Mechanism for relaxation of the phase of the electron wave function in *n*-type GaAs

O. V. Emel'yanenko, T. S. Lagunova, and T. A. Polyanskaya
A. F. Ioffe Physicotechnical Institute, Academy of Sciences of the USSR

(Submitted 3 August 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **36**, No. 6, 199–201 (20 September 1982)

The phase relaxation time is estimated from the magnetic field dependences of the conductivity at liquid helium temperatures. It is shown that the phase relaxation time is determined by the electron—phonon collisions and the lifetime of single-particle excitations under conditions with short mean free paths.

PACS numbers: 72.20.Jv, 72.20.My, 72.80.Ey, 71.38. + i

It is shown in a number of experimental papers[1] that the theory of quantum corrections to conductivity[2–5] which explains the phenomenon of negative magnetoresistance in semiconductors in the metallic conduction range, agrees well with experiment. This allows using the theory to determine the parameters which describe the behavior of the electron gas. In particular, for the simplest case of noninteracting electrons and the standard conduction band, as in *n*-GaAs, the relaxation time for the phase of the electron wave function τ_φ determines the change in the conductivity in a magnetic field as follows[2]:

$$\Delta\sigma_L(H) = a_L \frac{G_0}{2l_L}\sqrt{x_L}\, f_3(x_L), \tag{1}$$

where $G_0 = e^2/2\pi^2\hbar$, $x_L = (2l_L/l_H)^2$, $l_L = \sqrt{D\tau_\varphi}$, $f_3(x_L) \equiv F(\delta^{-1})$ is the function presented in Ref. 2, $l_H = \hbar c/eH$ is the magnetic length, D is the diffusion coefficient, and $a_L = 1$. It is shown in Refs. 3 and 4 that α_2 can be less than unity by an amount $\beta(\lambda)$, where λ is the electron interaction constant and $\beta(\lambda)$ is the function computed in Ref. 4. The remaining quantities in (1) are well known or are determined from experiment.

Figure 1 compares the experimentally measured magnetoconductivity $\Delta\sigma_3(H) = \rho^{-1}(H) - \rho^{-1}(0)$ (ρ is the specific resistance of the specimen) as a function of the magnetic field H in *n*-GaAs with electron concentration $(1.7-83)\times 10^{16}$ cm^{-3} to the theoretical dependences constructed using (1) with the parameters β and τ_φ, giving better agreement with experiment. The corresponding values of β and τ_φ for different specimens are presented in Figs. 2 and 3 as a function of the electron concentration n and temperature T. The quantity β varies on the average from 0.7 to 0.3 with increasing concentration (Fig. 2). The values of τ_φ found were compared with the damping time for single-electron excitations $H \simeq 10$ and $\Delta\sigma_I(H)$ and to the electron-phonon collision frequency h/τ_φ. In order to esimate τ_{ak} in GaAs, we used the numerical factor computed in Ref. 7. The dependences of $\hbar/\tau_{ee}^{(1)} + \hbar/\tau_{ak}$ and $\hbar/\tau_{ee}^{(2)} + \hbar/\tau_{ak}$ on the electron concentration are shown in Fig. 2 (in calculating $\tau_{ee}^{(2)}$, we used the average value of the mobility for the specimen studied $\mu = 1500$ cm^2/V·s). The experimental values of $\hbar/\tau_\varphi$ agree well with the values of $\hbar/\tau_{ee}^{(2)} + \hbar/\tau_{ak}$. Figure 3 presents the temperature dependence of $\hbar/\tau_\varphi$ for a specimen with concentration $n = 3.7\times 10^{16}$

 0021-3640/82/180246-04$01.00

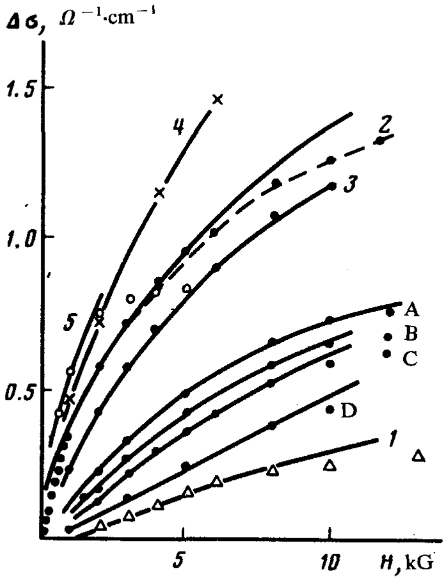

FIG. 1. The magnetoconductivity $\Delta\sigma$ as a function of the magnetic field H. The symbols indicate the experimental values for specimens with concentration n (10^{16} cm^{-3}): 1) 1.7, 2) 17, 3) 27, 4) 30, 5) 83; (A)–(D) 3.7; the temperature T (K) is 1–5) 4.2; (A) 2.1; (B) 3; (C) 4.2; (D) 7.5. The continuous lines indicate the calculation of $\Delta\sigma_L(H)$ (1) and the dashed line indicates $-\Delta\sigma_L(H)-\Delta\sigma_I(H)$.

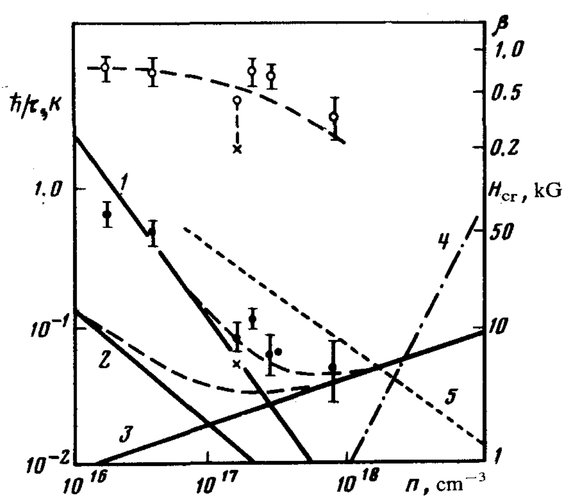

FIG. 2. Dependence of $\hbar/\tau$(K), β, and H_{cr} (kG) on the electron concentration. The dots indicate experimental values. Calculation: 1) $\hbar/\tau_{ee}^{(2)}$; 2) $\hbar/\tau_{ee}^{(1)}$; 3) $\hbar/\tau_{ph}$; 4) $\hbar/\tau_{SO}$; 5) H_{cr}. Dashed lines: 1a) $\hbar/\tau_{ee}^{(2)}+\hbar/\tau_{ph}$, 2a) $-\hbar/\tau_{ee}^{(1)}+\hbar/\tau_{ph}$.

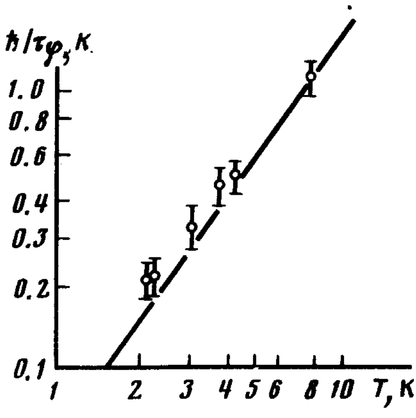

FIG. 3. $\hbar/\tau_\varphi$ (K) as a function of temperature T(K). The points indicate the experimental values and the line indicates the calculation of $\hbar/\tau_{ee}$.

cm^{-3} (curves $A - \Gamma$ in Fig. 1), which is close to the dependence $T^{3/2}$ predicted theoretically in Ref. 6 for $\hbar/T_{ee}^{(2)}$.

Thus, the phase relaxation time in GaAs is determined by the energy relaxation time $T_{ee}^{(2)}$ with $n \sim 10^{17}$ cm^{-3} and electron-phonon collisions with $n \sim 10^{18}$ cm^{-3}.

We shall make several remarks. 1) The applicability of the theory in Refs. 2–5 is restricted by the condition $k_F\, l > 1$, where k_F is the wave vector of the electron with energy $\mathscr{E}_F$, l is the free path. In spite of this, the values of τ_φ and β for specimen 1 with $k_F\, l \simeq 0.5$ do not disagree with the remaining results (Fig. 2). 2) The other condition of the theory requires that the inequality $l_H < l^2$ be satisfied (Ref. 2) and restricts the possibility of comparing $\Delta\sigma_3(H)$ with the dependence (1) to values

$$H < H_{\text{cr}}(\text{KG}) = 10^5/k_F\, l\mu(\text{cm}^2/\text{V}\cdot\text{s}). \qquad (2)$$

For specimen 5 ($\mu = 2000$ $\text{cm}^2/V{\cdot}s$), $H_{\text{cr}} = 4.5$ kG and the saturation of the dependence $\Delta\sigma_3(H)$ for this specimen is possibly related to this (Fig. 1). The dashed line in Fig. 2 corresponds to the electron concentration dependence of H_{cr} for $\mu = 1500$ $\text{cm}^2/V{\cdot}s$. 3) It is shown in Ref. 3 that in n-GaAs the dependence (1) change (a section with $\Delta\sigma < 0$ appears in a weak magnetic field) if

$$\tau_{S0} \leqslant \tau_\varphi, \qquad (3)$$

where τ_{S0} is the electron spin relaxation time in the presence of an interaction with an orbital angular momentum. If it is assumed that the disagreement between the experimental and computed values of $\Delta\sigma$ at $H < 0.5$ kG for specimen 2 with $n = 1.7 \times 10^{17}$ cm^{-3} (Fig. 1) is related to this phenomenon, then in order for theory to agree with experiment, including this range of fields, it must be assumed that $\hbar/\tau_{S0} = 2\hbar/\tau_\varphi$ and new values of τ_φ and β, shown by the cross marks in Fig. 2, must be used. The same figure shows the electron concentration dependence of $\hbar/\tau_{S0}$ calculated using the theory in Ref. 8.[1] It is ievident from the figure that the inequality $\tau_{S0} \leqslant \tau_\varphi \simeq \tau_{ak}$ is satisfied for $n \geqslant 2 \times 10^{18}$ cm^{-3}. In this case conditions (2) and (3) overlap and a dependence of the type (1) is no longer applicable. (It is possible that in specimen 2 the dependence

$\Delta\sigma_3(H)$ at $H<0.5$ kG is related to contact phenomena[9].) 4) It is shown in Refs. 3 and 4 that electron interaction leads to additional corrections to the magnetoconductivity: $\Delta\sigma_I(H)$ is related to the repulsion of electrons and $\Delta\sigma_S(H)$ is related to the spin interaction of electrons. The correction $\Delta\sigma_s(H)$ is less than 1% of the magnitude of $\Delta\sigma_3$ for all specimens at $H\simeq 10$ kG and it may be ignored. Taking into account $\Delta\sigma_I(H)$ (dashed line in Fig. 1) improves the agreement between theory and experiment. The values of $\hbar/\tau_\varphi$ and β in this case do not change significantly. The interaction constant, necessary to calculate $\Delta\sigma_I$, was calculated from Eq. (14a) in Ref. 3 and a starting value of the interaction constant $\bar{\lambda}=1$ (this estimate of λ is substantially incorrect only if $\bar{\lambda}\ll 1$).

We are deeply grateful to A. G. Aronov and B. L. Al'tshuler for many discussions of the problems considered in this paper, to Yu. V. Shmartsev and A. A. Rogachev for support and interest in this work, and to A. N. Titkov for consultation on the problem of spin-orbital splitting in n-GaAs.

1) In order to calculate τ_{S0}, we used the theoretical parameter[8] $\alpha=0.04$, which characterizes the spin splitting of the conduction band of GaAs. This parameter was provided to us by A. N. Titkov.

[1]T. A. Polyanskaya, I. I. Saĭdashev, Pis'ma Zh. Eksp. Teor. Fiz. **34**, 378 (1981) [JETP Lett. **34**, 361 (1981)]; A. N. Ionov and I. S. Shlimak, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 160 (1982) [JETP Lett. **35**, 196 (1982)]; A. N. Ionov, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 378 (1982) [JETP Lett. **35**, 466 (1982)].
[2]A. Kawabata, J. Phys. Soc. Jpn. **49**, 621 (1980).
[3]B. L. Al'tshuler, A. G. Aronov, D. E. Khmel'nitskiĭ, and A. I. Larkin, Zh. Eksp. Teor. Fiz. **81**, 768 (1981) [Sov. Phys. JETP **54**, 44 (1981)].
[4]A. I. Larkin, Pis'ma Zh. Eksp. Teor. Fiz. **31**, 239 (1980) [JETP Lett. **31**, 219 (1980)].
[5]T. F. Rosenbaum, R. F. Milligen, G. A. Thomas, P. A. Lee, T. V. Ramakrishnan, and R. N. Bhatt, Phys. Rev. Lett. **47**, 1758 (1981).
[6]B. L. Al'tshuler and A. G. Aronov, Pis'ma Zh. Eksp. Teor. Fiz. **30**, 514 (1979) [JETP Lett. **30**, 481 (1979)].
[7]T. Katoda and T. Sugano, J. Electrochem. Soc. **121**, 1066 (1974).
[8]M. I. D'yakonov and V. U. Perel', Fiz. Tverd. Tela **13**, 3581 (1971) [Sov. Phys. Solid State **13**, 358 3023 (1971)].
[9]T. A. Polyanskaya and I. I. Saĭdashev, Fiz. Tekh. Poluprovodn. **9**, 153 (1975) [Sov. Phys. Semicond. **9**, 102 (1975)]; P. L. Li and B. E. Paton, J. Phys. **E10**, 1222 (1977).

Translated by M. E. Alferieff
Edited by S. J. Amoretty