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Femtosecond ultrafast dynamics study on the photoemission performance of reflection-mode GaAlAs photocathode

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ABSTRACT

The photoemission characteristic of reflection-mode GaAlAs photocathode has been investigated, while a convenient and nondestructive method for evaluating the photocathode performances will be introduced. In this paper, two same reflection-mode photocathode structures with different research methods are adopted. One way is using multi-information measurement system to measure the photoemission characteristic curve of GaAlAs photocathode. Another method is the femtosecond transient reflection spectroscopy. The ultrafast dynamics property of the GaAlAs carrier is studied with the femtosecond transient reflectivity change, and the quantitative calculating is also shown. According to the results of two experimental methods, we analyze some photoemission performance parameters, such as carrier lifetime, diffusion length etc. The results show that the surface electron escape probability P and the drift length L_{DE} are different, while are the same of the back recombination velocity S_v by the two method. In a word, compared with multi-information measurement system, the femtosecond ultrafast dynamics method is more suitable to research on the photoemission characteristic of reflection-mode GaAlAs photocathode which is no damage and accurate.

1. Introduction

With the advantages of high quantum efficiency, low energy spread and high spin polarization, negative electron affinity (NEA) photocathodes have been widely used in night vision image intensifiers, photomultipliers, detection and potential polarized electron sources for the next-generation electron acceleration [1–5]. It is well known that the response wavelengths of different photocathode materials are different. The binary III-V NEA photocathodes have many important applications. However, their the spectral response ranges are limited due to the fixed band gap. In order to meet the needs of submarine exploration, submarine communication and undersea imaging, the blue-green light extension GaAlAs/GaAs photocathodes are fabricated [6]. The addition and variation of the Al component allows the spectral response ranges of GaAlAs photocathodes to be controlled. Facilitated by material growth techniques such as molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD), fabrication of GaAlAs photocathodes has become much easier. In particular, since NEA photocathodes are typically manufactured with p-type doped semiconductors [7], zinc doping becomes a critical process for forming p-type GaAlAs NEA photocathodes on GaAs substrates.

According to the three-step model of light absorption, electron transfer and electron escape, it is easy to see that electron diffusion length, carrier lifetime and back interface recombination all play important roles in the photoemission performance of NEA photocathodes [8–11]. In this paper, two different research methods are adopted to analyze the same reflection-mode structures. One method is measuring the photoemission characteristic parameters by the traditional way of multi-information measurement system. The other is using the femtosecond ultrafast dynamic to show photoemission performances. By studying the transient properties, the photoemission performances of exponential doping reflection-mode GaAlAs photocathode can be obtained and analyzed, such as the carrier lifetime, diffusion length etc.

2. Experiments

The two identical reflection-mode GaAlAs photocathode samples are grown on n-type GaAs substrates by MOCVD for this experiment. The epitaxial layer is composed of a p-type exponentially doped GaAlAs with a thickness of 1.2 μm, a GaAlAs buffer layer, and a GaAs protection

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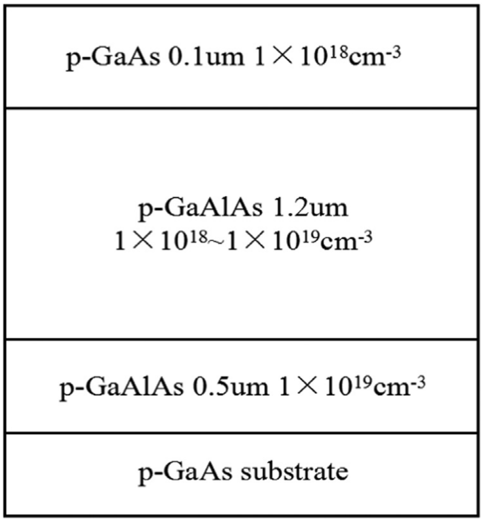

Fig. 1. Structure of the reflection-mode GaAlAs photocathode sample.

layer, as shown in Fig. 1. Chemical etching is used to remove the protection layer of p-type GaAs and make the sample surface form NEA surface combining the mechanism of Cs-O activation. And the experiments of multi-information measurement system and femtosecond ultrafast dynamic all are carried out at room temperature and in ultra-high vacuum systems operating in the 800 nm wavelength.

The energy band structure diagram of the reflection-mode GaAlAs photocathode is shown in Fig. 2. A double dipole model with two different slope barriers is used to describe the surface of the cesium-oxygen activation layer, which forms the NEA that permits easier escape of the photoelectrons from the cathode surface into vacuum [12]. When the incident light is irradiated on the photocathode surface, some photons with high energy are absorbed. At the same time, carriers are generated in the body of GaAlAs photocathode and diffuse into the band bending region and then transfer to the vacuum. To experimentally characterize this process, two methods are used to study the quantum efficiency of photocathode. The conventional research method is using multi-information measurement system to measure the spectral response curve of the photocathode sample. Then the experimental curve of the quantum efficiency can be obtained by transforming spectral response curve according to the following equation [13]:

$$Y(h\nu) \approx 1.24 \times \frac{S_\lambda}{\lambda} \tag{1}$$

where Y(hν) is the quantum efficiency, S_λ is the spectral response value

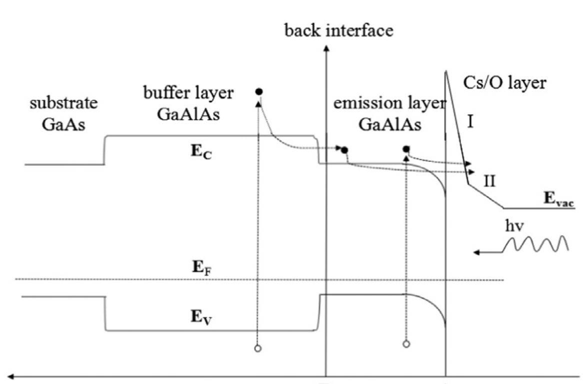

Fig. 2. The energy band structure diagram of the reflection-mode GaAlAs photocathode. E_V is the maximum value in valence band, E_F is the Fermi level, E_C is the minimum value in conduction band, E_{vac} is the vacuum level.

of the corresponding wavelength λ.

And the quantum efficiency formula of exponential-doping reflection-mode GaAlAs photocathode is as follow [14]:

$$Y_{RE} = \frac{P(1-R)\alpha_{h\nu}L_D}{{\alpha_{h\nu}}^2 L_D - \alpha_{h\nu}L_E - 1} \times \left[\frac{N(S - \alpha_{h\nu}D_n)e^{\frac{L_E T_e}{2{L_D}^2} - \alpha_{h\nu}T_e}}{M} - \frac{Q}{M} + \alpha_{h\nu}L_D \right] \tag{2}$$

where

$$\begin{aligned} N &= \sqrt{L_E^2 + 4L_D^2} \\ S &= \mu|E| + S_\nu \\ L_E &= \mu|E|\tau = \frac{q|E|}{k_0 T} L_D^2 \\ M &= (ND_n/L_D)\cosh(NT_e/2L_D^2) + (2SL_D - D_n L_E/L_D)\sinh(NT_e/2L_D^2) \\ Q &= SN\cosh(NT_e/2L_D^2) + (SL_E + 2D_n)\sinh(NT_e/2L_D^2) \end{aligned}$$

where P is the probability of surface electron escape, R is the reflectivity of photocathode surface, $\alpha_{h\nu}$ is the absorption coefficient, L_D is the electron diffusion length in the GaAlAs layer, L_E is the electron drift length under an internal electric field E, N is the doping concentration, D_n is the diffusion coefficient of electron, τ is the lifetime of minority carrier, T_e is the thickness of reflection-mode GaAlAs photocathode emission layer, T is the absolute temperature and q is the electron charge.

Under the action of constant internal built electric field E, the one-dimensional continuity equation followed by the minority carrier of reflection-mode GaAlAs photocathode is given by [15]:

$$D_n \frac{d^2 n(x)}{dx^2} - \mu|E| \frac{dn(x)}{dx} - \frac{n(x)}{\tau} + \alpha_{h\nu} I(1-R) e^{[1-\alpha_{h\nu}(T_e - x)]} = 0,\ x \in [0,\ T_e] \tag{3}$$

And the boundary condition of the reflection-mode GaAlAs photocathode can be defined as [15]:

$$\left[D_n \frac{dn(x)}{dx} - \mu|E|n(x) \right]\bigg|_{x=0} = S_V n(x)|_{x=0},\ \ n(T_e)| = 0 \tag{4}$$

where n(x) is the concentration of photo-generated electrons, I is the intensity of incident light.

Expression of the probability P of surface electron escape from the photocathode surface into the vacuum is expressed as [16]:

$$P(h\nu) = P_0 e^{[k(1/1.42 - 1/h\nu)]} \tag{5}$$

where P_0 is the probability of photo-generated electrons excited to escape when the incident light energy is 1.42 eV, k is a factor for reflecting the shape of photocathode surface potential barrier.

The average distance of photoelectrons moving to the surface is defined by the electron diffusion and drift length L_{DE} in the exponential-doping GaAlAs [17]:

$$L_{DE} = \frac{1}{2}\left(\sqrt{{L_E}^2 + 4{L_D}^2} + L_E\right) \tag{6}$$

$$E = -\frac{k_B T}{q} \cdot \frac{\ln(N_0/N_s)}{T_e} \tag{7}$$

where k_B is the Boltzmann constant, N_0 is the back interface doing concentration of the emission layer, N_s is the surface doping concentration.

Meanwhile, ultrafast dynamics method has also been used to study the photoemission performance of reflection-mode GaAlAs photocathodes. A femtosecond pump-probe transient reflectivity system with 300 nm wavelength is developed to investigate the carrier relaxation process of GaAlAs photocathode samples. Fig. 3 shows the pump-probe transient reflectivity system and the 8fs sapphire laser is the light source which can generate 540 mW power. First, the divergence-compensating

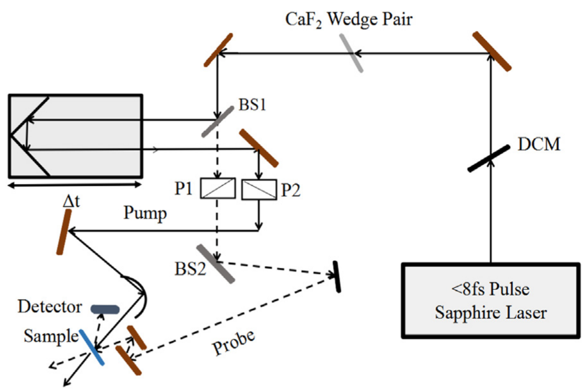

Fig. 3. The pump-probe system of measuring transient reflectivity. DCM: divergence-compensating mirror; BS1 and BS2: beamsplitter; P1 and P2: polarizer.

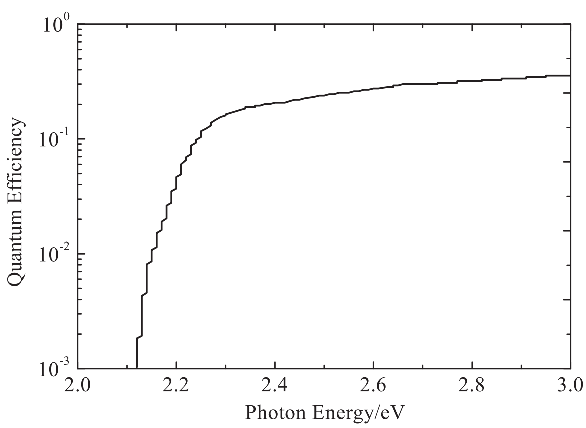

Fig. 4. Experimental quantum efficiency curve for the reflection-mode GaAlAs photocathode.

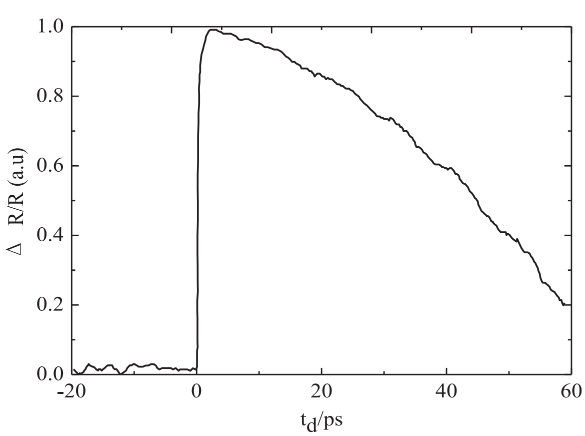

Fig. 5. The transient reflectivity change of GaAlAs photocathode.

mirror (DCM) pair and CaF_2 wedge pair are used to balance the diverging light. Second, the beamsplitter (BS1) is to split the pump and probe beams. Finally, the periscopes (P1 and P2) are used to generate the vertical polarization in order to reduce interference. The average pump energy is 270 mW and focused on the sample of GaAlAs photocathode. And the probe beam is 20 mW and focused on the sample at 15° which is smaller than the pump in the focusing area, so that the excitation region detected by probe beam is consistent. When the pump pulse excites the sample device, the increase in electron population in the conduction band and hole population in the valence band causes an increase in the reflection of the sample surface and produces saturable

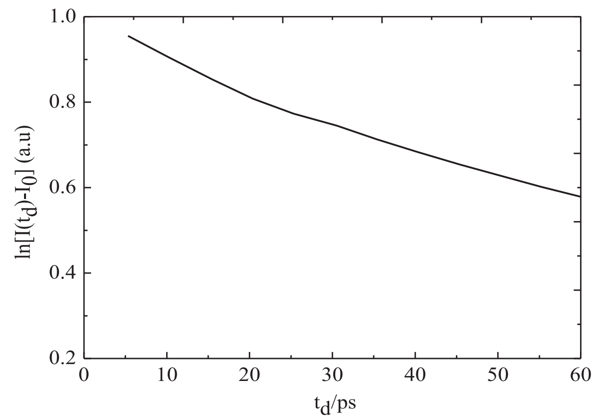

Fig. 6. The change curve of the probe light intensity with the delay time of the reflection-mode GaAlAs photocathode.

Table 1
The quantum efficiency parameters of the reflection-mode GaAlAs photocathode using the two different measurement methods.

Measuring method	S_v(cm/s)	P	L_{DE}(um)
Traditional method	1×10^6	0.40	0.81
Femtosecond method	1×10^6	0.52	0.83

absorption. With the recombination of stimulated carriers, the saturation effect degenerates and the reflection of the probe decreases. This relaxation process is sampled by the probe pulse at different time delay. By measuring the time evolution of the relative reflectivity of the probe beam ΔR/R, we can obtain the dynamic process of the nonequilibrium carriers distribution of the reflection-mode GaAlAs photocathode.

3. Results and discussion

By using the conventional method of multi-information measurement system, we detect the photoemission performance of the reflection-mode GaAlAs photocathode, and fit the experimental curve by Eq. (1). Our result is shown in Fig. 4, where quantum efficiency is plotted against photon energy. Quantum efficiency is the most important characteristic parameter for evaluating the performance of a photocathode in aspects such as electron diffusion length, carrier lifetime, and recombination velocity of photocathode back interface [18]. The band gap of GaAlAs photocathode is 2.0 eV, and through research quantum efficiency curve. It can be found that the excited electrons can escape from the surface and enter into vacuum system with maximum efficiency when the incident photon energy is 2.3 eV. Subsequently, some high-energy photons are not fully absorbed in the emission layer of GaAlAs photocathode material with the continuous increase of photon energy.

In the femtosecond ultrafast dynamics experiments, the reflectivity of the GaAlAs photocathode sample is modulated due to the excitation of the pump pulse. The induced change in reflected probe power is measured at different time delays and the corresponding evolution of the relative reflectivity is shown in Fig. 5. As can be seen from Fig. 5, when the light incidents on the surface of GaAlAs photocathode, the free carriers increase with the stimulated carriers generation while the reflectivity decreases. With carriers relaxation down to the valence band bottom, reflectivity decreases initially. Accompanied with the phenomenon of the carriers recombination, the number of free carriers decrease and the reflectivity increases. Consequently, the delay time is the carriers relaxation time and is also the carriers lifetime, which can be obtained by fitting curve. And the fitting formula is shown as Eq. (8).

$$\ln[I(t_d) - I_0] = -\frac{1}{T_1}\cdot t_d + \ln(AWD_a d) \tag{8}$$

where I_0 is the intensity of probe light without pumping light, T_1 is the energy relaxation time after carrier transition in the sample, t_d is the delay time, A is the cross sectional area of light beam, W is the energy density of probe, D_a is the absorption change caused by pumping light, d is the sample thickness.

According to the measured experimental data, the change curve of the probe light intensity with the delay time of the reflection-mode GaAlAs photocathode are shown in Fig. 6. With the change of the delay time, the logarithm of the change of the detected light intensity shows a decreasing trend, which is consistent with the analysis of the photoemission properties using the femtosecond laser ultrafast dynamics. The carrier lifetime is obtained by using Eq. (8), which is the gradient of the curve.

For the photoemission performances of the reflection-mode GaAlAs photocathode, there are obtained by the traditional method and femtosecond ultrafast dynamics method, respectively. The results are shown in Table 1. As we can see that the difference of the surface electron escape probability P is obvious, while are the same of the back recombination velocity S_v. And the drift length L_{DE} is a little different. The reason why is that the P is determined by the electron energy distribution that has close relationship with the surface barrier, and the L_{DE} depend on the growth quality of the epitaxial layer material. However, the S_v mainly dominated by the lattice matching degree of the material back surface. Although using two different experimental methods, it is the same for the S_v due to the same experimental material. The higher surface electron escape probability and drift length indicate that are batter for formatting NEA GaAlAs surface. In this paper, we use the femtosecond ultrafast dynamics method to study the quantum efficiency of the exponential-doping reflection-mode GaAlAs photocathode without damage, efficiency and accuracy. In other word, this method is better.

4. Conclusion

In this paper, we performed a femtosecond method investigation of the quantum efficiency of the reflection-mode GaAlAs photocathode. First, using two same reflection-mode GaAlAs photocathode, while the investigated way is different. And the traditional way is using multi-information measurement system to measure the quantum efficiency of GaAlAs photocathode and then fit the experimental curve. Another way is using the femtosecond ultrafast dynamics. When the femtosecond interaction with the photocathode material, the carriers are excited and the reflectivity of the NEA photocathode material surface has been changed. Accompanied by the free carriers increase while the reflectivity decreases. Moreover, when the carriers recombination, it is increasing of the GaAlAs photocathode surface reflectivity. Then using the measured experimental data, we provide the change curve of the probe light intensity with the delay time. It is can be found that the logarithm of the change of the probe light intensity decreases with the delay time increasing and the curve gradient is the free carriers lifetime. According to the carriers lifetime, we can obtain the quantum efficiency. Last, we analyze these data and find that the back recombination velocity is the same, while the surface electron escape probability and the drift length are different by two way. The surface electron escape probability and drift length that obtained by the method of femtosecond ultrafast dynamics are higher than the traditional method and we use the method without damage, efficiency and accuracy for researching the quantum efficiency of the exponential-doping reflection-mode GaAlAs photocathode. Consequently, it is actually benefit for researching the quantum efficiency of the exponential-doping reflection-mode GaAlAs photocathode by using the femtosecond ultrafast dynamics method.

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