

Oscillating surface photoemf of hot electrons

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Oscillations caused by the interaction of an ensemble of nonthermalized photoelectrons with the surface of a semiconductor have been observed at helium temperatures in the spectra of surface photoemf in the fundamental absorption band of gallium arsenide.

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Characteristic oscillations, which are attributed to the stepwise relaxation process of the energy of photoelectrons with the emission of longitudinal optical (LO) phonons, have been observed in the low-temperature photoconductivity spectra of several semiconductors.¹ Similar oscillations were also observed recently in the photoresponse (PR) spectra of *n*-GaAs-metal Schottky barriers (SB)^{2,3} (we denote them as type “*D*”). The photoresponse in this case was attributed to an oscillation of the diffusion flow of nonthermalized photoelectrons within the semiconductor as a function of the photoexcitation energy $\hbar\omega$.³

In our work we have observed oscillations, which are “counterphase” to the *D* spectra, in the SB PR spectra of gallium arsenide. The physical cause of these oscillations (we call them type “*E*”) is attributed to oscillations of the flow I_n^E of nonthermalized photoelectrons to the semiconductor surface. This causes corresponding oscillations of the recombination flow through the surface states (SS) or states in the space-charge region (SCR). The observed effect can be used to study the distribution function of hot electrons and surface recombination, especially in semiconductors with small diffusion lengths of the minority carriers.

The samples were prepared by the deposition of a 3 × 4-mm semitransparent Al layer on the surface of epitaxial *n*-GaAs with a free-electron density $n_0^{77} = 2 \times 10^{14} - 10^{16} \text{ cm}^{-3}$ at 77 K, which was grown on a semi-insulating substrate. Before the deposition of Al, the samples were kept in the air for a long time; this ensured the presence of a thin oxide layer with a thickness of 40–50 Å. The imperfection coeffi-

cient, which was determined from the forward branch of the I-V characteristic at 300 K, was equal to 1.6-2 for the different samples. The through current at reverse biases of less than 1-2 V can be ignored for most SB and, therefore, they can be regarded as metal-insulator-semiconductor structures. This arises from the following experimental data. When the SB was illuminated by a constant light flux with $\hbar\omega > E_g$ and the load was 10 G Ω , a steady-state, "frozen" photoemf appeared across the SB with values in the range of 0 to 0.9 V, depending on the light intensity and time. For $\bar{I}_0 \approx 10^{15}$ photons/cm² sec a value of 0.9 V was established in 5-6 min, which remained after the light was turned off, and then disappeared after the SB was short-circuited. The appearance of this photoemf is apparently due to a transfer of photoexcited electrons from the metal to the semiconductor.⁴

The variable photoemf \tilde{V}_{ph} measured at a monochromatic flux intensity of $\tilde{I}_0 \approx 10^{12}$ photons/cm² sec, which was modulated with a frequency of 500 Hz, was equal to 30-100 μ V for a load resistance of 1 M Ω . Figure 1 shows the first three oscillations in the E and D spectra. It can be seen that they have the same period $E_{LO}(1 + m_e/m_h) = 42$ meV (E_{LO} is the energy of the LO phonon) and opposite phases.

We shall examine the surface photoemf \tilde{V}_1 assuming that the surface recombination and surface trapping of holes have a decisive influence on its formation. The quasi-steady-state band bending qV_s can be estimated from the condition that the flow of holes \tilde{I}_p to the surface is equal to the flow of thermalized electrons. An estimate gives a value of $qV_s \approx 15 k_0 T$. The energy of the LO phonon at 4.2 K for GaAs is equal to $\sim 100 k_0 T$. Therefore, the band bending is less than E_{LO} and for $E > E_{min} \approx 15 k_0 T$ the electrons reach the surface unhindered. The value of \tilde{V}_1 in the harmonic approximation is proportional to the difference $(\tilde{I}_p - \tilde{I}_{nr})$, where $\tilde{I}_{nr} = I_n^E \sigma_n N_t^0$, and σ_n is the capture cross section of electrons in the empty surface states with a density N_t^0 .

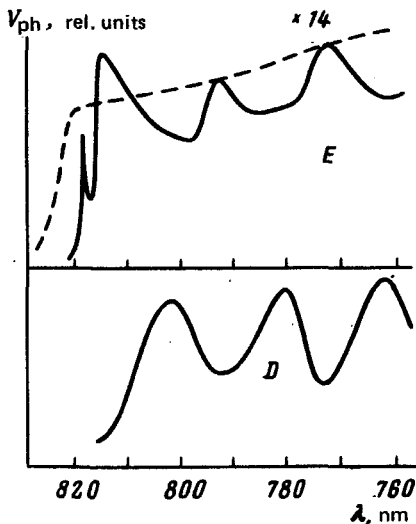


FIG. 1. Spectral dependences of the photoresponse for an n-GaAs-Al SB at 4.2 K; E spectrum—for SB with $n_0^{77} = 4.6 \times 10^{14}$ cm⁻³, solid curve—for a bias of 0 and 0.85 V, dashed curve—for reverse bias of -8 V, D spectrum—for SB with $n_0^{77} \lesssim 10^{13}$ cm⁻³.

Let us determine the expression for I_n^E . An estimate of the diffusion length of hot electrons by using the characteristic relaxation times from Ref. 5 shows that for $E > 10 k_0 T$ it exceeds the GaAs film thickness $d = 30 \mu\text{m}$ and then increases rapidly. This makes it possible to assume that the photoelectron gas is homogeneously distributed between the surface and the specularly reflecting semi-insulating substrate for $10 k_0 T < E < E_{LO}$. The photoelectron distribution function in this case can be written in the form⁵ $f(E) = \tilde{I}_0 \tau_E^A / d \rho(E) E$, where $\rho(E)$ is the density of states, and τ_E^A is the relaxation time by acoustic phonons.⁵ For the photoexcitation of electrons in the passive region (PR) of energies $E_{\min} < E < E_{LO}$ [$E = (\hbar\omega - E_g)/(1 + m_e/m_h)$], we obtain

$$I_n^E = \int_{E_{\min}}^E \frac{v(E')}{4} f(E') \rho(E') dE' = \frac{\tilde{I}_0}{16\sqrt{2}d} \left(\frac{E_{LO}^3}{m^3 e s^4} \right)^{1/2} \tau_{DA} \ln \left\{ \frac{1 + \frac{\tau_{pA}}{\tau_{DA}} \frac{E}{E_{LO}}}{1 + \frac{\tau_{pA}}{\tau_{DA}} \frac{E_{\min}}{E_{LO}}} \right\}.$$

Here m_e and m_h are the effective electron and hole masses, s is the velocity of sound, and τ_{pA} and τ_{DA} are the characteristic scattering times by piezoelectric and deformation potentials.⁵ It can be seen that the flux I_n^E increases monotonically with increasing $\hbar\omega$, and the value of \tilde{V}_1 must decrease correspondingly; this also accounts for the phase of the E spectra. At $E > E_{LO}$ the electron finds itself in the PR almost instantaneously (in $\sim 10^{-12}$ sec) because of strong LO scattering; therefore, \tilde{V}_1 depends periodically on $\hbar\omega$ with the period indicated above. The maximum ratio I_n^E/\tilde{I}_0 for the PR "ceiling" is ~ 30 . The oscillation amplitude of the E spectra is comparable to \tilde{V}_1 for $\tilde{I}_p \sim I_n^E$ or, in other words, for $\sigma_n N_t^0 \sim 10^{-3}$; for $N_t^0 \sim 10^{13} \text{ cm}^{-2}$ this corresponds to real capture cross sections, $\sigma_n \sim 10^{-16} \text{ cm}^2$. A qualitatively similar picture is also obtained when recombination in the SCR has a key role.

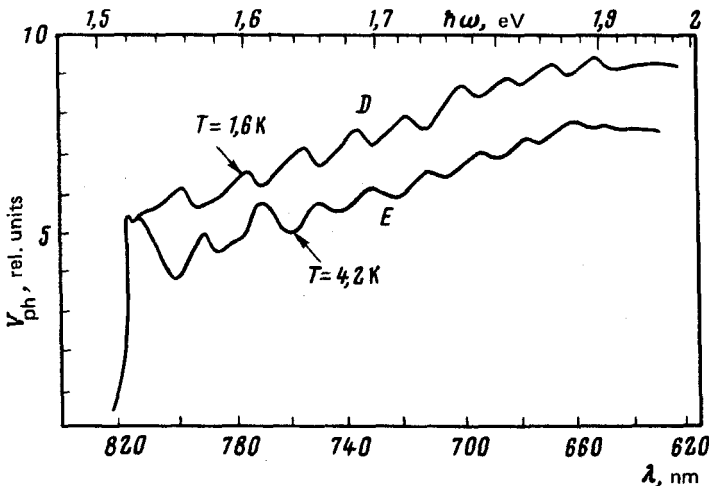


FIG. 2. Change in the photoresponse with a change in temperature (same samples as in Fig. 1 E).

Thus the photoemf \vec{V}_{ph} at the SB with an insulator layer opaque to the holes is the sum of the oscillating surface photoemf \vec{V}_1 and the oscillating Dember emf \vec{V}_D . The PR spectral dependence is determined by the larger value of the emf. Since \vec{V}_1 (for $\vec{V}_1 < k_0 T$) does not depend on the temperature and \vec{V}_D increases with decreasing temperature,³ we can see a change in the PR in the same sample with a change in T . This example is shown in Fig. 2. At a constant temperature the PR is determined by the degree of sample doping. In fact, at 4.2 K the E spectrum is observed in the samples with $n_0^{77} \geq 2 \times 10^{14} \text{ cm}^{-3}$ and the D spectrum is observed in the samples with $n_0^{77} \leq 10^{13} \text{ cm}^{-3}$.

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