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Direct observation of magnetoplasmon-phonon coupled modes in the magnetophotoluminescence spectra of the two-dimensional electron gas in $In_xGa_{1-x}As/GaAs$ quantum wells

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Novel well-resolved emission lines in the spectral range of phonon replicas were observed in low-temperature magnetoluminescence spectra of the two-dimensional electron gas in $In_xGa_{1-x}As/GaAs$ quantum wells. These lines were assigned to Landau-level transitions with an emission of coupled magnetoplasmon–LO-phonon modes. The couplings were found to increase strongly near the resonances between the energies of the LO phonon and multiples of the cyclotron energies.

In polar semiconductors, the electron interaction with the electric field is associated with longitudinal-optical (LO) phonons. This leads to a coupling between plasmons and LO-phonons which is strongly enhanced if the frequencies of the LO phonon ω_{LO} and plasmon ω_p are comparable. Unlike the three-dimensional (3D) case where ω_p at zero wave number, $q=0$, is finite, in 2D plasmas[1] the dispersion of $\omega_p(q)$ at $q \rightarrow 0$ varies as $q^{1/2}$ and the resonance conditions are hardly accessible. In a strong magnetic field perpendicular to the plane of the 2D electron gas (2DEG), the magnetoplasmon (MP) frequency approaches the cyclotron frequency ω_c at $q=0$. So the magnetic field can be used to sweep the electron collective excitation frequency through ω_{LO} and achieve a strong coupling between these modes.[2]

Recently a strong 2D MP–LO-phonon coupling was predicted to occur in weak polar semiconductor quantum wells[2–4] (QW's) and superlattices[5,6] near the resonances $N\omega_c=\omega_{LO}$. However, there are only a few experimental studies addressing this problem. 2D MP-phonon coupling has been detected by cyclotron resonance (CR) measurements in InSb inversion layers[7] as well as in $In_xGa_{1-x}As/InP$, $In_xGa_{1-x}As/Al_yIn_{1-y}As$, and $GaAs/Al_xGa_{1-x}As$ heterojunctions[8,9] only near the main ($N=1$) resonance $\omega_c=\omega_{LO}$. The effect decreased strongly in a high-mobility 2DEG with increasing electron density.[9] The related problem of electron-phonon coupling in the dilute electron gas has been extensively investigated. This coupling was observed near $N\omega_c=\omega_{LO}$ ($N=1-4$) in bulk GaAs (Ref. 10) (hot electron CR), in a $GaAs/Al_xGa_{1-x}As$ double-barrier system[11] (tunnel spectroscopy) and was well described in the framework of the one-magnetopolaron theory.[10–13]

In this paper we present a method to study the 2D MP–LO-phonon coupling, namely, low-temperature magnetoluminescence spectroscopy in the spectral range of the optical phonon replicas. Contrary to CR measurements, this method allows us to observe the 2D MP-phonon coupling at large q. The photoluminescence was investigated in a dense 2DEG [$n_e=(0.65-1.1)\times10^{12}$ cm^{-2}] of an $Al_{0.2}Ga_{0.8}As/In_{0.15}Ga_{0.85}As/GaAs$ single QW at $H<14$ T. The strong 2D MP–LO-phonon coupling was clearly detected in the range $H=5-14$ T for all resonances, $N\omega_c=\omega_{LO}$ ($N=2,3,4$).

Selectively doped single QW heterostructures were grown by molecular-beam epitaxy using solid source evaporation material.[14] We used (001)-oriented substrates of semi-insulating GaAs on which the layers were grown in the following succession: a 0.5-μm GaAs buffer layer, an undoped 12-nm-thick $In_{0.15}Ga_{0.85}As$ QW, an undoped 10-nm $Al_{0.2}Ga_{0.8}As$ spacer, and a Si-doped 50-nm-thick $Al_{0.2}Ga_{0.8}As$ layer ($N_{Si}\sim10^{18}$ cm^{-3}).

Photoluminescence measurements were carried out with the use of a cw He-Ne laser with $\lambda=632.8$ nm. The sample was immersed in liquid helium in a cryostat with a superconducting coil. The plane of the QW was oriented normally to the magnetic field. A 0.6-mm quartz fiber was used to transmit both the excitation and luminescence light. The latter, after passing a grating monochromator was detected by a cooled photomultiplier with an S-1 photocathode.

Figure 1 shows luminescence spectra from a QW filled with electrons ($n_e=0.95\times10^{12}$ cm^{-2}) due to selective doping in the $Al_xGa_{1-x}As$ layer. The spectra were recorded at 4.2 K for low excitation intensity, $P=10^{-2}$ W/cm^2, and different magnetic fields. In order to simplify the figure, they are displayed only for energies below the QW energy gap, in the spectral range corresponding to optical phonon replicas. For higher energies the spectra were similar to those from $In_xGa_{1-x}As/GaAs$ QW's studied earlier.[15,16] They consist of a strong principal no-phonon (NP) line 0_e-0_h corresponding to allowed transition between the zero electron and hole Landau levels (LL), $j_e=j_h=0$, and a few weak NP lines j_e-0_h ($j_e=1,2,\ldots$) corresponding to forbidden transitions from occupied electron LL's. The latter appear mainly due to QW imperfections.[15,16]

The NP transition energies shown in Fig. 2 increase

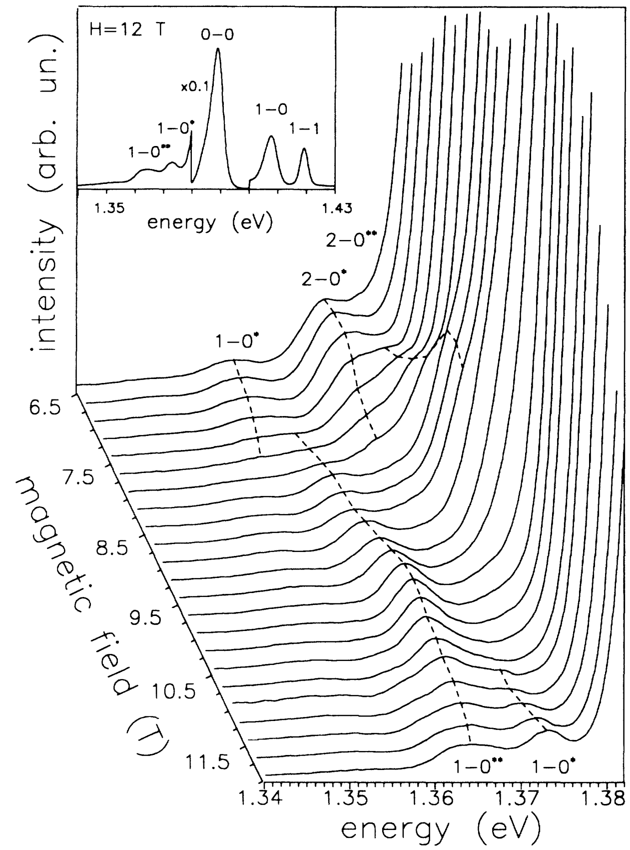

FIG. 1. Emission spectra from n-$Al_{0.2}Ga_{0.8}As$/$In_{0.15}Ga_{0.85}As$/GaAs single QW ($n_e = 9.5 \times 10^{11}$ cm^{-2}) in the energy range of phonon replicas for different magnetic fields at 4.2 K and $P = 10^{-2}$ W/cm^2. The dashed lines are guides for the eye. Inset: the emission spectrum at $H = 12$ T.

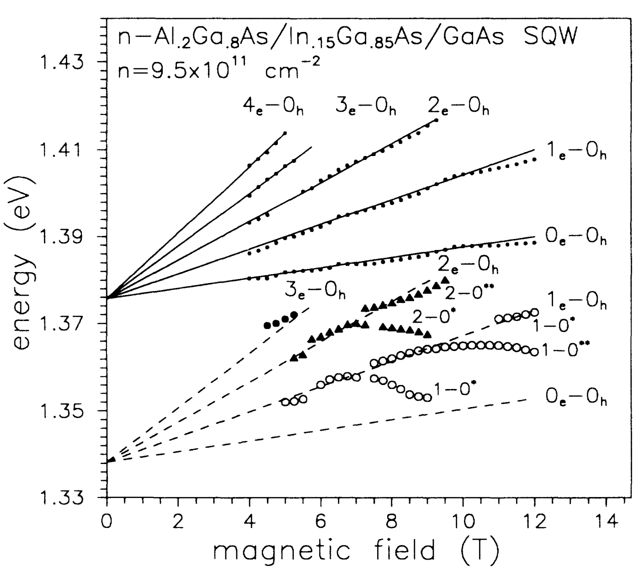

FIG. 2. Transition energies as a function of H for the main and satellite lines. The size of the signs corresponds to the experimental error. The solid lines are linear extrapolations of the main LL transitions while the dashed ones show the expected LO-phonon replicas.

nearly linearly with H. Minor deviations from the linear dependence connected with many-particle effects[17] can be neglected in the first approximation. The dependence of the satellite line energies is quite different from the expectations for the LO-phonon replicas shown by the dashed lines and indicates another origin of the observed lines.

To establish a unique relation between the satellite and the NP j_e-0_h transitions we analyzed the change of their energies and intensities as a function of both the magnetic field and electron density. First, Fig. 1 shows that the intensity ratio for the pairs of lines marked as j-0* and j-0** strongly depends on H at fixed density (cf. Fig. 3). However at fixed H, this ratio is independent of n_e in different samples with various electron densities (and, hence, filling factor ν) (cf. inset in Fig. 4). Therefore the lines j-0* and j-0** are supposed to be satellites of the same NP transition j-0. The change of the satellite line intensities with ν due to an increased magnetic field or 2DEG density is presented in Figs. 3 and 4. This analysis enabled us to assign these lines as shown in Figs. 1 and 2. Notice that the satellite line intensities followed the filling of the corresponding LL, however, the magnetic-field values of the anticrossings (11, 7, and 5.5 T) are independent of electron density.

The energies of the additional quasiparticles emitted at the e-h recombination are shown in Fig. 5 for several transitions as a function of H. These energies were determined from the spectra as the difference between the NP peaks j_e-0_h and their replicas. The coincidence of the emitted particle energies for the 1-0 and 2-0 transitions indicates that the same quasiparticles are emitted. The quasiparticle energies are compared in Fig. 5 with $\hbar\omega_{LO}$ (horizontal dashed line) and multiples of the cyclotron energies (straight dashed lines). In the first approximation, the latter were determined from the emission spectra as the energy difference, Δ_{j0}, between the j-0 and 0-0 transitions.

Figure 5 provides strong evidence that quasiparticles emitted at the e-h recombination originate from two

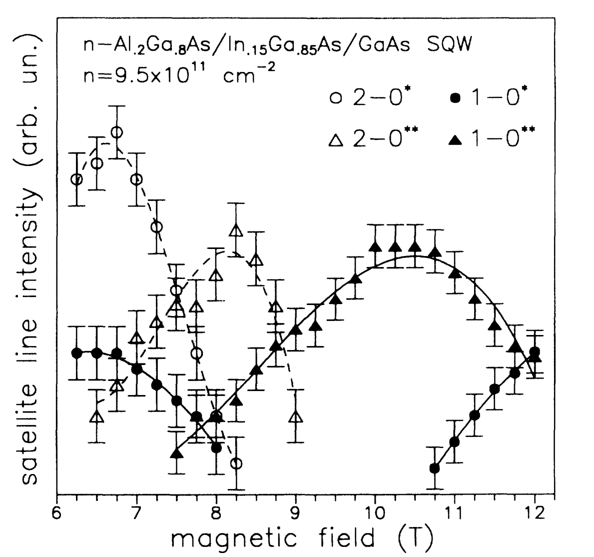

FIG. 3. The magnetic-field dependence of the satellite line intensities. The lines are guides for the eye.

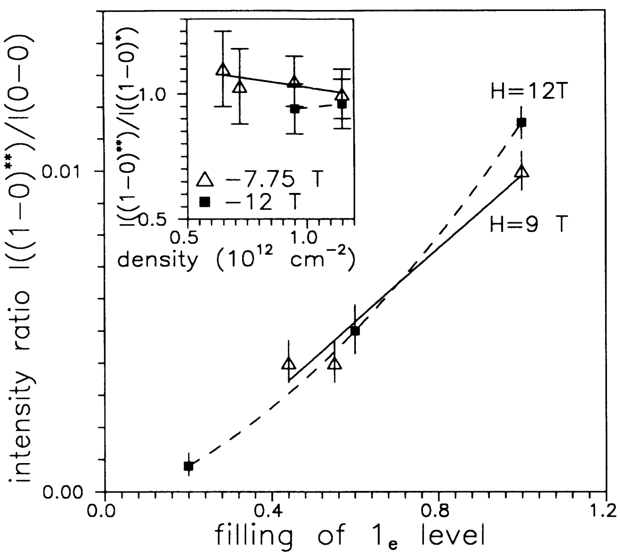

FIG. 4. The 1-0** satellite line intensities, normalized to the 0-0 line intensities, as a function of the 1_e LL filling (different samples) taken at $H=9$ and 12 T. Inset: the 1-0** to 1-0* line intensity ratio vs 2DEG density taken at $H=7.75$ and 12 T.

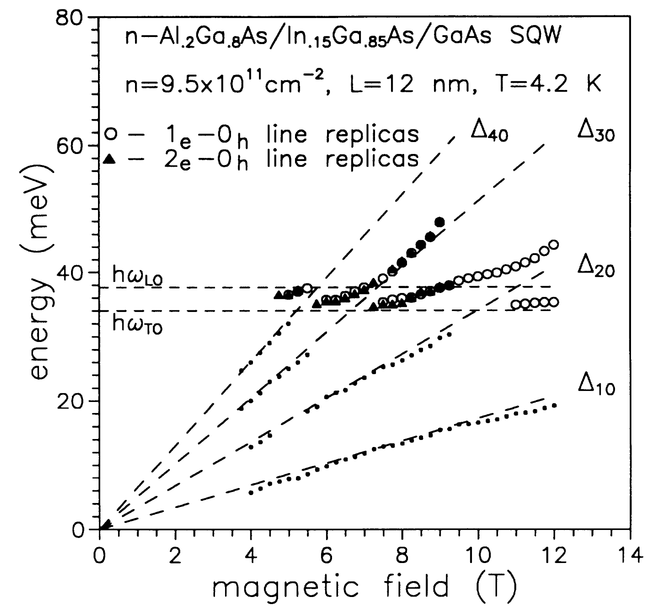

FIG. 5. The measured energy of the quasiparticles, emitted at the *e-h* recombination, as a function of the magnetic field for the 1_e-0_h (open circles) and 2_e-0_h (filled triangles) transitions. The horizontal dashed lines represent the energies of the GaAs LO and TO phonons. The cyclotron frequency harmonics are marked Δ_{j0}. The latter were taken as a linear extrapolation of the difference between the j_e-0_h and 0_e-0_h transition energies (experimental values are shown by the small filled circles).

branches of the coupled 2D MP–LO-phonon modes. First, every j_e-0_h transition has only one string replica[18] far from the crossing points between the LO-phonon and cyclotron harmonics, e.g., at $H\sim6.5$ and ~9.5 T. At these fields the energy gap between the NP line and its replica is approximately equal to $\hbar\omega_{\rm LO}$ in accordance with the weak 2D MP–LO-phonon coupling far from the resonance condition.[2–4] With increasing H, the phononlike satellite line moves from the LO phonon to MP branch near every $N\omega_c=\omega_{\rm LO}$ resonance. In addition, a new satellite line appears near the crossover point which corresponds to the second, MP-like, mode (cf. also Fig. 1). Its appearance is due to an increased admixture of the phonon weight in this mode.[3] With increasing H the replica transforms into the phononlike mode and then back again into an MP-like mode but now corresponding to $(N-1)\hbar\omega_c$ rather than $N\hbar\omega_c$. Note that the anticrossing behavior cannot be connected with Landau levels crossing the Fermi energy as the magnetic-field values of the crossings are independent of electron density in a wide range of $n_e=(0.5-1.1)\times10^{12}$ cm^{-2}.

The anticrossing behavior of the j-0* and j-0** satellite lines at the resonance fields can also be observed from the magnetic-field dependence of their intensities, shown in Fig. 3. The line intensity is mainly determined by the phonon weight in the corresponding coupled mode.[3] Therefore, the LO-phonon-like replica is strong whereas the MP-like replica is absent far from the resonance magnetic fields (e.g., at $H\sim6.5$ and 9.5 T). In the region of the resonance the phononlike mode gradually transforms into a MP-like one whose intensity decreases in accordance with the reduced phonon weight whereas the MP-like mode transforms into phononlike and becomes dominating in the spectrum. The reduction of the 2-0** line intensity at $H=8.25-9$ T (cf. Fig. 3) is connected with depopulation of the second electron LL occurring at $H=6.5-9.75$ T.

The resonant MP-phonon coupling arises from the singularities in the 2DEG contribution to the dielectric function.[2–4] These correspond to electron excitations with transition of electrons from an occupied n level to an unoccupied $n'=n+N$ level. Since the matrix element decreases[2–4] with increased difference $N=n'-n$ the coupling weakens for higher harmonics, which is in agreement with our experimental data [cf. the splitting of the lines j-0** and j-0* for $N=2$, 3, and 4 ($H\sim11$, 7, and 5.5 T, respectively) in Fig. 5].

The MP-phonon coupling in the 2DEG observed in our measurements at $(2-3)\omega_c=\omega_{\rm LO}$ considerably exceeds the coupling detected in CR measurements[7–9] at the main $\omega_c=\omega_{\rm LO}$ resonance. This can be explained as follows. In general, the MP-phonon coupling in the 2DEG depends on the wave vector and disappears[2–4] at $q=0$ in the dense 2DEG. This means that the weak coupling observed in CR measurements has to be mainly due to the admixture of the finite-momentum MP states to the $q=0$ one (e.g., by impurity scattering). A reduction of this mixing of states with carrier density and reduced disorder in the system explains the strong reduction of the MP-phonon coupling effect in CR of 2DEG. On the contrary, in magnetoluminescence spectroscopy we measure MP-phonon coupling directly at large q. This follows from the fact that the $j_e\neq j_h$ Landau transitions accompanied by emission of an additional quasiparticle become allowed when the quasiparticle carries away momentum of the order of an inverse magnetic length. This is a range of q where the 2D MP-phonon coupling is effective[2–4] even at high multiples of the cyclotron frequency.

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[18]For the forbidden j-0 transitions the phonon replica intensity is much greater than for the allowed 0-0 one, mainly because the momentum phase space for the phonons allowed in one-phonon recombination enlarges with increasing j and magnetic-field strength.