Photoconductivity of a gapless semiconductor produced as a result of formation of an energy gap

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The measurement of interband photoconductivity is an effective method for observing the energy gap formed in a gapless semiconductor by a quantizing magnetic field or a uniaxial deformation. Resonance recombination transitions with the participation of longitudinal optical phonons are observed.

The new class of semiconductors—semiconductors with a zero forbidden band or semimetals (SM)—are interesting objects to study in solid state physics because of their specific properties. Study of the semimetal-semiconductor (SM-SC) transition in such materials, which is induced by a magnetic field, pressure, or uniaxial deformation, is apparently of greatest interest.[1–3]

In a SM-SC transition, an energy gap $E_y > 0$ forms between the conduction band and the valence band, which is generally accompanied by freezing electrons out of the conduction band. For this reason, in order to record an SM-SC transition, the dependences of equilibrium kinetic coefficients (resistance, Hall coefficient) on the magnitude of the corresponding external perturbation are usually measured. However, this method encounters considerable difficulties, primarily due to the fact that when the external perturbation, such as a magnetic field, is applied, the resistance of the sample changes as a result of formation of an energy gap and as a result of a change in the probability of scattering of the current carriers (magnetoresistance).

In this letter we demonstrate that an effective method for investigating the SM-SC transition is to measure the interband photoconductivity (PC). In the gapless state ($E_g \leqslant 0$) the recombination rate of nonequilibrium electrons and holes is so high that PC is negligible due to the deviation of the density of current carriers from the equilibrium density. At the same time, the concept of recombination becomes meaningless (it is no longer distinguishable from scattering).[4]

The formation of an energy gap under the action of a quantizing magnetic field, for example, must lead to the appearance of interband PC. In this case, because of the small energy gap between the conduction band and the valence band, and because of the low effective mass of electrons m_n^*, the interband collisional recombination (Auger recombination) makes the main contribution to recombination processes, even at very low temperatures. Since the rate of Auger recombination depends quadratically on the density of equilibrium electrons n, the increase in the energy gap, accompanied by the decrease in n, leads to a sharper dependence of PC on E_g than the dependence of equilibrium kinetic coefficients, which are linear functions of n. Therefore, PC is a more sensitive characteristic of the energy gap. It is also important that in measuring PC the magnetoresistance can be excluded from the analysis.

Another important characteristic of PC is the possibility of the manifestation of resonance recombination transitions with the participation of longitudinal optical phonons.

The experimental studies of PC under the conditions of formation of an energy gap in a gapless semiconductor were conducted using the ternary compound $Hg_{1-x}Cd_xTe$ ($x = 0.150$–0.155). To form the energy gap, we placed the samples in a magnetic field ($H \leqslant 70$ kOe), and then subjected them to uniaxial deformation ($P \leqslant 3.0$ kbar). The measurements of PC were conducted under the conditions of a weak light signal $\Delta\sigma \ll \sigma$, where σ is the thermal conductivity, and $\Delta\sigma$ is the change in the conductivity of the sample with illumination; the light sources were a CO_2 laser and a LG-126 laser. The ratio $(\Delta\sigma/\sigma)(H) = V_{PC}(H)$, scanned as a function of the magnetic field, was recorded. Such a tracing excludes from the analysis in $V_{PC}(H)$ the H dependence of the mobility and density of equilibrium electrons. Assuming that the photoelectrons are thermalized we have $V_{PC} \sim \tau$ (lifetime of the current carriers).

The field dependences of the galvanomagnetic coefficients of the gapless $Hg_{1-x}Cd_xTe$ ($x = 0.155$) are shown in Fig. 1. The region of Shubnikov–de-Haas (SH) oscillations is bounded by $H \leqslant 2.5$ kOe (not shown in the figure). The electron density determined from the period of the SH oscillations ($n \simeq 3 \times 10^{15}$ cm^{-3}) agrees well with the value of n obtained from the Hall measurements in the limit $H \to 0$.

A section with an anomalously rapid growth of the magnetoresistance, which is evidently related to the drop in the electron density in the conduction band as a result of formation of the energy gap in the magnetic field, appears in the field dependences of $\Delta\rho_\perp/\rho_0$ and $\Delta\rho_\parallel/\rho_0$ in the region $H = 3$–12 kOe.

In the absence of a magnetic field gapless $Hg_{1-x}Cd_xTe$ is basically photoinsensitive. The imposition of a magnetic field, beginning with values of $H = 2.5$–3 kOe, leads to the appearance of an appreciable photosignal, which then grows rapidly with the field (Fig. 2). The field dependence of V_{PC} is sharper than $\rho(H)$ near fields corresponding to freezing out of electrons.

As is evident from Fig. 2, the dependence $V_{PC}(H)$ is oscillatory with an appreciable oscillation amplitude, although the field dependences of ρ and R_x are monotonic in

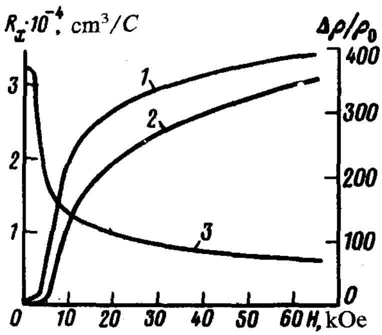

FIG. 1. Field dependences of the magnetoresistance and of the Hall coefficient. 1—$\Delta\rho_\perp/\rho_0$; 2—$\Delta\rho_\parallel/\rho_0$; 3—$R_x$. $T = 4.2$ K.

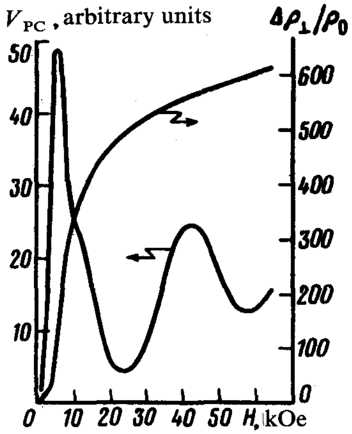

FIG. 2. Photoconductivity and $\Delta\rho_\perp/\rho_0$ in a magnetic field. $T = 4.2$ K.

nature in this region of H. It also turned out that the wavelength of the radiation has no effect on the characteristics of $V_{PC}(H)$. Therefore, the oscillations of $V_{PC}(H)$ are related to the nonmonotonic dependence of τ on the magnetic field. The minima in the dependence $\tau(H)$ should be observed when the condition $E_g(H) = n\hbar\omega_{LO}$ ($n = 1,2...$) is satisfied as a result of the resonance recombination transition of electrons through the energy gap with the participation of optical photons. An estimate of the energy gap from the relation $E_g(H) = 1/4\hbar(eH/m_n^* c)$ gives for the first minimum of $V_{PC}(H)$ the value $E_g = 16.8$ meV, which is approximately equal to the energy of the LO phonon of the HgTe primary sublattice of the crystal $Hg_{0.845}Cd_{0.155}Te$ ($\hbar\omega_{LO} = 17.2$ meV).

Another possibility for the formation of the energy gap in a gapless semiconductor with a cubic structure is the imposition of uniaxial deformation, which removes the degeneracy of the energy bands at the point Γ_8 by lowering the symmetry of the

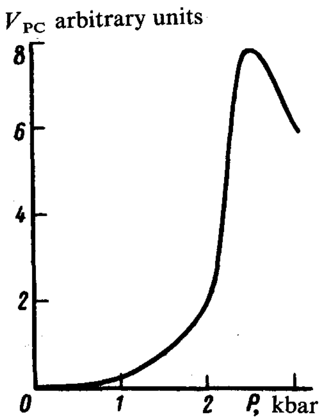

FIG. 3. Photoconductivity of $Hg_{1-x}Cd_xTe$ ($x = 0.155$) with uniaxial deformation.

crystal. In our experiments the uniaxial compression was applied at $T = 4.2$ K along the direction $P \perp \langle 111 \rangle$. It is evident from Fig. 3 that the dependence $V_{PC}(P)$ is qualitatively similar to the beginning section in the dependence $V_{PC}(H)$: the photosignal begins to grow markedly at $P \geqslant 1.5$ kbar and reaches a maximum at $P \simeq 2.5$ kbar. According to Ref. 5, the dependence $E_g(P)$ is nearly linear and at $P = 3$ kbar, according to our estimates, reaches a value ~ 12 meV. This is insufficient for observing the resonance $E_g(P) = \hbar\omega_{LO}$ in $V_{PC}(P)$, which is in fact confirmed experimentally.

Thus the quantizing magnetic field and the uniaxial deformation have a strong effect on the photoconductivity of a gapless semiconductor. The measurement of PC is a sensitive method of observing the formation of an energy gap. It also permits observing resonance recombination transitions with the participation of longitudinal optical photons.

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