Interaction between intersubband Bernstein modes and coupled plasmon-phonon modes

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In a quasi-two-dimensional (2D) electron system under a perpendicular magnetic field, we have observed resonant interaction between intersubband Bernstein modes and coupled intersubband-plasmon–LO-phonon modes. By changing parameters of the 2D electron system, a transition from strong to weak regimes of coupling between the plasmon and LO phonon was considered. In the strong-coupling regime, we have observed a double-resonance splitting of the first intersubband Bernstein mode with both intersubband-plasmon–LO-phonon modes, whereas in the weak-coupling regime only a single resonance splitting with the intersubband-plasmon-like mode has been found.

In polar semiconductors, collective excitations in the electron system (plasmons) interact with LO phonons via macroscopic electric fields, thus forming coupled plasmon-phonon modes. Advances in the fabrication of semiconductor structures confining the electron motion in one of the space directions brought to life quasi-two-dimensional (2D) plasma excitations (2D plasmons).[1–5] The spectrum of such confined 2D plasmons consists of two different branches, namely, modes of an essentially 2D nature (intrasubband) and modes associated with polarization of electronic media in directions perpendicular to the 2D plane (intersubband). Whereas the former are Landau damped at characteristic LO-phonon frequencies, and, therefore, their mutual interaction with LO phonons has not been experimentally investigated, the interaction of the latter with LO phonons can be observed in resonant inelastic light scattering.[2]

When subjected to an external homogeneous magnetic field, a quasi-2D electron system becomes effectively zero dimensional, and the Landau damping of the intrasubband plasmon-phonon modes no longer occurs. The intrasubband single-particle excitation (SPE) continuum, responsible for the Landau damping,[6,7] transforms to Bernstein modes, which can interact with interface and bulk LO phonons.[8–12] Similarly, a magnetic field transforms the intersubband single-particle excitation continuum in intersubband Bernstein modes (ISBM's), which involve electron transitions with a simultaneous change of the Landau Level (LL) and quantum subband indices.[9,13] ISBM's thereby combine properties of intrasubband and intersubband magnetoplasma excitations. For example, unlike the principal intersubband plasma mode or charge-density excitation (CDE), their energies at zero in-plane momentum (q) contain neither a contribution from the macroscopic polarization in the electron system perpendicular to the 2D plane (depolarization shift) nor excitonic corrections due to interaction between the excited electron and the hole left behind below the electron Fermi surface. The ISBM's energies satisfy a general equation

$$E_{\mathrm{ISBM}_{\pm n}} = |\hbar\Omega_{10} \pm n\hbar\omega_c|, \tag{1}$$

which is very similar to the Kohn theorem for intrasubband excitations.[14] Here Ω_{10} and $\omega_c = eB/m_e$ are the electron intersubband and cyclotron frequencies, and n is a nonzero integer representing the change in the LL index. It is remarkable that Eq. (1) does not include any other features of the 2D confining potential except the intersubband energy $\hbar\Omega_{10}$.

Equation (1) is no more valid at a nonzero in-plane momentum. An each ISBM has its own dispersion curve, which is particularly sensitive to the interaction of the ISBM with other collective excitations in the 2D system.[13] One of the most striking examples of such interaction is a coupling between the ISBM's on one side, and charge- and spin-density excitations on the other, through the many-body Coulomb interaction. At first, it was observed in a titled magnetic field,[15,16] and then was studied at finite in-plane momenta in a perpendicular magnetic field.[17,18] The Coulomb interaction is in turn screened by LO phonons, which significantly modifies the interaction picture. That is, the screening is responsible for an anomalous dependence of the interaction strength on the 2D electron concentration found in Ref. 17. A more careful consideration of the effect of LO phonons on the ISBM's spectrum is made in the present paper. We show that, in contrast to the interaction with CDE, the interaction of ISBM's with LO phonons is negligible at the small q available in the experiment. Rather ISBM's interact with coupled CDE–LO-phonon modes through the polarization induced by the CDE part of CDE–LO-phonon modes, thus forming combined ISBM–CDE–LO-phonon collective excitations. In the experiment, this effect manifests itself as a double-resonant splitting between an ISBM with $n=1$ (ISBM_{+1}) and both CDE–LO-phonon coupled modes, the splitting being controlled by the coupling constant between CDE and LO phonons. The experimental results were compared to simulations based on the time-dependent local-density approximation (TDLDA),[14,19,20] and close agreement between experiment and theory has been obtained.

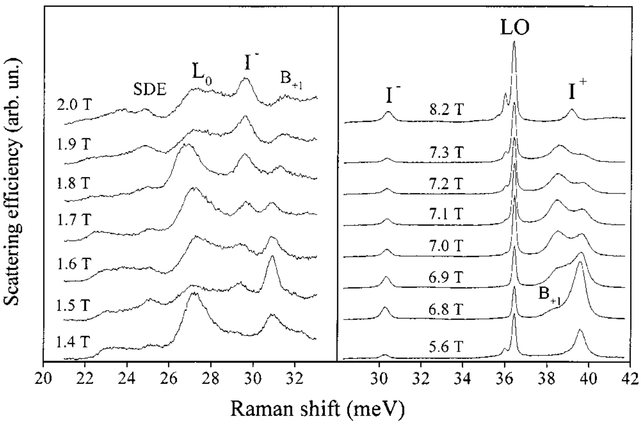

FIG. 1. Inelastic light scattering spectra of a sample with a QW width of 250 Å and $n_s = 6.8\times10^{11}$ cm^{-2} measured at $q = 1.1\times10^{5}$ cm^{-1}, $E_L = 1.59$ eV, and magnetic fields where resonances between ISBM$_{+1}$ and I$^-$ (left), and ISBM$_{+1}$ and I$^+$ (right) occur.

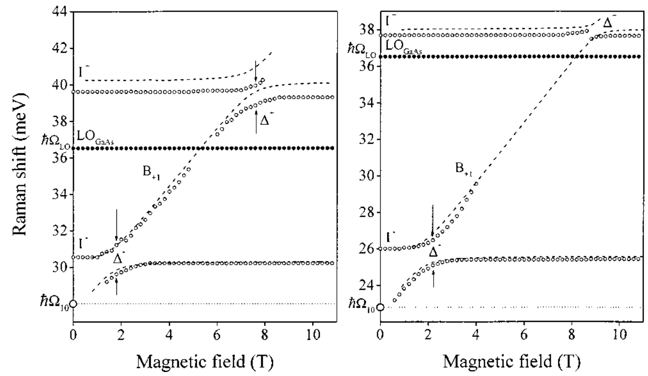

FIG. 2. Fan plot of the intersubband magnetoexcitations at $q = 1.1\times10^{5}$ cm^{-1} (open dots) measured in samples with a quantum well width of 250 Å and $n_s = 6.8\times10^{11}$ cm^{-2} (left) and $n_s = 3.8\times10^{11}$ cm^{-2} (right). As a reference, energies of the uncoupled LO phonons are shown by the solid dots. The dotted lines are guides for the eye, pointing the $\hbar\Omega_{10}$ as determined from the maxima of SPE branches at $B = 0$ T (large open dots). Simulated energies are plotted by dashed lines.

In the reported study, we used a set of asymmetrically doped high-quality semiconductor heterostructures with a single Al$_x$GaAs$_{1-x}$/GaAs quantum well (QW) of 250-Å width, an electron concentration (n_s) varying between 2.7 and 6.8×10^{11} cm^{-2}, and a mobility of 1.5–2×10^{6} cm^2/(V s). QW samples were placed at the center of a superconducting solenoid generating fields ranging from 0 to 11 T at a base temperature of 1.5 K. Inelastic light-scattering spectra were obtained using a Ti-sapphire laser tunable above the fundamental band gap E_0. The excitation power density was about 0.1–1 W/cm^2. A two-fiber optical system was utilized in measurements.[17,21] One fiber was used for photoexcitation, and the other collected and conducted scattered light out of the cryostat. The in-plane momentum was transferred to the quasi-2D electron system via the light-scattering process. Its value was controlled by the arrangement of the fibers relative to the sample surface. The scattered light was dispersed by a Ramanor U-1000 double grating monochromator and recorded by a charge-coupled detector (CCD) camera. Further experimental details can be found in Ref. 17.

Figure 1 shows two sets of inelastic light-scattering spectra taken from a sample with $n_s = 6.8\times10^{11}$ cm^{-2} at $q = 1.1\times10^{5}$ cm^{-1} in two different spectral regions below (left) and around (right) the energy of the bulk LO phonon in GaAs. Owing to the resonant interaction between CDE and LO phonons, two branches of CDE–LO-phonon coupled modes, I^- and I^+, are observed in the spectrum below and above the bulk LO-phonon energy, respectively.[2] Inelastic light scattering by uncoupled LO phonons is also observed (Fig. 1, right). Around the critical fields, where the energy of ISBM$_{+1}$ coincides sequentially with those of the I^- and I^+ modes, the energy and intensity of ISBM$_{+1}$ undergo a modification, clearly demonstrating interaction between ISBM$_{+1}$ on one side, and I^- and I^+ on the other.

The experimentally determined energies of the Raman lines observed in the studied range of magnetic fields are plotted in a single graph. Figure 2 (left) shows the energies of ISBM$_{+1}$, both the I^- and I^+ modes, and an uncoupled LO phonon in GaAs taken as a reference. Other spectral features irrelevant to the matter discussed in the paper [ISBM's with $n \neq +1$, spin density excitations (SDE's), and L_0] are omitted for simplicity, and these were considered in a recent publication.[17] The energy of ISBM$_{+1}$ (B_{+1}) undergoes two anticrossings when it resonates with the energies of both the I^- and I^+ modes. The anticrossing behavior signals the formation of combined ISBM$_{+1}$—CDE-LO-phonon modes of a complex character. The interaction between the ISBM$_{+1}$ and the coupled CDE–LO-phonon modes is essentially different from the interaction between CDE and LO phonons. In fact, the CDE and the bulk LO phonons confined in the quantum well are already coupled at zero in-plane momentum, with the coupling energy being as large as the depolarization shift responsible for the formation of CDE.[2] As concerns the coupling between I^- and I^+ on one side and ISBM$_{+1}$ on the other, this occurs at a nonzero in-plane momentum, the coupling energy being considerably smaller than that due to the coupling between the CDE and LO phonon. Moreover, in the long-wave limit ($ql_B \ll 1$, where $l_B = \sqrt{\hbar/eB}$ is the magnetic length) accessible experimentally, the ISBM$_{+1}$ mode interacts with the I^- (I^+) mode mostly through the polarization induced by the CDE part of the CDE–LO-phonon coupled modes, which is evident from the dependence of the coupling strength on the degree of admixing of the LO phonon to the CDE discussed below.

The degree of admixing can be varied by changing the parameters of the 2D electron system. In our case it was done by changing the 2D electron density n_s. The density n_s determines the profile of the QW confinement, which, in turn, determines the intersubband energy between the ground and first excited subbands. Thus, by changing n_s, we are able to tune the coupling conditions between the CDE and the LO phonon. The energy spectrum measured in the sample with a reduced electron density ($n_s = 3.8\times10^{11}$ cm^{-2}) is given in Fig. 2 (right). The detuning of the CDE energy from the resonance with the LO-phonon energy is seen to have little effect on the coupling between the CDE-like mode (I^-) and ISBM$_{+1}$, even though it dramatically weakens the coupling between the LO-phonon-like mode (I^+) and ISBM$_{+1}$. The further detuning of the CDE and LO-phonon energies from the resonance with reducing the electron density from 3.8

$\times 10^{11}$ cm^{-2} to 2.7×10^{11} cm^{-2} still has a small effect on the coupling between the CDE-like mode and ISBM$_{+1}$,[17] whereas it completely wipes out the coupling between the LO-phonon-like mode and ISBM$_{+1}$. This leads us to the conclusion that the coupling between the ISBM$_{+1}$ and bulk LO phonons is negligible in the long-wave limit considered here, and that the combined ISBM$_{+1}$–CDE–LO-phonon modes are formed largely through the polarization induced by the CDE component of the CDE–LO-phonon coupled modes.

We modeled the experimental energy spectra on the base of the TDLDA approximation, which has already produced a remarkable description of intersubband magnetoplasma modes.[17,19] The spectra are proportional to the imaginary part of the polarization function $\tilde{\chi}_i^{10}(q,\omega)$ (the subscript refers to the charge or the spin-density response), which results in

$$1-\mathrm{Re}\,\gamma_i(q)\chi^{10}(q,\omega)=0,$$
$$\mathrm{Im}\,\gamma_i(q)\chi^{10}(q,\omega)=0, \tag{2}$$

where $\chi^{10}(q,\omega)$ is the intersubband part of the polarization function of noninteracting quasi-2D electron systems in a magnetic field.[9,13] The function $\gamma_i(q)$ represents many-body effects, and is expressed in terms of the depolarization shift and the excitonic corrections.[6,19] The long-wave approximation $\chi^{10}(q,\omega)\ \sim(ql_B)^2$ is used, which implies neglecting electron transitions with $|n|>1$. It can be easily verified that the long-wave approximation is well justified in the range of magnetic fields of interest, where the anticrossings between the I^- (I^+) and ISBM$_{+1}$ energies are observed. The effect of dynamic screening of the direct Coulomb interaction by long-wave LO phonons is incorporated through a frequency-dependent dielectric function

$$\epsilon(\omega)=\epsilon_\infty\frac{\omega^2-\omega_{\mathrm{LO}}^2}{\omega^2-\omega_{\mathrm{TO}}^2}, \tag{3}$$

where ω_{LO} and ω_{TO} are the frequencies of the bulk LO and TO phonons, respectively. This approximation is most commonly used if dynamic phonon effects on the intersubband magnetoplasma modes are investigated.[9,13] The results of the simulations are plotted in Fig. 2 by dashed lines. The resonant splittings between the ISBM$_{+1}$ and I^-, I^+ $(\Delta^-,\ \Delta^+)$ are fairly adequately reproduced in the simulated spectrum, even though there is a systematical overestimation of the coupling strength between CDE and the LO phonons within our model (Fig. 2). As shown previously,[17] the coupling strength between CDE and ISBM$_{+1}$ is a linear function of the in-plane momentum as long as the in-plane momentum is small as compared with the reciprocal magnetic length. We studied the dispersions of both splittings Δ^- and Δ^+ in the sample with $n_s=6.8\times 10^{11}$ cm^{-2}. Both Δ^- and Δ^+ have been found to be nearly linear functions of the in-plane momentum and are in good agreement with dispersions simulated using the TDLDA (Fig. 3). It is worth noting that, when the in-plane momentum tends to zero, the coupling vanishes. This observation provides an experimental proof that fundamental equation (1) does not fail in polar semiconductors like GaAs, where the Coulomb interaction is dynamically screened by LO phonons. Such invariance of Eq. (1) with respect to the form of the interparticle interaction resembles a similar invariance described by the widely known Kohn theorem, which applies to a fairly wide range of shapes of the two-particle interaction potential.

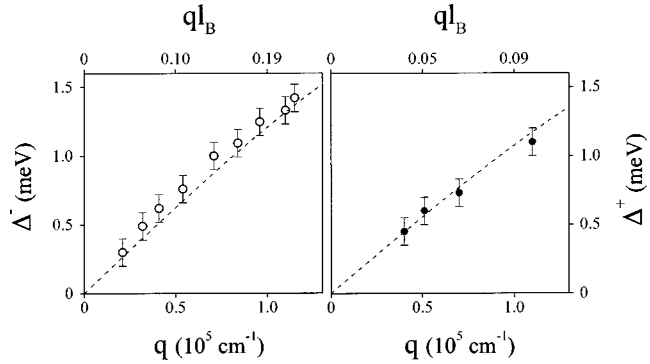

FIG. 3. Dispersions of Δ^- (left), and Δ^+ (right) measured in a sample with a QW width of 250 Å and $n_s=6.8\times 10^{11}$ cm^{-2}. The dashed lines plot simulations of dispersion curves.

In the reported study we have willingly limited our discussion to the interaction of ISBM$_{+1}$ with CDE–LO-phonon coupled modes, and have not considered ISBM's with higher indices, since ISBM's with $|n|>1$ couple to CDE in higher orders of ql_B.[13] Their energies are in perfect agreement with formula (1), and are negligibly affected by the coupling with CDE in the long-wave limit discussed here.[17] For example, the coupling between CDE and ISBM$_{+2}$ becomes experimentally detectable only at $q\sim 1.2\times 10^5$ cm^{-1}, which is close to the upper limit accessible in our experimental configuration. In conclusion, we have considered the spectrum of intersubband excitations modified by interaction with bulk LO phonons. We have observed an interesting effect, namely, the formation of combined ISBM–CDE–LO-phonon modes. The first intersubband Bernstein mode interacts with coupled CDE–LO-phonon modes at nonzero in-plane momenta through the polarization induced by the CDE part of the coupled modes with the interaction magnitude, being a linear function of the in-plane momentum in the long-wave limit.

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