Magnetic cooling of excitons in GaAs

Yu. V. Zhilyaev, V. V. Rossin, T. V. Rossina, and V. V. Travnikov

A. F. Ioffe Engineering Physics Institute
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Anomalous enhancement of polariton luminescence has been observed in ultrapure epitaxial GaAs layers. Studies of how the rate of increase in luminescence intensity depends on excitation intensity, the purity of the samples, and temperature have revealed that the enhancement effect is determined by the change in exciton kinetics in the magnetic field. An analysis of the polariton luminescence and phonon echo spectra reveals that the effective polariton temperature diminishes and the total number of polaritons rises in the magnetic field. It is demonstrated that the energy relaxation rate of the electrons due to piezoelectric scattering by acoustical phonons grows in a quantized magnetic field, while the electron temperature diminishes. Electron cooling serves to increase the exciton production probability while exciton heating diminishes due to exciton-electron scattering processes.

1. INTRODUCTION

Magnetooptic studies of excitons in GaAs to date have largely focused on magnetoabsorption[1] and magnetoreflection.[2] The purpose of such studies has been to analyze the effect of the magnetic field on the energy structure of the excitons, i.e., the diamagnetic shift and Zeeman splitting of the ground and excited states.

We have previously observed intense, clearly-expressed resonance exciton luminescence in ultrapure epitaxial GaAs layers; this luminescence has been described comprehensively within the framework of the polariton model.[3] The form of the polariton luminescence (PL) spectrum is determined by spatial polariton diffusion and polariton energy relaxation.[4] It is possible to investigate exciton kinetics by analyzing the change in the PL spectrum under different external actions. We recently reported the discovery of a new effect, strong PL enhancement of GaAs in a magnetic field.[5] The results of a detailed analysis of this effect, which is directly related to the magnetic field effect on exciton kinetics, are presented in this paper.

The experimental manifestations of this effect are described in Sec. 2. It is demonstrated in Sec. 3 based on the analysis carried out here that PL enhancement in GaAs is related to effective exciton cooling in the magnetic field to nearly the lattice temperature. It is assumed that the reduction in the exciton effective temperature in the magnetic field is due to the increase in the energy relaxation rate of the electrons and their cooling. A theoretical calculation of the energy relaxation rate of the electrons in the magnetic field is carried out in Sec. 4. The proposed PL enhancement mechanism is discussed in Sec. 5.

2. EXPERIMENTAL RESULTS

The primary experiments were carried out at a temperature $T = 1.7$ K. The samples—pure epitaxial $n^2 =$ GaAs layers obtained by gas-phase epitaxy in a chloride system—were placed in a superconducting solenoid. The magnetic field was as high as $B \approx 7$ T. The magnetic field was applied perpendicularly to the sample surface (if not stipulated otherwise). An Ar^+-laser ($\lambda = 4880$ Å) served as the photoexcitation source; the laser radiation was focused on a spot ≈ 0.5 mm in diameter. The luminescence spectra were recorded by a DFS-12 double diffraction spectrometer with a 0.1 meV resolution.

Strong PL enhancement was discovered from analysis of the luminescence of ultrapure GaAs samples (total concentration of shallow impurities substantially below 10^{13} cm^{-3}). The intensity of the lower polariton branch (LPB) grows by a factor of 17 under specific conditions in fields of $B = 6.7$ T.

The photoexcitation intensity has a strong effect on the enhancement of exciton luminescence (Fig. 1a). The degree of increase in luminescence intensity is nonmonotonically dependent on the excitation intensity (I_{exc}) and is maximized at certain average I_{exc}. An increase in LPV emission is observed up through fields of $B \approx 3$ T with small I_{exc}, followed by saturation.

In addition to the intensity, the PL spectral line shape (Fig. 2) also changes: The spectral line diminishes, followed

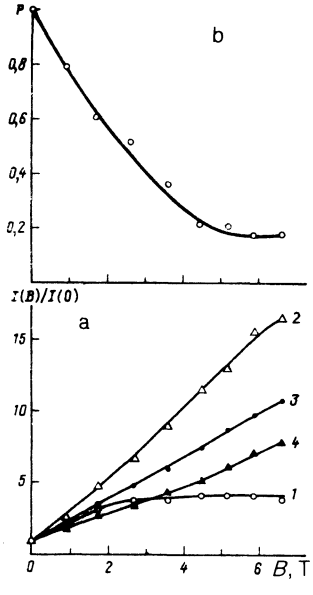

FIG. 1. a—LPB line intensity versus magnetic field magnitude for various excitation intensities I_{exc} (W/cm^2): 1—0.2; 2—0.8; 3—2; 4—4.5. b—The ratio P of integral line intensities (D^+,x) and (D^0,x) plotted as a function of the magnetic field for $I_{exc} = 0.8$ W/cm^2 ($P = I_{(D^+,x)}/I_{(D^0,x)}$).

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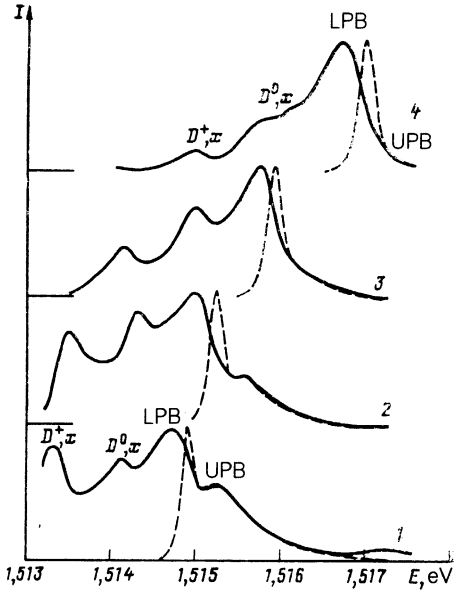

FIG. 2. The luminescence spectra of the GaAs sample at different magnetic field values $B(T)$: 1—0; 2—1.7; 3—3.6; 4—5.2; $I_{exc} = 0.8$ W/cm^2. Solid lines: Experiment; dashed lines: Calculation.

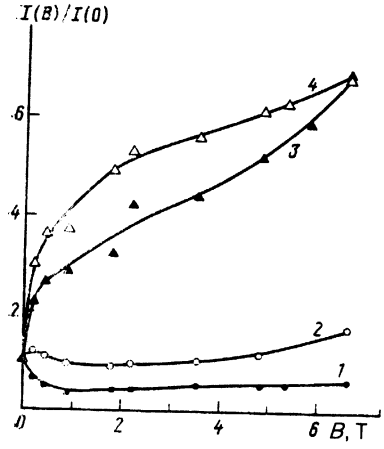

FIG. 3. The LPB line intensity plotted as a function of a magnetic field parallel to the sample surface for different I_{exc} (W/cm^2): 1—0.1; 2—0.25; 3—0.8; 4—4.5.

by a vanishing of the trough between the LPB and UPB (upper polariton branch) lines; the relative intensity of the UPB line diminishes.

An increase in the emission intensity of the bound excitons is observed simultaneously with the increase in PL intensity in the magnetic field. The redistribution of intensities of the (D^0,x) line (the exciton bound to the neutral donor) and the (D^+,x) line (the exciton bound to the ionized donor) is immediately evident. As we see from Fig. 1b, the intensity ratio $I_{(D^+,x)}/I_{(D^0,x)}$ diminishes with increasing magnetic field.

The rate of increase in luminescence intensity is dependent on the impurity concentration in GaAs. In a sample with a shallow donor concentration $N_D \approx 10^{14}$ cm^{-3} the maximum increase in PL intensity was 3.7. In a sample with $N_D \approx 10^{15}$ cm^{-3} this quantity was even smaller: 1.4. The decrease in this effect with increasing shallow donor concentration may explain why it was not observed in Ref. 6, which apparently did not analyze ultrapure crystals.

The rate of increase in PL intensity in a magnetic field is also dependent on the lattice temperature. The rate of increase in LPV emission intensity in a field $B = 4.5$ T drops by a factor of two as the temperature rises from 1.7 K to 4.2 K.

We investigated circular polarization of exciton luminescence in a magnetic field under unpolarized excitation. We found that to within measurement error the degree of PL circular polarization was equal to zero through fields $B \approx 3.2$ T. At the same time, a significant increase in luminescence intensity and changes in its spectral lines were observed in these same fields. In strong magnetic fields, the degree of PL circular polarization becomes nonzero, reaching $\approx 25\%$ for $B = 6.7$ T. Presumably such polarization results from Zeeman splitting of the exciton band.[2]

In order to determine the effect of the magnetic field orientation on the PL enhancement effect, we applied the field parallel to the sample surface and perpendicular to the direction of the laser light. A reduction in exciton luminescence intensity in this geometry was discovered in Ref. 6 in GaAs and was attributed to a reduction in the coefficient of diffusion of the electrons from the sample surface in the magnetic field and an increase in the role of surface recombination. We also observed a reduction in exciton luminescence intensity in the weak magnetic field range ($B < 1$ T) with low I_{exc}. However, with high I_{exc} the opposite effect was observed: the exciton luminescence intensity increases (Fig. 3). The PL spectral line shape also changes (Fig. 4, spectra 1–4): The trough between the LPB and UPB lines grows, and the short-wavelength decay of UPB emission flattens out. Note the reduction in PL intensity compared to the bound exciton lines. These changes in the luminescence spectra in fact contradict those noted above. The same effect is observed in strong magnetic fields parallel to the sample surface ($B > 1$ T) as in fields perpendicular to the sample

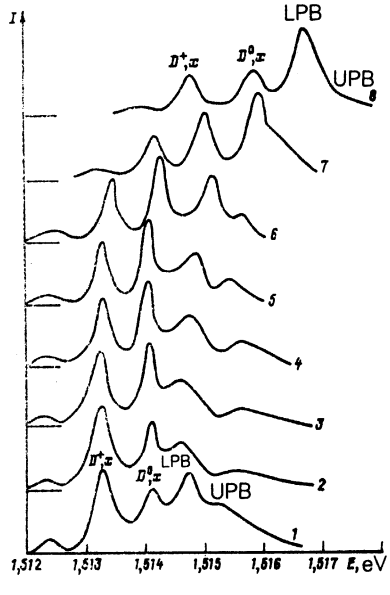

FIG. 4. Luminescence spectra at different magnetic field values $B(T)$, parallel to the sample surface: 1—0; 2—0.45; 3—0.18; 4—0.42; 5—0.9; 6—1.8; 7—3.8; 8—5.8; $I_{exc} = 0.8$ W/cm^2.

surface. The same changes in the PL spectral line shapes occur, as is evident from Fig. 4 (spectra 5–8). The PL intensity also rises for all I_{exc}. However, for small I_{exc} this increase does not make it possible to achieve a zero field level.

3. ANALYSIS OF EXPERIMENTAL RESULTS

The oscillator strength of a free exciton rises in a strong magnetic field due to the transverse compression of the wave function relative to electron and hole motion. At first glance it is natural to attribute the increase in exciton luminescence intensity to this rise. The increase in exciton luminescence in stressed Ge (which was significantly less clearly-expressed than in our case) was attributed to specifically this mechanism in Ref. 7. However this magnetic field test range for GaAs is an intermediate range, i.e., $r_B/r_0 \approx 1$, where r_B is the Bohr radius of the exciton, while $r_0 = (\hbar/eB)^{1/2}$ is the magnetic length. Here $r_B \approx 140$ Å for GaAs, while the minimum value (for $B = 7$ T) is $r_0 \approx 100$ Å. The increase in the oscillator strength for $B \approx 7$ T will only reach a value of 2 in the intermediate range of magnetic fields, according to variational calculations,[8] which is significantly below the observed changes. Moreover, within the framework of the polariton representation, the increase in oscillation strength as well as the longitudinal-transverse splitting energy only gives rise to spectral broadening near exciton resonance in lowest order.

In a magnetic field the exciton production probability can grow in principle due to both an increase in the probability of cascade coupling to the shallow hydrogen-like state[9,10] and due to an increase in the probability of LO-phonon emission by spatially-correlated electrons and holes.[11] The first process becomes significant only in strong magnetic fields ($r_0 \ll r_B$). Moreover, neither of these processes explains the observed changes in the PL spectra.

The dependence of the rate of magnetic field effect on PL on the purity of the material, the excitation intensity, and the temperature suggest that the effect is directly related to the magnetic field effect on exciton kinetics.

Initially we can anticipate that the magnetic field will have an effect on the spatial distribution of polaritons. Then the most clearly exhibited effect would be observed in a field parallel to the sample surface. However, PL enhancement in the range $B > 1$ T is less in this geometry compared to the case of a field perpendicular to the surface, while changes in the spectral line shapes are analogous for the two experimental geometries. Therefore, PL enhancement in a magnetic field can hardly be attributed to a change in the spatial distribution of polaritons. At the same time, changes in intensity and the spectral line shapes are observed only in a field parallel to the sample surface in the range $B < 1$ T, which suggests that the spatial distribution of polaritons plays a role. The mechanisms observed in this range can be explained as follows. The reduction of the ambipolar diffusion coefficient due to spiraling of electron trajectories in the magnetic field has two consequences: A reduction in the total number of electrons due to surface recombination and an increase in the maximum of the electron concentration profile. The first circumstance serves to reduce the total number of excitons, while the second causes an increase in their number due to the increased probability of electron and hole binding to produce excitons (in GaAs this bimolecular process is the fundamental exciton production channel[12]).

The increase in the role of surface recombination is responsible for the reduction in total PL intensity with increasing magnetic field with small I_{exc}. With increasing I_{exc}, the rise in the bimolecular binding probability of electrons and holes to produce excitons may cancel the effect of surface recombination. Moreover, the surface recombination channels may be partially saturated with increasing I_{exc}. This is apparently the cause of the rise in PL intensity in the low magnetic field range with large I_{exc}.

The changes in the spectral line shapes can be attributed to an increase in exciton-electron scattering probability due to the elevation of the peak of the electron density profile. The increase in the exciton-electron scattering probability is responsible for the expansion of the trough between the LPB and UPB lines as well as the increase in the effective polariton temperature. The changes in the PL spectra in a weak magnetic field parallel to the GaAs crystal surface represent significant evidence in favor of the importance of accounting for exciton-electron scattering in the formation of the PL spectrum.

Note that the significant spectral changes as well as variations in luminescence intensity are initiated at fields $B \approx 0.045$ T which is more than an order of magnitude lower than observed in Ref. 6. The ambipolar diffusion coefficient in the magnetic field is equal to[6]

$$D = \frac{2D_{p0}}{1+(1+\mu_n^2 B^2) D_{p0}/D_{n0}}, \qquad (1)$$

where D_{n0}, D_{p0} are the electron and hole diffusion coefficients in zero magnetic field, μ_n is electron mobility. In this magnetic field range we would only anticipate changes in the electron diffusion coefficient. A significant reduction in D occurs for

$$(1+\mu_n^2 B^2) D_{p0}/D_{n0} > 1. \qquad (2)$$

Substituting $D_{p0}/D_{n0} \approx 0.1$ and $B_c = 0.045$ T we obtain $\mu_n > 7 \cdot 10^5$ cm^2/V·s, which exceeds the corresponding mobility value in samples from Ref. 6 by an order of magnitude and confirms that the material is pure. The mobility estimate corresponds to the value $\mu_n = 3 \cdot 10^6$ cm^2/V·s obtained from a classical cyclotron resonance experiment on the same sample.[13] We were not able to carry out Hall measurements to directly determine mobility due to the high resistivity of the samples. The situation in photoexcitation is generally different from an ordinary equilibrium case in which transport mobility is measured, since the impurities are partially neutralized. However, the mobility is still rather high for the case of total impurity neutralization, which can naturally be attributed to the low shallow impurity concentration and the large impurity scattering time.

We compared experimental and calculated PL spectra in order to determine the dynamics of the variation in the kinetic parameters of the polaritons from the magnetic field. The details of the calculation and the GaAs parameters used are reported in Ref. 14. In the calculation the energy of a longitudinal exciton E_L as a function of magnetic field (diamagnetic shift) was determined on the basis of the position of the spike in the reflection spectrum. The increase in longitudinal-transverse splitting energy E_{LT} was accounted for in accordance with the data of Ref. 8. As we see from Fig. 2, the changes in the PL spectral lines in a magnetic field are described satisfactorily by a change in a single parameter: A

reduction in the effective polariton temperature T^* (the reasons for the discrepancies in the vicinity of the LPB are discussed in Refs. 3, 14). A reduction of T^* serves to increase the population of the lower energy regions near exciton resonance. This is responsible for the anomalous enhancement of LPB luminescence and the decrease in the contribution of UPB emission, which is determined by the population of states above the longitudinal excitation energy.

Figure 5 shows how the fitting values of T^* depend on the magnetic field level. The derived values of T^* were used to calculate the increase in the maximum LPB emission intensity Y_{max} assuming the total polariton concentration remains unchanged (Fig. 5). It is clear that with small I_{exc}, the calculated degree of increase in the luminescence intensity is lower, as is observed in experiment. This is due to the fact that the initial value of T^* for $B = 0$ and small I_{exc} is lower, while the position of T^* is bounded by the finite lower limit equal to the lattice temperature. We believe that the exciton luminescence enhancement effect in a magnetic field decreases as the lattice temperature rises from $T = 1.7$ K to $T = 4.2$ K due specifically to the latter factor.

The dependence of T^* on B can also be determined from an analysis of the emission spectra of excitons producing an LO-phonon. Figure 6 shows the experimental and calculated phonon echo spectra. Note that the values of T^* determined from an analysis of the PL and phonon echo spectra are virtually identical. With large I_{exc}, the value of T^* in a magnetic field diminishes to a greater value than observed with small I_{exc}.

However, a single variation in the effective polariton temperature is insufficient to provide a quantitative explanation for the exciton luminescence enhancement effect. In addition to the change in spectra, the integral phonon echo intensity also rises. The integral luminescence intensity of excitons emitting a phonon is proportional to the total number of excitons. We can therefore conclude that the total number of excitons also grows with increasing magnetic field (although the increase in the integral intensity of the phonon echo is partially related to the increase in the exciton oscillator strength in the magnetic field).

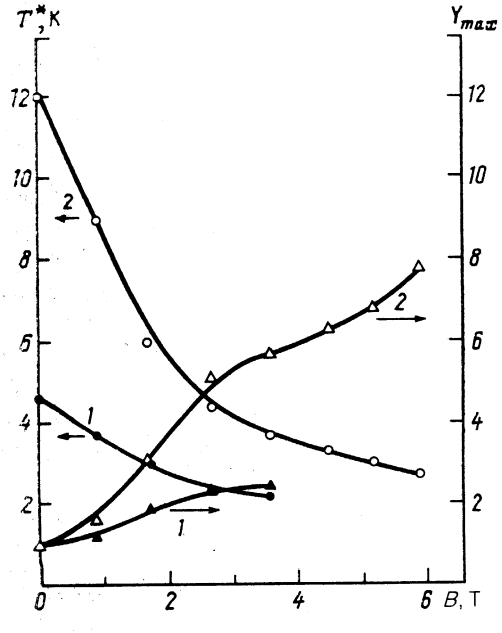

FIG. 5. The effective polariton temperature T^* and the calculated increase in the intensity of the PL maximum Y_{max} plotted as a function of magnetic field: 1—$I_{exc} = 0.2$ W/cm^2; 2—$I_{exc} = 0.8$ W/cm^2.

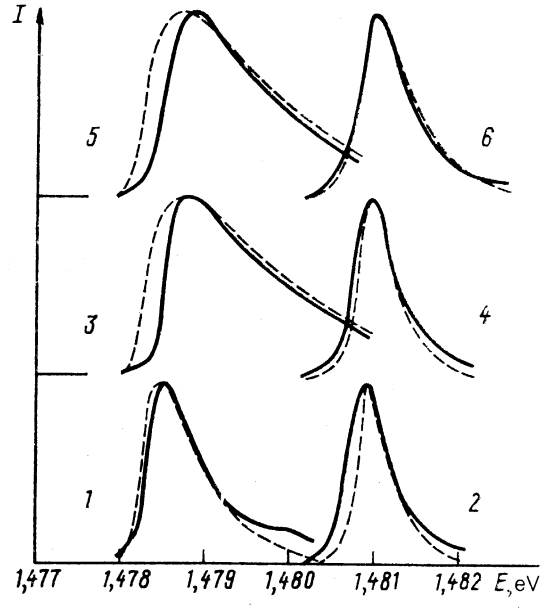

FIG. 6. Experimental (solid lines) and calculated (dashed lines) emission spectra of excitons producing an LO-phonon (1, 3, 5—$B = 0$; 2, 4, 6—$B = 6.7$ T) for various I_{exc} (I_{exc} (W/cm^2): 1, 2—0.2; 3, 4—0.8; 5, 6—4.5) and T^* [T^* (k): 1—5; 2—2.7; 3—12; 4—3; 5—11; 6—4.3].

We now discuss possible causes of the reduction in the effective temperature and the rise in polariton concentration in the magnetic field. One possible cause is related to the reduction in the nonradiative polariton destruction probability. This would immediately suggest an increase in polariton concentration and an increase in the degree of polariton thermalization during their lifetime. The decrease in the probability of nonradiative trapping by an impurity in principle may be related to compression of the wave function of the impurity complex in the magnetic field.[15] However, in the case of shallow impurities responsible for cascade trapping with acoustical phonon emission, the trapping probability in a magnetic field in fact behaves in the opposite manner and grows.[9,10] The dimensions of the wave function of the deep localized centers in this magnetic field range can hardly undergo a significant change.

The second possible cause is related to acceleration of polariton energy relaxation due to an increase in exciton-phonon interaction probability in the magnetic field. The mechanism of this increase is related to compression of the exciton wave function and an increase in the probability of interaction between excitons and the short-wavelength acoustical phonons with a wavelength shorter than the Bohr radius of the exciton. However in this case a significant change would be anticipated only in the strong magnetic field range and at rather high exciton energies.

Before addressing the third, most likely cause, we will discuss the source of the effective polariton temperature in zero magnetic field. In principle polaritons as particles of relatively large mass are rapidly thermalized. A different

situation occurs with nonequilibrium electrons that are created from external excitation and exist in conjunction with the polaritons in the crystal. Electrons in GaAs have a small effective mass ($m_e^* = 0.0667\ m_0$) and their energy relaxation rate is less than that of polaritons due to acoustical phonon emission. Hence the effective temperature of the nonequilibrium electrons is always higher than that of the polaritons, and with our values of I_{exc}, $T^* \approx 10$–20 K (Ref. 16). The polaritons may be heated from exciton-electron interaction. The rise of their effective temperature with increasing I_{exc} may also be attributed to this interaction.

As we show in the next section, the energy relaxation rate of electrons by acoustical phonons in a magnetic field rises, while their effective temperature drops to nearly the lattice temperature. This directly eliminates the polariton heating channel from electron interaction, and will reduce their effective temperature. With very large I_{exc}, the polariton effective temperature can be related to both the interactions with nonequilibrium acoustical phonons and exciton-exciton collisions. Hence the value of T^* decreases in a magnetic field to a certain large value, which serves to suppress the PL enhancement effect. The reduction in effective electron temperature may also be responsible for the increase in the total number of excitons due to the fact that the probability of charge carrier binding to produce an exciton grows with diminishing exciton kinetic energy.[12]

4. ENERGY RELAXATION OF ELECTRONS BY PHONONS IN A MAGNETIC FIELD

In this section we show that the energy relaxation rate of electrons by acoustical phonons rises in a magnetic field. Physically this is related to the fact that localization of transverse electron motion violates the law of conservation of transverse quasimomentum and serves to increase the number of possible final states of the scattering process. The effect becomes significant for $k_T r_0 < 1$, where

$$k_T \approx (k_B T_e m_e^*/\hbar^2)^{1/2}$$

is the average electron thermal momentum, while T_e is the electron effective temperature. This condition is equivalent to the case where the distance between the Landau subbands exceeds the electron temperature: $\hbar\omega_c > k_B T_e$, where $\omega_c = eB/m_e^*$ is the cyclotron frequency. For $T_e = 15$ K the characteristic magnetic field magnitude at which the effect is manifested is $B \approx 0.75$ T, which is entirely consistent with experimental results.

Reference 17 reports expressions for the momentum and energy relaxation times in the ultraquantum case when only the lower Landau subband is taken into account. The average energy relaxation rate $\bar{Q}$ is calculated in Ref. 18 for this case (the power contributed to the lattice by the electrons averaged over the quasi-equilibrium distribution function). We consider the case of random magnetic field values and determine how the effective electron temperature depends on B. The average electron energy relaxation rate is given by

$$\bar{Q} = \sum_{i,f} f_i (E_i - E_f) w_{if} \Big/ \sum_i f_i, \tag{3}$$

where E_i, E_f is the electron energy in the initial (i) and final (f) states; w_{if} is the scattering probability, f_i is the distribution function. The electron state in the magnetic field is described by the longitudinal wave vector k_z (the z axis runs along B) and the number of the Landau subband l. We consider piezoelectric scattering by acoustic phonons, since this mechanism is predominant in GaAs at low temperatures.[19] Moreover, for simplicity we only account for phonon emission (the case where the lattice temperature $T_L = 0$). We can then obtain for the probability of scattering by a phonon with the wave vector q (Ref. 17)

$$w_{if}(\mathbf{q}) = \frac{2\pi}{\hbar} V_{pe}^2(q) J_{l_i l_f}(q_\perp r_0) \delta_{k_{zi}, k_{zf}+q_z} \times \delta\left[\hbar\omega_c(l_i - l_f) + \frac{\hbar^2}{2m_e^*}(k_{zi}^2 - k_{zf}^2) - \hbar u q\right], \tag{4}$$

$$J_{l_i l_f}(t) = \frac{l_1!}{l_2!} \exp\left(-\frac{t^2}{2}\right)\left(\frac{t^2}{2}\right)^{l_2 - l_1}\left[L_{l_1}^{l_2 - l_1}\left(\frac{t^2}{2}\right)\right]^2, \tag{5}$$

$$l_1 = \min(l_i, l_f),\ l_2 = \max(l_i, l_f).$$

Here $L_n^\alpha(t)$ is an associated Legendre polynomial, δ_{xy} is the Kronecker symbol, $q_\perp$ is the magnitude of the component of $\mathbf{q}$ perpendicular to $\mathbf{B}$, and V_{pe} is the matrix element of electron-phonon interaction:

$$V_{pe}^2(q) = \frac{C_{pe}}{q}, \quad C_{pe} = \frac{8\pi^2 e^2 e_{14}^2 \hbar}{\varkappa^2 \rho u} a, \tag{6}$$

where e_{14} is the piezoelectric tensor component of the crystal, x is the permittivity, ρ is density, u is the acoustic velocity, and a is the geometrical factor associated with averaging of anisotropic piezoelectric scattering. We neglect changes in a in the magnetic field for simplicity. Generally speaking, transverse phonons make the primary contribution to piezoelectric scattering in strong magnetic fields. In this case if the field is applied along the [100] direction, we have $a = 0.5$ (Ref. 18). In zero magnetic field for scattering by transverse phonons we have $a = 0.46$ (Ref. 20).

Substituting Eq. (4) into Eq. (3), integrating with respect to the initial and final electron states and the phonon wave vectors, and summing over all Landau subbands, while taking the Maxwellian distribution function with temperature T_e, we obtain

$$\bar{Q} = \bar{Q}_0 \frac{\gamma}{4}[1 - \exp(-\gamma)] \sum_{l_i=0}^{\infty} \sum_{l_f=0}^{\infty} \exp\left(-\frac{l_i + l_f}{2}\gamma\right) \times \int_0^\infty J_{l_i l_2}(t)\, t \exp\left(-\frac{\beta t}{2}\right) K_0\left(\left|\frac{\beta t}{2} - \frac{l_i - l_f}{2}\gamma\right|\right) dt. \tag{7}$$

The dimensionless parameters $\gamma = \hbar\omega_c/k_B T_e$, $\beta = \hbar u/k_B T_e r_0$ are introduced here; K_0 is a modified Bessel function. The quantity $\bar{Q}_0$ represents the average energy relaxation rate of electrons by acoustical phonons due to piezoelectric scattering in zero magnetic field:[19]

$$\bar{Q}_0 = C_{pe} u \left(\frac{2m_e^*}{\pi\hbar^2}\right)^{1/2} (k_B T_e)^{1/2}. \tag{8}$$

We note that in integrating the δ-function from Eq. (4) the quantity q was replaced by $q_\perp$. This is justified by the fact that in weak fields, phonon scattering is nearly elastic ($u \ll V$, where V is electron velocity), while we can assume $q_\perp \gg q_z$ in strong magnetic fields.[17]

Expression (7) can be simplified. For this purpose the double sum must be divided into two parts. One part corre-

sponds to scattering within the Landau subband ($l_i = l_f$), while the other sum corresponds to band-to-band scattering. In this second part we pull the function $\Phi(t)$ evaluated for $t = 0$ out from under the integral, where

$$\Phi(t)=\exp\left(-\frac{\beta t}{2}\right)K_0\left(\left|\frac{\beta t}{2}-\frac{l_i-l_f}{2}\gamma\right|\right). \quad (9)$$

This is possible in the weak magnetic field range for $\beta \ll 1$, which corresponds to $\hbar\omega_c \ll (k_B T_e)^2/m_e^* u^2$. In the strong magnetic field range $\beta > 1$ at moderately low temperatures $T_e (k_B T_e \gg m_e^* u^2)$ the condition $\gamma \gg 1$ holds. In this case the part of expression (7) corresponding to band-to-band scattering is exponentially small. Then, subject to the fact that

$$\int_0^\infty J_{l_i l_i}(t)\, t\, dt = 1,$$

we obtain

$$\bar{Q}=\bar{Q}_0\frac{\gamma}{2}\left\{\frac{1-\exp(-\gamma)}{2}\sum_{l=0}^{\infty}\exp(-l\gamma)\int_0^\infty J_{ll}(t)\, t\exp\left(-\frac{\beta t}{2}\right)\right.$$

$$\left.\times K_0\left(\frac{\beta t}{2}\right)dt+\sum_{l=1}^{\infty}\exp\left(-\frac{l\gamma}{2}\right)K_0\left(\frac{l\gamma}{2}\right)\right\}. \quad (10)$$

It is quite clear from Eq. (10) that $\bar{Q}$, as expected, tends towards $\bar{Q}_0$ as $B \to 0$ ($\gamma, \beta \to 0$), since

$$\frac{\gamma}{2}\sum_{l=0}^{\infty}\exp\left(-\frac{l\gamma}{2}\right)K_0\left(\frac{l\gamma}{2}\right)\underset{\gamma\to 0}{\longrightarrow}\int_0^\infty \exp(-x)K_0(x)\,dx=1. \quad (11)$$

With very large $B(\gamma, \beta \to \infty)$

$$\bar{Q}\to\bar{Q}_0\frac{\gamma}{3\beta^2}=\bar{Q}_0\frac{1}{3}\frac{k_B T_e}{m_e^* u^2}. \quad (12)$$

In this case $\bar{Q}$ will be independent of B in accordance with Ref. 17. At moderately low temperatures (for GaAs parameters, $T_e > 0.2$ K), as we see from Eq. (12), the maximum average electron energy relaxation rate far exceeds its value in zero magnetic field. At moderately large B ($\gamma \gg 1, \beta \ll 1$) an expression corresponding to the result from Ref. 18 can be obtained for $\bar{Q}$:

$$\bar{Q}=\bar{Q}_0\frac{\gamma}{4}\left(\ln\frac{2^{3/2}}{\beta}-\frac{C}{2}\right), \quad (13)$$

where C is Euler's constant.

If we account for the finite lattice temperature, then in accordance with Ref. 19, it is necessary to introduce the additional multiplier $(T_e - T_L)/T_e$ in Eq. (8). For $T_e = T_L$ the electrons are in equilibrium with the phonons and their energy relaxation rate is zero. Figure 7 shows the dependence of the average electron energy relaxation rate calculated by Eq. (10) on electron temperature T_e for different magnetic fields.

In order to determine $T_e(B)$ we assume that the energy contribution to the electron system is independent of the magnetic field magnitude. Then, establishing a specific value of $T_e(0)$, it is possible to obtain the relation $T_e(B)$ by setting the energy relaxation rate equal in zero field and in the presence of a field:

$$\bar{Q}[B,\ T_e(B)]=\bar{Q}_0[T_e(0)]. \quad (14)$$

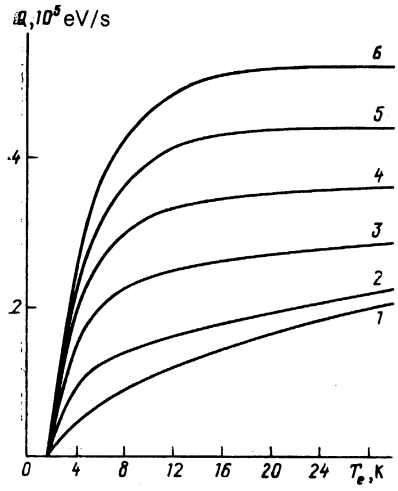

FIG. 7. The average rate of piezoelectric electron relaxation by acoustical phonons in GaAs plotted as a function of electron temperature in different magnetic fields $B(T)$: 1—0; 2—1; 3—2; 4—3; 5—4; 6—5.

Figure 8 demonstrates how the electron temperature in the magnetic field diminishes for different values of T_e in zero field.

5. DISCUSSION

We have attributed polariton cooling in a magnetic field to a reduction in the effective electron temperature due to a rise in their rate of energy relaxation by acoustical phonons in a magnetic field. The polariton temperature is dependent on electron temperature due to effective exciton-electron scattering. The corresponding scattering probability $w_{ex\text{-}el}$ is determined by the expression:[21]

$$w_{ex\text{-}el} \approx 20\frac{\hbar n r_B}{m_e^*}, \quad (15)$$

where n is electron concentration. For $n = 10^{12}$ cm^{-3} for GaAs $w_{ex\text{-}el} = 0.47 \cdot 10^9$ s^{-1}, which is close to the probability of exciton scattering by acoustical phonons near exciton resonance. If we take into account that exciton-electron

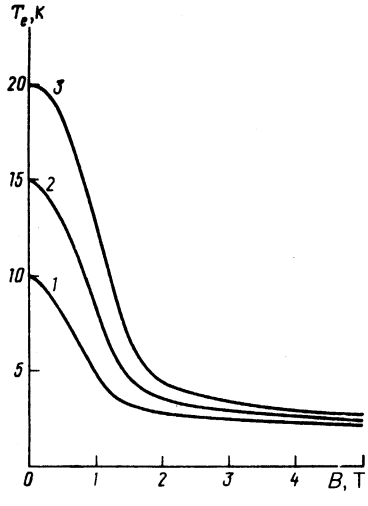

FIG. 8. Electron temperature versus magnetic field at different electron temperatures in zero field $T_e(0)$ (K): 1—10; 2—15; 3—20.

scattering, unlike exciton-phonon scattering, is essentially inelastic, we find that exciton-electron scattering makes the dominant contribution to the formation of the exciton energy distribution. The reduction in electron temperature will also serve to increase the probability of electron trapping by ionized donors.[22] Hence the redistribution of line intensities (D^+, x) and (D^0, x) in a magnetic field (Fig. 1b) is an independent confirmation of electron cooling.

It is immediately evident that T_e diminishes significantly as early as $B = 1$–2 T in the calculated $T_e(B)$ (Fig. 8), which is inconsistent with the experimental $T^*(B)$ relations (Fig. 5). This discrepancy may be related to calculation errors. We assumed a Maxwellian electron distribution function with a temperature T_e. Thermodynamic quasi-equilibrium is established from electron-electron collisions. In GaAs the distribution function with $T_e \approx 15$ K is established for $n > n_c \approx 10^{11}$ cm^{-3} (Ref. 17). however, electron-electron collisions are suppressed in a magnetic field.[17] Hence, introduction of the electron temperature in a magnetic field may not be justified. Moreover, we have assumed that energy contribution to the electron system is independent of the magnetic field magnitude, and have neglected other scattering mechanisms. All these factors may retard the relation $T_e(B)$.

It is important to emphasize that the electron cooling mechanism in a magnetic field examined here operates when scattering by acoustical phonons predominates. At low temperatures ($T_L = 1.7$ K) this, obviously, is possible only in ultrapure crystals in which there is little inelastic scattering by impurities. The probability of the latter will hardly increase in the magnetic field range analyzed here. Violation of the law of conservation of quasimomentum in the magnetic field is not important in this case, since quasimomentum is not conserved in scattering by impurities.

6. CONCLUSION

It has been established from these studies that excitons are effectively cooled through the lattice temperature in pure epitaxial GaAs layers in magnetic fields up to 7 T, which is the cause of the anomalous enhancement of polariton luminescence. The polariton energy distribution function is largely determined by exciton-electron scattering processes, and therefore polariton temperature is dependent on electron temperature. The effective temperature of nonequilibrium electrons in the magnetic field range examined here diminishes significantly due to the increase in their energy relaxation by acoustical phonons.

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