[3] In this case, however, we must measure the quantity $\varkappa(\omega)$ in a sufficiently wide frequency range, which, incidentally, is now possible if we use synchrotron radiation for the ellipsometric measurements.

[4] The experimental errors for the data given in Fig. 3 can be estimated to be, on the average, 10–20%. A more exact determination of their values from the estimates of the various experimenters—estimates which are difficult to compare—proved to be impossible.

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Investigation of free excitons in Ge and their condensation at submillimeter wavelengths

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Results are presented of an investigation of free excitons in Ge in the submillimeter wavelength range for low as well as for high excitation levels when interaction between the excitons becomes important. The free-exciton energy spectrum is discussed. It is shown that the drop radii and their concentrations can be determined by measuring the temperature dependence of the free-exciton concentration. A section of the phase diagram is obtained in the 0.5–2.8 K temperature range for the free excitons+condensate system.

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1. INTRODUCTION

The spectroscopy of excitons in Ge in the submillimeter wavelength band corresponding to their binding energy was initiated only recently. It was shown in[1–3] that these investigations can yield additional information on the energy spectrum of the excitons and their behavior in external fields, as well as on collective effects at low temperatures. In[2–5,7,8] using spectrometers with backward-wave tubes (BWT), the absorption spectrum was obtained in the 2–0.35 mm band, while in [3–5] we investigated, in addition, the photoconductivity spectra of free excitons. The energy spectrum of the excitons was constructed from a comparison of the absorption and photoconductivity spectra and from the temperature dependence of the absorption line intensity. At sufficiently high excitation levels, when the interaction between the excitons becomes appreciable in the absorption spectra, starting with certain temperatures that depend on the excitation level, an abrupt decrease of the intensity of all the spectral lines is observed,[4,8] and a resonant-absorption band appears with a maximum at ~150 μ.[1,2]

The study of collective effects for free excitions in Ge is being quite diligently pursued of late. What are registered in experiment directly are either the nonequilibrium electrons and holes (for example,[9]), or the condensed phase (for example,[10,11]), or else free excitons (for example,[11,10]). The latter are usually identified by spectroscopic methods in the optical band (as a rule one investigates a luminescence line with energy $\varepsilon = 714$ meV). However, the observation of the luminescence of free excitons at low temperatures is limited by the sensitivity of the apparatus, and also by the associated resolution in the spectrum: if the resolution is insufficient, the intense and broad line of the condensate ($\varepsilon = 709$ meV) rapidly overwhelms the exciton luminescence. Therefore exciton luminescence can be observed at an exciton concentration $n_e \gtrsim 10^{12}$ cm^{-3} and $T \gtrsim 1.8$ °K; at $T \gtrsim 2.5$ °K this is possible only for excitation levels that do not exceed greatly the levels at which the system of excitons becomes stratified into two phases. At the same time, it is of undisputed interest to study the properties of an exciton gas at low temperatures under conditions when the gas is appreciably supersaturated.

Measurement of the gas branch of the phase diagram (the gas of free excitons + condensate) was carried out by several workers[9,11,12] and also encounters certain difficulties. First, the accuracy of the absolute measurement of the exciton concentration is low: usually, the method used in these studies to calibrate the excitation level against the photoconductivity of the sample at room temperature is apparently reliable only up to order of magnitude. Second, a sufficiently simple interpretation of the data is possible only if thermodynamic equilibrium is established in the system consisting of the free excitons, the condensate, and the free carriers without overheating, something difficult to realize when the sample is intensely excited. Furthermore, the results can depend on the excitation conditions, on the distribution of the excitons over the sample volume, etc.

Submillimeter spectroscopy of free excitons affords additional possibilities for the study of their interaction, and the high sensitivity of the method makes it possible to carry out the investigations starting with $n_e \sim 10$ cm^{-3}, and by the same token to investigate in detail the condensation down to the lowest temperatures. At the same time it becomes apparently possible to increase the accuracy with which the concentration of the free excitons is measured, and also to study the exciton gas under conditions when it is considerably supersaturated.

We present here the results of an investigation of the system of free excitons in Ge in the submillimeter band for both low and sufficiently high excitation levels, when the interaction between the excitons becomes appreciable.

2. EXPERIMENTAL PROCEDURE

The free excitons in Ge were investigated in the wavelength range 250–1000 μ using a spectrometer with traveling wave tubes (TWT) in the temperature interval 4.2–0.5 °K. The absorption and photoconductivity spectra were recorded by continuously scanning the radiation frequency of the TWT with automatic equalization of the amplitude-frequency characteristic.[5] The absorption spectra could be registered when the sample absorbed more than 0.01% of the incident submillimeter-radiation power, corresponding to $n_e \sim 3 \cdot 10^{10}$ cm^{-3}, and the photoconductivity spectra could be registered even at concentrations lower by one order of magnitude. The attained spectrometer resolution was $\sim 10^5$, but the resolution in the spectra was determined by the width of the exciton lines and was smaller by almost three orders of magnitude. The radiation frequency was determined with the aid of an open Fabry–Perot resonator and was verified against the position of the cyclotron-resonance lines of the electrons in n-Ge. The frequency measurement accuracy was 0.1%, which is perfectly adequate for the investigation of free excitons, since the line width in the spectra is $\Delta\lambda/\lambda \gtrsim 0.5\%$. To reduce interference distortion in the absorption and photoconductivity spectra, the submillimeter radiation was applied to the investigated sample immersed in liquid helium through a hollow dielectric lightpipe with absorbing walls.[13] An n-InSb receiver, shielded against the exciton-producing radiation with black paper, was placed directly behind the Ge sample. The submillimeter quasioptical channel termined in a matched load. For measurements in a magnetic field we used superconducting Helmholtz coils; the n-InSb receiver was in this case placed outisde the magnetic field.

The absorption coefficient α and the photoconductivity were measured as functions of the temperature, the excitation levels, etc., at a fixed submillimeter frequency, in a somewhat different manner. The high-frequency radiation was applied to the sample through a round oversized waveguide. The flange of the waveguide in front of the sample was sealed hermetically by a quartz plate, in order to avoid parasitic modulation of the submillimeter-radiation power by the boiling helium at temperatures above the λ point. The radiation that produced the excitons eliminated two opposite faces of the sample.

The investigated Ge samples had a shallow-impurity density from 10^{10} to 10^{12} cm^{-3} and a free-exciton lifetime from 1 to 8 μsec. The sample dimensions were $8 \times 3 \times 2$ mm. To measure the superconductivity, potential and current contacts were deposited on the sample. Excitation throughout the volume was achieved by selecting glass filters with known characteristics, and in the individual experiments we used thin (~100 μ) cooled filters of pure Ge and mechanical polishing of the sample surface. The electron-hole generation rate was 10^{15}–10^{19} cm^{-3} sec^{-1} in experiments in He^4 and was smaller by two orders of magnitude in He^3.

The upper limit of the employed generation level was determined by the overheating of the sample relative to the helium bath. The overheating was monitored in two ways: first, the strong dependence of the exciton concentration on the temperature, owing to their condensation under overheating conditions, led to a jump of the concentration on going through the λ point of the liquid helium, owing to the change in the heat outflow. Second, we were able to monitor the temperature of the exciton gas by measuring the relative intensity of the absorption lines of transitions from two levels of the ground state of the exciton.[4] Figure 1 shows the changes that appeared in the absorption spectrum as a result of overheating the sample: the presence of overheating at a high excitation level changed the ratio of the line intensities (for example, 3.14 and 2.86 meV) connected with transitions from the lower and upper levels of the ground state. To decrease the overheating due to formation of bubbles in helium near the sample, at a temperature above the λ point, pulsed excitation was used, by covering up all but one of the holes in the light-chopping disc. The pulse duration was such (about 0.5 msec at a repetition frequency 50 Hz) that the exciation could be regarded as stationary. This made it possible to raise the excitation level by approximately one order of magnitude (up to 10^{19} $\text{cm}^{-3}\cdot\text{sec}^{-1}$) without noticeable overheating of the sample.

To determine the absolute value of the exciton concentration n_0 in the Ge at a given excitation level, one usually measures and recalculates correspondingly the photoconductivity of the sample at room temperature.[10,11] We used still another method, in which we measured the absorption coefficient α_{ph} due to the photoionization of the excitons; the quantity α_{ph} is connected with n_e by the relation $\alpha_{\text{ph}} = \sigma_{\text{ph}} n_e$, where σ_{ph} is the exciton photoionization cross section and can be calculated by using the hydrogen-like model: $\sigma_{\text{ph}} = 1.1 \cdot 10^{-18} \varepsilon_{\text{ph}}^{-2}$[14] ($\varepsilon_{\text{ph}}$ is the binding energy of the free exciton). We measured α_{ph} at a wavelength 318 μ ($\varepsilon = 3.9$ meV), while the long-wave boundary of the photoionization corresponds to a quantum energy 3.8 meV (see Fig. 3 below). This method of calculating σ_{ph} for the exciton is justified by the fact that for shallow impurities in Ge (both for shallow donors and acceptors) it makes it possible to determine σ_{ph} with accuracy ~20%.[14] Comparison of the exciton concentration n_e, determined from the photoconductivity at room temperature and from the absorption coefficient in photoionization of the exciton, has shown that in our experiments the former method usually overestimated n_e by a factor 2–3.

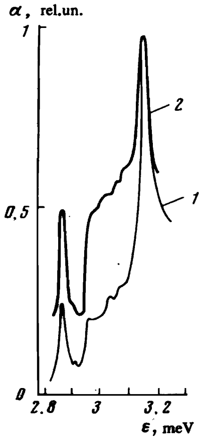

FIG. 1. Section of the absorption spectra at two excitation levels G ($G_1 < G_2$), $T = 2.5\,°\text{K}$. The intensity of the spectrum 2 is decreased by a factor of 10.

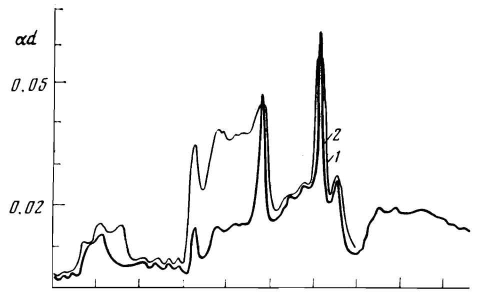

FIG. 2. Absorption spectra: 1—at $T = 4.2\,°\text{K}$, 2—at $T = 2\,°\text{K}$; $n_e = 5 \cdot 10^{14}$ cm^{-3} (d is the sample thickness).

3. SUBMILLIMETER EXCITON SPECTRA AT LOW EXCITATION LEVEL

1. Figure 2 shows the absorption spectrum of pure Ge at $T = 4.2$ and $2\,°\text{K}$ and at exciton concentrations $n_e = 5 \cdot 10^{11}$ cm^{-3}. One can see the lines due to exciton transitions from two levels of the ground state to different excited states and the photoionization band. When the temperature is decreased from 4.2 to 2 °K, the intensity of the first series of lines ($\varepsilon = 2.52$; 2.86; 2.96; 3.06 meV) relative to the second ($\varepsilon = 2.34$; 2.42; 3.14; 3.28; 3.36; 3.42; 3.50 meV) decreases exponentially with activation energy $\Delta \approx 0.4$ meV. These results agree well with the data of [7,8].

Lines with energies $\varepsilon = 2.34$; 2.52; 2.86; 2.96 and 3.06 meV are poorly resolved in the spectra, so that their position may be determined with an appreciable error. In addition, weak lines with energies $\varepsilon = 2.78$; 2.74; 2.69; 2.59 meV, etc. can be observed in the absorption spectra, but their nature is at present not clear to us. They, too, seem to be connected with free excitons, since the dependence of their intensity on the excitation level, on the temperature, and on the electric field applied to the sample is close to corresponding dependences for the second series of the exciton-photoexcitation lines.

These lines, however, do not appear in the photoconductivity spectrum (Fig. 3). Here we observe the long-

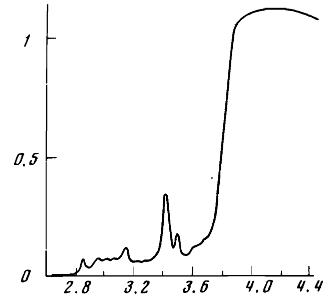

FIG. 3. Photoconductivity spectrum at $E = 2$ V/cm, $T = 2\,°\text{K}$, and $n_e = 5 \cdot 10^{11}$ cm^{-3}.

wave limit of the photoconductivity ($\varepsilon = 3.8$ meV) and the exciton-photoexcitation line. The relative intensity of the lines in the photoconductivity spectrum is significantly different from that in the absorption spectrum; with increasing temperature, as reported earlier,[4] an additional photoconductivity band appears, shifted approximately 0.4 meV towards lower energies. The width of the absorption and photoconductivity spectral lines decrease with decreasing temperature, down approximately to $T \sim 2\,^\circ$K, after which they remain practically constant and amount, for the line with $\varepsilon = 3.14$ meV, to 0.06 and 0.025 meV at $T = 4.2$ and 2 °K, respectively, and for the 2.85 meV line to 0.05 and 0.035 meV at the same temperatures.

In a magnetic field H, splitting of some of the spectral lines is observed; in particular, we registered four components each for the lines with $\varepsilon = 3.14$ and 3.42 meV. The energy shift of the Zeeman components turns out to be essentially nonlinear even at such low values of H, when they only begin to be resolved, in contrast to the assumption made in[15].

2. From the aggregate of the data on the photoconductivity and absorption we can obtain the energy spectrum of the indirect excitons in Ge.[4] The exciton binding energy, determined by measuring the long-wave boundary of the nonresonant photoconductivity, turns out to be 3.8 meV. Then the energy position of the second exciton-photoexcitation series of lines yields the energies of the excited states of this series. To obtain another series of levels it is necessary to know the energy gap Δ between the levels of the ground state of the exciton. The temperature dependence of the absorption line intensity yields 0.4 meV. However, since the measurements occurred at relatively high temperatures ($T = 4.2$–$2\,^\circ$K), we need apparently a more complicated interpretation of the experimental data, since the exciton band is not parabolic.[16] The additional band in the photoconductivity spectrum is observed also only at high temperature ($T \sim 4\,^\circ$K) in the presence of exciton-photoexcitation lines, which can distort the form of the nonresonant band.

The widths of the exciton photoexcitation lines, obtained in our experiments, are close to the results of[8] and just as for shallow impurities at low concentrations,[17] can be attributed to the relatively short lifetime of the excitons in the excited and in the ground states, owing to transitions to other states with phonon emission or absorption. Then, as the temperature is decreased, owing to the decrease in the probability of the thermal excitation from the lower to the upper level of ground state, the contribution of the broadening of the lower level decreases like $(e^{\Delta/kT} - 1)^{-1}$, and amounts to $\Delta\varepsilon \approx 0.1$ meV at $T = 4.2\,^\circ$K. The contribution of the excited levels and of the upper level of the ground state to the widths of the corresponding lines also decreases with decreasing temperature but tends to a constant value due to the transition of the exciton to low-lying states with spontaneous emission of phonons. The foregoing explanation is in satisfactory agreement with the result of experiments on the temperature dependence of the line widths.

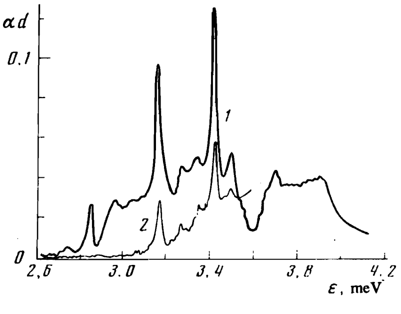

FIG. 4. Absorption spectra: 1) $T = 2\,^\circ$K; 2) $T = 1.4\,^\circ$K at the excitation level G_4 (see Fig. 5).

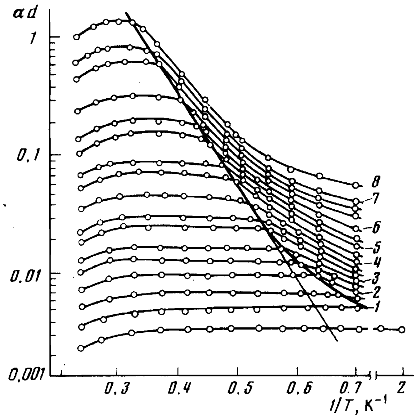

FIG. 5. Dependence of the absorption coefficient on the temperature for the 3.14-meV line at different excitation levels G ($G_1 < G_2 < \ldots < G_8$). The same numbering of the excitation levels is retained also in the following figures 6, 8, and 9.

4. MANIFESTATION OF COLLECTIVE EFFECTS IN SUBMILLIMETER SPECTRA OF FREE ELECTRONS

1. If the temperature is lowered and the excitation level is kept constant and sufficiently high, then starting with a certain temperature, an abrupt decrease of the intensity of the entire absorption spectrum takes place (Fig. 4). At the lowest temperatures ($T \lesssim 1.6\,^\circ$K) and at high excitation levels, an additional broad band appears in the absorption spectrum, and drops off towards lower energies. This is apparently the longwave part of the same resonant-absorption band of the condensed phase which was observed in[1,2].

The next figure (Fig. 5) shows the dependence of the absorption coefficient of the radiation for the transition with energy 3.14 meV on the reciprocal temperature at different excitation levels. The intensity of the remaining lines of the transitions from the lower level of the ground state of the exciton varies in analogous fashion, but on the short-wave section of the spectrum the result can become somewhat distorted by the additional absorption of the condensed phase. It is seen from Fig. 5 that, starting with a certain threshold temperature T_{thr}, the absorption decreases sharply. The $\alpha d = f(1/T_{\text{thr}})$ values at high temperatures fit a nearly-exponential curve, and at low temperatures this curve becomes more gently sloping. Below a certain excitation level, corresponding to $\alpha d \sim 10^{-2}$, the absorption coefficient

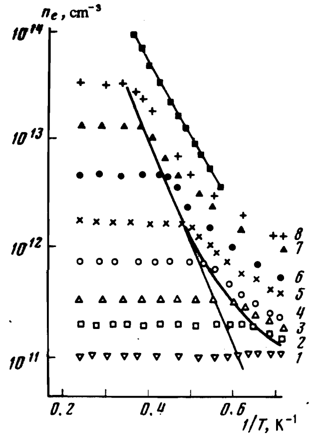

FIG. 6. Temperature dependence of the exciton concentration at different excitation levels G. ■—values of $n_{e\ \mathrm{thr}}(1/T)$ from [11].

does not decrease, down to the lowest temperatures ~0.5 °K. In the temperature range 4.2–3 °K, the value of αd increases weakly (by ~1.5 times) at all excitation levels.

2. Figure 6 shows the temperature dependences of the concentration of the free excitons n_e at several excitation levels. The values of n_e were calculated from αd (Fig. 5) with account taken of the difference between the values of α for the photoionization of the exciton and for the 3.14-meV transition (see Fig. 2). It should be noted that the value of α for the 3.14 meV line is proportional to the total exciton concentration only at $T \lesssim 3$ °K. At large values of T, a noticeable redistribution of the excitons among the two levels of the ground state takes place. This is the cause of the decrease of α with increasing T for the 3.14-meV line corresponding to the transition from the lower level of the ground state. The recalculation of n_e from αd on Fig. 6 was carried out with allowance for the occupation of both levels of the ground state.

It is seen from Fig. 6 that the concentration of the free excitons does not depend on T up to a certain value T_{thr} that depends on the excitation level. The exciton concentration less than ~10^{11} cm^{-3} turned out to be independent of temperature in our experiments in the entire investigated interval, down to ~0.5 °K.

Inasmuch as under conditions when the exciton concentration decreases strongly at low temperatures the absorption photoconductivity spectra reveal no onset of additional lines that might be associated with excitonic molecules, we interpret the results from the point of view of exciton condensation into electron-hole drops. A line drawn through the threshold points, $n_{e\ \mathrm{thr}}(1/T)$, separates on the diagram of Fig. 6 the region in which the exciton system is single-phase (only the exciton gas exists) from the region where two phase coexist and the exciton gas is supersaturated. Figure 6 shows also the results of [11] for the phase coexistence curve, obtained from measurements of the dependence of the threshold intensity of the exciton-luminescence line $\varepsilon = 714$ meV on the temperature at which the drop luminescence line $\varepsilon = 709$ meV appears. The obtained section of the phase diagram in the region of relatively high temperatures yields the value of the work function φ of the exciton-hole pair from the condensate to the exciton. In our measurements $\varphi = 1.65 \pm 0.1$ meV, as against 1.54 ± 0.25 meV obtained in [11], so that the difference between the results is within the limits of errors, but the absolute value of the concentration n_e at the given temperature differs by almost one order of magnitude. It appears that this is due to the insufficient accuracy with which the exciton concentration is determined from measurements of the photoconductivity of the sample at room temperature, as was done in [11].

In Fig. 7 are compared the data for the phase-coexistence curve reconciled at a single point; these are the curves of Fig. 6 and of [9,12], in which the absolute values of the exciton concentration are not given. We see that at high temperatures the results of the relative measurements are close, but at low temperatures considerable discrepancies are observed, with the values of $n_{e\ \mathrm{thr}}(1/T)$ from [9,12] higher than ours. The differences seem to be due to the higher sensitivity of the submillimeter measurements.

From the measurements of $n_e(T)$ in the region of coexistence of the two phases we can estimate the radii of the drops and their concentration at different temperatures and excitation levels. If the exciton concentration in the volume and near the drop are assumed to be the same and if the supersaturation is attributed only to the recombination of the electron-hole pairs in the drop, then we get according to [10,18]

$$n_e - n_{e\ \mathrm{thr}} = {}^1/_3 R n_0 / v_T \tau_0, \tag{1}$$

where $v_T = (kT/2\pi m^*)^{1/2}$, and n_0 and τ_0 are the concentration and lifetime of the electron-hole pairs in a drop of radius R.

The values of R calculated with the aid of (1) at the highest light intensities employed by us and at high temperatures reach 20 μ, and greatly exceed the values of R obtained under analogous conditions in experiments on the scattering of infrared radiation by the drop.[19,20] At large n_e and at high T it is necessary to take into account the diffusion of the excitons from the volume to the surface of the drop and their scattering by acoustic phonons, and this complicates the relation between n_e and R[21]:

$$n_e = n_{e\ \mathrm{thr}} + \frac{n_0 R}{3 v_T \tau_0}\left(1 + \frac{v_T}{D} R\right), \tag{2}$$

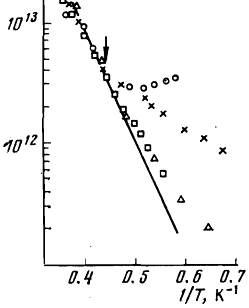

FIG. 7. Section of phase diagram $n_{e\ \mathrm{thr}}(1/T)$: ▲—our measurements, □—measurements in [11], ○—in[12], ×—in[9]. The arrow shows the value of T at which the results of all measurements are reconciled.

where D is the diffusion coefficient measured in [10] ($D = 1.5 \cdot 10^3$ cm^2/sec at $T = 3$ °K). Estimates show that in expression (2) the second term in the parentheses is significant only at high excitation levels, when $n_e \sim 10^{13}$ cm^{-3}. At low excitation levels, relation (2) goes over into (1).

Plots of R against $1/T$ for different excitation levels, calculated from (2) using the data of Fig. 6, are shown in Fig. 8. It is seen that the drop dimension increases with increasing temperature and excitation level, and at high values of T and G the obtained data are in good agreement with the results of experiments on the scattering of light from the drops. [19,20,22] Near the threshold temperature T_{thr}, however, the radius of the drops decreases abruptly, something not observed in the scattering experiments, owing to the insufficient sensitivity of the method. For the same reason, the region of low temperatures and low excitation levels was not investigated in the scattering measurements.

Let us estimate the drop concentration N_d in the volume of a semiconductor from the data of Fig. 6. Since the free-carrier density is much lower than n_e, we have under stationary conditions

$$G=\frac{n_e}{\tau_e}+\frac{4\pi}{3}R^3\frac{n_0}{\tau_0}N_d\,. \qquad (3)$$

When only a gas of free excitons is present in the semiconductor ($T > T_{\text{thr}}$), then $G = n_e^*/\tau_e$, where n_e^* is the concentration of the free excitons at $T > T_{\text{thr}}$, and τ_e is their lifetime. Under condensation conditions $T \lesssim T_{\text{thr}}$ and

$$n_e^{*}-n_e=\frac{4\pi R^3}{3}n_0\frac{\tau_e}{\tau_0}N_d\,. \qquad (4)$$

The values of $N_d(1/T)$ obtained in this manner at different excitation levels G are shown in Fig. 9. It is clearly seen that the drop concentration depends little on the excitation level and increases sharply with decreasing temperature.

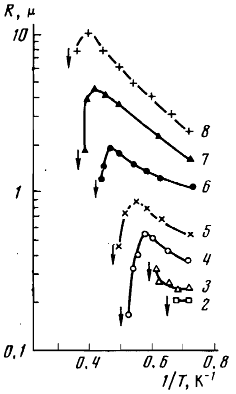

FIG. 8. Dependence of the radius of the drops on $1/T$ at different excitation levels G. The arrows show the value of T_{thr} for each excitation level.

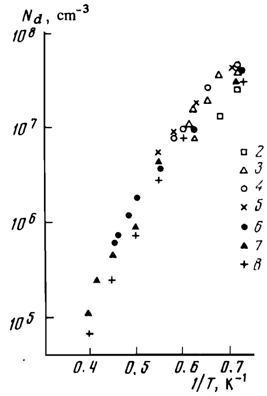

FIG. 9. Dependence of the drop concentration on $1/T$ at different excitation levels G.

The generation of the drops can occur either as a result of fluctuations of the exciton density, or on condensation centers, when the probability of the fluctuation mechanism decreases abruptly near the threshold temperature. If the condensed phase is produced by the first process, then the probability of the onset of a nucleus of critical radius is determined by the expression[23]

$$W \sim \exp\left\{\frac{16\pi\sigma^3}{3n_0^2\varphi^2 kT[(T_{\text{thr}}-T)/T]^2}\right\}$$

where σ is the surface-tension coefficient. In our experiments, the dependence of N_d on $T/(T_{\text{thr}} - T)^2$ turned out to be exponential only at the highest excitation levels employed by us (8, 7, 6) and at low temperatures. The argument of the exponential corresponds to $\sigma = 1.60 \cdot 10^{-4}$ erg/cm^2, which is close to the value given in[23,11]. At lower excitation levels there is no exponential section of the plot of N_d against $T/(T_{\text{thr}} - T)^2$ in the entire employed temperature region, and this apparently indicates that the condensation centers play a decisive role when drops are generated under these conditions.

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A possible resonance method for investigating electron-impurity exchange interaction in semiconductors

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An analysis is made of carrier states localized on a paramagnetic impurity in a nondegenerate semiconductor subjected to crossed magnetic and electric fields. It is shown that the exchange part of the electron-impurity interaction, which couples the orbital and spin coordinates of an electron, may give rise to electric-dipole transitions between the electron-impurity multiplet states. The probabilities of these transitions are calculated and found to be several orders of magnitude higher than the probabilities of magnetic-dipole transitions.

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I. INTRODUCTION

In a static magnetic field a potential well, no matter how shallow, creates a localized state with the binding energy[1,2]

$$\varepsilon_b \propto \Omega (a/l)^2, \tag{1}$$

where Ω is the cyclotron frequency, $l=(c/eH)^{1/2}$ is the magnetic length, and a is the scattering length of an electron interacting with a potential center in the absence of a magnetic field ($\hbar=1$). We shall show later that a similar situation arises when an impurity center has spin (paramagnetic impurity). In this case the energy spectrum of localized states created by a magnetic field has a characteristic structure of an electron–impurity spin multiplet.

We shall show that in addition to the usual magnetic-dipole transitions between the states of this multiplet, which can be investigated by the ESR methods, there may be also transitions of the electric-dipole type whose intensities are several orders of magnitude higher than those of magnetic-dipole transitions. The separation between the energy levels of a multiplet and the transition probabilities are functions of the parameters of the electron–impurity exchange and it is natural to expect that these parameters may be determined most conveniently using electric-dipole resonant transitions.

The interaction between a paramagnetic impurity center, whose spin is S, and a free carrier (electron) can be described by the model Hamiltonian

$$\mathscr{H}_{\rm int}=V(r)+J(r)\,\mathbf{S}\cdot\mathbf{s}. \tag{2}$$

We shall assume that a paramagnetic center has a spin $S=\frac{1}{2}$. Moreover, we shall postulate that the interaction (2) corresponds to attraction in both spin states (singlet and triplet) of the electron–impurity system.

We shall be interested primarily in the case when the electron–impurity interaction results in localization of an electron only in the presence of a magnetic field. The resultant localized states are characterized by a low binding energy ($\varepsilon_b \to 0$ for $H \to 0$) and large spatial dimensions, given by the quantity l at right-angles to the magnetic field and by $(2m\varepsilon_b)^{-1/2}$ along the field. Therefore, states of this kind can be described by the approximation of "zero-radius" potential, which improves in precision with decreasing H. In this approximation the interaction Hamiltonian (2) is governed entirely by two scattering lengths: a_t and a_s, corresponding to the triplet and singlet spin states of the electron–impurity system. In this model, the main contribution of the exchange forces is given by