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Research on surface photovoltage for GaAs photocathodes

LIANG CHEN[a,b*], YUNSHENG QIAN[a], BENKANG CHANG[a]
[a]*Institute of Electronic Engineering & Optoelectronics Technology, Nanjing University of Science and Technology, 210094, Nanjing, China*
[b]*Institute of Optoelectronics Technology, China Jiliang University, 310018, Hangzhou, China*

To achieve high quantum efficiency and good stability has been a main direction to develop GaAs photocathodes recently. The performance of GaAs photocathodes lies on the electron diffusion length and activation techniques. In this paper, we discuss the feasibility of measuring the electron diffusion length of photocathodes by surface photovoltage wave from theory and deduce the calculation equations. The principle of the surface photovoltage wave and the measuring techniques are discussed particularly using the electro-static equilibrium condition and the consideration of energy-valley scattering and surface barriers. Through experiments, the fitting calculation curve and experiment curve fit very well. The surface photovoltage fitting calculation in consideration of energy valley scattering shows a better method to study the material properties and activation techniques for GaAs photocathodes.

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Keywords: GaAs photocathode, Surface photovoltage, Electron diffusion length

1. Introduction

Negative-electron-affinity (NEA) GaAs photocathodes have already found widespread applications in night vision image intensifiers and are potential sources for next-generation electron accelerators due to their high spin polarization, low energy spread, and emittance. The quantum efficiency of NEA GaAs photocathodes mainly depends on the performance of the material and the technique of preparation. The electron diffusion length is the main parameter for the GaAs photocathode materials. A short electron diffusion length leads to bad performance of GaAs materials, which limits the development of NEA GaAs photocathodes. In early research, the photocathode performance parameters, such as electron diffusion length, electron escape probability, and back interface recombination velocity and etc were mainly obtained from the fitting of spectral response curves after activation. Because the spectral response curve is affected by the properties of body photocathode material、CS-O activation techniques、surface potential barrier and other factors, thus the parameters of GaAs photocathodes could not be exactly measured only through spectral response curve after activation. The surface photovoltage method is a powerful non-destructive and contactless characterisation technique, which has been successfully used to study the electronic properties of a wide range of semiconductor bulk materials and multilayer. Because surface photovoltage curve is only in contact with properties of body photocathode material, so some parameters of GaAs photocathodes could be exactly measured through surface photovoltage fitting. In this paper we deduced the surface photovoltage equation and spectral response equation in consider of energy valley scattering. Through experiments and fitting calculations, we found the electron diffusion length could be well fitted. The surface photovoltage shows a better mean to carry varied doping GaAs photocathode techniques and activation techniques in the future.

2. Principles

In early research, photoemission from NEA GaAs photocathodes has been described as a three step process of photo absorption and spectral response equation of photocathodes can be deduced from diffusion equations based on three step process. As is shown in Fig. 1, when photon energy is lower, the electrons excited to Γ energy valley play the dominant role. Along with the photon energy increasing, the inter-valley diffusion from Γ to L or X plays a more important role in the energy-relaxation mechanisms. Indeed the diffusion rate from Γ to L or X is ten times of magnitude larger than the inverse process. To agree with Gunn Effect, the hot electrons excited to X energy valley could be neglected in contrast to L energy valley. This phenomenon of GaAs photocathodes will result in emitted electron energy-distribution shift towards higher energies with the increasing photon energy.[4-5] Thus we should take the inter-valley diffusion into account for measuring the surface photovoltage and the spectral response properties for GaAs photocathodes.

When photoelectrons arriving at the surface, they must traverse surface potential barriers prior to emit into vacuum. Band structure and surface potential barrier of GaAs: Cs-O reflection photocathodes are shown in Fig.2. Surface potential barrier profile comprises two approximately beelines with different slopes named potential barrier I and

II, this profile was proposed based on double-dipole model. So escape probability P has close relation with the profile of surface potential barrier. Thus the escape probability P should not be considered to be a constant value for the whole wavelength as early research. Because the electron energy of each valley is different, so the escape probability of different valleys should be considered separately. From above analysis, we modify the electron diffusion equation for GaAs photocathodes in account of Γ and L energy valley distribution as Eq.1 and Eq.2.[6-10]

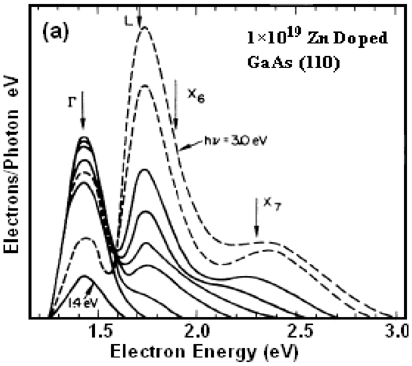

Fig. 1. Electron energy distribution curve of different incident photon energies for reflection photocathodes.

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$$D_\Gamma \frac{d^2 n_\Gamma(x)}{dx^2} - \frac{n_\Gamma(x)}{\tau_\Gamma} + \frac{n_L(x)}{\tau_L} + \alpha I_0(1-R)F_\Gamma \exp(-\alpha x) = 0 \quad (1)$$

$$D_L \frac{d^2 n_L(x)}{dx^2} - \frac{n_L(x)}{\tau_L} + \alpha I_0(1-R)F_L \exp(-\alpha x) = 0 \quad (2)$$

Where *x* is the distance between some points inside photocathodes and emitting surface, D_Γ and D_L are electron diffusion coefficient of Γ energy valley and L energy valley, τ_Γ and τ_L are photoelectron lifetime of Γ energy valley and L energy valley.

For reflection GaAs photocathodes, the boundary condition is shown as Eq.3

$$n_\Gamma(x)\big|_{x=0} = 0, n_\Gamma(x)\big|_{x=\infty} = 0, n_L(x)\big|_{x=0} = 0, n_L(x)\big|_{x=\infty} = 0 \quad (3)$$

According to diode theory, the surface photovoltage is shown as Eq.4

$$\Delta V = \frac{KT}{q}\ln(1+\frac{j_w}{c}), J_w = D_n \frac{dn(x)}{dx}\Big|_{x=0} \quad (4)$$

Where ΔV is surface photovoltage for GaAs
p m
p

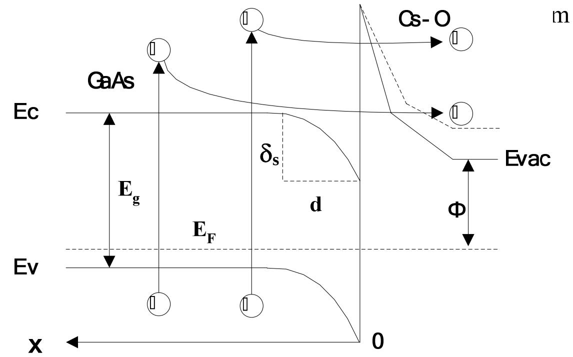

Fig. 2. Band structure and surface potential barrier of GaAs: Cs-O photocathodes for reflection photocathodes.

Thus we could get the solution for surface photovoltage as Eq.5

$$\Delta V_L = \frac{KT}{qc}\frac{F_L I_0(1-R)}{1+1/\alpha_{h\gamma}L_L}$$

$$\Delta V_\Gamma = \frac{KT}{qc}\frac{I_0(1-R)}{1+1/\alpha_{h\gamma}L_\Gamma}\left[F_\Gamma + \frac{F_L L_\Gamma}{\alpha_{h\gamma}L_L(L_\Gamma+L_L)(1+1/\alpha_{h\gamma}L_L)}\right] \quad (5)$$

Where F_L is the fraction which is excited to L energy valley, F_Γ is the remaining fraction of excited electrons to Γenergy valley, $\alpha_{h\gamma}$ is absorption coefficient of photocathode material, L_Γ and L_L are electron diffusion lengths for L and Γ energy valley respectively.

$$L_L = \sqrt{D_L \tau_L}, L_\Gamma = \sqrt{D_\Gamma \tau_\Gamma} \quad (6)$$

From above deduction, we could fit the electron diffusion length through we found the main difference between surface photovoltage and spectrum response current is surface escape probability P.

3. Analyses

As is shown in Fig.3, the fitting curves for different electron diffusion length of Γ energy valley follow the equation as Eq.5. The fitting values for Γ energy valley and L energy valley is shown in Table 1.

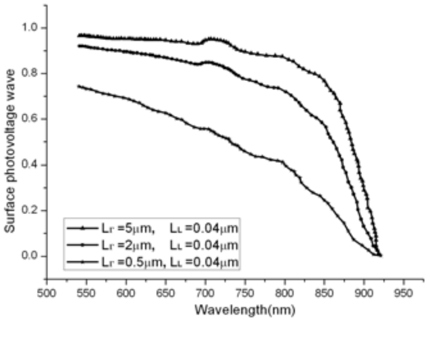

Fig. 3. Fitting curves for different electron diffusion length of Γ energy valley.

Table 1. Fitting values for Γ energy valley and L energy valley.

Curve	Curve1	Curve2	Curve3
L_Γ(μm)	5	2	0.5
L_L(μm)	0.04	0.04	0.04

As is shown in Fig. 4, the fitting curves for different electron diffusion length of L energy valley follow the equation as Eq.5. The fitting values for Γ energy valley and L energy valley is shown in Table 2.

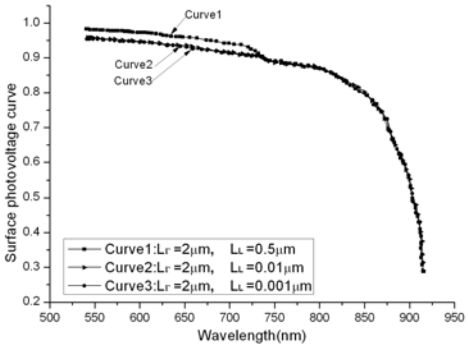

Fig. 4. Fitting curves for different electron diffusion length of L energy valley.

Table 2. Fitting values for Γ energy valley and L energy valley.

Curve	Curve1	Curve2	Curve3
L_Γ(μm)	2	2	2
L_L(μm)	0.5	0.01	0.001

From the above fitting calculation, we could find the electron diffusion length of Γ energy valley draws the main role of the whole wavelength band for surface photovoltage; the electron diffusion length of L energy valley will affect the increasing slope of short wavelength band. There is a sidestep near the wavelength of 725μm and the sidestep becomes more clear along the rising of electron diffusion length. Because the electron diffusion length L_Γ which is about several micrometers is larger than the electron diffusion length L_L which is about several scores of nanometers, so the excited electrons from Γ energy valley draw the main role of surface photovoltage.But along the rising of shining photo energy, the scatting from Γ energy valley to L energy valley becomes more and more larger. The scattering ratio of different energy valley is shown as Fig. 5. The reason for the sidestep near 725 μm is that the scattering ratio slope changes greatly near 725 μm as Fig. 5. Thus we should take the energy valleys scattering in the surface photovoltage fitting calculation.

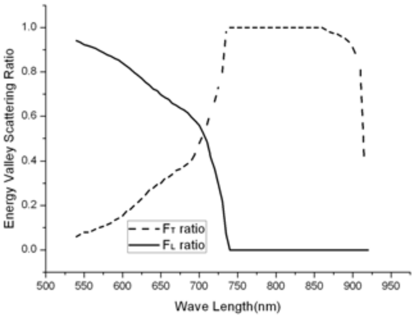

Fig. 5 Energy Valley Scattering Ratio for L and Γ energy valley.

4. Experiments

For experiments, reflection-mode GaAs photocathode material was grown over GaAs wafer (100) by MBE with p-type beryllium doping, doping concentration is 1×10^{19}cm^{-3} and the active layer thickness is 1.6 μm. Before measuring the surface photovoltage, the GaAs photocathode material must be passed through acetone、hydrofluoric acid、absolute ethyl alcohol in turn for ultrasonic washing in order to wipe off surface oxidation layer and impurity. The system of surface photovoltage measurement is shown as Fig. 6 [6]. The surface photovoltage measurement system consists of light source、lens、grating monochromator、photovoltage pond、lock-in amplifier、light chopper、computer and measuring software etc. Light source passes through lens and modulated by light chopper, focused on grating monochromator, monochromatic light irradiating on samples. Lock-in amplifier could amplify the sample signal and collected by computer. The scanning rate and sample temperature are also controlled by computer. The whole system could ensure accuracy and validity. [12-14]

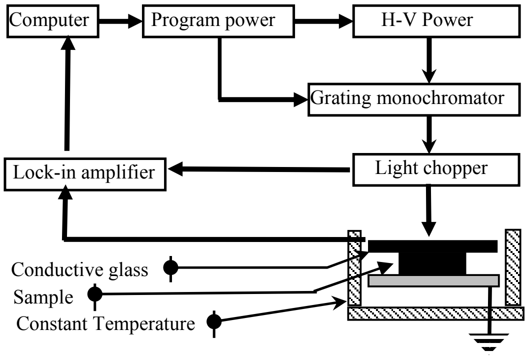

Fig. 6. Surface photovoltage measurement system before activation.

As is shown in Fig. 7, Curve1 is the fitting curve in early research; the fitting calculation is as Eq. 7 which has not shown consideration for the scattering between energy valleys. Curve 2 is the fitting curve as Eq. 5, the fitting value is L_Γ = 2.1 μm, L_L= 0.05 μm. Curve 3 is the experiment curve for surface photovoltage.

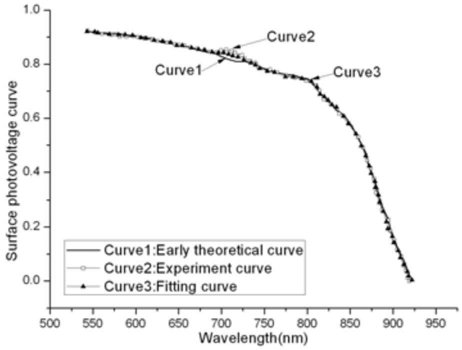

Fig. 7. Experimental and theoretical curves for surface photovoltage.

From the fitting calculation, we could find that the fitting equation in consideration of the scattering between energy valleys shows a better effect than early research.

4. Conclusions

By considering of the diffusion between different energy valleys, we deduced the formula for surface photovoltage curve. Through the fitting calculation, we could get the exact value of electron diffusion length from surface photovoltage curve. Along with the spectral response research after activation, we could carry out comparative research between before activation and after activation in order to exactly measure body material characteristics、Cs-O activation techniques and surface barriers for GaAs photocathodes in the future [15-16].

Acknowledgements

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*Corresponding author: sunembed@yahoo.com.cn