Weak localization of electrons in CdS at 77 K observed by the acoustoelectronic amplification method

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A weak localization of electrons in CdS was detected at 77 K by the method of acoustoelectronic amplification. It is suggested that weak localization of electrons is caused by a quasielastic electron-phonon scattering.

Afonin *et al.*[1–3] showed that weak localization[4,5] can be achieved not only in disordered conductors at low temperatures, in which the electrons are scattered elastically by impurities and in which they satisfy Fermi statistics, but also in pure materials at higher temperatures at which the electron-phonon scattering becomes quasielastic. If the condition $\tau_\varphi \gg \tau$ is satisfied, the scattering by phonons has a twofold role: on the one hand, it creates an interference; on the other hand, it destroys it. Here $\tau_\varphi \sim \tau/(\omega\tau)^{2/3}$ (Refs. 6 and 7) is the time scale of the electron phase relaxation, τ is the electron-phonon-relaxation time, and $\hbar\omega$ is the characteristic energy transferred to the electron as a result of collision. Accordingly, there are two temperature intervals in which a weak localization may occur: at low temperatures, where the localization is caused by the scattering of electrons by impurities, and at relatively high temperatures, where the localization is caused by the scattering of electrons by acoustic phonons.[1)]

The objective of the present study is to prove experimentally that there are localization corrections to the electron mobility at high temperatures.

To obtain a weak localization, the electron concentration should be at a level that would permit the electron gas to be nondegenerate and would not make it possible for electron-electron collisions to determine τ_φ. In the case of a degenerate electron gas, the localization corrections and the quantum corrections resulting from the electron-electron interaction[8] coexist, whereas the localization corrections in a nondegenerate electron gas can be studied in a "pure" form.[9] A useful object for such a study is a photoconductive CdS, for which rather low electron concentrations (10^{12}–10^{13} cm^{-3}) can easily be obtained. At nitrogen temperatures the electrons are scattered by acoustic phonons. This scattering is known to be quasielastic. The energy transferred to the electron as a result of the collision is $\hbar\omega = (3m^*kTw)^{1/2}$, where m^* is the effective electron mass ($\approx 0.2m_0$), and w is the velocity of sound ($\approx 10^5$ cm/s). At $T =$ 77 K we thus have $\hbar\omega \approx 10^{-15}$ erg. Assuming $\tau \approx 10^{-13}$ s (Ref. 10), we find $(\omega\tau)^{2/3} \approx 0.1$ and $\tau_\varphi = 2\tau/(\omega\tau)^{2/3} \approx 10^{-12}$ s, i.e., $\tau_\varphi \gg \tau$. The condition under which the occurrence of strong localization is remote $(pl/\hbar)^2 \gg 1$ is also satisfied [$(pl/\hbar)^2 \approx 30$], where p is the electron momentum, and l is its mean free path. Moderate values of the mobility [$\mu \sim 10^3$ cm^2/(V·s)] render the classical magnetoresistance unimportant, making it possible to identify the localization corrections from the characteristic variation of the mobility in the magnetic field (from the negative magnetoresistance).[11,12] For a photo-

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conductive CdS with the parameters given above, the magnetic field H_c, in which the effective destruction of interference occurs, is ~ 1 kOe.

Since CdS is a piezoelectric semiconductor, it can amplify sound in the external electric field. Under actual experimental conditions the acoustoelectric gain Γ can be written in the form

$$\Gamma \sim \frac{\Omega}{w} \frac{\mu E - w}{\mu},$$

where E is the drift electric field, and Ω and w are the frequency and velocity of sound, respectively. A change in the mobility $\Delta\mu(H) = \mu(H) - \mu(0)$, produced as a result of the destruction of interference in a magnetic field, leads to a change in the acoustoelectronic gain $\Delta\Gamma = (\partial\Gamma/\partial\mu)\Delta\mu \sim (w/\mu^2)\Delta\mu$, where $\Delta\Gamma > 0$, since $\Delta\mu > 0$.[2)] The change in the magnitude of the acoustic signal upon application of a magnetic field was measured experimentally: $\Delta J(H) = J(H) - J(0)$.

Standard procedure was used to obtain acoustoelectronic gain and to measure it.[13] A block diagram of the measuring apparatus is shown in Fig. 1. The length of the drift-field pulses (≈ 3 μs) corresponded to a single-transit amplification mode. The electron density ($\approx 5\times 10^{12}$ cm^{-3}) was attained by illumination from a stabilized incandescent lamp through light filters CZS-20 and CZS-23. A sample ($5.2\times 5\times 6$ mm) in a holder was immersed into liquid nitrogen in a glass Dewar vessel which in turn was placed between the poles of a magnet. The first directly transmitted acoustic pulse, which was amplified in a drift field, was isolated and its amplitude was measured using a stroboscopic device (Fig. 1). The signal was then fed to a plotter where its time evolution was recorded. The magnetic field was alternately applied and removed every 7 or 8 minutes. A typical trace of the signal is shown in Fig. 2.

At $H < 400$ Oe the difference $\Delta J(H)$ is undetectable at the noise level. With an increase in the magnetic field, $\Delta J(H)$ increases, reaching saturation at $H \gtrsim 1$ kOe. A similar behavior of $\Delta\mu(H)$ was predicted by the weak localization theory.[11,12] As experiments have shown, $\Delta J(H)$ depends strongly on the magnetic field, beginning

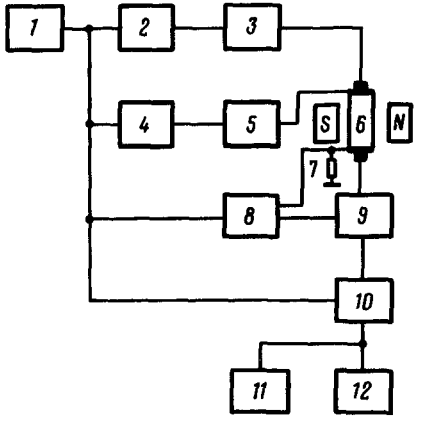

FIG. 1. Block diagram of the measurement apparatus. 1—Synchronizer; 2—variable acoustic-pulse-delay generator; 3—rf pulse generator; 4—variable drift-field pulse-delay generator; 5—drift-field pulse generator; 6—sample; 7—measuring resistance; 8—oscilloscope; 9—rf receiver; 10—stroboscope; 11—plotter; 12—digital voltmeter.

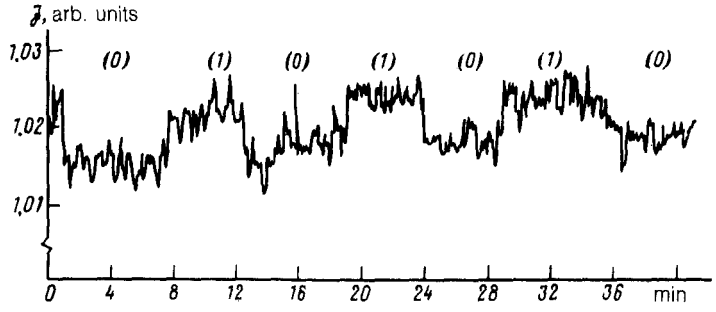

FIG. 2. Signal variation plotted as a function of time, with the magnetic field $H = 1$ kOe switched on (1) and with the magnetic field switched off (0).

with $H \gtrsim 700$ Oe, in order-of-magnitude agreement with the estimate of H_c given above. Assuming that this experimental value of the magnetic field has in fact the significance of H_c, we find 3×10^{-13} s from the relation $H_c = \cos \hbar/4eD\tau_\varphi$ (Refs. 11 and 12), where D is the diffusion coefficient of electrons. Quantitatively, this value is characteristic of the electron-phonon-relaxation time. Upon increasing the input power of sound from 10^{-5} to 10^{-2} W, the value of $\Delta J(H)$ decreased from a peak value to zero. This decrease might be caused by the destruction of interference resulting from piezoelectric rf field of the sound wave which acts in a way similar to that of the external rf electric field.[6] At $T = 300$ K, $\Delta J(H) = 0$, which probably stems from inelastic scattering of electrons by optical phonons.

In summary, the results of this study lead us to assume that the effect which we have observed is attributable to a weak localization of electrons due to a quasielastic electron-phonon scattering.

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[1)]It should be noted that the "short-lived" localization of electrons, which occurs as a result of their quasielastic scattering by phonons, was studied previously,[7a] both experimentally and theoretically, in the absence of a magnetic field in a different class of substances: organic metals with a quasi-one-dimensional spectrum.

[2)]Afonin *et al.*[9] showed that at frequencies at least two orders of magnitude higher than those used in our experiment, the localized corrections to the absorption coefficient of sound have a more complicated nature and therefore cannot be expressed directly in terms of the mobility.

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