Magnetic-impurity oscillations in gallium arsenide

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Oscillations that are periodic in the inverse magnetic field, which are due to inelastic scattering of electrons by neutral excited donors, were observed while studying low-temperature photoconductivity of *n*-GaAs.

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At low temperatures fine impurities in an excited state can make a considerable contribution to the kinetic parameters of the system of nonequilibrium carriers in semiconductors. This was first pointed out in Ref. 1, where magnetic-impurity oscillations were observed while studying the magnetic-field dependence of the photoconductivity of *p*-Ge. These oscillations are due to inelastic scattering of thermalized electrons by excited acceptors, which make the transition from the lowest excited state to the ground state during scattering and which give up their energy to the electrons.

The presence of an appreciable population of the lowest excited states of acceptors in photoexcited germanium is due to the fact that the energy relaxation of the center proceeds comparatively rapidly compared to the excited states, while the transition to the ground state is characterized by a time $\tau^* \approx 10^{-7}$ *s* one to two orders of magnitude longer and is inhibited. Estimates show that approximately the same high value of τ^* should be expected for donors in GaAs and, therefore, magnetic-impurity oscillations can also be observed in this material.

In the present work magnetic-impurity oscillations were observed while studying the photoconductivity of specimens of epitaxial *n*-GaAs with thickness $\sim 100\,\mu$m with the concentration difference $N_D - N_A = 2\times 10^{14}$ cm^{-3}. Specimens fitted with low-resistance indium contacts were placed in liquid helium at the center of a superconducting solenoid. Infrared radiation from the warm parts of the cryostat was used to create nonequilibrium electrons. The signal, proportional to the photo current J or the derivative dJ/dH, was recorded as a function of the inverse magnetic field H^{-1} with constant voltage on the contacts, creating an electric field ~ 1 V/cm. The measurements were performed in the geometry $\mathbf{J}\|\mathbf{H}\|[110]$. The temperature could be varied in the range 4.2–1.3 K. In this case, the photocurrent varied approximately by an order of magnitude, dropping with a decrease in temperature.

An example of the experimental traces is shown in Fig. 1. As is evident from the figure, dJ/dH oscillates periodically as a function of H^{-1}. Only the first minimum, whose depth is about 10% of the total current, can be seen in the dependence $J(H^{-1})$. The arrows in the figure indicate the values of the magnetic fields for which the resonance condition

$$n\hbar\Omega = E_{2p_{-1}}, \qquad n = 1,\ 2,\ \ldots, \tag{1}$$

is satisfied, where $\Omega = eH/mc$ is the cyclotron frequency of electrons, m is the cyclo-

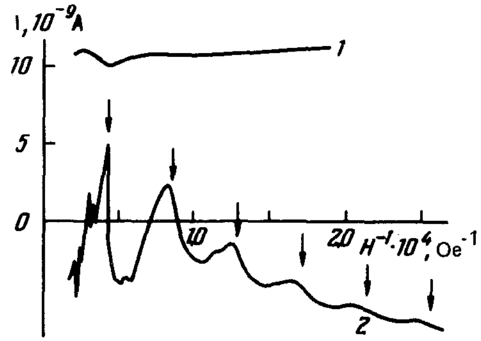

FIG. 1. Photocurrent I (curve 1) and dI/dH (curve 2, relative units) as a function of the inverse magnetic field. $T = 1.3$ K.

tron mass, $m = 0.0665\ m_0^2$, and $E_{2p_{-1}}$ is the lowest excitation potential of the donor. The quantity $E_{2p_{-1}}$ and its dependence on H were taken from Ref. 3 for a donor for which the chemical shift of the ground state is close to the average value for different impurities (line IV in Ref. 3). The H dependence of the excitation potentials of the donor for a number of excited states is shown in Fig. 2. The values of the resonance fields, for which relation (1) is satisfied for the first four numbers, are indicated in Fig. 2 by the arrows. Relation (1), as can be seen from Fig. 1, describes well the periodicity of the oscillations. This fact, as well as the fact that a period corresponding only to the lowest excitation potential of the donor occurs in the dependence $dJ/dH(H^{-1})$, permits asserting that the oscillations are due to inelastic scattering of electrons by excited donors.

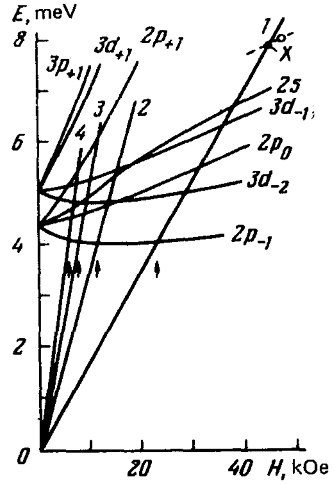

FIG. 2. Magnetic field dependence of the energies of the excited states of the donors, constructed from the data in Ref. 3. The straight lines indicate the quantities $n\hbar\Omega$ as a function of H for the first four numbers. The open circle corresponds to the line observed in Ref. 4.

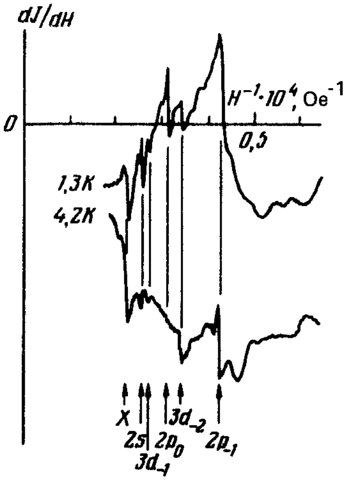

FIG. 3. $(dJ/dH)(H^{-1})$ for high fields at different temperatures.

The opposite process could also give the same periodicity: cooling of hot electrons due to excitation of impurities. However, in this model it would be impossible to explain the separation of the lowest excited states of the impurity. In addition, only hot electrons with energy $E \geqslant E_{2p_{-1}} \approx 40$ K are important here. The strong temperature dependence of the photoconductivity indicates that the contribution of such carriers to the current is small, and it is difficult to explain their resonant scattering by the observed large amplitude of the oscillations.

In addition to the magnetic-impurity oscillations, in high magnetic fields, a number of additional features are observed in the dependence $(dJ/dH)(H^{-1})$. In Fig. 3 this region is shown on an enlarged scale for two different values of the temperature. The arrows indicate the values of the magnetic fields calculated according to the data in Ref. 3, for which the energy $\hbar\Omega$ is comparable to the excitation potentials of donors for several low-lying excited states. The values of the fields obtained describe quite accurately the position of the extrema. It is difficult to identify the line X ($H_X = 45$ kOe), since we do not have reliable data on the H dependence of the energy of the excited states lying above the 2s state. Apparently, this line must be attributed to the level at which transitions are observed in the field $H = 47.9$ kOe in experiments on laser spectroscopy of GaAs (see Fig. 2).[4]

Thus, aside from magnetic-impurity oscillations, resonance lines are also observed in the dependence $(dJ/dH)(H^{-1})$ with lower amplitude, corresponding to inelastic scattering of electrons by donors, with which transitions occur with participation of the ground and excited states lying above the state $2p_{-1}$. We note that the amplitudes of the lines corresponding to these transitions differ quite strongly from one another, while the relation between the amplitudes depends on the temperature (Fig. 3). Starting from the coincidence of the line shape, which corresponds to the $2p_{-1}$ level in Fig. 3, and the lines lying in high fields, we can assume that the observed resonances are caused by the same type of processes as those occurring in magnetic-impurity oscillations. Thus the amplitude of the observed lines must reflect the degree of population of the excited states, normalized to the probablility of inelastic scattering of the electron by a donor in a corresponding excited state.

Unfortunately, this proposition cannot be checked because of the lack of data either on the degree of population of excited states of donors in GaAs under conditions of photoexcitation or on the probabilities of inelastic scattering of electrons by hydrogenlike impurities in the region of intermediate magnetic fields.

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[1] V. F. Gantmakher and V. N. Zverev, Zh. Eksp. Teor. Fiz. **69**, 695 (1975) [Sov. Phys. JETP **42**, 352 (1976)].

[2] G. E. Stillman, C. M. Wolfe, and J. O. Dimmock, Solid State Commun. 7, 921 (1969).

[3] E. M. Gershenson, G. N. Gol'tsman, and A. I. Elant'ev, Zh. Eksp. Teor. Fiz. **72**, 1062 (1977) [Sov. Phys. JETP **45**, 555 (1977)].

[4] P. E. Simmonds, J. M. Chamberlain, R. A. Hoult, R. A. Stradling, and C. C. Bradley, J. Phys. C: Solid State Phys. **7**, 4164 (1974).

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