal thickness of GaN is the same as the simulation value at 290 nm, but the wavelength where the maximum QE appears changes. $T_{\rm e} = 150$ nm is used in our experiment, and the maximum QE appears at 290 nm. In the simulation, the optimal $T_{\rm e}$ is taken to be 90 nm, with $T_{\rm e}$ decreasing, the wavelength where the maximum QE appears shifts toward the short wavelength. That is because the thinner the GaN, the less long wavelength light is absorbed and the less the long wavelength light will contribute to the final QE. Relatively, the QE at short wavelength increases with the GaN thickness decreasing.

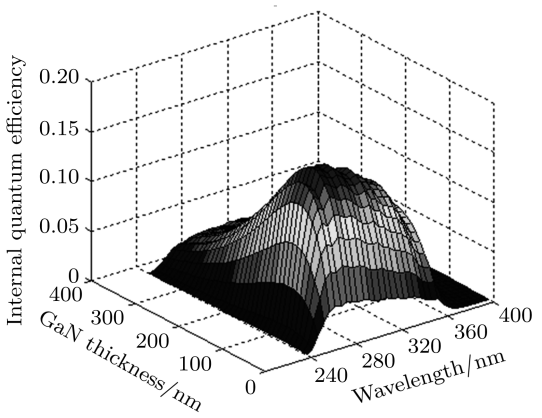


Fig. 5. Three-dimensional profile of QE varying with thickness $T_{\rm e}$.

4. Conclusions

In this paper, we investigated the influence of GaN thickness on QE of a t-mode NEA GaN photocathode. The QE equation of the t-mode NEA GaN photocathode is solved from the diffusion equation. The GaN sample is activated by Cs/O and a QE of 13.0% appears at 290 nm. According to the equation, the influence of GaN thickness on the QE of The t-mode GaN photocathode is simulated. For a t-mode GaN photocathode with 10^{17} cm^{-3} doping concentration, the optimal GaN thickness is found to be 90 nm, and the QE will reach 15.6% at 290 nm and 15.9% at 275 nm when the GaN thickness is 90 nm.

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