Influence of size-effect quantization of energy levels in semiconductors on the photoelectron emission

V. L. Korotkikh, A. L. Musatov, and V. D. Shadrin

Institute of Radio and Electronics
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We investigate the photoelectron energy distribution for GaAs photocathodes with negative electron affinity. It is concluded that the photoelectrons emerge to the vacuum from two-dimensional surface subbands that arise in the region of the bending of the semiconductor bands as a result of size-effect quantization.

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Photocathodes with negative electron affinity (NEA) constitute strongly doped *p*-type semiconductors (impurity density $N_a \sim 10^{19}$ cm^{-3}), whose work function is lowered in such a way that the vacuum level lies below the bottom of the conduction band in the interior of the semiconductor.[1,2] At this degree of semiconductor doping, the width of the region of band bending near its surface is of the order of the electron wavelength, so that size-effect quantization of the energy levels can take place in this region. In the present communication we present results of an investigation of the distribution of the photoelectrons in energy for a GaAs photocathode with NEA; these results attest to the influence of the size-effect quantization on the photoelectron emission.

The photocathodes were based on epitaxial GaAs layers doped with zinc at $N_a \sim 10^{19}$ cm^{-3}. The photocathode work function was $\phi = 1.12$ eV,[3] so that the level of the vacuum was 0.3 eV below the bottom of the conduction band in the interior of the semiconductor. The photoelectron spectra were investigated by a method developed

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by us, consisting of measuring the dependence of the quantum yield of the photoemission on the work function[3] and differentiating this characteristic either graphically or with a computer. In this method, the role of the retarding potential is played by the barrier on the interface with the vacuum, so that in fact one measures the distribution of the photoelectrons with respect to the normal component of the energy.

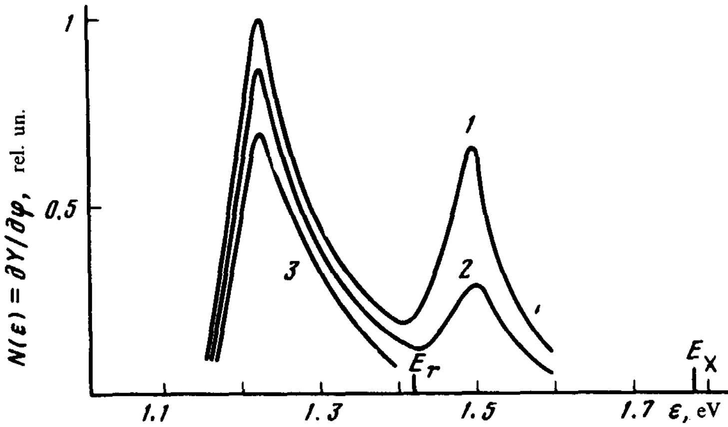

FIG. 1. Photoelectron energy distribution for GaAs with NEA. E_Γ and E_X—positions of the corresponding minima of the conduction band in the interior of the semiconductor: 1—$h\nu = 3$ eV, 2—$h\nu = 2$ eV, 3—$h\nu = 1.45$ eV.

The photoelectron energy distribution for GaAs with NEA is shown in Fig. 1. The energy spectrum consists of two maxima corresponding to photoelectrons thermalized at the Γ and X minima of the conduction band. As seen from the figure, the maxima are shifted toward lower energies in comparison with the positions of Γ and X of the maxima of the conduction band in the interior of the semiconductor, and this shift is different for the Γ ($\Delta\epsilon_\Gamma = 0.18$ eV) and the X ($\Delta\epsilon_X = 0.29$ eV) minima. At the same time, the peaks are quite narrow and their half-width does not exceed 0.1 eV.

Since the mean free path of the hot electrons at the Γ minimum of the conduction band ($l_{p0} \approx 700$ Å)[4] greatly exceeds the width of the band-bending region ($l_D \approx 100$ Å), the observed decrease of the photoelectrons energy cannot be attributed to electron-phonon interaction in the region of the bending of bands with continuous energy spectra of the electronic states.[5] In our opinion, the presence on the energy spectrum of the photoelectrons of narrow peaks shifted towards lower energies in comparison with the position of the Γ and X minima of the conduction band in the volume of the semiconductor points to the existence in the region of the band bending of discrete energy levels.

To calculate the spectrum of the electronic states in the region of the band bending, we consider the energy level scheme of GaAs with NEA, as shown in Fig. 2. It should be noted that the surface of a semiconductor with NEA has a large reflection coefficient for the conduction-band electrons.[6-7] The reflection coefficient of our photocathodes can be estimated from the data on the probability of the photoelectron

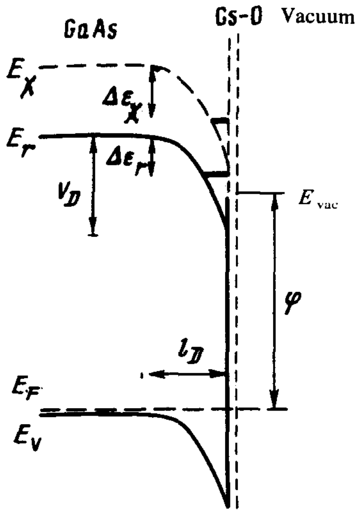

FIG. 2. Energy level scheme of GaAs with NEA. $\Delta\epsilon_\Gamma$ and $\Delta\epsilon_X$ indicate the positions of the bottom of the lower surface subbands relative to the corresponding minima of the conduction band in the interior of the semiconductor.

yield in vacuum when conditions of zero electron affinity are realized ($X=0$, $B\sim 1\%$.)[3] Although at $\chi=0$ all the photoelectrons pass through the region of the band bending and reach the surface with an energy exceeding the vacuum level ($l_{p0} \gg l_D$), only a small fraction of the total number of photoelectrons emerge to the vacuum. This means that the reflection coefficient is close to unity and in first-order approximation the surface can be regarded as an ideally reflecting wall, and the band-bending region can be regarded as a one-dimensional potential wall for the electrons.

The energy spectrum of the lower electron states localized in the band-bending region was calculated in the effective-mass approximation. The potential of the band-bending region was approximated in this case by a triangular potential well with infinite walls. The eigenfunctions of the effective-mass equation are in this case an Airy function with nodes on the semiconductor surface, and the spectrum of the electronic states for the Γ and X minima of the conduction band is given by

$$\epsilon_{\Gamma,X}(n,p_\parallel) = \left(\frac{\hbar^2 e^2 F^2}{2m^*_{\Gamma,X}}\right)^{1/3} \lambda_n + \frac{p_\parallel^2}{2m^*_{\Gamma,X}},$$

where λ_n are the zeros of the Airy function, $m^*_{\Gamma,X}$ is the effective mass in the Γ or X minimum, respectively, F is the average electric field intensity in the band-bending region, and $eF \simeq V_D/L_D$. The energy is reckoned from the bottom of the potential well at each minimum.

As seen from the foregoing expression, the electron spectrum in the region of the band-bending constitutes a set of two-dimensional surface subbands. Let us estimate the energy corresponding to the bottom of the lower ($n=0$, $\lambda_0=2.34$) surface subband in each minimum of the conduction band–$\epsilon_{\Gamma_0}(0)$ and $\epsilon_X(0)$. Assuming a band bending $V_D=0.5$ eV,[2] $l_D=100$ Å ($N_a=10^{19}$ cm^{-3}), we obtain $\epsilon_\Gamma(0)=0.3$ eV and

$\epsilon_X(0)=0.12$ eV. The estimate shows that the bottom of the lower surface subband for the Γ minimum lies lower than the corresponding minimum of the conduction band in the interior of the semiconductor, by an amount $\Delta\epsilon_\Gamma=0.2$ eV. For the X minimum we have $\Delta\epsilon_X=0.38$ eV. The obtained values are close to the experimentally observed shifts of the peaks of the photoelectron spectrum (see Fig. 1). In our opinion this confirms the proposed model.

The results makes it necessary to revise our ideas concerning photoemission from semiconductors with NEA. Owing to the large reflection coefficient from the semiconductor boundary (the Cs–O layer), the overwhelming majority of the photoelectrons are reflected from the boundary and are incident after scattering on the two-dimensional surface subbands that arise in the region of the band bending as a result of the size-effect quantization and emerge from them to the vacuum. To obtain effective emission it is therefore necessary to lower the work function of the semiconductor in such a way as to realize the condition of the NEA for electrons situated on the bottom of the lower surface subband.

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