Effect of electron thermalization on the photoresponse spectra of gallium arsenide–metal structures at 1.6 K

V. P. Al'perovich, A. F. Kravchenko, N. A. Pakhanov, and
A. S. Terekhov

Institute of Semiconductor Physics, Siberian Division, USSR Academy of Sciences

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Oscillations due to thermalization of hot photoexcited electrons with emission of optical phonons were observed in the photoresponse spectra of GaAs–metal structures. A new electron thermalization channel, due to their scattering in the lateral minimum of the conduction band, is observed.

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The influence of exciton effects on low-temperature spectra of the photoresponse of surface–barrier structures based on GaAs was observed and investigated in Refs. 1 and 2. In this paper we report observation of an oscillating photo-response spectrum of such structures in the fundamental absorption band.

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We used for the measurements structures prepared by vacuum sputtering of aluminum on the surface of highly purified expitaxial *n*-GaAs. The concentration of the free electrons and their mobility, measured at 77 K, were $n \lesssim 10^{14}$ cm^{-3} and $\mu \gtrsim 100000$ cm^2/V-sec, respectively. The samples were placed in a cryostat with liquid helium. The temperature was lowered to 1.6 K by pumping off the vapor. The light source was a monochromator with linear dispersion 4.5 Å/mm. The photoresponse was measured with a selective nanovoltmeter in the photo-emf regime.

The measured photo-emf is shown in Fig. 1. The section of the spectrum in the vicinity of the exciton peak is shown in greater detail in Fig. 2. The latter figure shows clearly a fine structure due to excitation of the exciton-impurity complex X_1 and of the ground $n = 1$ and excited $n = 2$ states of the exciton. It is seen from Fig. 1 that at photon energies $\hbar\omega$ exceeding the width E_g of the forbidden band the photo-emf oscillates as a function of $\hbar\omega$, with a period 42.5 meV. Besides the monotonic damping, "beats" of the oscillation amplitudes can be noted, as well as a rapid attenuation of the amplitudes at a photon energy $\hbar\omega \approx 1.907$ eV.

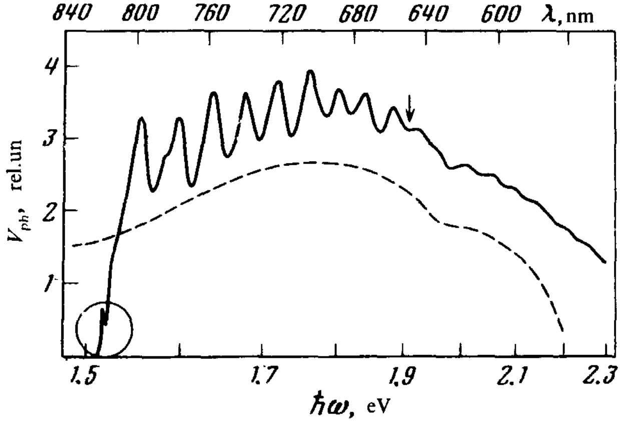

FIG. 1. Photo-emf spectrum at 1.6 K (solid line). The arrow shows the start of the thermalization of the electrons through the lateral minimum. The circled part of the spectrum is shown in greater detail in Fig. 2. Dashed line—spectrum of radiation from the monochromator.

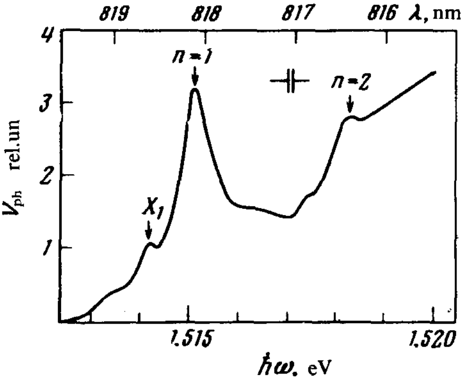

FIG. 2. Photo-emf spectrum at 1.6 K near the intrinsic absorption edge.

Oscillations similar to those shown in Fig. 1 were observed earlier in the spectra of the photoconductivity (PC),[3,4] and of the photomagnetic effect,[5] and in the photoluminescence excitation spectra. From the period of the oscillations, which in all cases was approximately 42 meV, it was established that their appearance is due to the steplike process of thermalization of the electrons with emission of longitudinal optical phonons, and to the dependence of the electron lifetime τ_e on the electron energy.[3,4] The extrema in the spectra were observed at photon energies

$$\hbar\omega = E_g + K\hbar\Omega_{LO}\left(1 + \frac{m_e^*}{m_h^*}\right),$$

where $\hbar\Omega_{LO} = 36.7$ meV is the energy of the longitudinal-optical phonons, m_e^*/m_h^* is the ratio of the effective masses of the electron and holes, and K is an integer. The "beats" in the oscillating spectra were observed earlier and are satisfactorily explained as being due to interference between the contribution of the heavy and light hole bands.[3]

Despite the common cause (this follows from the period of the oscillations of the photo-emf) and the outward similarity, there is a fundamental difference between the oscillations in the spectrum of the photo-emf and the previously observed oscillations.[3-5] It is known[6] that the photo-emf depends on the thickness $l = w + L_p$ of the region in which the minority carriers are gathered (w is the thickness of the space-charge region and $L_p = (D\tau_p)^{1/2}$ is the diffusion length of the holes). Consequently, the oscillations of the photo-emf are due to oscillations of the lifetime τ_p of the holes and not of the electrons as in the other effects. Thus it turns out that the average electron energy determines not only their own lifetime, which manifests itself in the photo-emf oscillations, but also the hole lifetime. By comparing the photoconductivity and the photo-emf oscillations we can verify that all their main singularities are close, and consequently the oscillations of τ_e and τ_p are "in phase." The apparent explanation for this fact is that in pure GaAs at helium temperatures the electrons and holes leave their bands predominantly in pairs and become bound into excitons. It should be noted that the very fact that oscillations were observed in the photo-emf spectrum, as well as in the fine exciton structure (Fig. 2), is due to the small thickness l of the gathering region compared with the absorption depth of the light.[2]

An important feature of the spectrum, observed in all the investigated structures, is the strong damping of the photo-emf oscillation amplitude, starting with a photon energy $\hbar\omega_{\text{thr}} \approx 1.907$ eV. This indicates, in our opinion, that a new electron-thermalization channel is turned on. This channel is apparently the transfer of the electrons from the central valley into the lateral minimum of the conduction band. It is known[7] that starting with certain electron energies the probability of such a transfer in Ga is higher than the probability of the LO-phonon emission in the central valley. The electrons that are returned to the central valley by the inverse transitions acquire an energy "smearing" because of the dispersion of the optical phonons, because the short-wave acoustic phonons take part in the intervalley scattering, and also because of possible thermalization in the lateral minimum. This energy "smearing" leads to damping of the oscillations. From the damping threshold

$$\hbar\omega_{\text{thr}} = E_g + \left(\Delta + \hbar\Omega_{iv}\right)\left(1 + \frac{m_e^*}{m_h^*}\right)$$

($\hbar\Omega_{iv}$ is the energy of the phonons that participate in the intervalley scattering) we can determine the energy gap Δ between the bottom of the conduction band and the lowest lateral minimum. Assuming that the main contribution to the intervalley transitions is made by LO phonons (i.e., assuming $\hbar\Omega_{iv} = \hbar\Omega_{LO} = 36.7$ meV), we obtain $\Delta = 297 \pm 10$ meV. This value differs substantially from the value[8] $\Delta = 360$ meV which was assumed for a long time to be reliably established for GaAs (Ref. 9). At the same time, the value of Δ determined by us agrees splendidly with the $\Delta = 296$ meV obtained recently by Aspnes[10] and a number of subsequent investigations,[11] in which earlier notions concerning the locations of the nearest lateral minimum in GaAs were reviewed. Thus, a new experimental confirmation has been obtained for the structure proposed in Ref. 10 for the conduction band of gallium arsenide.

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