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Theoretical energy distributions of electrons from a large exponential-doping GaAs photocathode

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Abstract: Theoretical calculation indicates that the large exponential-doping GaAs photocathodes have a much narrower electron energy distribution than traditional GaAs NEA cathodes, and the excellent performance attributes to the special structure characters of the band-bending region and lower negative electron affinity of the new-type GaAs photocathodes. The effects of surface doping concentration and work function on the energy distribution are discussed in details, and the FWHM of the energy distribution is less than 100meV. The simulation results indicate that the large exponential-doping mode further improves the features of the electron energy spreads for GaAs photocathodes, which may meet the further demand of next generation of electron guns.

Introduction

The low energy distribution of photoelectrons emitted from the Cs:O surface of GaAs photocathodes have greatly potential application as the next generation of electron guns[1]. The typical value of the energy spread is less than 100meV for the futural electron source. J. S. Escher *et al* [2] and G. Vergara *et al* [3] calculate the energy distribution of GaAs photocathodes, and the calculation results are consistent with the experimental results. The gradient-doping mode can obtain rapid response speeds for GaAs NEA cathodes because of the existence of a strongly built-in electric field in GaAs absorption layer [4]. By the semiconductor theory[5], GaAs photocathodes with the gradient-doping mode can obtain ultrafast response when the strongly built-in field is formed in the GaAs layer. While the characteristics of the photoelectron energy distribution have not been discussed for the new-type GaAs photocathodes. Then, based on the successful calculation model mentioned above[2], a large exponential-doping GaAs photocathodes is constructed, and the characteristics of energy distribution for the new-type NEA cathodes are theoretically analyzed in details, in order to meet further application of the high-quality electron sources.

In this letter, it is for the first time that the electron energy distributions of the large exponential-doping GaAs photocathodes are theoretically calculated. The analysis is concluded that the new-type GaAs photocathodes have much narrower energy distributions than traditional GaAs NEA cathodes, the outstanding properties of which may offer a more promising development and application in the photoelectron devices.

The structure of the new-type GaAs photocathodes

The design structure of the large exponential-doping transmission-mode GaAs photocathodes is introduced in detail in this section, and the GaAs layer is divided by two zone: (1) To I zone, the high response speed can be obtained; (2) To II zone, the surface barrier of electrons can be eliminated after Cs: O activation based on the semiconductor theory.

Fig.1. shows the schematic of energy band structure for the new-type GaAs NEA cathodes, where, E_c, E_v are the energy level of the conduction band and the valence band, respectively. E_g is the forbidden band width of GaAs semiconductor, E_F is the Femi level of the new-type GaAs

photocathodes after Cs:O activation. E_0 is the vacuum energy, Φ is electron work function, δ is surface band bending after activated by Cs: O, E_{Aeff} is the absolute value of NEA. Assuming that zero energy corresponds to E_F in this letter.

(1.) To I zone in Fig.1., the concentration $N(x)$ of the p-GaAs layer can be described as follows,

$$N(x) = N_0 \exp(-\beta x) \tag{1}$$

Where N_0=$N(0)$=$10^{19}cm^{-3}$, $N(L)$=$10^{15}cm^{-3}$, L is the width of p-GaAs absorption layer, L>>d. The value β=4×ln10/L can be obtained.

Then, the built-in electric field in p-GaAs absorption layer is approximatively obtained[5].

$$F = -\frac{dV}{dx} = -\frac{kT}{q}\beta \tag{2}$$

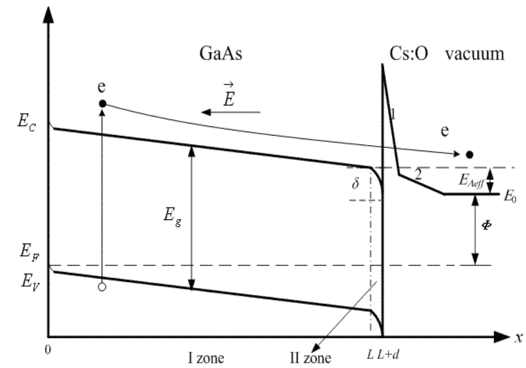

Fig.1. The schematic energy band diagram of the large exponential-doping photocathode.

(2.) To II zone, a heavily-doped p-GaAs layer d is designed and used as the emitted layer of GaAs photocathodes, for high quantum efficiency guaranteed and surface charge limit (SCL) effect eliminated [6,7], as is shown in Fig.1. The doping concentration of the layer varies in the range of 10^{18} - 10^{19} cm^{-3}. The surface electron barrier can be eliminated when the photocathodes are activated by Cs: O.

Thus, the thickness of the thin emitted layer d is expressed by the Schottky model, when the effect of energy band induced by the various doping concentration is considered.

$$d \sim \sqrt{\frac{2\varepsilon(E_B - \frac{kT}{q}\ln\frac{N_v}{N(L)})}{qN_A}} \tag{3}$$

where N_A is the doping concentration of the thin emitted layer d, q is electron charge, ε is the dielectric constant of GaAs, E_B of 0.5 – 0.7V is the band bending of the normal GaAs photocathodes [8]. N_v is the effective valence band density of states. k is Boltzmann constant, T=300K.

As Fig.1. shows, the surface band bending after activated by Cs: O is expressed by[5]:

$$\delta = \frac{E_g}{3} - \frac{kT}{q}\ln\frac{N_v}{N(L)} \tag{4}$$

The electron field in II zone can be written by[2,5]:

$$F_{sur} = \frac{\delta}{d} \tag{5}$$

Theoretical analysis and discussion

The transport of photoelectrons for the large exponential-doping GaAs photocathodes is divided into three processes: firstly, the photoelectrons are accelerated by the built-in field F in I zone; secondly, the high speed electrons across the surface band bending in II zone; at last, the photoelectrons tunnelling through Cs: O activation region emit into vacuum with a certain probability. Change of the structures will result in original behaviors, therefore, it is necessary to discuss energy distributions of electrons emitted from the new-type GaAs photocathodes.

The traversing electrons will have a certain kinetic energy in I zone because of the existence of the built-in field F, then, the energy distributions of photoelectrons determined by Maxwell-Boltzmann distribution at the interface between I and II zones in Fig.1[2], should be revised. The revisal is that, the room temperature T is substituted by electron temperature T_e[9], as Eq.(6)shows:

$$n_d(\Delta E) \propto \Delta E^{1/2} \exp(-\Delta E / kT_e) \tag{6}$$

where, electron temperature T_e is determined by the electric field F at room temperature[9], ΔE is the kinetic energy of electrons in the band-bending region. E is electron energy.

Based on the model of ref[2,3] and Eq.(1-6), electron energy distributions of the emitted from the new-type GaAs NEA cathodes is theoretical analyzed, as Fig.2-4. shows.

Fig.2. shows comparison of energy distribution of emitted electrons for the two GaAs photocathodes. the simulated curves indicate that, the new-type GaAs photocathodes have narrower energy distributions of emitted electrons than normal GaAs NEA cathodes, and the FWHM of energy distributions of the former, less than 100meV, is about 65% of that of the latter, which means that the former will have a better feature in the electron energy spreads, and can be fulfilled with the next generation of electron guns[1]. The reason for the narrower energy distributions attributes to the lower E_{Aeff} and the narrower δ based on the calculation, that is, the special structure of the novel GaAs photocathodes results in the special feature of electron energy distribution.

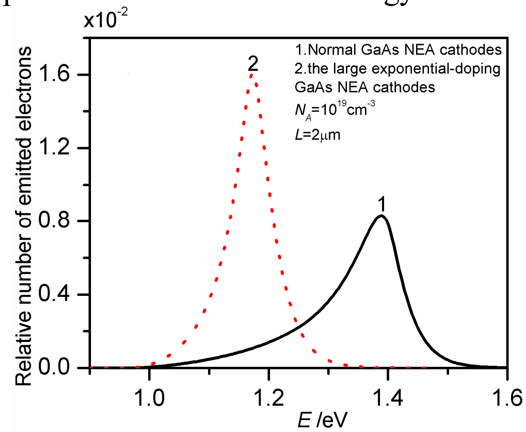

Fig.2. Comparison of energy distributions of emitted electrons for the two GaAs photocathodes.

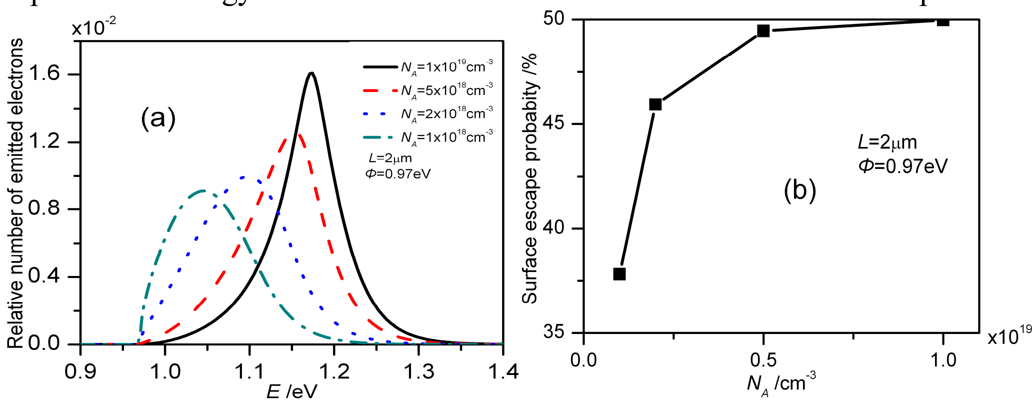

Fig.3. Energy distribution of emitted electrons (a) and surface escape probability (b) in different N_A for the new-type GaAs photocathodes.

Fig.3. shows that energy distributions (a) and escape probability (b) of emitted electrons varies with the surface doping concentration N_A in II zone. The simulation results indicate that, the FWHM of the electron energy spreads become small, and escape probability enhances when N_A increasing, which shows that high N_A is benefit to the energy distributions and escape probability. The curves of the escape probability will be close to a stable level with N_A>5×10^{18}cm^{-3}. The calculated results are consistent with the simulated analysis of traditional GaAs photocathodes[2,3].

Fig.4. describes the influnce of the work function Φ on electron energy distributions (a) and escape probability (b). Fig.4. indicates that, the higher Φ is, the narrower electron energy distributions are, and the lower escape probability is. With work function Φ increasing, escape probability decreases rapidly. Therefore, higher work function Φ for the new-type GaAs photocathodes is necessary for the high escape probability, while for narrower electron energy spreads, lower work function Φ is suiltable.

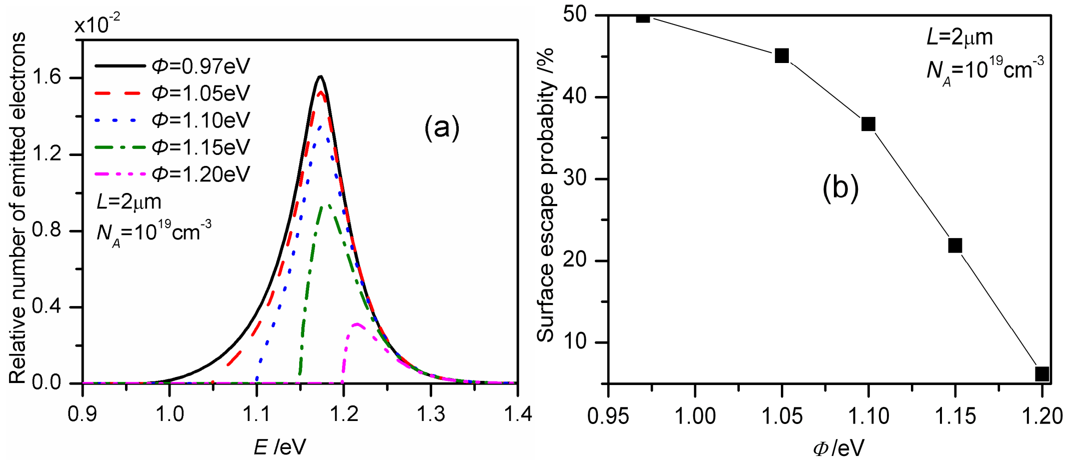

Fig.4. Energy distributions of emitted electrons (a) and surface escape probability (b) in different work functions.

In summary, The electron energy distribution with different parameters, such as N_A, Φ, are discussed. The simulated results indicate that, the large exponential-doping GaAs photocathodes have better features of the electron energy distributions than traditional GaAs photocathodes.

Conclusions

The characteristics of the electron energy distribution for the large exponential-doping GaAs photocathodes are discussed in details. The theoretical analysis indicate that, the new-type GaAs NEA cathodes have much narrower the electron energy distribution than traditional GaAs photocathodes, and the electron energy distribution strongly despends upon the structural features of the band-bending region. The calculated results suggest that the structure model of the novel GaAs NEA cathodes is a technical innovation in practice, and is benefit for further development and application for NEA semiconductor cathodes. More rigorous analysis of electron energy distributions needs further study for the large exponential-doping NEA photocathodes.

Acknowledgements

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