Filling-factor–dependent oscillations of the coupled intersubband plasmon-LO phonon mode in a tunneling coupled-bilayer system

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We have investigated an $Al_{0.33}Ga_{0.67}As$/GaAs tunneling coupled-bilayer heterostructure with magnetotransport and far-infrared spectroscopy. With a front gate the charge density could be tuned. A grating coupler was prepared to investigate the collective excitations. We observed an intersubband plasmon which is coupled to the GaAs LO phonon. In a magnetic field applied perpendicular to the two-dimensional electron gas plane, the mode exhibits a strong filling-factor–dependent oscillation of the resonance energy.

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Tunneling coupled-bilayer systems show remarkable effects due to the interplay of Coulomb interaction and tunneling. In these systems each subband splits due to tunneling into two states $|n\mathrm{S}\rangle$ and $|n\mathrm{AS}\rangle$ with a symmetric and an antisymmetric wave function, respectively. By applying a gate voltage, the space symmetry of a bilayer system can be tuned. This change in the electrostatic potential results in a strong variation of the energy gap Δ_{SAS}. The space asymmetry also gives rise to a growing localization of the wave functions in each layer.[1,2] Additional interesting effects occur in bilayer systems by applying a magnetic field. For example, effects like magnetic-field-driven collapse of the Δ_{SAS} have been investigated both theoretically and experimentally.[3,4]

We have recently studied the intra- and intersubband plasmons in tunneling coupled-bilayer system with tunable space symmetry.[5] Intersubband plasmons can also be understood as intersubband transitions affected by many-body effects, namely the depolarization and exciton shift.[6–8] Of particular interest is the coupled intersubband plasmon–LO-phonon mode caused by the electron-phonon interaction. The behavior of this mode in a magnetic field has not yet been well investigated experimentally. Its possible influence on cyclotron resonance is now under discussion[9–11] with rather controversial polaron pictures.

In this paper we present experimental results on a coupled intersubband plasmon–LO-phonon mode in a tunneling coupled-bilayer system. We study the mode dispersion systematically by applying a gate voltage as well as a magnetic field. We find interesting filling-factor–dependent oscillations of the mode energy. We compare our experimental results with calculations that include electron-electron and electron-phonon interaction as well as the magnetic-field dependent self-consistent charge redistribution effect.

The bilayer system was grown by molecular-beam epitaxy (MBE) and had the following layer structure: 280 nm superlattice (period 5.6 nm), a buffer of 500 nm GaAs, 250 nm $Al_{0.33}Ga_{0.67}As$ with a Si δ-donor layer, 30 nm $Al_{0.33}Ga_{0.67}As$, 15 nm GaAs, 1 nm $Al_{0.33}Ga_{0.67}As$, and 15 nm GaAs were grown, followed by 20 nm $Al_{0.33}Ga_{0.67}As$, a Si δ-donor layer, 10 nm $Al_{0.33}Ga_{0.67}As$, another Si δ-donor layer, 10 nm $Al_{0.33}Ga_{0.67}As$, and a 5 nm GaAs cap layer. A macroscopic Hall bar of approximately 3×5 mm^2 has been prepared. The two-dimensional electron gases (2DEGs) have been connected with ohmic contacts by depositing AuGe alloy followed by annealing. The charge density can be varied with a Ti front gate. A grating coupler of Au with a period of $a=2\,\mu$m, where half the period is metal, has been prepared on top of the front gate to allow the excitation of the intersubband plasmons.

The magnetotransport experiments were conducted in a cryostat with a 12 T superconducting magnet at 2.2 K. From the Shubnikov–de Haas oscillations which were performed in parallel with the far-infrared (FIR) measurements we determine the charge density. The results for different gate voltages V_g are given in Fig. 1. For gate voltages higher than -325 mV two different charge densities N_{S} and N_{AS} exist, which belong to the first symmetric and antisymmetric subband, respectively. The single-particle energy gap Δ_{SAS} can be obtained from the relation $\Delta_{\mathrm{SAS}}=(N_{\mathrm{S}}-N_{\mathrm{AS}})/D_2$. $D_2=m^*/\pi\hbar^2$ is the two-dimensional density of states, and m^* is the effective mass. We have performed self-consistent cal-

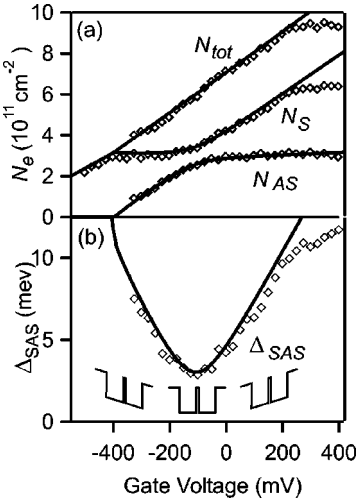

FIG. 1. (a) Gate-voltage dependence of charge densities of the lowest symmetric subband N_{S}, lowest antisymmetric subband N_{AS}, total charge density N_{tot}, and (b) single-particle energy gap Δ_{SAS}. The solid curves in (a) and (b) are results of a self-consistent calculation. The symmetry of the conduction band of the bilayer system is drawn schematically.

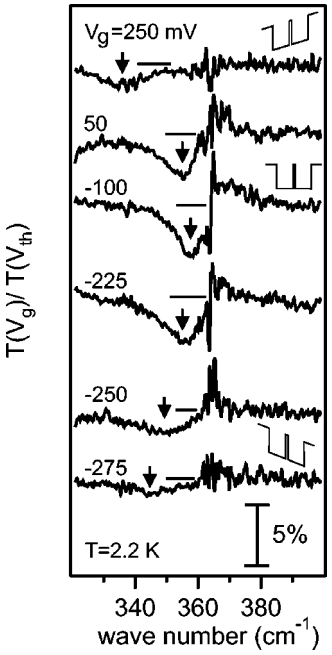

FIG. 2. Experimental spectra at different symmetries of the bilayer system. The conduction band is depicted schematically. For the symmetric situation the resonance energy is at the maximum. The asymmetric line shape and overshooting of the relative transmission over unity is caused by a change in the dielectric constant due to an AlAs-like TO phonon at about 364 cm^{-1}. The horizontal lines indicate unity.

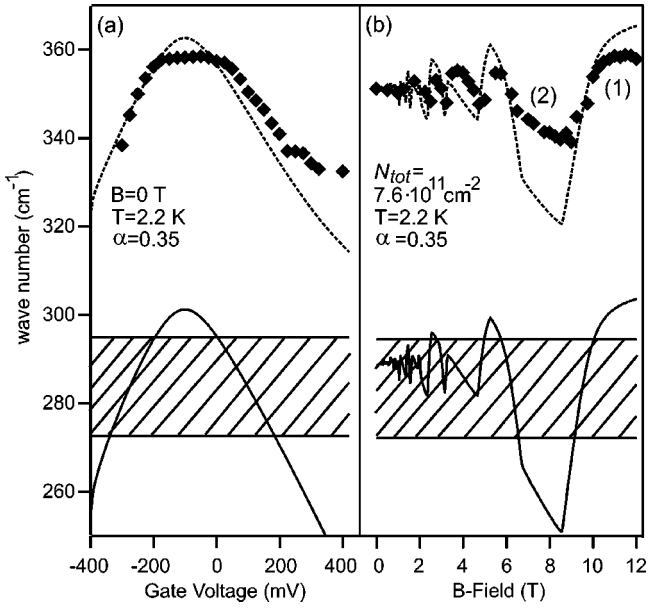

FIG. 3. (a) Gate-voltage dispersion at 0 T and (b) magnetic-field dependence at fixed gate voltage of $V_g = 100$ mV with $N_{\mathrm{tot}} = 7.6 \times 10^{11}$ cm^{-2} of the intersubband resonance. ♦ denotes the experimental resonance position and the solid line the calculated intersubband energy $E_{2S} - E_{1AS}$. The dashed line is the energy ω_+ determined by Eq. (1) of the coupled intersubband resonance-phonon mode with a depolarization shift of $\alpha = 0.35$. The hatched area is the reststrahlen band of GaAs. Situations (1) and (2) in (b) are explained in the text.

culations within the local density approximation. The results are given by the solid lines in Fig. 1. An excellent agreement between theory and experimental data is achieved. FIR spectra were taken with a Fourier spectrometer which was connected to the cryostat via a waveguide system. The measured spectra at gate voltages V_g were divided by the structureless spectra taken at a threshold voltage $V_{\mathrm{th}} = -1.2$ V. The result is the relative transmission $T(V_g)/T(V_{\mathrm{th}})$.

Figure 2 shows representative spectra taken at 0 T. An increase of the gate voltage up to -75 mV shifts the resonance position to higher energy. Further increase lowers the energy of the mode because tuning the bilayer system asymmetric results in an increase of the energy gap of the tunneling split nth-subbands between $|n\mathrm{S}\rangle$ and $|n\mathrm{AS}\rangle$. The energy difference $E_{2S} - E_{1AS}$ between the first antisymmetric $|1\mathrm{AS}\rangle$ and the second symmetric $|2\mathrm{S}\rangle$ subband is lowered. Due to the presence of an AlAs-like TO phonon the dielectric constant changes drastically around 364 cm^{-1}. This causes an asymmetric resonance curve and an overshooting of the relative transmission over unity.

The mode energy dispersion is shown in Fig. 3(a). At a first sight one could attribute the observed mode to the intersubband transition between these two subbands. Its maximum is reached for the symmetric situation. With self-consistent calculations we determined the energy gap between the $|1\mathrm{AS}\rangle$ and $|2\mathrm{S}\rangle$ subband. It is plotted as a solid line in Fig. 3(a). The observed mode energy lies more than 50 cm^{-1} higher. Since the self-consistent calculations reproduce well the charge densities and the energy gap Δ_{SAS}, such a large discrepancy here cannot be explained by the uncertainty in choosing the sample structure parameters. We note the calculated intersubband energy is very close to the LO-phonon energy of GaAs. Therefore electron-phonon interaction might significantly influence the intersubband energy by forming coupled intersubband plasmon–LO-phonon modes. The resonance energies of such coupled modes are given by[10,12]

$$\omega_{\pm}^2 = \tfrac{1}{2}\left(\omega_{\mathrm{LO}}^2 + \tilde{\omega}_{\mathrm{ISR}}^2\right) \pm \tfrac{1}{2}\sqrt{\left(\omega_{\mathrm{LO}}^2 + \tilde{\omega}_{\mathrm{ISR}}^2\right)^2 - 4\omega_{\mathrm{ISR}}^2\left(\omega_{\mathrm{LO}}^2 + (\alpha - \beta)\omega_{\mathrm{TO}}^2\right)}, \tag{1}$$

where ω_{LO}, ω_{TO}, are, respectively, the LO- and TO-phonon energies. ω_{ISR} and $\tilde{\omega}_{\mathrm{ISR}} = \omega_{\mathrm{ISR}}\sqrt{1 + \alpha - \beta}$ are the intersubband resonance energies between the $|1\mathrm{AS}\rangle$ and $|2\mathrm{S}\rangle$ subband without and with the many-body corrections, respectively. α describes the depolarization shift and β the exciton shift. In our case with a large charge density ($>4 \times 10^{11}$ cm^{-2}) and a strong population of the $|1\mathrm{AS}\rangle$ subband the exciton shift is small and can be neglected ($\beta \approx 0$).[13,14] Exact calculation of the depolarization shift is a cumbersome task since we need considering a three energy level system with two subbands occupied. We choose the symmetric situation to estimate its magnitude and apply the theory developed in Refs. 6 and 15. By using the approximation that $(E_{1AS} - E_{1S}) \ll (E_{2S} - E_{1AS}) \approx (E_{2S} - E_{1S})$, we obtain a value of $\alpha = 0.35$. This is a reasonable value if we compare it with

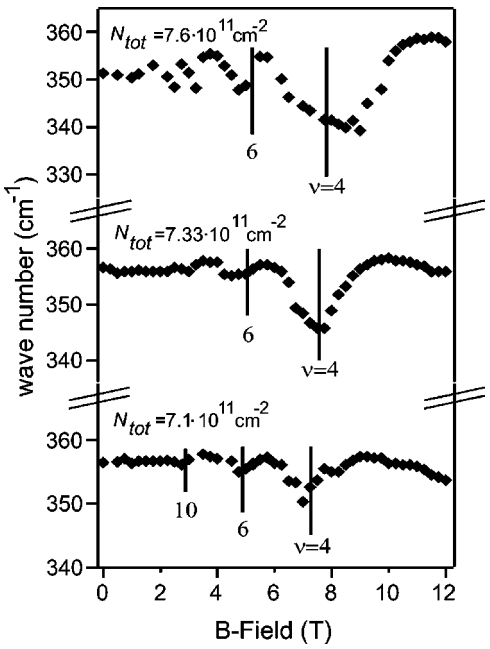

FIG. 4. Dispersion curves for $N_{\mathrm{tot}}=7.6\times10^{11}\ \mathrm{cm}^{-2}$, $7.33\times10^{11}\ \mathrm{cm}^{-2}$ and $7.1\times10^{11}\ \mathrm{cm}^{-2}$. An oscillatory behavior is clearly observable. Solid lines show the positions of filling factors.

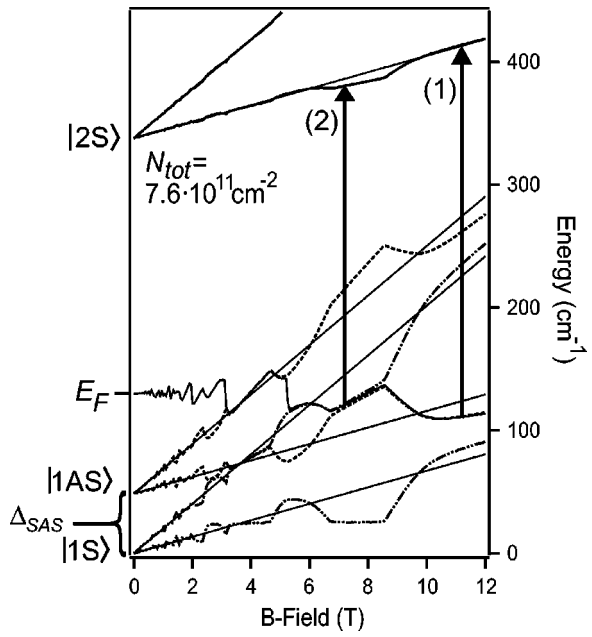

FIG. 5. Self-consistent Landau level energies of the $|1\mathrm{S}\rangle$, $|1\mathrm{AS}\rangle$, and $|2\mathrm{S}\rangle$ subband as well as the Fermi energy E_F relative to the $|1\mathrm{S}\rangle$ subband at $B=0$ T. The thin lines are the single-particle Landau levels. The arrows show the intersubband transition $|1\mathrm{AS}\rangle$ to $|2\mathrm{S}\rangle$. In situation (1) only the lowest Landau levels of the $|1\mathrm{S}\rangle$ and $|1\mathrm{AS}\rangle$ are occupied. At lower magnetic field [situation (2)] the next Landau level of $|1\mathrm{S}\rangle$ becomes occupied. The self-consistent potential is changed due to a magnetic-field-induced redistribution of the electrons between the two subbands. The electron-phonon interaction is not taken into account in this picture.

the result $\alpha\approx3.5$ for the depolarization shift of the intersubband transition between the $|1\mathrm{S}\rangle$ and $|1\mathrm{AS}\rangle$ subbands, which we have directly measured in the same sample.[5] The depolarization shift is roughly inversely proportional to the intersubband energy. In our sample, the intersubband energy between the $|1\mathrm{AS}\rangle$ and $|2\mathrm{S}\rangle$ subbands is about ten times larger than that between the $|1\mathrm{S}\rangle$ and $|1\mathrm{AS}\rangle$ subbands. Equation (1) has two solutions. We plot in Fig. 3(a) the calculated mode dispersion for the mode ω_+ with energy higher than the LO-phonon energy with the dashed line. Since the value of α is quite small, we neglect for our estimation its gate-voltage dependence. Apparently, even in such a rough estimation, the observed resonance can be reasonably attributed as the coupled intersubband plasmon–LO-phonon mode.

Further evidence of the intersubband plasmon–LO-phonon coupling comes from the change of the oscillator strength with gate voltage as shown in Fig. 2. The observed resonance decreases in amplitude while increasing in width as its resonance energy approaches the LO-phonon energy. This can be understood as the mode becomes more and more phonon like and the excitation loses oscillator strength. The second solution, ω_- of Eq. (1), is not observable because it is more phononlike in the whole gate-voltage regime we studied .

We now study the mode behavior by applying a magnetic field up to 12 T perpendicular to the 2DEG plane. The measured magnetic-field-dependent mode dispersion for a total charge density $N_{\mathrm{tot}}=7.6\times10^{11}\ \mathrm{cm}^{-2}$ is depicted in Fig. 3(b). It shows a clear oscillatory behavior. To clarify the origin of the oscillation, we measured the mode dispersion for different charge densities and show them comparatively in Fig. 4. One can clearly see that the oscillation depends on the charge density, with its minima coinciding with the filling factors of the system. The magnetic-field-dependent intersubband energy for $N_{\mathrm{tot}}=7.6\times10^{11}\ \mathrm{cm}^{-2}$ is depicted in Fig. 3(b) with a dashed and a solid line, respectively, for the cases of with and without intersubband plasmon–LO-phonon coupling. The calculated dispersion assuming a constant depolarization shift value of $\alpha=0.35$ agrees qualitatively with the experimental result. To improve the agreement, a detailed theoretical investigation is needed to include the change of the depolarization shift in the magnetic field that is caused due to the change of the subband wave functions.

Such an oscillatory behavior can be intuitively understood. In the single-particle picture each tunneling split subband forms a Landau fan, separated by Δ_{SAS} (depicted as thin solid lines in Fig. 5). By changing the magnetic field, the density of states of each Landau level changes. At integer filling factors, situations can occur in which electrons have to redistribute between different Landau levels which belong to different subbands.[16] Such a case is situation (2) in Fig. 5. The ratio of the charge densities of the symmetric and antisymmetric subband changes, which results in a variation of the self-consistent potential and hence the subband energies. As shown in Fig. 5, the effect is larger for the $|1\mathrm{AS}\rangle$ subband than that for the $|2\mathrm{S}\rangle$ subband. Such a difference results in the filling-factor–dependent oscillation of the intersubband energy.

In conclusion, we have investigated a $Al_{0.33}Ga_{0.67}As$/GaAs tunneling coupled-bilayer heterostructure with magnetotransport and far-infrared spectroscopy. We have observed a coupled intersubband plasmon–LO-phonon mode. Its mode energy shows a filling-factor–dependent oscillatory behavior. We find it is caused by the change of the self-consistent potential due to the magnetic-field-induced redistribution of the electrons between the symmetric and antisymmetric subband.

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