Photokinetic magnetic-impurity quantum oscillations in germanium at helium temperatures

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Photoconductivity oscillations were observed in a transverse magnetic field and oscillations of the photomagnetic emf were observed at helium temperatures in *p*-Ge samples doped with boron. It is established that the oscillations are periodic in the reciprocal magnetic field and are due to quantization of the energy spectrum of the electrons. The period of the oscillations for samples with different doping impurities turned out to be different. From the values of the period it was possible to obtain the values of the characteristic energies $\mathscr{E}^{Ga} = 6.8$ meV and $\mathscr{E}^{B} = 6.2$ meV, which agree with good accuracy with the energy difference between the ground and the first excited states of the corresponding impurity centers in germanium. To explain the oscillations, a mechanism of inelastic resonant scattering of the photoelectrons by the neutral acceptors is proposed. A detailed investigation is made of the dependence of the oscillations on the temperature and on the intensity of the light. It is established that when the intensity is varied the oscillations of the photconductivity and of the photomagnetic emf undergo inversion, namely, the maxima give way to minima and vice versa. The inversion of the oscillations of the photomagnetic emf was observed also following variation of the temperature.

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There are several quantum effects in which the parameters of the metal or of the semiconductor vary periodically in terms of the reciprocal magnetic field, i.e., with a constant period in the 1/H scale. First of them is the de Haas–van Alphen effect and related phenomena due to the successive passage of the Landau levels through the Fermi level of the degenerate electron gas. The period of these oscillations is determined by the relation

$$(n+\gamma)\hbar\Omega_n=\mathscr{E}, \quad n=1.\ 2.\ 3.\ldots. \tag{1}$$

between the Fermi energy $\mathscr{E}$ and the Larmor frequency $\Omega_n = eH_n/mc$ in the field H_n (e and m are the charge and cyclotron mass of the carriers). The quantity γ in (1) characterizes the phase shift of the oscillations ($\gamma = -1/2$ in the free-electron model). It follows from (1) that

$$1/H_n=nP+\gamma P, \quad P=\Delta(1/H)=\hbar e/mc\mathscr{E}. \tag{2}$$

A second effect of this type is the magnetophonon resonance, in which the probability of carrier scattering by optical phonons oscillates with the magnetic field (the Gurevich–Firsov effect; see the review[1]). Since the density of states near the bottoms of the Landau subbands has maxima, the average probability $1/\tau$ of carrier scattering increases when the energy of the optical phonon coincides with the distance between any two Landau levels. In contrast to effects of the de Haas–van Alphen type, neither degeneracy nor the stringent restriction $kT \ll \hbar\Omega$ on the temperature is needed to realize magnetophonon resonance; it suffices to satisfy the condition

$$\Omega\tau \gg 1, \tag{3}$$

which ensures the existence of a Landau structure of the spectrum. The period of the magnetophonon oscillations is also determined by relation (1), except that $\mathscr{E}$ is in this case the energy of the optical phonon, and the phase γ is determined by different kinetic relations, for example by the relative contribution of the scattering by optical phonon to the total collision frequency.[1] There are also known experiments in which the period of the magnetophonon oscillations is determined by the sum of the energies of two optical[1] and even two acoustic phonons of limiting frequency.[2]

Oscillations that are periodic in the reciprocal field are possible also under disequilibrium conditions. For example, they should occur when it becomes possible to produce in a semiconductor, by illumination, a monoenergetic group of electrons.[3] In this case $\mathscr{E}$ in (1) is already the energy of the carriers reckoned from the bottom of the band, while the period P depends on the energy of the illumination that produces these carriers.

Thus, in all the aforementioned phenomena, which differ in their character, the period P is determined by the same relation (2) between the characteristic energy $\mathscr{E}$ and the cyclotron mass m, and the experimental manifestations of these effects, for example in the dependence of the resistance on the magnetic field, can be very similar. This brief description defines the group of phenomena in which we have searched for an explanation of the mechanism of the oscillations of the photoconductivity of germanium at helium temperatures, which we have observed earlier.[4] The hypothesis advanced in[4], that the oscillations have a Van der Waals character and are due to the presence of an exciton condensate in the germanium,[5] were not confirmed subsequently. We describe in this paper experiments aimed at determining the nature of the observed oscillations.

EXPERIMENT

The main series of experiments consisted of two type types: measurements of the photoconductivity in a transverse magnetic field (both the light flux **G** and the magnetic field **H** perpendicular to the surface of the sample—Fig. 1a), and measurements of the photomagnetic emf (the Kikoin-Noskov effect, see[6]; the field **H** is along the sample surface, and the emf is also measured along the surface, but in a direction perpendicular to **H**—Fig. 1b). Sample 1 was placed directly in superfluid helium in the center of a superconducting solenoid and could be rotated in both cases about an axis perpendicular to **H** through approximately $\pm 10°$.

The light source in most experiments was an He-Ne

laser (0.63 μ), the beam of which entered the dewar through a window in the upper cover and was focused, by a short-focus cylindrical lens placed inside a solenoid, into a narrow strip 2 crossing the gap between the contacts 3 on the sample. The lens served simultaneously as a filter cutting off the thermal radiation in the upper part of the cryostat. Generally speaking, the width of the strip 2 was not very important and in some of the experiments the lens was replaced by a plane-parallel glass plate. In the measurements of the photomagnetic emf, a mirror placed between the lens and the sample rotated the beam through 90°. The maximum laser power was about 20 mW and could be decreased with calibrated filters.

The measured quantities (the photocurrent J at a constant drawing electric field E, or the field E_{GH} of the photomagnetic effect, equal to the photomagnetic emf divided by the distance between the contacts) were registered with an x-y recorder as functions of the reciprocal magnetic field 1/H. The source of the signal proportional to 1/H was a system that maintained automatically the voltage u on a Hall pickup placed alongside the sample. The current feeding the pickup was then $i \sim u/H$, so that the voltage across the resistance connected in series with the supply circuit was proportional to 1/H. In measurements of the photoconductivity, part of this signal could be fed to the Y coordinate of the recorder in series with the measured signal J. The point is that when H is varied from 60 to 10 kOe the value of J changes by approximately one order of magnitude. The addition of the signal a/H has made it possible to compensate to a considerable degree for the monotonic course of the J(1/H) curve and thus increase the gain. We note that such a hyperbolic compensation is much better than the linear one used by us in [4]. All the plots of the photocurrent J (except those of Fig. 3, see below) represent just such a compensated signal.

The germanium samples were plates measuring approximately $4 \times 4 \times 0.3$ mm with [100] axis along the normal to the surface (the deviation of the axis from normal did not exceed 1.5°). After mechanical polishing, the samples were bright-etched (hot hydrogen peroxide to which lye was added), and contacts were made on them either by fusing-in an In-Ga alloy in the form of two strips, or by spot-welding a gold wire of 80 μ diameter to many points, so that the contact had the form of a line. The quality of the contacts was verified against the value of the photo-emf and against the symmetry of the current-voltage characteristic in a magnetic field; in the case of good contacts the photo-emf did not exceed 10 mV and the current changed by not more than 5% when the voltage polarity was reversed. The gap between contacts was usually about 1 mm.

The experiments were performed on germanium doped with gallium with concentration 2×10^{14} cm^{-3} (altogether eight samples), boron with concentration 4×10^{14} cm^{-3} (two samples), and zinc with approximate concentration 10^{15} cm^{-3} (one sample). In addition, many experiments were performed on p-germanium and on n-germanium with a total random-impurity concentration less than 5×10^{13} cm^{-3}. To carry out quantitative and control measurements in accordance with the four-contact scheme, four linear contacts were produced on one of the gallium-doped samples (G1) instead of two, namely two external ones of In-Ga alloy and two internal ones of gold wire.

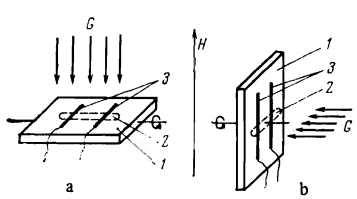

FIG. 1. Placement of the sample in measurements of the magnetoresistance (a) and of the photomagnetic emf (b).

A question to which special attention must be paid is that of the carrier-gas parameters that determine the kinetics in our experiments. We did not measure directly the number of produced carriers. All the estimates given below are based on the number of light quanta per second and per unit sample volume. The excited volume in our experiments was about 10^{-4} cm^3, so that a maximum intensity of 20 mW corresponded (disregarding reflection losses) to a generation rate $\nu_{max} \approx 5 \times 10^{20}$ cm^{-3}sec^{-1}.

There is apparently no doubt that the evolution of the produced carriers proceeds mainly in the following manner: rapid cooling by optical phonons to an approximate energy 300°, relatively slower energy loss due to acoustic phonons

$$\frac{d\varepsilon}{dt} = -\frac{2\sqrt{2}}{\pi}\frac{\Delta^2 m^{3/2}}{\hbar^4 \rho}\varepsilon^{1/2} \qquad (4)$$

(Δ is the deformation potential and ρ is the density), binding into excitons, and finally exciton recombination. Different situations are possible here, depending on whether the electrons have time to be cooled to an energy $\epsilon \approx kT$, whether there is time for thermodynamic equilibrium between the electrons and excitons to be established, etc. We have therefore performed a number of measurements of the dependence of the photoresistance on the temperature. Figure 2 shows by way of example one of the typical curves. The strong temperature dependence of R(T) is undisputed evidence that the average energy of the carriers that determine the photocurrent is governed by the temperature of the bath.

To estimate the density of the cold carriers and the time τ_b of their binding into excitons, we use the experimental value for the kinetic coefficient of the binding of carriers in silicon at low temperatures [7]: $\kappa = 10^{-3}T^{-2}$ [cm^3/sec] (the value of κ for germanium hardly differs from it by more than one order). We then find that the maximum generation rate in our experiment has corresponded to an electron concentration $N \approx (\nu_{max}/\kappa)^{1/2} \approx 10^{12}$ cm^{-3}, and a generation rate $\nu = 10^{-4}\nu_{max}$ corresponded to a concentration $N \approx 10^{10}$ cm^{-3}. The same estimates for N are obtained also from the photoresistance in a zero field if it is assumed that the carrier mobility is equal to

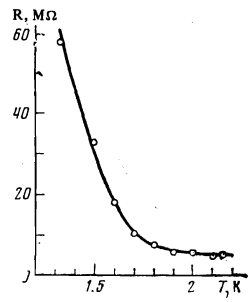

FIG. 2. Temperature dependence of the magnetoresistance. Sample G1, H = 21 kOe, relative intensity $I = \nu/\nu_{max} = 4 \times 10^{-2}$, $E \approx 1$ V/cm, $H \parallel [100]$.

10^6 cm^2/V-sec. On the other hand, the generation rate ν multiplied by the exciton lifetime (2×10^{-6} sec) determines the exciton density N_{ex}; it is found to equal 10^{15} and 10^{11} cm^{-3}, respectively.

From the fact that the ratios N/N_{ex} greatly exceed the values expected under thermodynamic equilibrium at $T \leq 2°K$, it follows that there is practically no inverse process, namely the decay of exciton in the carriers, at these temperatures.

The condition that the carrier gas be cold can be obtained by comparing the time of cooling to the temperature T

$$\tau_c(T) = \int_{\infty}^{kT} \left(\frac{d\varepsilon}{dt}\right)^{-1} d\varepsilon$$

with the time of binding into excitons

$$\tau_b(T) = (\varkappa N)^{-1} = (\nu\varkappa)^{-1/2}.$$

We have

$$\tau_c(T) \ll \tau_b(T), \quad \nu \ll \tau_c^2 \varkappa^{-1}. \tag{5}$$

Violation of this inequality means that the number of cold carriers is smaller than that of those that have not been cooled, and that the carrier distribution function has a maximum at a value $\epsilon_1 > kT$ determined by the condition $\tau_c(\epsilon) = \tau_b(\epsilon_1)$.[8] Substituting the value τ_c (2°K) = 10^{-8} sec we find that our maximum generation rate is precisely the critical value above which the contribution of the hot carriers to the conductivity becomes appreciable. On the other hand, under the conditions $\nu < \nu_{max}$ in which most experiments were performed we dealt with a thermalized carrier gas.

It must be emphasized that inequality (5) is determined by the internal properties of the electron-exciton system and is not connected in any way with the overheating of the sample itself.

RESULTS

In the range of fields 70—10 kOe, in p-Ge with an acceptor (element of group III) concentration $(2-5) \times 10^{14}$ cm^{-3}, we observed oscillations of the transverse magnetoresistance and of the photomagnetic-effect voltage (see Fig. 3). The oscillations were seen even in the purest of the germanium samples at our disposal, both p-type and n-type, with a total impurity density $(1-5) \times 10^{13}$ cm^{-3}, but in that case they were of much lower amplitude, almost at the noise level. The experimentally obtained facts concerning these oscillations can be summarized in the following manner:

1. The oscillations are not connected with the region next to the contacts. The results do not depend on whether the contacts were prepared by welding gold wire or by fusing-in an indium-gallium alloy. In addition, the oscillations were observed also in measurements of the magnetoresistance by the four-point scheme: the voltage on the potential contacts oscillated at a constant measuring current.

2. In the better samples we succeeded in observing seven extrema (the first extremum is not shown in Fig. 3: see, however, Fig. 5). Their periodicity in the reciprocal field is clearly seen from Fig. 4, in which 1/H is plotted as a function of the number n in three different cases. The slopes of the lines determine the period P:

$$P_{100}^{Ga} = 1.25 \cdot 10^{-5}\ \text{Oe}^{-1},\ P_{100}^{B} = 1.37 \cdot 10^{-5}\ \text{Oe}^{-1},\ P_{110}^{Ga} = 1.71 \cdot 10^{-5}\ \text{Oe}^{-1} \tag{6}$$

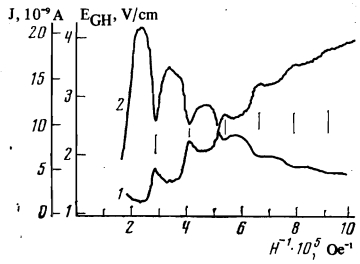

FIG. 3

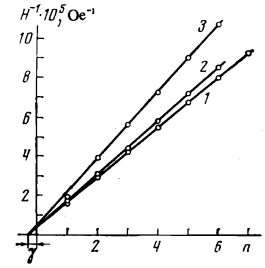

FIG. 4

FIG. 3. Oscillations of the photocurrent (1) and of the photomagnetic emf (2) in Ge:Ga samples; $T \approx 1.6°K$, $I \approx 10^{-2}$, $\mathbf{H} \parallel [100]$. For curve 1, the drawing field is E = 3.5 V/cm.

FIG. 4. Dependences of the positions of the oscillation extrema in the reciprocal field on the number n: 1—Ge:Ga sample, $\mathbf{H} \parallel [100]$; 2—Ge:B sample, $\mathbf{H} \parallel [100]$; 3—Ge:Ga sample, $\mathbf{H} \parallel [110]$.

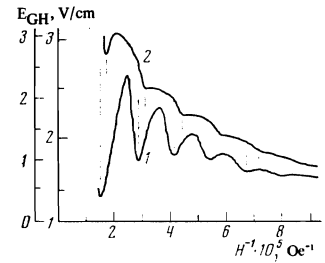

FIG. 5. Oscillations of the field E_{GH} in samples with different doping impurities; T = 1.6°K, I = 10^{-2}, $\mathbf{H} \parallel [100]$. Curve 1—Ge:Ga (left-hand ordinate scale), 2—Ge:B (right-hand ordinate scale).

(the indices of P indicate the doping impurity and the direction of the magnetic field).

3. It is seen from the lower two lines of Fig. 4, and from the plots of Fig. 5 themselves, that the period depends on the doping impurity. It was impossible at all to observe oscillations in the sample doped with zinc.

4. When the field is inclined to the [100] direction, the extrema split into three or two, depending on whether the field was rotated in the plane {110} or {100} (see Figs. 6a and 6b). The magnitude of the splitting corresponds exactly to the anisotropy of the effective mass of the electrons.[9] The ratio $P_{100}^{Ga}/P_{110}^{Ga}$ of the periods is also equal with good accuracy to the ratio of the cyclotron masses of the electrons.

5. The period of the oscillations does not depend on the frequency of the interband illumination. In the control experiments we used as the source of the interband illumination laser radiation of 1.15 μ wavelength, and also light from an incandescent lamp. The photoconductivity curves remained practically unchanged.

6. The value of the drawing electric field E used in the magnetoresistance measurement has likewise no effect on the period of the oscillations. The large field E, however, did not make it possible to trace the oscillations in the region of weak magnetic fields, owing to the onset of low-temperature breakdown (see Fig. 7).

7. As seen from the figures, the oscillations are not sinusoidal but have distinct, more or less narrow, extrema. This determines uniquely the phase of the oscillations—the quantity γ in (1). From Fig. 4 we get $\gamma \sim 0.3$.

8. Neither the period nor the phase of the oscillations depends on the direction of the current in the measurements of the magnetoresistance—we directed the current both along the $\langle\bar{1}00\rangle$ and the $\langle\bar{1}\bar{1}0\rangle$ axes.

9. The period of the oscillations is also independent of the intensity of the exciting light. However, by varying the intensity it was possible to observe inversion of the oscillations, wherein the maxima gave way to minima at the same values of the magnetic field—see Figs. 8 and 9. As seen from these figures, the inversion of the magnetoresistance and of the photomagnetic emf occurs at essentially different intensities. The critical value of the light flux at which the inversion occurs varied insignificantly from experiment to experiment; it could be decreased somewhat by increasing the drawing field E or by raising the temperature.

10. The variation of the $E_{GH}(1/H)$ curves with temperature is illustrated by Fig. 10. The most interesting here is the inversion at $T < 1.5°K$. It should be noted that it was not observed in all samples, and is apparently very sensitive to the sample quality. In the case of the sample used to obtain the curves of Fig. 10, the inversion disappeared after numerous coolings to helium temperatures and gave way to a monotonic decrease of the oscillation amplitude below 1.6°K.

It was impossible to see the inversion on the J(1/H) curves after lowering the temperature. The absolute magnitude of the magnetoresistance oscillations has a maximum at $T \approx 2°K$ (see Fig. 11). It must be borne in mind, however, that a decrease in temperature is accompanied also by a strong decrease of the photocurrent itself—Fig. 2. The relative magnitude of the oscillations, normalized to the value of the photocurrent at 50 kOe, is a function that decreases monotonically with increasing temperature, at least above 1.5°K. Our accuracy, however, is still insufficient to determine the sign of the change of this relative quantity at $T < 1.5°K$.

DISCUSSION

In the discussion that follows we refer to relation (1).

The splitting of the extrema as the field is rotated, and the dependence of the period P on the direction of H (Figs. 4 and 6) prove beyond a doubt that the oscillations are determined by electrons and not by holes. This makes it possible to determine directly from the periods (6) the energy $\mathscr{E}$ in (1):

$$\mathscr{E}^{Ge}=6.86\,\text{meV},\ \mathscr{E}^{B}=6.25\ \text{meV}. \qquad (7)$$

The obtained value of the energy is the first argument against the assumption that the oscillations are determined by electron-hole drops—the Fermi energies in the drops are much smaller.[5] A second no less important argument is based on the presently known exciton—drop phase diagram.[5,10] By raising the temperature and decreasing the illumination intensity (the lower curves in Figs. 10 and 11) it is possible to obtain oscillations at concentrations that are under the most optimistic estimates smaller by at least one order of magnitude than those at which condensation begins. Thus, the electron-hole drops have no bearing on the observed oscillations.

The problem consists of finding in the crystal the en-

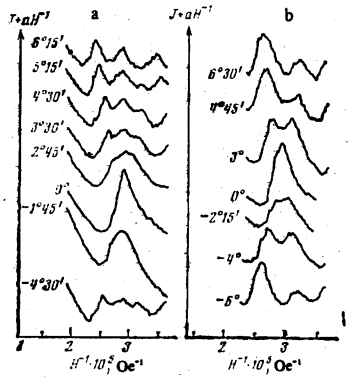

FIG. 6

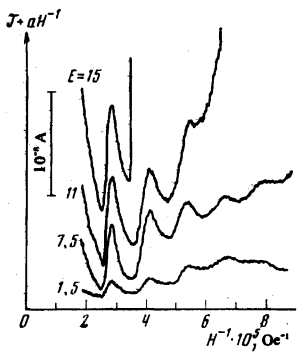

FIG. 7

FIG. 6. Change in the shape of the J(1/H) curves when H deviates from the [100] direction: a—rotation of H in the (011) plane, b) rotation of H in the (010) plane; T = 1.5°K, I = 10^{-2}, E = 3.5 V/cm.

FIG. 7. Oscillations of the photocurrent at various values of the drawing electric field E; sample Ge:Ga, T = 1.6°K, I = 10^{-2}, H ∥ [100]. The curves are tagged by the values of E in V/cm.

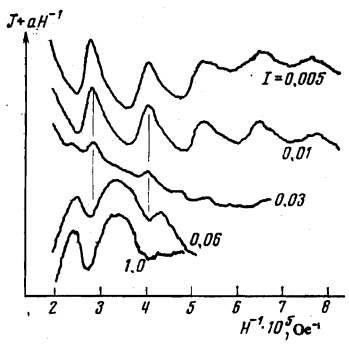

FIG. 8. Oscillations of the photocurrent at different intensities of illumination of Ge:Ga; T = 1.5°K, E = 3.5 V/cm, H ∥ [100]. The two lower curves were recorded with the gain decreased by a factor of five.

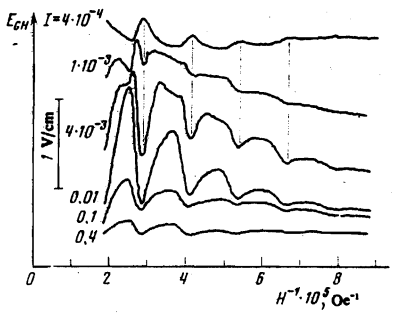

FIG. 9. Oscillations of the field E_{GH} at different illumination intenities; Ge:Ga sample, T = 1.63°K, H ∥ [100].

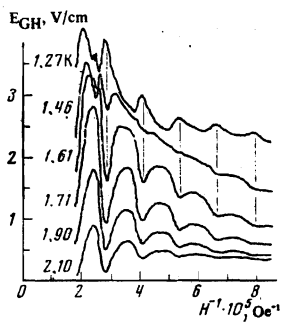

FIG. 10

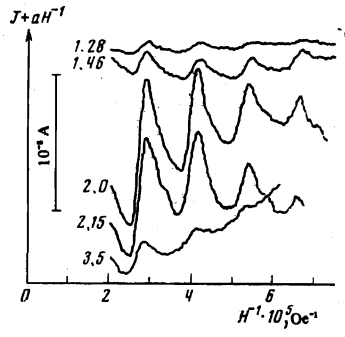

FIG. 11

FIG. 10. Oscillations of the field E_{GH} at various temperatures; I = 4×10^{-3}, H ∥ [100]. The curve at T = 1.27°K is shifted upward by 0.6 V/cm.

FIG. 11. Oscillations of photocurrent at various temperatures; Ge:Ga, I = 10^{-2}, E = 3.5 V/cm, H ∥ [100].

ergies (7). Strictly speaking, the fact that the oscillations have a much larger amplitude for doped samples than for pure ones still does not mean that these energies must be sought in the impurity spectrum. It is known, for example, that in some cases it is possible to observe magnetophonon oscillations in doped samples at helium temperatures,[11] whereas in pure samples they are seen only at a higher temperature. According to[12] (see also[1,13]), the role of the impurities reduces to an increase in the number of the equilibrium carriers, and the oscillations are due under these conditions to the competitions of two mechanisms of cooling the nonequilibrium electrons—emission of optical phonon and electron-electron collisions.

In germanium, however, from among all the characteristic phonons (the optical phonon with k = 0, the phonons that participate in the indirect interband transitions, and those participating in the hopping of the electrons from one valley to another), the lowest energy is possessed by the TA phonon, which is produced in an indirect transition, and this energy, 9.1 MeV, is much higher than the energy (7).

The exciton ionization energy $\mathscr{E}_{ex}$, to the contrary, is much less than (7). This excludes the possibility of the oscillations being determined by inelastic resonant scattering of the electrons by excitons. The ionization energy of exciton-impurity complexes is also too low, it exceeds E_{ex} by approximately 10% of the ionization energy of the corresponding impurity.[14,15] For the indium atom in germanium this energy is approximately 5.1 meV,[15] and for gallium and boron it should be even less.

The role of the characteristic energy in (1) could also be assumed by the energy corresponding to some singularity in the electron distribution function, say the maximum produced when the inequality (5) is violated.[8] However, the estimates presented above, and also the fact that both the photomagnetic effect and the magnetoresistance are so sensitive to the temperature (Figs. 21, 10, 11) makes it necessary to discard also this assumption.

Let us turn finally to the spectra of the impurities themselves. The quantities (7) within the limits of our accuracy coincide with the energy difference between the ground and first-excited states of the neutral acceptors Ga and B in germanium: according to[16], $\mathscr{E}^{Ga}$ = 6.74 meV and $\mathscr{E}^{B}$ = 6.24 meV. The dependence of the impurity spectrum itself on H[17] alters (1) insignificantly. Indeed, substituting in (1) the energy in the form of the series $\mathscr{E}(H) = \mathscr{E}_0(1 + \alpha H + \beta H^2)$, we obtain in place of (2)

$$1/H_n+\alpha+\beta H_n=nP+\gamma P, \quad P=\hbar e/mc\mathscr{E}_0. \tag{8}$$

We see therefore that the linear term in $\mathscr{E}(H)$ does not affect the measured period at all, producing only a phase shift of the oscillations, and deviations from the linear dependence $H_n^{-1}(n)$ are due only to the quadratic term. However, this term is small. According to[17], at H ∥ [100] the transition from the ground to the first excited state of the acceptor splits into four. For the boron atom, for the line corresponding to the lowest energy of these four, we have $\alpha = -0.03 \times 10^{-5}$ Oe^{-1} and $\beta = -0.32 \times 10^{-10}$ Oe^{-2}. If we plot in Fig. 4, as a function of n, not H_n^{-1} but the quantity $H_n^{-1} + \alpha + \beta H_n$, then all the points will be shifted downward ($\alpha < 0$, $\beta < 0$), the linearity is preserved, the phase shift decreases to $\gamma \approx 0.05$, and the period increases to 1.40×10^{-5} Oe^{-1}, from which we get $\mathscr{E}^{B}$ = 6.14 meV. The difference between this value and the data of[16] does not exceed the limits of our accuracy (1—2%); furthermore, it must be borne in mind that in[17] the measurements were made only to 20 kOe, and therefore the values of α and β are quite approximate.

Although our samples with the gallium and boron had slightly different impurity concentrations, and the independence of P of the concentration was not verified in special experiments, we believe on the basis of the foregoing that the oscillations are indeed determined by the acceptor spectrum. This means that the kinetic parameters of our system are influenced by oscillations of the probability of the inelastic scattering of the electrons by the neutral acceptors, accompanied by a change in the state of the acceptor. There are two such processes: first, at $\mathscr{E} = n\hbar\Omega$ an electron with energy $\epsilon \geq \mathscr{E}$ can move down n Landau levels in energy, transferring thereby the acceptor from the ground state to the excited state, and second, a cold electron with energy $\epsilon \approx kT$, after being scattered by an excited acceptor and transferring it to the ground state, can shift upward by an amount $n\hbar\Omega$.

According to the measurements of[18] the probability of scattering of the electrons by neutral acceptors at low temperatures and at our concentrations is $\tau_A^{-1} \approx 2 \times 10^9$ sec^{-1}, which corresponds to a cross section $\sigma_A \approx 0.5 \times 10^{-11}$ cm^{-2}. From a comparison of τ_A with the cooling time τ_c (2°K) $\approx 10^{-8}$ sec and τ_c (70°K) $\approx 10^{-9}$ sec it is seen that the process of scattering of hot electrons by acceptors is perfectly feasible and it should decrease the electron cooling time. However, it is not quite clear, first, how the acceleration of the cooling affects the kinetic parameters of the cold carriers, which determine the photocurrent. It is possible that this acceleration decreases the probability of electron capture by the acceptors with subsequent recombination—a process that takes place, according to the data of[14,19], at electron energies $\epsilon \gtrsim 20$°K. Second, in cooling by the impurities, the transition of the impurity center to the first excited level (we shall call it arbitrarily the transition 1 → 2) does not seem to offer any advantages over transitions to higher levels. Yet the experimental curves show no traces whatever of periods corresponding to other transitions.

The second type of inelastic scattering, by excited acceptors, has the advantage that it affects the cold carriers directly. It presupposes, however, that excited acceptors are present in the system. We can point out a number of processes that should lead to excitation or ionization of the acceptor, namely, the capture of hot electrons by a neutral acceptor[14,19] with subsequent capture of a hole on the excited level[20]; the so-called "two-electron" processes of exciton annihilation or an acceptor, which leave the acceptor in one of the excited states[14,19] (the intensity of such processes is about 10% of the total intensity of the radiative recombination[15,21]); the inelastic resonant scattering of hot electrons, which was discussed above; the absorption of nonequilibrium relatively short-wave phonons produced in indirect transitions and in the decay of optical phonons—several dozen of such phonons should be produced for each electron-hole pair and they can have a relatively long lifetime.[22]

It is important that if the excited acceptor can have a long lifetime at all, it is only in the lowest of the excited

states. It rolls down rapidly from the higher states, emitting long-wave phonons. On the other hand the last transition, $2 \rightarrow 1$, is made relatively difficult because the wavelength of the corresponding phonon turns out to be much less than the dimension of the impurity center. From a theoretical calculation made for the donor in germanium in accord with the hydrogenlike model it follows that the probability of the $2s \rightarrow 1s$ transition is smaller by a factor 50 than that of the $3s \rightarrow 2s$ transition.

We have already mentioned the experimentally measured[18] cross section for the scattering of electrons by a neutral acceptor, $\sigma_A \approx 0.5 \times 10^{-11}$ cm^2. Recognizing that the cross section for the excited state is larger than for the ground state and that resonance takes place, we use for estimating purposes $\sigma_A^* \approx 10^{-10}$ cm^2. We then obtain for the lifetime τ^* of the excited acceptor the inequality

$$\tau^* > (N\sigma_A^* v)^{-1} \approx 10^{-6} - 10^{-7} \text{ sec},$$

where v is the thermal velocity of the electrons. When this inequality is violated, the excited acceptor goes over to the ground state before it collides with any of the electrons. There are no experimental data on τ^*. A theoretical estimate[23] for a hydrogenlike donor yields for the $2 \rightarrow 1$ transition a time 10^{-8}–10^{-9} sec. This estimate, however, as applied to acceptors, is not reliable enough to reject on its basis the possibility of the scattering of the electrons by excited centers.

In conclusion, a few words concerning the observed inversion of the curves (Figs. 8–10). Since we are still in the initial stage of the study of this phenomenon, we confine ourselves only to some general remarks. Resonance-curve inversions of various kinds have already been observed in semiconductors and explained numerous times.[24-27] Although outwardly our experimental curves are similar to those obtained in[25,27], in contrast to them, and also to those of[11], in our experiments the concentration of the equilibrium carriers was negligibly small and the entire kinetics was due only to the photocarriers. (This circumstance does not permit, for example, direct application of the theory of the photomagnetic effect to our experiments under conditions when the carriers are heated by light[28].)

In this connection, we wish to call attention to the fact that in magnetic-impurity resonance, owing to the absence of a stabilizing background of equilibrium carriers, changes can take place simultaneously not only in such electron-gas parameters as the mobility μ and the lifetime t, but also in the concentration N, the diffusion length L, etc. In view of the fact that the measured kinetic characteristics—the transverse magnetoresistance and the photomagnetic emf—depend on complicated combinations of these parameters, the signs of the changes of the measured quantity can be different. For example, in the simplest case the transverse conductivity is proportional to the ratio $\sigma_{xx} \approx N/\mu$. If both N and μ decrease at resonance, then the sign of $\Delta\sigma_{xx}$ can be arbitrary, depending on which is larger, $\Delta N/N$ or $\Delta\mu/\mu$. But the ratio of these quantities can change with changing ν or T even if the type of the scattering process remains unchanged. From this point of view it is not surprising that the inversion of the curves $E_{GH}(1/H)$ is not accompanied by inversion of the magnetoresistance curve at the same values of ν and T: after all, they are determined by different combinations of the quantities N, μ, t, L, ... We hope that a future study of the inversions will be of great help in the investigation of the mechanism of the oscillations.

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