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Research on quantum efficiency of GaN wire photocathode

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ABSTRACT

On the basis of three-dimensional continuity equation in semiconductors and finite difference method, the carrier concentration and the quantum efficiency of GaN wire photocathode as a function of incident photon energy are achieved. Results show that the quantum efficiency of the wire photocathode is largely enhanced compared with the conventional planar photocathode. The superiority of the wire photocathode is reflected in its structure with surrounding surfaces. The quantum efficiency of the wire photocathode largely depends on the wire width, surface reflectivity, surface escape probability and incident angle of light. The back interface recombination rate, however, has little influences on the quantum efficiency of the wire photocathode. The simulation results suggest that the optimal width for photoemission is 150–200 nm. Besides, the quantum efficiency increases and decreases linearly with increasing surface escape probability and surface reflectivity, respectively. With increasing ratio of wire spacing to wire height, the optimal incident angle of light is reduced. These simulations are expected to guide the preparation of a better performing GaN wire photocathode.

1. Introduction

GaN photocathode has long time been applied into ultraviolet detection due to its wide bandgap, direct interband transition and strong chemical stability [1–3]. Moreover, the attention and studies of GaN photocathode are always focused on the improvement of quantum efficiency (QE), which will directly reflect the photoemission characteristics of the detector [4–6]. In the past years, the QE of GaN photocathode is continuously increased with the development of p-type doping technology, surface cleaning technology, surface activation technology and gradient doping structure [4,7–10]. However, there are still many bottlenecks to be overcome, such as the conflict of photon absorption depth and electrons diffusion length [7,11]. In reflection-mode (r-mode) planar photocathode, the incident photons need thick photoemission layer to be fully consumed while the excited photoelectrons need thin photoemission layer to reduce the recombination with holes. This disadvantage can hardly be avoided in conventional planar GaN photocathode.

Recently, a new wire structure photocathode has been proposed and has been successfully applied into Si photocathode, Cu_2O photocathode, Ag photocathode and GaAs photocathode [12–18]. These nano/microwire photocathodes, as expected, exhibit better performance, due to the combination of long optical paths and short electron transport distances, which simultaneously ensures enough absorption of incident light and the collection of photogenerated charge carriers. Additionally, the wire photocathode possesses a larger ratio of volume to surface for its surrounding surface structure compared with planar geometry of conventional planar photocathode. These excellent properties of wire photocathode are expected to further promote the QE of GaN photocathode.

In this study, on the basis of three-dimensional continuity equation and finite difference method, the carrier concentration in GaN wire under continuous parallel light exposure is obtained. Furthermore, the QE of GaN wire photocathode is obtained. Finally, the effects of the wire width, back interface recombination velocity, surface reflectivity, surface escape probability and incident angle of light on the QE are simulated. According to the simulation, high-performance GaN wire photocathode is possibly to be prepared and applied into high performance vacuum electron sources and parallel electron beam lithography.

2. Theoretical method

The model of a single GaN square wire photocathode is shown in

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Fig. 1. The wire is grown on the GaN substrate for a lower lattice mismatch. The parallel incident light irradiates the wire along x axis direction. The x axis coordinate value of the incident plane of light is set as zero. The axial direction of the wire (along the height direction of the wire) is set as z axis. The direction perpendicular to the incident light is set as y axis, which is shown in Fig. 1. The photoelectrons excited by the incident photons diffuse to the surface of the wire (four sidewalls and the top surface). According to the drift-diffusion model in semiconductors and the wire structure, the three-dimensional continuity equation can be concluded as follows:

$$D_n \nabla^2 \cdot n(x,y,z) - U(x,y,z) + G(x,y,z) = 0 \tag{1}$$

where $n(x,y,z)$ represents the carrier concentration in the wire; $U(x,y,z)$ represents the carrier recombination rate per unit volume; $G(x,y,z)$ denotes the generation rate of photoelectrons per unit volume; D_n denotes the diffusion coefficient of electron. $D_n \nabla^2 \cdot n(x,y,z)$ is the accumulated carrier number in per unit time and unit volume. The carrier recombination rate $U(x,y,z)$ is usually associated with the lifetime of the carrier. The generate rate of photoelectrons $G(x,y,z)$ is the same as planar photocathode since the incident light is parallel. Therefore, $U(x,y,z)$ and $G(x,y,z)$ can be given as:

$$U(x,y,z) = \frac{n(x,y,z)}{\tau} \tag{2}$$

$$G(x,y,z) = I_0(1-R)\alpha \exp(-\alpha x) \tag{3}$$

where τ represents the lifetime of photoelectrons; I_0 represents the intensity of incident light per unit area; R represents surface reflectivity of the photocathode; α represents the absorption coefficient of GaN wire. At every point of the wire, the lifetime of photoelectrons, the absorption coefficient and the diffusion coefficient of photoelectrons are deemed to be unchanged, respectively.

After the absorption of photons, the excited carriers diffuse to the surface of the wire. In this model, there are five surfaces of the wire including four sidewalls and the top surface, from where the electrons escape. Besides, the back interface where the substrate and the wire are connected is also considered one of the boundary equations. Combining the back interface recombination velocities and the surface emitting electrons, the boundary equations should be:

$$\left\{\begin{array}{l} n(0,y,z) = 0; \\ n(d,y,z) = 0; \\ n(x,0,z) = 0; \\ n(x,d,z) = 0; \\ n(x,y,H) = 0; \\ D_n \nabla \cdot n(x,y,z)|_{z=0} = S_v n(x,y,0) \end{array}\right\} \tag{4}$$

where d and H represent the width and the height of the wire, respectively, S_v denotes the back interface recombination velocity. According to Eqs. (1)–(4), the carrier concentration in the wire can finally be obtained. However, the analytic solutions of $n(x,y,z)$ can hardly be derived or the analytic solutions are too complicated. Therefore the finite difference method is adopted to achieve the carrier concentration of each very small unit in the wire. Taking a model with $d = 100$ nm and $H = 500$ nm for example, the wire can be divided into 100 × 100 × 500 cells. The volume of each cell is 1 nm^3. The first-order partial derivative and the second-order partial derivative of the carrier concentration can be expressed as a linear relation between carrier concentrations of the adjacent cells. Therefore, the partial derivative of $n(x,y,z)$ in Eqs. (1) and (4) can be expressed by the iteration of the carrier concentrations of the adjacent cells. Combining with the cycle calculation (at least ten thousand times) in MATLAB, the carrier concentration at every point of the wire can be obtained. The distribution of the carrier concentration in the cross section and vertical section of the wire are shown in Fig. 1.

Then, based on the carrier concentration that achieved above, the electron flow can be expressed as follows:

$$\left\{\begin{array}{l} J_1 = PD_n \int\limits_{z=0}^{H} \int\limits_{y=0}^{d} \left[\left.\frac{\partial n(x,y,z)}{\partial x}\right|_{x=0} + \left.\frac{\partial n(x,y,z)}{\partial x}\right|_{x=d} \right]; \\ J_2 = PD_n \int\limits_{z=0}^{H} \int\limits_{x=0}^{d} \left[\left.\frac{\partial n(x,y,z)}{\partial y}\right|_{y=0} + \left.\frac{\partial n(x,y,z)}{\partial y}\right|_{y=d} \right]; \\ J_3 = PD_n \int\limits_{y=0}^{d} \int\limits_{x=0}^{d} \left[\left.\frac{\partial n(x,y,z)}{\partial z}\right|_{z=H} \right]; \\ J = J_1 + J_2 + J_3 \end{array}\right\} \tag{5}$$

where P denotes the surface electron escape probability; J_1, J_2 and J_3 represent the electron flow of the two sidewalls that vertical to the incident light, the two sidewalls that parallel to the incident light and the top surface, respectively; J is the total electron flow.

The QE of a single GaN square wire photocathode can be finally achieved by the ratio of the electron flow to the incident photon flow, which is described as:

$$Y = \frac{J}{I_0 S} \tag{6}$$

where S is the cross section area of the wire exposed by the incident light.

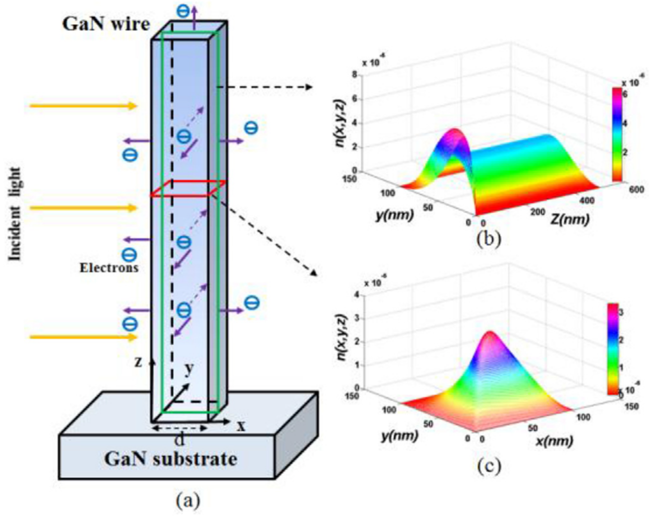

Fig. 1. The sketch map of GaN wire structure photocathode, (a) the geometry of the photocathode; (b) the carrier concentration on the vertical section of the wire and (c) the carrier concentration on the cross section of the wire.

3. Simulation and discussion

On the basis of the method introduced above, the QE of a single GaN square wire photocathode as a function of the energy of incident photon from 3.2 eV to 5.4 eV (the wavelength from 380 nm