Experimental investigation of magnetoimpurity oscillations in gallium arsenide

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An investigation was made of magnetoimpurity oscillations of the photoconductivity of n-type GaAs in a quantizing magnetic field at low temperatures. These oscillations were due to a nonmonotonic field dependence of the probability of inelastic scattering of thermalized electrons by neutral donors, resulting in the transfer of electrons from the lowest excited state $2p_{-1}$ to the ground state. Several resonance lines corresponding to inelastic scattering of electrons by donors in excited states higher than $2p_{-1}$ were also observed in magnetic fields $H \gtrsim 28$ kOe. This inelastic electron scattering was found to influence strongly the intracenter relaxation of donors and the relaxation time of the lowest excited state was found to be determined completely by such scattering when the photoelectron density was $n \gtrsim 10^9$ cm^{-3}. A simple kinetic model, describing the influence of the populations of the excited states on the nonequilibrium electron density, accounted for the main experimental results.

INTRODUCTION

An earlier investigation of the magnetic-field dependence of the low-temperature photoconductivity of n-type GaAs illuminated with infrared radiation revealed magnetoimpurity oscillations.[1] This effect was first observed[2] in p-type Ge and found to be due to inelastic scattering of carrier by neutral shallow impurities in a quantizing magnetic field.

When a magnetic field H is varied, the probability of such processes increases strongly every time that the energy ΔE transferred by inelastic scattering becomes comparable with the separation between any two Landau levels, i.e., when the following resonance condition is satisfied:

$$\mathcal{N}\hbar\Omega=\Delta E, \quad \mathcal{N}=1, 2, \ldots \tag{1}$$

Here, $\Omega = eH/mc$ is the cyclotron frequency of carriers and m is the cyclotron mass. It follows from Eq. (1) that the resonance values of the magnetic field are distributed periodically on the H^{-1} scale and the period is

$$P=e\hbar/mc\Delta E. \tag{2}$$

It can now be regarded as established that the magnetoimpurity oscillations observed in the low-temperature conductivity of p-type Ge (Ref. 2) and n-type GaAs (Ref. 1) are due to inelastic scattering of thermalized electrons by excited impurities and not by the inverse process of the scattering of hot electrons by impurities accompanied by the transitions of impurities to excited states. The main argument in favor of the former of these two processes is that the experiments[1,2] always revealed just one period associated with the energy of the lowest excited impurity state, i.e., the characteristic energy ΔE in Eq. (1) is equal to the difference between the energies of the ground and first excited states of an impurity center. This selection of the lowest excited state of an impurity within the framework of a model based on inelastic scattering of electrons by excited centers is to be expected because the lowest excited state of a shallow impurity is usually the longest-lived. Consequently, under nonequilibrium conditions the population of this state is considerably higher than the populations of any other excited states.

At low temperatures the energy of an excited center relaxes by spontaneous emission of acoustic phonons.[3,4] A carrier captured by an ionized center loses its energy relatively rapidly by transitions between highly excited states accompanied by the emission of long-wavelength phonons. The most probable are those transitions which are characterized by $qa \approx 1$ (q is the wave vector of a phonon and a is the effective Bohr radius of a center). However, the transition to the ground state is difficult because the wavelength of the emitted phonon is found to be much smaller than the size of an impurity center ($qa \gg 1$). For example, a calculation reported in Ref. 4 shows that in the case of a hydrogenic center the probability of the $3s \rightarrow 2s$ transition is 170 times greater than the probability of the $2s \rightarrow 1s$ transition. Therefore, an excited impurity center spends practically all its time in the lowest excited state before the transition to the ground state and this is why the transitions involving the former state predominate in the process of inelastic scattering of electrons by excited impurities.

The spectrum of shallow donors in GaAs can be described quite accurately by the hydrogenic model.[5] If $H = 0$, the $2s \rightarrow 1s$ transition is characterized by $qa \approx 13$ and the lifetime of the lowest excited state τ_{2s} calculated using the formulas of Ref. 4 is of the order of 10^{-6} sec. A magnetic field splits the impurity levels so that the lowest excited state is $2p_{-1}$ and the lifetime of this state should be $\sim (qa)^2$ times greater than the lifetime τ_{2s} (Ref. 3). A calculation of the probability of the $2p_{-1} \rightarrow 1s$ transition, carried out by substituting the appropriate wave functions into Eq. (3) of Ref. 4, given value $\tau_{2p_{-1}} \approx 2 \times 10^{-4}$ sec for $H = 0$ (the necessary parameters of GaAs were taken from Ref. 6).

In the range of moderate magnetic fields of interest to us (these fields correspond to $\hbar\Omega = \mathrm{Ry}^*$, where Ry^* is the effective Rydberg energy) the energy spectrum of a donor differs considerably from the spectrum in $H = 0$ (Fig. 1), which should affect the probability of intracenter transi-

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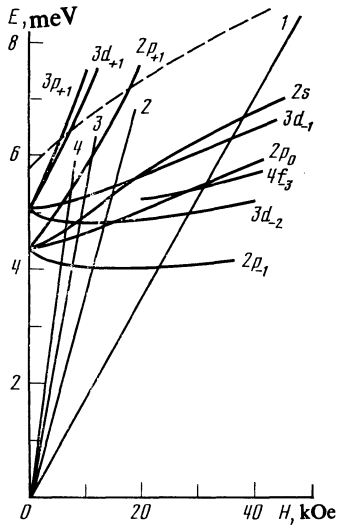

FIG. 1. Dependence of the energy E excited donor states on the magnetic field H, plotted using the results of Ref. 5. The straight lines are the dependences of $\mathcal{N}\hbar\Omega$ on H for the first four numbers. The dashed curve represents the position of the bottom of the conduction band obtained by fitting the results of a calculation reported in Ref. 16 to the level $2p_0$.

tions. However, calculations of this kind have not yet been made for moderate values of H. It is known in the limit of a strong field corresponding to $\hbar\Omega \gg \mathrm{Ry}^*$ the probabilities increase on increase in H because of a reduction in the size of the wave functions of the bound states in a direction transverse to the field.[7] In the range $\hbar\Omega \approx \mathrm{Ry}^*$ such changes should affect greatly the higher excited states, the "dimensions" of which are considerably greater than the Bohr radius of a center, and should affect less the state $2p_{-1}$, so that we can expect the lifetime of this state to remain of the same order as in $H=0$. Therefore, the intracenter relaxation pattern should generally be the same as in the absence of the field, i.e., the lowest escited state should have a lifetime considerably greater than the lifetime of the higher excited states. This is suppported by the results of our experiments.

A magnetoimpurity resonance in n-type GaAs was detected in Ref. 8 by optical methods and the lifetime of the $2p_{-1}$ state was found to be 0.5 μsec and 30 nsec at resonance and off resonance, respectively. Since the experiments reported in Ref. 8 were carried out under conditions of high-power laser pumping, such a very short lifetime $\tau_{2p_{-1}}$ off resonance may be due to inelastic scattering of electrons by excited donors.

We investigated in detail the magnetoimpurity oscillations in n-type GaAs in order to identify the actual mechanism of the influence of inelastic scattering of electrons by donors on the conductivity of a sample. We developed a simple model which was capable of accounting for all the main experimental results.

EXPERIMENTAL METHOD

The main series of experiments was carried out on samples of expitaxial n-type GaAs with a net impurity density $N_D - N_A = 2\times 10^{14}\ \mathrm{cm}^{-3}$ and a mobility $\mu(77\ \mathrm{K}) = 91\,000\ \mathrm{cm}^2\cdot V^{-1}\cdot\mathrm{sec}^{-1}$, grown on high-resistivity GaAs substrates. The thickness of epitaxial films was ~ 0.1 mm. Samples had two low-resistance contacts formed by alloying with indium. The distance between the contacts was usually ~ 1 mm.

A magnetic field up to 60 kOe was applied using a superconducting solenoid. Experiments were carried out in the temperature range from 1.3 to 7 K. At temperatures below 4.5 K a sample was immersed directly in liquid helium and the temperature was varied by altering the pressure of saturated helium vapor. In the range $T > 4.5$ K a sample was placed inside a chamber filled with gaseous helium and separated from a helium bath by a vacuum gap. The temperature was then varied by altering the power dissipated by a heater and it was monitored by a germanium thermometer.

Carries were photoexcited by room-temperature infrared radiation emitted by the warm parts of the cryostat. A stainless-steel tube was used as a light pipe. The radiation flux was reduced in some experiments by placing a metal stop in front of the sample across the light pipe. At the maximum rate of carrier generation the nonequilibrium electron density was $n \approx 5\times 10^9\ \mathrm{cm}^{-3}$ at 4.2 K, as deduced from the conductivity. Hence, assuming that the electron lifetime was $\tau \approx 10^{-7}$ sec (Ref. 6), we found that the rate of electron generation was $n/\tau \approx 5\times 10^{16}\ \mathrm{cm}^{-3}\cdot\mathrm{sec}^{-1}$. Cooling to 1.3 K reduced the photocurrent by approximately an order of magnitude because of an increase in the recombination probability.

A sample was subjected to a constant voltage and then the photocurrent J as well as its derivative with respect to the magnetic field dJ/dH were determined either as a function of the magnetic field or of its reciprocal H^{-1}.

The derivative dJ/dH was determined by modulating the magnetic field at a frequency of 20 Hz using an additional coil; the modulation amplitude was ~ 100 Oe. This created an alternating component of the current, proportional to dJ/dH, in the circuit of the sample and this component was recorded with a narrow-band amplifier and a lock-in detector. In some cases the monotonic component of the dependence of dJ/dH on H was compensated by adding to the measured signal a voltage proportional to H^{-1}.

The photoconductivity measurements were carried out in an electric field which was usually ~ 1 V/cm. In stronger electric fields the current-voltage characteristic became nonlinear because of the heating of the electron subsystem by the electric field. We investigated the magnetic-field dependence of the dark current and of its derivative dJ/dH under these conditions using electric fields up to ~ 30 V/cm.

The influence of the substrate on the observed dependence was determined by control experiments carried out on a sample from which the substrate and part of the epitaxial film were removed by a mechanical polishing followed by chemical etching in a $\mathrm{HCl}:\mathrm{CrO}_3$ solution.

EXPERIMENTAL RESULTS

Figure 2 shows an example of a record of the magnetoimpurity oscillations of the photocurrent J and of its derivative dJ/dH. The arrows above the curves give the values of the resonance magnetic fields H_{res} in which the condition (1)

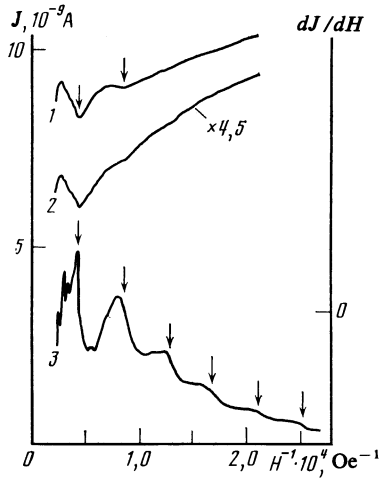

FIG. 2. Dependences of the photocurrent J (curves 1 and 2) and of the derivative dJ/dH (curve 3) on the reciprocal of the magnetic field at $T = 1.3$ K. Curve 3 corresponds to a carrier generation rate approximately five times less than for curve 1.

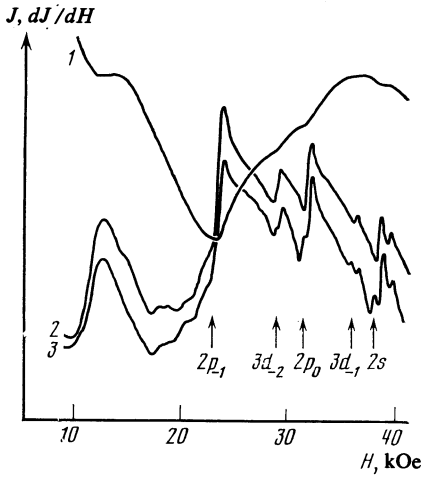

FIG. 3. Dependences of $J(H)$ (curve 1) and dJ/dH on H (curves 2 and 3) in high magnetic fields at $T = 1.3$ K.

is satisfied by the energy ΔE equal to the lowest excitation potential $E_{2p_{-1}}$ of a donor (Fig. 1). It is clear from Fig. 2 that the values of H_{res} agree well with the positions of the minima of the dependence $J(H^{-1})$ and with the corresponding steep parts of the dependence of dJ/dH on H^{-1}. In the calculations of H_{res} we used the cyclotron mass $m = 0.665m_0$ taken from Ref. 9. The value of $E_{2p_{-1}}$ and its dependence on H were taken from Ref. 5 for a donor characterized by chemical shift of the ground state close to the average value for different impurities (line IV in Ref. 5). We can see from Fig. 1 that the energy $E_{2p_{-1}}$ depended weakly on H so that there was no significant deviation from the periodicity of the oscillations plotted on the H^{-1} scale.

The magnetoimpurity oscillations were exhibited clearly by the dependences of dJ/dH on H^{-1}. The photocurrent curves $J(H^{-1})$ revealed reliably the first two minima. The depth of the first minimum δJ was about 10% of the value of the photocurrent J at a resonance. The value of $\delta J/J$ for the first minimum will be called the relative amplitude of the oscillations. We can see from Fig. 2 that this amplitude was practically independent of the rate of carrier generation. On the other hand, an increase in temperature reduced rapidly relative amplitude of the oscillations and at $T \gtrsim 3$ K the dependences of the photocurrent on the magnetic field no longer showed any oscillations.

In addition to the oscillations of the dependence of the photocurrent and of dJ/dH on the magnetic field, there were several additional singularities at high magnetic fields. The range of high fields is shown in Fig. 3 on an extended scale of the magnetic field itself. The arrows in this figure are the values of H at which the energy $\hbar\Omega$ became comparable with the excitation potential of donors in several of the low excited states. In the calculation of the resonance values of H we used the data from Ref. 5 for the excitation potentials of the same donor impurity as in the calculation of H_{res} of the main period of the magnetoimpurity oscillations. It is clear from Fig. 3 that the calculated resonance fields fitted quite well the positions of the observed lines. Curve 3 in Fig. 3 represents a sample made from a GaAs ingot for which the values of $N_D - N_A$ and $\mu(77\text{ K})$ differed little from the same parameters of the main batch of samples. However, this ingot is clearly less homogeneous in respect of the chemical composition of the impurities. This was indicated by the splitting of the resonance lines exhibited by curve 3, which may be attributed to the presence of donor impurities with a binding energy of the ground state different from the corresponding energy of the dominant impurity. The splitting of the $2s$ line, amounting of $\delta H/H \approx 2\%$, together with the dependence of the energy E_{2s} on H yielded $\delta E \approx 0.1$ meV, in agreement with the characteristic value of the chemical shift of the ground state of shallow donors in GaAs subjected to a magnetic field.[5]

The relationship between the amplitudes of the main series of the magnetoimpurity oscillations and of the additional resonances can be deduced from the dependence $J(H)$ shown in Fig. 3. The resonances of $J(H)$ appear as barely distinguishable minima with depth tens of times less than the depth of the minimum corresponding to the first oscillation of the main magnetoimpurity series.

The influence of temperature on the dependence of dJ/dH on H is illustrated in Fig. 4. It is interesting to note that the resonance lines did not disappear simultaneously when temperature was increased. For example, the line corresponding to the $2p_0$ level disappeared already at $T \approx 4.4$ K (Fig. 4). A further increase in temperature suppressed also the remaining additional lines, so that at $T \approx 6.5$ K only the line corresponding to the $2p_{-1}$ level remained.

All the curves shown in Figs. 2, 3, and 4 were recorded in the $\mathbf{J} \| \mathbf{H}$ geometry. Measurements of the transverse photoconductivity ($\mathbf{J} \perp \mathbf{H}$) also revealed magnetoimpurity oscillations and the extrema had the same profile as in the longitudinal geometry. Figure 5 shows an example of a record $J(H^{-1})$ obtained in the transverse geometry. Detection of oscillations in this case is difficult because of the strong magnetic-field dependence of the photocurrent. Moreover, in experiments of this kind the magnetoresistance of a sample is

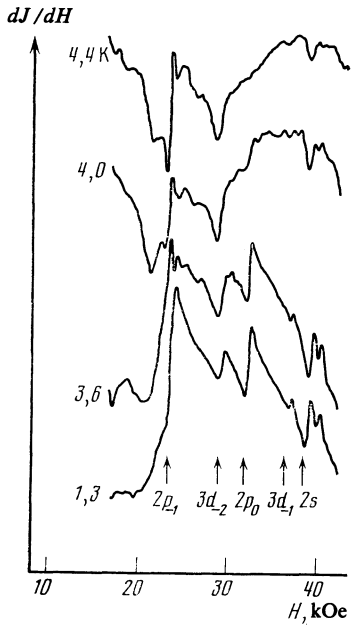

FIG. 4. Influence of temperature on the dependence of dJ/dH on H in the range of high magnetic fields.

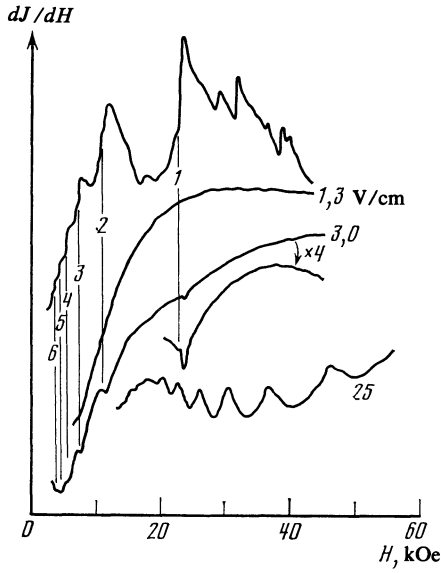

FIG. 6. Dependences of dJ/dH on H in the absence of background radiation, obtained for different values of the electric field in a sample given on the right of each curve. $T = 4.2$ K. For comparison, the uppermost curve shows the dependence of dJ/dH on H in the presence of infrared radiation.

high compared with the longitudinal geometry and this results in a shunting action of a region of the epitaxial film in contact with the substrate, where the concentration of the scattering centers is high. The curves in Fig. 5 represent a sample from which the substrate and part of the adjoining epitaxial film were removed. It was found that the amplitude of the magnetoimpurity oscillations was practically the same as in the longitudinal geometry. On the other hand, the samples with the substrate showed no magnetoimpurity oscillations of the dependence $J(H)$ in the $\mathbf{J}\perp\mathbf{H}$ geometry and the oscillations were observed only in the dependence of dJ/dH on H.

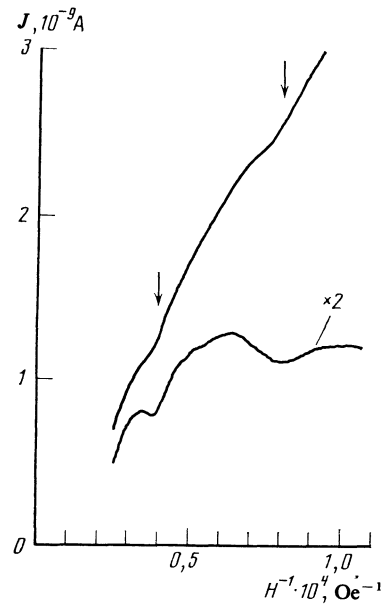

FIG. 5. Dependence $J(H^{-1})$ in the $\mathbf{J}\perp\mathbf{H}$ geometry. The lower curve is plotted after compensation for the monotonic dependence. $T = 1.3$ K.

In the absence of infrared radiation at temperatures in the range 1.3–7 K there were no oscillations of the dependences of J and dJ/dH on H in the region corresponding to the linear part of the current-voltage characteristic. An example of the dependence obtained then at 4.2 K is shown in Fig. 6 (second curve from the top). However, in higher electric fields the dark conductivity exhibits singularities at positions described by Eq. (1), indicating that they are associated with the processes of inelastic scattering of electrons by donors. It is important to note that in the absence of infrared radiation under conditions of heating by the field the additional resonances are not observed in high fields.

It is clear from Fig. 6 that the magnetoimpurity oscillations of the photocurrent and dark current are opposite in phase. For example, a resonance corresponding ot $\mathcal{N} = 1$ in the derivative of the photocurrent represents a steep rise of the signal on increase in H, whereas the derivative of the dark current exhibits a steep fall under the same conditions and this should correspond to the maximum of the dark current at a resonance. However, in view of the small amplitude of the magnetoimpurity oscillations of the direct current, it is not possible to observe these oscillations directly in the dependence $J(H)$.

The oscillations of the dark current were observed both in the longitudinal ($\mathbf{J}\|\mathbf{H}$) and transverse ($\mathbf{J}\perp\mathbf{H}$) geometries. The position on the magnetic field scale and the profiles of the extrema were independent of the experimental geometry.

A further increase in the electric field resulted in low-temperature breakdown (in $H = 0$ at $T = 4.2$ K the breakdown field was ~ 3.4 V/cm). The magnetoimpurity oscillations were not observed in fields above the breakdown value. However, in this range there were oscillations periodic on the H^{-1} scale and the period was $P = 5.5 \times 10^{-6}$ Oe^{-1} (low-

est curve in Fig. 6). The oscillations with this period had been observed earlier[10] in the longitudinal magnetoresistance of n-type GaAs heated by an electric field at higher temperatures of the order of $T \approx 11$ K (see also the review of Ref. 11) and it was established that they were due to the processes of resonant transfer of electrons from the Landau levels to the ground state levels of donors accompanied by the emission of optical phonons. It was also reported in that paper that magnetoimpurity oscillations with a period corresponding to the lowest excitation potential of the donor were superimposed on the background of the oscillations due to the resonant capture of electrons by donors. Our experiments were carried out at lower temperatures and in the prebreakdown range of electric fields we observed only the magnetoimpurity oscillations, whereas above the breakdown we found only the oscillations due to the resonant capture of electrons by donors accompanied by the emission of optical phonons.

DISCUSSION OF RESULTS

All the experimental results obtained by us in an investigation of the magnetoimpurity oscillations of the photoconductivity confirm the conclusion reached in Ref. 1 that in n-type GaAs the elementary process resulting in oscillations of the photocurrent is the inelastic scattering of the thermalized electrons by excited donors accompanied by the transitions of donors to the ground state and of electrons to higher Landau levels. The dominant role of the thermalized electrons in the kinetics of such a system follows from the strong temperature dependences of all the measured quantities and the identification of the period corresponding to the energy of the lowest excited state of a donor precludes the possibility that these oscillations are due to resonant excitation of donors as a result of the scattering of hot electrons by them.

The fact that additional resonance lines associated with the excited states of donors lying above the $2p_{-1}$ state have the same profiles as the lines of the main series of the magnetoimpurity oscillations (with the photocurrent minima at the resonances) and the influence of temperature on the relative intensities of these lines both suggest that the additional resonances are also associated with the inelastic scattering of electrons by donors which are in the appropriate excited states.

The magnetoimpurity oscillations of the dark conductivity under conditions of heating by an electric field were observed for the first time in n-type GaAs at $T \approx 11$ K (Ref. 10) and were attributed to resonant cooling of hot electrons as a result of their inelastic scattering by donors. However, the presence in the oscillatory magnetic-field dependence of dJ/dH of just one period corresponding to the lowest excitation potential of donors clearly indicates that under these conditions (as in the case of illumination with infrared radiation) the oscillations are due to resonance deexcitation of donors because of the scattering of electrons by them. This is supported also by the results of Ref. 12, where it was established that when n-type GaAs was heated by an electric field the energy in magnetoimpurity resonances was transferred to the electron system.

We shall no discuss the data on the magnetoimpurity oscillations of the photoconductivity and try to identify the specific mechanism which relates the inelastic scattering processes to the kinetic parameters of the nonequilibrium carrier system.

We shall develop a kinetic model starting from the assumption that the observed oscillations of the photoconductivity are due to oscillations of the nonequilibrium electron density. In fact, in the case of oscillations of the mobility it would be difficult to explain why the magnetoimpurity oscillations have the same line profiles and amplitudes in the longitudinal ($\mathbf{J} \| \mathbf{H}$) and transverse ($\mathbf{J} \perp \mathbf{H}$) geometries. An additional argument in support of this conclusion is that under equilibrium conditions at temperatures up to 7 K, when the concentration of excited donors is already considerable,

$$N^* \approx (N_D - N_A) \exp(-E_{2p_{-1}}/kT) \approx 10^{12}\ \text{cm}^{-3},$$

the dependences of the current and of dJ/dH on H are monotonic. If the inelastic scattering by excited donors had a strong influence on the electron mobility, we would expect magnetoimpurity oscillations also under equilibrium conditions.

At the resonances an increase in the probability of the inelastic scattering of electons by donors reduces the lifetime[8] and, consequently, the population of the lowest excited state of donors. If the release of electrons from this state to an allowed band has a significant influence on the density of free electrons n, a reduction in the population of this state should lower n and this can be the cause of the oscillations of the conductivity when H is varied in our experiments.

We shall analyze the influence of the population of the long-lived excited state of donors on the electron density in the conduction band by considering the kinetics of a system of nonequilibrium electrons formed as a result of ionization of shallow donors by infrared radiation (Fig. 7). We shall consider only the ground and lowest excited states of donors on the assumption that the higher excited states make no significant contribution to the kinetics of the system in view of the low populations of such states. Then, the free-carrier density n and the populations of the excited N^* and ground N_0 states of donors are described by the following system of kinetic equations:

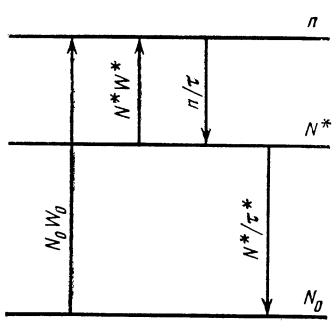

FIG. 7. Schematic representation of the transitions allowed for in Eq. (3), between two lowest donor levels in the conduction band in the presence of infrared radiation.

$$n/\tau=N_0W_0+N^*W^*, \quad N^*/\tau^*+N^*W^*=n/\tau,$$
$$N_0+N^*+n=N_D-N_A. \tag{3}$$

Here, W_0 and W^* are the probabilities of ionization of the ground and lowest excited states of a donor; τ is the lifetime of free carriers governed by the capture by ionized donors; τ^* is the lifetime of an excited donor before a transition to the ground state. It follows from Eq. (3) that the free-electron density is

$$n=(N_D-N_A)W_0\tau\frac{1+W^*\tau^*}{1+W_0(\tau^*+\tau+W^*\tau^*\tau)}. \tag{4}$$

The expression (4) allows us to analyze the influence of the lifetime τ^* of an excited donor state on the carier density in the conduction band. When the rate of generation is low, i.e., when the probabilities W_0 and W^* are small compared with the probability $1/\tau^*$ of a donor transition from an excited to the ground state, the change in the lifetime τ^* at a resonance results in a relative change in the free-carrier density by an amount

$$\delta n/n\approx(W^*-W_0)\delta\tau^*. \tag{5}$$

This result is easily understood on the basis of simple qualitative considerations. If $W^*=W_0$, a redistribution of the populations of the ground and excited states because of a change in τ^* does not alter the overall rate of carrier generation and, therefore, we hae $\delta n=0$. However, if $W^*\neq W_0$, the change in the rate of generation is governed mainly by the change in the population of that state which is characterized by the highest mobility of ionization.

Let us consider the factors which govern the probabilities of ionization of the ground and first excited states of a donor under our experimental conditions. In th range of temperatures of interest to us, $T\lesssim 3\,K$, when the magnetoimpurity oscillations are exhibited by the dependence $J(H)$, the probabilities of thermal ionization of these states are low[3] and we can ignore them compared with the photoionization probabilities. If we assume that the photoionization predominates in the case of both states, we can then use the known values of the photoionization cross sections of hydrogenic centers[13] and allow for the Planck distribution of thermal infrared radiation to obtain $W_0/W^*=W_{1s}/W_{2s}\approx 2.5$, i.e., $W_0>W^*$.

However, we shall show that in our experiments the excited donors are ionized mainly when photoelectrons are scattered by them. The impact ionization probability is proportional to the density n_h of hot carriers:

$$W^*\approx n_h v_h\sigma_i^*\approx W_0N_0\tau_c v_h\sigma_i^*. \tag{6}$$

Here, τ_c is the cooling time of a photoelectron to an energy equal to the ionization energy of the $2p_{-1}$ state; σ_i^* is the impact ionization cross section of a donor in this state by hot electrons of velocity v_h. The thermalization of hot electrons may occur because of the emission of acoustic phonons and also because of impact ionization when electrons are scattered by donors. If we assume that an electron interacts with the lattice via the deformation potential,[14] and that the cross section σ_i^0 for the ionization of a neutral donor by electron impact is close to the geometric cross section of the donor center,[15] we obtain the following ratio of the rates of energy losses for these two cooling mechanisms:

$$\left(\frac{d\varepsilon}{dt}\right)_{ac}\left(\frac{d\varepsilon}{dt}\right)_i^{-1}=\frac{2\Delta^2m^3}{\hbar^4\rho N_0a^2}\left(\frac{\varepsilon}{E_i}\right)$$

(Δ is the deformation potential constant, E_i is the donor ionization energy, and ρ is the density of the investigated crystal). In the range of energies of interest to us, $\varepsilon\gtrsim E_i$, this ratio is of the order of 5×10^{-2} for our samples, i.e., the cooling time τ_c is governed by the ionization of neutral donors. We then find from Eq. (6) that $W^*/W_0\approx\sigma_i^*/\alpha_i^0\approx 10$.

It follows that instead of Eq. (5), we can write down

$$\delta n/n\approx W^*\delta\tau^*. \tag{7}$$

The relationship (7) gives the correct sign of the change in the carrier density at a resonance, i.e., we have $\delta n<0$ when the time τ^* decreases. The relative amplitude of the magnetoimpurity oscillations, which is approximately 0.1 and 1.3 K, gives

$$\delta\tau^*\approx\frac{\delta n}{n}(W^*)^{-1}\approx10^{-5}\ \text{sec}.$$

Since there is a considerable reduction in τ^* at a resonance (according to Ref. 8, the value of $\tau_{2p_{-1}}$ decreases at a resonance by more than one order of magnitude), we can assume that $\delta\tau^*\approx\tau^*$. This value is approximately an order of magnitude less than the lifetime of the state $2p_{-1}$ which is governed by spontaneous emission of acoustic phonons (see Introduction). On the other hand, an estimate of τ^* obtained on the assumption that the transition of an excited donor to the ground state off resonance occurs because of inelastic scattering of thermalized electrons, gives a similar value $\tau^*\approx(nv_T\sigma^*)^{-1}\approx2\times10^{-5}$ sec.

It means that in our experiments the lowest excited state of a donor has a lifetime which is governed by the inelastic scattering of electrons by donors. The value of τ^* should depend on the electron density as n^{-1}. Since the probability W^* is proportional to the rate of carrier generation, the product $W^*\tau^*$ and, consequently, also the quantity $\delta n/n$ in Eq. (7) are both independent of the generation rate. This accounts for the absence of a dependence of the relative amplitude of the oscillations on the carrier generation rate found in our experiments.

The influence of temperature on the oscillation amplitude is also explained in a natural manner by the proposed model. In fact, variation of temperature in the range $kT\ll E_i$ should not affect the density of hot photoelectrons and, consequently, it should not influence W^*. However, the experimentally observed strong dependence of the photocurrent means that the majority of electrons do not become thermalized during the lifetime and the total electron density is a function of temperature, rising on increase in T. Therefore, τ^* should decrease on increase in T and, in accordance with Eq. (7), the amplitude of the magnetoimpurity oscillations should also decrease, as found experimentally.

We shall now consider the observation of the lines representing resonances with the participation of donor states

higher than $2p_{-1}$. First of all, we must point out that the ability to record the energy spectrum of excited donor states and to observe the chemical shift, is of interest in itself because the method used does not involve a spectroscopic instrument or a monochromatic radiation source. In our experiments the energy is scanned by variation of the cyclotron frequency of electrons caused by variation of H.

As already pointed out, the experimental observations indicated that the additional resonances are due to the inelastic of electrons by donors in appropriate excited states. The experimentally observed temperature dependence of the amplitude of the resonance lines may be a consequence of the influence of temperature of the populations of the excited donor states. For example, in a field $H \approx 32$ kOe corresponding to a resonance of the $2p_0$ state, the separation between the $2p_0$ and $2f_{-3}$ levels is $\delta E \approx 0.1$ meV. This means that if $kT \gtrsim \delta E$, the probability of the $2p_0 \rightarrow 4f_{-3}$ transition should rise considerably on increase in T because of transitions involving stimulated emission of phonons. It is possible that the resultant reduction in the population of the $2p_0$ state is the reason for the disappearance of the corresponding line at $T \gtrsim 4$ K (Fig. 4).

An important question is to what extent the amplitude of the lines corresponding to different excited states of a donor reflects the populations of these states. We can see from Fig. 3 that the additional minima in the dependence $J(H)$ are of depth tens of times less than the depth of the minimum corresponding to the first singularity of the magnetoimpurity oscillations. If we assume that the mechanism of the influence of the population of the short-lived excited states on the carrier density is the same as for the lowest excited state, we may conclude that the amplitude of the additional lines should be proportional to the change at the lifetime of these states at a resonance. If this change is large, i.e., if the ith state obeys the condition $\delta\tau_i^* \approx \tau_i^*$, the amplitude should be proportional to τ_i^* and the ratio of the amplitudes of the resonance lines represents the relative populations of the excited states of a donor.

However, we would like to point out that there is a mechanism which may enhance greatly the influence of the resonant scattering of electrons by donors in short-lived excited states on the kinetics of such a system. Let us assume that an electron captured by ionized donors descends successively between highly excited states and remains for relatively long time only at the lowest state. Then, a reduction in the population of the ith state at a resonance because of transitions caused by inelastic scattering directly to the ground state reduces the populations of all the lower excited states including that with the longest lifetime.

Under conditions of infrared illumination in our experiments it may be that this indirect mechanism of the influence of the populations of short-lived excited states of a donor on a density of electrons in an allowed band operates via the population of the longest-lived excited state. This enables us to explain the observation that the additional resonances of the dependence of dJ/dH on H are observed only in measurements of the photocurrent and are not exhibited by the dark conductivity under conditions when electrons are heated by an electric field. Obviously, the mechanism of the influence of the inelastic scattering processes on the dark conductivity differs from the proposed by us in order to describe the kinetics of the system under conditions of infrared illumination. This also follows from the fact that the magnetoimpurity oscillations of the photocurrent and dark current are opposite in phase. Clearly, in the range of electric fields below the breakdown value the release of electrons to an allowed band from the lowest excited donor state is not significant in the kinetics of the system and the oscillations are due to the additional heating of electrons as a result of their resonant scattering by excited donors. The transfer of energy from donors to electrons enhances the heating effect of an electric field and slows down the recombination rate, which explains the appearance of maxima at the resonances of the dependence of the dark current on the magnetic field.

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