Photoemission of graded-doping GaN photocathode*

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We study the photoemission process of graded-doping GaN photocathode and find that the built-in electric fields can increase the escape probability and the effective diffusion length of photo-generated electrons, which results in the enhancement of quantum efficiency. The intervalley scattering mechanism and the lattice scattering mechanism in high electric fields are also investigated. To prevent negative differential mobility from appearing, the surface doping concentration needs to be optimized, and it is calculated to be 3.19×10^{17} cm^{-3}. The graded-doping GaN photocathode with higher performance can be realized by further optimizing the doping profile.

Keywords: GaN photocathode, graded-doping, photoemission, quantum efficiency

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1. Introduction

In the negative electron affinity (NEA) photocathode, the built-in electric field can supply the electrons with extra energy and accelerate the electrons toward the surface and then these electrons can escape into the vacuum. A lot of efforts have been made to apply an electric field to the photocathode, such as the design of the field-assisted photocathode, in which a metal anode is used between the III–V semiconductor and the cesium / oxygen (Cs/O) activation layer.[1−4] But this method gives a very slight quantum efficiency (QE) enhancement and appears difficult to activate the surface with the complicated structure kept unchanged. A method proposed by our group is the body to surface graded doping, in which several built-in electric fields can be constructed due to the doping concentration gradients. The method has been proved to be very effective in increasing the QE for GaAs photocathodes, and with this method the GaAs photocathodes can be relatively easily realized.[5−9] We applied this graded-doping method to the GaN photocathode and obtained the increased QE. In the present paper we analyse the photoemission process and try to find the crucial factors influencing the QE enhancement, with the purpose of further optimizing the graded-doping profile design.

2. Experiment and results

A graded-doping GaN sample was grown on a 300 μm thick c-plane sapphire substrate with a 20 nm AlN buffer layer, which could act as a potential barrier to reflect the electrons back toward the surface. Four Mg-doped GaN layers with different doping concentrations were grown by metal organic chemical vapour deposition (MOCVD). The graded-doping structure of this GaN photocathode is shown in Fig. 1.

45 nm, 6×10^{16} cm^{-3}, GaN:Mg
45 nm, 2×10^{17} cm^{-3}, GaN:Mg
45 nm, 4×10^{17} cm^{-3}, GaN:Mg
45 nm, 1×10^{18} cm^{-3}, GaN:Mg
20 nm AlN buffer layer
300 μm sapphire substrate

Fig. 1. Structure of graded-doping GaN photocathode.

Before activation, the sample was degreased in an ultrasonic bath containing CCl_4, acetone, alcohol and de-ionized water, then etched with the solution of H_2SO_4:H_2O_2:H_2O=2:2:1 at 90 °C for about 10 min

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and blow-dried. The wafer was annealed at 700 °C in the vacuum with a base pressure of 1×10^{-7} Pa for about 20 min, and activated with Cs and O to achieve the NEA.

After activation, xenon lamp was used as a light source to test the spectrum response. The QE curve is shown in Fig. 2. The corresponding curve of the uniform-doping GaN sample is also listed here for comparison.

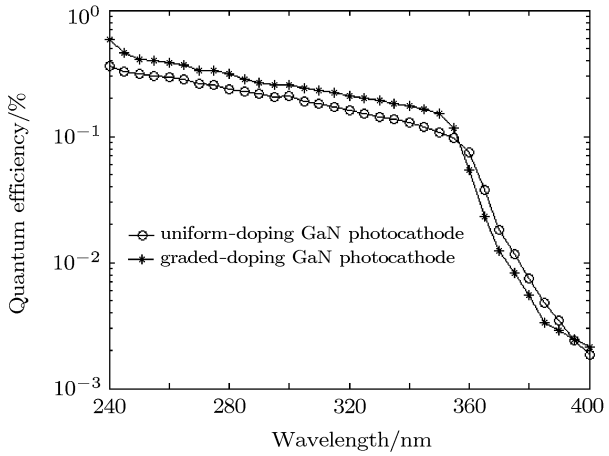


Fig. 2. QE curves of graded-doping GaN photocathode and uniform-doping GaN photocathode.

Figure 2 shows that the QE of the graded-doping GaN sample is increased compared with that of the uniform-doping GaN sample in a wavelength range of from 240 nm to 360 nm. The uniform-doping sample has been optimized in both the thickness of the emission layer and the use of AlN as the potential barrier. The crucial factor influencing the further enhancement of QE is the graded-doping structure.

3. Discussion

The photoemission of the graded-doping GaN photocathode can be analysed with Spicer's three-step model:[10] the photoexcitation of the electrons, the transport of the electrons through the crystal and the escape of the electrons over the surface barrier into the vacuum. These steps are sequentially described as follows.

Step 1 When the incident photon has energy hv higher than the energy gap (E_g), the electron will be excited from the valence band to the conduction band. The location of electron generation depends on the absorption coefficient α. According to the positions of the electric fields, we can divide the GaN emission layer into four regions as shown in Fig. 3. Here, we set the axis origin in the photocathode surface ($x = 0$), then the three built-in electric fields are positioned at $x = 45$ nm, 90 nm and 135 nm, respectively, along with another high field in the band bending region (BBR). There are totally four internal electric fields influencing the electrons.

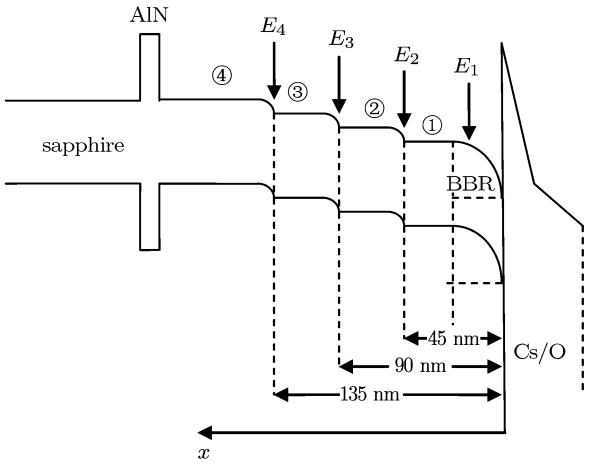


Fig. 3. Energy band diagram of graded-doping GaN photocathode and positions of the four built-in electric fields.

Step 2 The photo-excited electrons relax at the bottom of the conduction band and then are transported to the surface. In this step, the electrons can obtain extra energy from the built-in electric fields. The potential barriers in the three band bending areas can be calculated from the following formula:

$$\begin{aligned} qV_{\rm D} &= E_{\rm F_2} - E_{\rm F_1} \\ &= (E_{\rm v} + k_0T\ln\frac{N_{\rm v}}{N_{\rm A_2}}) - \left(E_{\rm v} + k_0T\ln\frac{N_{\rm v}}{N_{\rm A_1}}\right) \\ &= k_0T\ln\frac{N_{\rm A_1}}{N_{\rm A_2}}, \end{aligned} \tag{1}$$

where k_0T is usually 0.026 eV at room temperature, $N_{\rm A_1}$ is the higher doping concentration, and $N_{\rm A_2}$ is the lower doping concentration.

Considering the high temperature annealing process, by which the built-in electric fields can be improved by about 25% according to our research about GaAs photocathode,[11] we set the final potential barriers from body to surface to be 0.03 eV, 0.023 eV and 0.039 eV, respectively.

The widths of the band bending areas for E_2, E_3 and E_4 are written as[11]

$$X_{\rm D} = \sqrt{V_{\rm D}\left(\frac{2\varepsilon_{\rm r}\varepsilon_0}{q}\right)\left(\frac{N_{\rm A_1}+N_{\rm A_2}}{N_{\rm A_1}N_{\rm A_2}}\right)}, \tag{2}$$

where $V_{\rm D}$ is the built-in voltage, $\varepsilon_{\rm r}$ is the permittivity of GaN material, ε_0 is the vacuum permittivity, q is

the electric charge, N_{A_1} and N_{A_2} are the doping concentrations on both sides of the built-in electric fields respectively, with N_{A_1} being higher than N_{A_2}. The width of the surface BBR is written as[12]

$$d = \sqrt{\frac{2\varepsilon_r\varepsilon_0 V_{D_1}}{qN_A}}, \tag{3}$$

where V_{D_1} is the voltage of the BBR and N_A is the surface doping concentration.

Therefore, the electric field intensities of E_2, E_3 and E_4 can be calculated from

$$E = V_D/X_D, \tag{4}$$

and the electric field intensity of E_1 (BBR) can be calculated from

$$E = V_{D_1}/d, \tag{5}$$

with the general band bending barrier given to be about 1.5 eV[13] and V_{D_1} set to be 1.5 V. The results of the potential barriers and electric field intensities are listed in Table 1.

Table 1. Potential barriers and electric field intensities for built-in electric fields.

built-in electric field	potential barrier/eV	E/kV·cm^{-1}
E_1(BBR)	1.5	88.5
E_2	0.039	12.5
E_3	0.023	16.3
E_4	0.03	27.3

The QE for the opaque mode GaN photocathode is written as

$$Y(h\nu) = \frac{P(1-R)}{1+1/\alpha_{h\nu}L_D}, \tag{6}$$

where P is the escape probability, R is the reflection coefficient of the photocathode, and L_D is the diffusion length. Since R and α are both constants, the only way to increase the QE is to enhance the escape probability P or (and) the diffusion length L_D.

For the graded-doping GaN photocathode, because of the introduction of the electric fields, the energy that the electrons can gain in one unit of time is[12]

$$\frac{dQ}{dt} = q\mu E^2, \tag{7}$$

where Q is the energy of the electron, and μ is the mobility, which is written as

$$\mu = \frac{4ql_n}{3\sqrt{2\pi m_n^* k_0 T_e}}, \tag{8}$$

where l_n is the mean free path of electron , m_n^* is the effective mass, k_0 is the Boltzmann constant, and T_e is the electron temperature.

With the influence of the electric field, the electron drift velocity is written as

$$v_d = \mu E, \tag{9}$$

which means that the velocity of the electron can be increased linearly with the intensity of the electric field till the threshold about 180 kV/cm.[14−16]

On the other hand, with the built-in electric field, the drift length of the electron is

$$L_n(E) = E\mu\tau. \tag{10}$$

The total length L_{DE} that the electrons can transport can be written as[6]

$$L_{DE} = \frac{1}{2}(\sqrt{L_n^2(E) + 4L_D^2} + L_n(E)). \tag{11}$$

Equation (11) shows that the total transport length for the graded-doping GaN sample, L_{DE}, is much larger than that for the uniform-doping GaN sample, L_D.

The analysis above shows that the electric field can supply the electrons with extra energy, which will increase the escape probability. At the same time, the electron transport length is also increased. Therefore, the introduction of electric field is conducible to increasing the QE.

Although there exists an electric field in the uniform-doping GaN photocathode, it lies only in the BBR, which means that only those electrons diffusing into the BBR can be influenced by the high field in this region and acquire higher energy and velocity. For most of electrons, especially those that are generated in the deeper GaN bulk regions with lower energy, like regions IV and III in Fig. 3, they are easily affected by the back interface recombination velocity and recombined with defects, or do not have long enough diffusion length for traveling through to the BBR, so the influence of electric field in the uniform-doping GaN photocathode is very limited.

In the graded-doping GaN photocathode, due to the gradients of the doping concentration, there appear three built-in electric fields covering the whole GaN sample, which means wherever the electrons are generated, they can all be accelerated by the electric field and acquire extra energy from it. That is why the QE is increased for the graded-doping sample in the wavelength range from 240 nm to 360 nm as shown in Fig. 2.

The effects of the electric field on electrons generated at different locations are different. According to the adsorption coefficient, the lower energy electrons are generated in deeper GaN bulk regions and the higher energy electrons are generated near to the surface as shown in Fig. 3. Take electrons from location region IV for example, once they enter the region of electric field E_4, they are immediately attracted by the anode and drift to the surface. These electrons can obtain extra energy, which is proportional to the intensity of E_4. And with the high velocity they obtain from E_4, these electrons diffuse through the region between E_4 and E_3, and they experience another acceleration and receive an energy increment in the region of E_3. Therefore, before these electrons reach the BBR, they have experienced three built-in electric fields, which make them more energetic, that is, have higher probability to escape into the vacuum. On the other hand, the total transport length is also increased with electric field. That is why the QE enhancement for lower energy electrons, especially those that are generated by photons with wavelengths ranging from 320 nm to 360 nm, is much larger as shown in Fig. 2.

When the intensity of the electric field reaches the threshold about 180 kV/cm, the velocity will decrease with the increase of electric field and the negative differential mobility (NDM) comes into being. For the relationship between drift velocity and electric field intensity, details can be found at Ref. [14].

Such a phenomenon can be explained with the lattice scattering and the intervalley scattering. When there is an electric field, the electrons will obtain energy from it and then transfer the energy to the lattice. In a steady state, the energy the electrons obtain from the electric field is equal to that the electrons transfer to the lattice. But with very high electric field, the electrons obtain more energy than that they can transfer to the lattice and so the steady state is broken. The electrons then have higher temperature and higher velocity than those in the steady state. According to $\tau = l/v$, when the mean free path is kept unchanged, the mean free time is reduced, and then the mobility is also decreased.[12]

As to the intervalley scattering, a lot of electrons in Γ_1 valley will acquire enough energy to jump into the Γ_3 valley located at 340–400 meV above the conduction band minimum,[17] or even into the L–M valley located at 1.2 eV higher than Γ_1 valley and then relax their energy. The electrons in Γ_3 and L–M valleys each have a larger effective mass, lower mobility and slower velocity. When the electric field is too high, the NDM will appear, which means that some electrons will acquire enough energy to jump into an upper valley, where they each have a larger effective mass, lower drift velocity and negative mobility. Research shows that the threshold intensity to induce the NDM is about 180 kV/cm for GaN.[14−16] The corresponding surface doping concentration is about 3.19×10^{17} cm^{-3} , which is calculated from Eqs. (3) and (5). So to ensure that the electrons acquire the highest drift velocity with keeping the NDM from appearing, the optimized surface doping concentration is 3.19×10^{17} cm^{-3}.

Step 3 The electrons reaching the surface with enough energy and velocity will overcome the surface potential barrier and escape into the vacuum. In this process, what is the most important is the structure of the potential barrier, or the thickness of the Cs/O activation layer, which is also determined by the surface doping concentration. In this case, the higher the surface doping concentration the better in order to obtain higher QE. However, taking the NDM effect into account, the concentration should be carefully designed to compromise the two factors.

4. Conclusion

Through the study of photoemission process of the graded-doping GaN photocathode, it is clear that the introduction of built-in electric fields can accelerate the photo-excited electrons toward the surface with higher energy, thereby increasing the QE, which is effective especially for the lower energy electrons. Lattice scattering and intervalley scattering mechanisms are analysed to explore the influence of scattering on QE in a very high electric field. The optimized threshold surface doping concentration is calculated to be 3.19×10^{17} cm^{-3}, which gives the electrons the highest drift velocity with keeping the NDM from appearing. The optimized surface doping concentration should be further explored to compromise the influences of the thickness of the barrier and the NDM on QE enhancement. To realize some specific wavelength responses in application, locations and intensities of the built-in electric fields should be further optimized according to the positions of electron generation.

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