Effects of the interaction of intrasubband and intersubband magnetoplasmons in the emission spectrum of a quasi-2D electron gas

L. V. Butov, L. V. Kulik, V. D. Kulakovskiĭ, and T. G. Andersson[1)]
Institute of Solid State Physics, Russian Academy of Sciences, 142432, Chernogolovka, Russia

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A splitting of an emission line corresponding to a recombination of an electron from the zeroth Landau level of the first subband, 0_e^1, has been observed in the magnetoluminescence spectrum of a quasi-2D electron gas in an InGaAs quantum well at 4 K. This effect is observed near a resonance of the energies of intrasubband and intersubband magnetoplasmons when there are electrons in the second subband. This effect disappears as the temperature is raised. It can be explained on the basis of an interaction between magnetoplasmons of two types in the final state of the 2D electron gas (after the recombination of the 0_e^1 electron).

The magnetooptic properties of a 2D electron gas (2DEG) occupying several quantum-well subbands in InGaAs/GaAs and GaAs/AlGaAs heterojunctions and quantum wells have recently attracted considerable research interest.[1–4] Pronounced oscillations in the emission intensity in a magnetic field have been observed at the violet edge of the recombination-radiation band (near the Fermi level) of a 2DEG of this sort. In a sense, these oscillations constitute an optical analog of Shubnikov-de Haas oscillations.[1]

Our purpose in the present study was to learn about the behavior of the recombination radiation of electrons near the bottom of the main subband ($n_z = 1$) under conditions such that the next subband ($n_z = 2$) is partially filled by electrons. Analysis of emission spectra which we recorded at high temperatures ($T > 20$ K) showed that the energies of transitions between Landau levels were linear in the magnetic field H. This behavior agrees with ideas concerning the behavior of Landau levels for free electrons. When the temperature was lowered to 4 K, however, a qualitative change was found in the behavior of the $0_e^1 - 0_h^1$ line (this was a transition between the zeroth Landau levels of the electrons and holes from the main subband, $n_z = 1$): At certain values of H, the $0_e^1 - 0_h^1$ line split in two. This splitting ceased to occur when the second subband was emptied. In an effort to explain the effect, it was suggested that we should consider an interaction between excitations of two types (intrasubband and intersubband magnetoplasmons) in the final state of the 2DEG, after the recombination of the 0_e^1 electron. The manifestation of an interaction of magnetoplasmons of two types in the final state of the 2DEG seen in the emission spectrum ranks along with the recently observed effects of a modification of the 2DEG emission spectrum as the result of interactions of other types in the final state of the 2DEG (an interaction between a magnetoplasmon and an LO phonon[5] and a magnetopolaron interaction[6]).

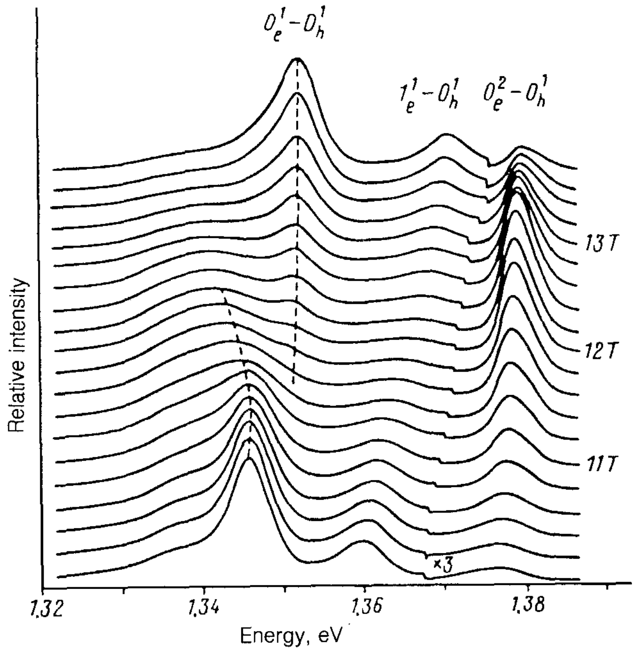

FIG. 1. Emission spectra of an n-$Al_{0.3}Ga_{0.7}As/In_{0.18}Ga_{0.82}As/GaAs$ heterostructure in strong magnetic fields at $T=4.2$ K.

We studied the photoluminescence spectra of the 2DEG in an InGaAs quantum well 20 nm wide at $T=4.2$ K in fields $H<14$ T. The $Al_{0.3}Ga_{0.7}As/In_{0.18}Ga_{0.82}As/GaAs$ heterostructures, with a selectively doped AlGaAs layer ($N_{Si}\sim 10^{18}$ cm^{-3}), were grown by molecular beam epitaxy. The concentration of equilibrium 2D electrons in the quantum well was 1.3×10^{12} cm^{-2}. Nonequilibrium carriers were excited by a cw argon laser ($\lambda=5145$ Å) with an excitation density $w\sim 10^{-2}$ W/cm^2. The concentration of photoexcited carriers was much lower than the equilibrium value. The samples were immersed in liquid helium in a cryostat with a superconducting solenoid. A quartz optical fiber was used to excite the sample and to collect the emission.

The magnetoluminescence spectrum of the 2DEG (Fig. 1) consists of several lines corresponding to transitions between filled levels in the conduction band (0_e^1, 1_e^1, and 0_e^2) and the 0_h^1 level in the valence band. The $0_e^1-0_h^1$ transitions are allowed. The dipole-forbidden transitions $j_e^1-0_h^1$ ($j\geqslant 1$) are allowed primarily because of scattering by defects. The $0_e^2-0_h^1$ transitions are allowed, and they are even more intense than the $0_e^1-0_h^1$ transitions, because of the strong electric field in the direction perpendicular to the plane of the well (in the z direction).[1–4]

Figure 2 shows the field dependence of the energy $E_{j,n}(H)$ and the intensity $I_{j,n}(H)$ for the $j_e^n-0_h^1$ transitions. The oscillations in the intensity of the $0_e^2-0_h^1$ line are due to oscillations in the filling of the 0_e^2 state by electrons. The oscillations in the

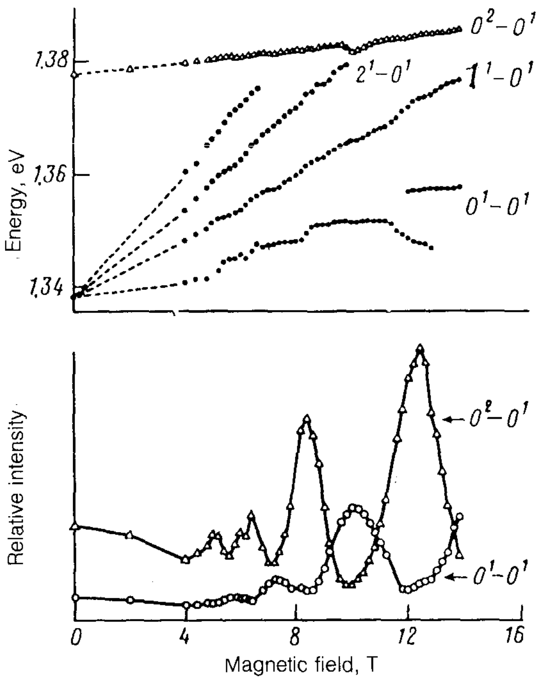

FIG. 2. The energy (a) and the intensity (b) of the transitions versus the magnetic field. The dashed line in frame a shows the spectral position of the LO-phonon repetition of the $2_e^1-0_h^1$ line.

intensity of transitions from the first subband, which are out of phase with the former oscillations, are a consequence of a change in the relative number of photoexcited holes which recombined with 0_e^2 electrons.

We see in Figs. 1 and 2 that the H dependence of the energy of the $0_e^1-0_h^1$ transition is greatly different from the linear dependence characteristics of free carriers. The energy $E_{0,1}$ increases abruptly at fields of 6.4 and 8.4 T. Near 12 T, the behavior of the $0_e^1-0_h^1$ line is characteristic of an anticrossing of two states, only one of which is optically active. At $H > 11$ T, the energy $E_{0,1}$ deviates from linearity in the low-energy direction. At the same time, a second branch of this line, at an energy ~ 6 meV higher, begins to intensify in the spectrum. As H is increased, there is a redistribution of emission intensity toward the high-energy branch. The latter becomes predominant in the spectrum at $H > 12$ T.

In the initial state, the 0_e^1 electron level is completely filled, so it cannot be split. The behavior of the $0_e^1-0_h^1$ line must therefore reflect a splitting of the final state. After an electron from the 0^1 level of the conduction band recombines, a hole is left there (we designate this hole by 0_h^{1c}). This hole is not free, because there is an interparticle Coulomb interaction. The excitation which is formed should be described[7-9] in terms of magnetoplasmons. There are two pertinent types of magnetoplasmons in a 2DEG with electrons in two subbands: intrasubband and intersubband magnetoplasmons.

The intrasubband magnetoplasmons correspond to excitations associated with transitions between levels within one subband (Fig. 3). Their energy is quantized with a quantum $\sim\hbar\omega_c$:

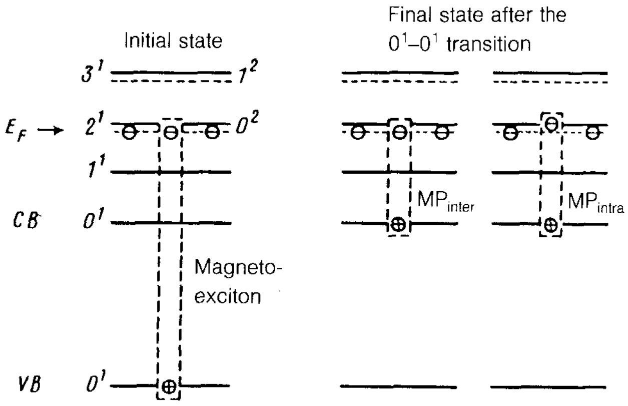

FIG. 3. Illustrative scheme of the initial and final states of the 2DEG (these final states form as a result of the recombination of a 0_e^1 electron). The Landau levels filled with electrons are shown by double lines; the 0^2 level is partially filled. CB—Conduction band; VB—valence band; E_F—Fermi energy; ME, $\mathrm{MP}_{\text{intra}}$, and $\mathrm{MP}_{\text{inter}}$—a magnetoexciton, an intrasubband magnetoplasmon, and an intersubband magnetoplasmon.

$$E_{\text{intra}} \sim n\hbar\omega_c + \delta(n,\mathbf{q}), \tag{1}$$

where $\hbar\omega_c$ is the electron cyclotron frequency, $n \leqslant N$, N is the number of filled Landau levels, and $\mathbf{q}$ is the quasimomentum.[7,8] At small values of $\mathbf{q}$, the corrections $\delta(n,\mathbf{q})$ are small in comparison with the Coulomb energy $E_C \sim e^2/\epsilon l$, where e is the charge of an electron, ϵ is the dielectric constant, and l is the magnetic length. At the magnetic fields of interest here, $H \sim 10$ T, we have $E_C < 1/3\hbar\omega_c$. The intersubband magnetoplasmons correspond to excitations associated with intersubband transitions in the conduction band. Their energy is close to the splitting of the subbands, $\Delta_{1,2}$:

$$E_{\text{inter}} \sim \Delta_{1,2} + \delta', \tag{2}$$

where δ' is determined by the Coulomb interaction[9] and has a value $\delta' < E_C$.

Under the experimental conditions (at a low temperature, with a partial filling of the 0_e^2 level by electrons), many of the photoexcited holes 0_h^1 are able, over their lifetime, to combine with 0_e^2 electrons to form magnetoexciton states. After the $0_h^1 - 0_e^1$ recombination, a $0_e^2 - 0_h^{1c}$ excitation (or an intersubband magnetoplasmon) remains in the 2DEG with $\mathbf{q}$ equal to the quasimomentum of the initial $0_e^2 - 0_h^1$ magnetoexciton ($q < l^{-1}$). Near a resonance of the energies of the intrasubband and intersubband magnetoplasmons, i.e., at $n\hbar\omega_c + \delta \sim \Delta_{1,2} + \delta'$, the $0_h^1 - 0_e^1$ transition may be accompanied by an annihilation of the $0_e^2 - 0_h^{1c}$ excitation, in a process involving the creation of an intrasubband magnetoplasmon (Fig. 3). Note that in this region the Coulomb interaction should lead to a resonant binding of two types of magnetoplasmons and thus to their anticrossing.[9] Accordingly, either of the two mixed states which is formed can result from the recombination of a 0_e^1 electron in the 2DEG, and two lines should be observed in the emission spectrum of the 0_e^1 electrons. As H is increased, the branch of intrasubband magnetoplasmons converts into an intersubband branch, and the corresponding recombination line becomes predominant in the emission spectrum (Fig. 1).

It can be seen from Fig. 1 that the appearance of an additional line with the $0_e^1-0_h^1$ radiative transition (Fig. 1) nearly coincides with a resonance of the energies of the $2_e^1-0_h^1$ and $0_e^2-0_h^1$ transitions. The reason is that the Coulomb corrections for the energies of the magnetoplasmons and the interband magnetoexcitons are small, so resonances for the energies of the $2_e^1-0_h^{1c}$ and $0_e^2-0_h^{1c}$ magnetoplasmons and the $2_e^1-0_h^1$ and $0_e^2-0_h^{1c}$ magnetoexcitons should be observed at essentially the same magnetic fields.

According to this explanation, the effect should disappear as the 0_e^2 level is emptied. To see whether the observed effect was sensitive to a filling of the Landau level in the second subband, we studied the change in the 2DEG emission spectra as the density $n_{2\mathrm{D}}$ was lowered (by hydrostatic compression of the sample). These measurements showed that the splitting of the $0_e^1-0_h^1$ line disappears when the 0_e^2 level is emptied. This behavior is evidence in favor of the model outlined above.

Since the energy of the Coulomb interaction decreases with decreasing field, an anticrossing is observed explicitly only at large H (>10 T). At fields of 8.4 and 6.4 T, the two branches are not resolved, because the transitions have a nonzero width. However, a pronounced broadening of the recombination line and an abrupt change in the transition energy are observed in the spectrum.

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[1)] Physics Department, Chalmers University of Technology, Gothenburg S-41296, Sweden.

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