Rabi splitting at intersubband transition assisted by longitudinal optical phonon

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Rabi splitting in absorption spectra of intersubband transition of a polar semiconductor quantum well is predicted if the intersubband frequency is near the longitudinal phonon frequency. The calculated value of the splitting for a GaAs quantum well changes from 1.82 meV to 6.86 meV, when the electron concentration varies from 10^{16} to 10^{17} cm^{-3}. It is also predicted that the absorptance is enhanced as compared to the one for a nonpolar quantum well with the same intersubband transition. The oscillator model of the dielectric function gives the same order of the splitting.

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I. INTRODUCTION

Intersubband absorption in a quantum well has attracted great attention due to its applications in quantum-well infrared detectors[1] and quantum cascade lasers.[1,2] Many accompanied effects have to be taken into account carefully for the design of such optoelectronic devices. One of such effects is Rabi splitting which is also of great importance from the fundamental point of view. It is known that absorption or emission spectra of an object can be altered if it is placed near a body which modifies the surrounding field distribution of the object. For example, the spectra will be changed dramatically if an atom or a semiconductor quantum well with two energy states of interest (two-level oscillator) is embedded in a resonator or microcavity.[3] In this case, a splitting of the corresponding transition emerges and is called Rabi splitting.[3–5] The role of the resonator is to select specific electromagnetic modes (resonator modes). The splitting becomes more evident when photon-matter coupling becomes stronger than the combined decay of the oscillator and the cavity modes. The Rabi effect has been studied for both atoms and semiconductor nanostructures. Rabi oscillation revival has been observed for atom maser.[6] The splitting of the absorption spectra has been measured for atoms,[7] and exciton[8] and intersubband[9] transitions in quantum wells embedded in a resonator. Strong coupling between an exciton and surface plasmons has been observed for organic semiconductors.[10] Special emphasis on investigating this phenomenon in nanostructures is recently stimulated by its much higher dipole moment as compared to atoms leading to higher values of the splitting and by its potential applications in quantum information processing. For example, exciton-cavity mode anticrossing has been demonstrated for single quantum dots in semiconductor microcavity system[11] or in a photonic crystal microresonator.[12] The Rabi splitting due to intersubband transition for GaAs quantum wells in a microcaviy has been predicted[13] and has also been observed in a waveguide.[14]

In this study, we theoretically show that such simple physical system as a polar semiconductor thin film (a quantum-well system) can reveal Rabi splitting in the absorption spectrum corresponding to its intersubband transition without using additional resonator or waveguide to introduce coupling. The polar semiconductor can be considered as a combination of lattice and electron subsystems. In considering its electromagnetic response, the electron subsystem is embedded in the lattice subsystem that serves a continuous dielectric medium. That is, the acting field on the electron subsystem is the field inside the film provided by the dielectric response of the lattice. Because the electronic response of interest here is the induced intersubband transition of the very thin dielectric film, the x and z components (parallel and perpendicular to film plane, respectively) of the electromagnetic field inside the film are given by $E_x = E_{0x}$ and $E_z = E_{0z}/\varepsilon$, where E_{0x} and E_{0z} are the incident field components. ε $(=\varepsilon' + i\varepsilon'')$ is the dielectric function of the polar semiconductor and reflects the lattice contribution of the electromagnetic response to the incident electromagnetic wave. E_z may have a sharp resonance at longitudinal optical (LO)-phonon frequency (ω_{LO}) at which $\varepsilon' = 0$ (plasmon-polariton resonance for a thin film)[15] and consequently is enhanced in the small frequency region around ω_{LO}. According to ε of GaAs,[16] the maximum of $1/|\varepsilon|$ at ω_{LO} is almost 2 orders higher than its value out of the resonance. It indicates that the enhancement factor of E_z can be more than 100. The width of this resonance represents damping of this giant oscillating lattice field. The intersubband absorption of the semiconductor film is expected to be greatly influenced by this field if the corresponding frequency matches with this resonance, because the absorption is mainly determined by the z component of the field.[17] This thin-film lattice subsystem essentially acts as a hidden resonator for the electron subsystem. Therefore, at the coincidence between the film polariton oscillation and the intersubband electronic transition, Rabi splitting may occur and the absorption spectrum corresponding to the intersubband transition may be greatly altered without a physical resonator.

II. APPROACH AND PARAMETERS OF SYSTEM

In solving this electron-lattice system, the analytical approach by Liu and Keller[18] for intersubband transitions in nonpolar quantum wells is used. For an electron subsystem embedded in a film with a dielectric function ε, the field $\vec{E}(\omega,z)$ inside the film at the frequency ω satisfies the Lippmann-Schwinger equation

$$\vec{E}(\omega,\vec{k}_{\|},z)=\vec{E}^{0}(\omega,\vec{k}_{\|},z)+i\omega\mu_0\int_0^l dz'\vec{\vec{G}}(\omega,\vec{k}_{\|},z,z')\times\int_0^l dz''\vec{\vec{\sigma}}(\omega,\vec{k}_{\|},z',z'')\vec{E}(\omega,\vec{k}_{\|},z''), \quad (1)$$

where $\vec{E}^0(\omega,z)$ is the field inside the semiconductor dielectric film (see, e.g., Ref. 19) without considering the electron subsystem, μ_0 is the permeability of free space, $\vec{\vec{G}}(\omega,\vec{k}_{\|},z,z')$ is the Green tensor which takes account of the dielectric film (see, e.g., Ref. 20), $\vec{\vec{\sigma}}(\omega,\vec{k}_{\|},z',z'')$ is the conductivity tensor, l is the thickness of the film, and $\vec{k}_{\|}$ is the projection of the wave vector on the film plane. Within the framework of random-phase approximation and in the long-wavelength and low-temperature limits, the conductivity tensor in the first order approximation of perturbation theory takes a diagonal form[18]

$$\sigma_{xx}(z,z')=\frac{ie^2}{\pi\hbar^2\omega}\frac{(E_2-E_1)(E_F-E_1)^2}{[\hbar(\omega+i/\tau)]^2-(E_2-E_1)^2}\phi(z)\phi(z'), \quad (2)$$

$$\sigma_{zz}(z,z')=\frac{ie^2}{2\pi m^*\,\omega}\frac{(E_2-E_1)(E_F-E_1)}{[\hbar(\omega+i/\tau)]^2-(E_2-E_1)^2}\Phi(z)\Phi(z'), \quad (3)$$

where $\phi(z)=\chi_1(z)\chi_2(z)$, $\Phi(z)=\chi_1(z)(d\chi_2(z)/dz)-\chi_2(z)(d\chi_1(z)/dz)$. $\chi_1(z)$ and $\chi_2(z)$ are the z-dependent electron wave functions of the two eigenstates with two energies, E_1 and E_2, respectively. The Fermi energy, the charge, and the effective mass of two-dimensional electron gas are given by E_f, e, and m^*, respectively. τ is the relaxation time associated with the intersubband transition between the energy states. The dielectric function has the form of an oscillator model:[21]

$$\varepsilon(\omega)=\varepsilon_\infty\frac{\omega_{LO}^2-\omega^2-i\gamma\omega}{\omega_{TO}^2-\omega^2-i\gamma\omega}, \quad (4)$$

where ω_{TO} is the transverse optical (TO)-phonon frequency, ε_∞ is the dielectric function at high frequencies, and γ is the damping constant. The kernel of the integral in Eq. (1) has a factorized form and, therefore, Eq. (1) can be solved analytically. Knowing the field $\vec{E}(\omega,z)$, one can find the reflection and transmission coefficients from boundary conditions and then the absorptance A.

Based on the derived equations above, numerical calculation was performed on the following conditions. First, the p-polarized light is incident on a GaAs film on a buffer AlAs layer with thickness 500 nm at an angle of 85° to have a large E_z. Because GaAs is almost lattice matched to AlAs, the chosen structure can be fabricated based on the existing semiconductor epitaxy technology.[22] The LO- and TO-phonon energies and the damping constant of bulk GaAs have been chosen as 36.2 meV (292 cm^{-1}), 33.22 meV (268 cm^{-1}), and 0.125 meV (1cm^{-1}), respectively; $\varepsilon_\infty=11$.[23] Similarly, the corresponding energies and damping constant of AlAs have been chosen as 50 meV (403.3 cm^{-1}), 44.8 meV (36.14 cm^{-1}), and 0.125 meV (1 cm^{-1}). The relaxation time for the intersubband transition $\tau=4$ ps is chosen.[24] The effective electron mass $m^*=0.0665m_e$ is used in the calculations, where m_e is the free electron mass. The infinitely deep potential barrier and the intersubband transition between the lowest two levels in the conductivity band of GaAs were considered in numerical calculations. The barrier height between the GaAs quantum well and the AlAs buffer layer is about 1 eV. The estimated values of the wave functions of the two lowest subbands at the GaAs/AlAs interface are less than 1% of their maximum values. The corresponding penetration depths of the two wave functions in the AlAs layer are less than 0.5 nm. The infinitely deep potential thus can be a good approximation in this case. The Fermi energy E_F is associated with the electron concentration N_e by the relation $E_F-E_1=\pi\hbar^2N_el/m^*$.[25]

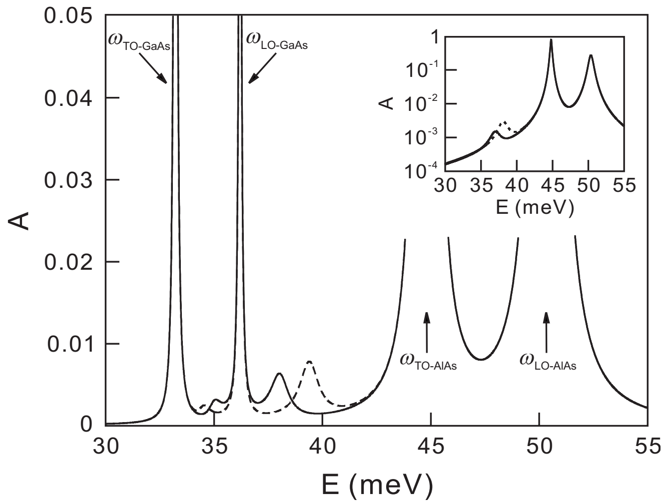

FIG. 1. Absorption spectra of the intersubband transition in GaAs film at different electron concentrations: 10^{16} cm^{-3} (solid line), 5×10^{16} cm^{-3} (dashed line). Absorption spectra for a nonpolar film ($\omega_{TO}=\omega_{LO}$) are given in the inset for the same electron concentrations.

III. RESULTS AND DISCUSSION

Absorption spectra at two different electron concentrations (10^{16} and 5×10^{16} cm^{-3}) and for the case of $E_2-E_1=\hbar\omega_{LO}$ (the corresponding thickness of the film is about 22 nm) are presented in Fig. 1. For comparison, absorption spectra at the same concentrations for a nonpolar film ($\omega_{TO}=\omega_{LO}$) are given in the inset of the figure. Three prominent features can be found from these calculation results. First, four strong absorption peaks at the TO- and LO-phonon frequencies of GaAs and AlAs are attributed to the lattice absorption which can be simply checked with the use of Fabry-Pérot formula. Second, in contrast to the nonpolar film, the weaker doublet around the LO-phonon frequency of GaAs appears. These lines correspond to the absorption of the intersubband transition and reveal Rabi splitting. The value of the splitting increases with the electron concentration and changes from 1.82 to 4.765 meV. Third, the absorptance of the intersubband transition in the polar film at 10^{16} cm^{-3} is

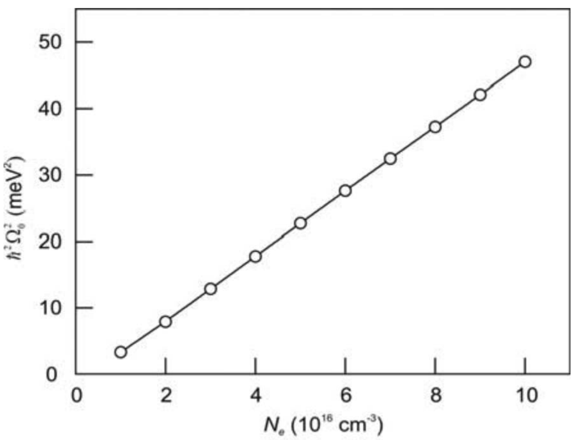

FIG. 2. Dependence of the square of Rabi splitting, $\hbar^2\Omega_0^2$, on the electron concentration N_e.

20 times higher than the one in the nonpolar film where the absorption feature is due to the intersubband transition. For higher concentrations, the intersubband absorption magnitude for the polar film is still larger than the one for nonpolar film but the ratio between them becomes smaller. Notice that this ratio decreases with the splitting of the doublet. The difference in the magnitudes of the split lines may be explained by their nonsymmetrical positions with respect to the LO-phonon frequency and dispersion of the dielectric function. The nonsymmetrical positions with respect to the LO-phonon frequency can be caused by the Lamb shift, as can also be seen from the inset of Fig. 1 (see also Refs. 18 and 26).

The phenomena can be compared with the known Rabi-splitting behaviors observed in a resonator in the following three aspects. First, $\hbar^2\Omega_0^2$ shows an almost linear dependence on the electron concentration (Fig. 2), where $\hbar\Omega_0$ is the Rabi splitting for $E_2-E_1=\hbar\omega_{LO}$. This dependence is similar to the resonator case where the Rabi splitting is proportional to the square root of the numbers of photons (see, e.g., Ref. 27). Second, Rabi frequency, $\Omega=\sqrt{\Omega_0^2+[(E_2-E_1)/\hbar-\omega_{LO}]^2}$, shows a similar dependence on the detuning energy, $\Delta E=E_2-E_1-\hbar\omega_{LO}$. Figure 3(a) displays the dependences of the upper and lower peak energies on ΔE. Notice that the figure is plotted for $\Delta E>-2$ meV. This is so because as ΔE becomes smaller than -2 meV the upper and lower branches gradually merge with the absorption peaks of the LO phonon and the TO phonon, respectively. A detailed examination of the dependence of $k=\hbar^2(\Omega^2-\Omega_0^2)/\Delta E^2$ on ΔE is presented in Fig. 3(b). The large deviation from unity at small ΔE is probably associated with damped Rabi oscillations,[28] the asymmetrical dependence of ε on the frequency around ω_{LO} due to the nearby ω_{TO}, as shown in Eq. (4), and the Lamb shift mentioned above. To identify the origin of this behavior, we artificially modified the damping constant γ and found almost no effect on this large deviation. We further moved the TO-phonon frequency to 10 meV which is far away from the LO-phonon frequency. The resultant dependence of k on ΔE (not shown here) displays similar behavior as Fig. 3(b), indicating that the spectral dependence of ε does not play a significant role here. Finally, as demonstrated above in the inset of Fig. 1, the absorption spectra of a nonpolar quantum-well structure show a red shift (Lamb shift) of 0.824 meV ($=\Delta E_L$) for $N_e=2\times10^{16}$ cm^{-3}.[18,26] With the consideration of the Lamb shift, a new detuning energy ΔE_1 can be defined as $\Delta E_1=\Delta E_L+E_2-E_1-\hbar\omega_{LO}$. The dependence of $k_1=\hbar^2(\Omega^2-\Omega_1^2)/\Delta E_1^2$ on ΔE_1 is presented in Fig. 3(c), where $\hbar\Omega_1$ is the Rabi splitting for $E_2-E_1+\Delta E_L=\hbar\omega_{LO}$. Notice that k_1 approaches unity for large ΔE_1. The analysis above shows that the Lamb shift effect plays an important role in Rabi splitting.

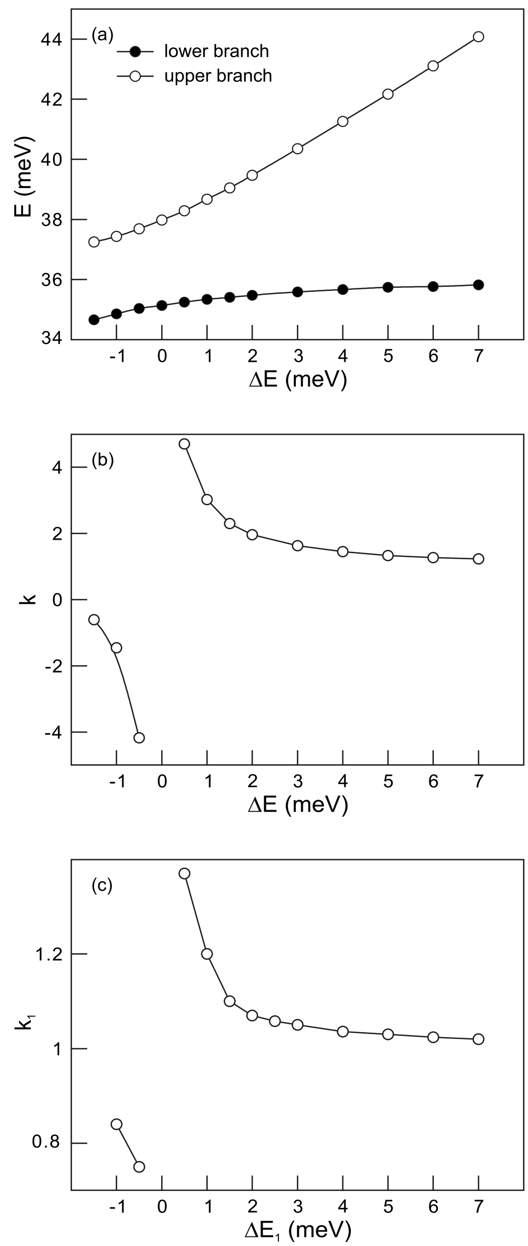

FIG. 3. Dependences of the upper and lower branches (a) and $k=\hbar^2(\Omega^2-\Omega_0^2)/\Delta E^2$ on $\Delta E=E_2-E_1-\hbar\omega_{LO}$ (b), and $k_1=\hbar^2(\Omega^2-\Omega_1^2)/\Delta E_1^2$ vs $\Delta E_1=\Delta E_L+E_2-E_1-\hbar\omega_{LO}$ (c) at $N_e=2\times10^{16}$ cm^{-3}. ΔE_L is Lamb shift and $\hbar\Omega_1$ is the Rabi splitting for $E_2-E_1+\Delta E_L=\hbar\omega_{LO}$. The lines are guides to eyes.

Third, in the simplest interpretation, the Rabi splitting can be considered as a result of coupling of two oscillators (mat-

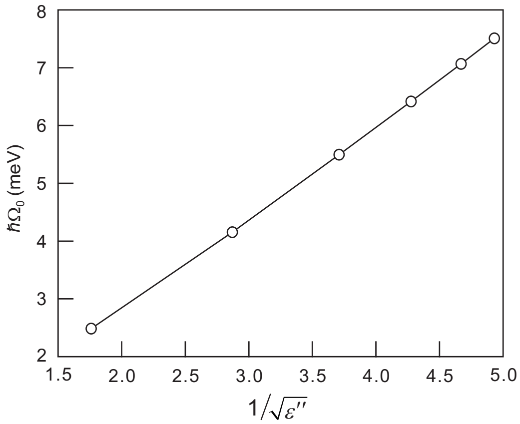

FIG. 4. Dependence of Rabi splitting $\hbar\Omega_0$ on $\sqrt{1/\varepsilon''}$ at $\omega=\omega_{LO}$ and $N_e=2\times10^{16}$ cm^{-3}.

ter and vacuum field) and therefore is proportional to the coupled field. Since the vacuum field in dielectric depends on the dielectric function as $1/\sqrt{\varepsilon}$,[29] the value of the Rabi splitting is expected to be proportional to $1/\sqrt{\varepsilon}$. In this case, one can set $\omega=\omega_{LO}$, resulting in $\varepsilon\approx i\varepsilon''$ $(\varepsilon'=0)$, because $\gamma \ll \omega_{LO},\omega_{TO}$. The dependence of Rabi splitting on $1/\sqrt{\varepsilon''}$ can be calculated at $N_e=2\times10^{16}$ cm^{-3}. The variation of ε'' was done by varying $\hbar\omega_{TO}$ from 34 to 10 meV while fixing $\hbar\omega_{LO}$ at 36.2 meV. It is seen from Fig. 4 that the Rabi splitting, $\hbar\Omega_0$, is indeed approximately proportional to $1/\sqrt{\varepsilon''}$.

In order to check our quantitative results, the simple Lorentz oscillator model[30] of the intersubband transition has been applied. The zz component of the dielectric tensor of total system (including both phonon and electron subsystems) may be written as follows:

$$\varepsilon(\omega)=\varepsilon_\infty\frac{\omega_{LO}^2-\omega^2-i\gamma\omega}{\omega_{TO}^2-\omega^2-i\gamma\omega}+\frac{N_e e^2 f}{m^*\varepsilon_0}\frac{1}{(\omega_{21}^2-\omega^2)-i\beta\omega}, \quad (5)$$

where ε_0 is the permittivity of free space and f, $\omega_{21}=(E_2-E_1)/\hbar$, and β are the oscillator strength, the frequency, and the damping constant of the intersubband transition, respectively. The oscillator strength is related to the dipole matrix element d: $f=(2m^*\omega_{21}d^2)/\hbar$. As mentioned above, the absorption peaks for a thin film can be determined at the resonance condition, $\mathrm{Re}[\varepsilon]=0$. Equating the expression in Eq. (5) to zero, one can find that the solution gives three frequencies (one of them at $\omega=\omega_{LO}$). Taking the dipole element for an infinitely deep quantum well,[17] we have found that the Rabi splitting at $N_e=2\times10^{16}$ cm^{-3} is about 2.21 meV. The model based on Eq. (1) gives a comparable value (2.82 meV) at the same electron concentration. As a final note, in order to check experimentally the predicted behaviors, it is suggested to use multiple quantum wells where the value of the splitting is higher than that for single quantum well.[13] Furthermore, photoconductive spectroscopy can be used to detect this Rabi-splitting behavior without the infrared absorption background from the various phonon sources in the system.[1]

We note that the spin-orbit interaction between electron spins and the electrical field in polar semiconductor low-dimensional systems can induce comparable energy splitting.[31] It has two contributions: Dresselhaus and Rashba interactions.[32] The electrical field in the former case is originated from the intrinsic inversion asymmetry of the bulk noncentrosymmetric materials (bulk inversion asymmetry), while the field in the latter contribution is induced by the asymmetric potential of the semiconductor quantum structures (structure inversion asymmetry). In general, this effect can occur in our system. Bandyopadhyay and Sarkar have theoretically predicted that the infrared absorption spectra of a quantum wire for linearly polarized light exhibit one prominent peak corresponding to the transitions between the two parallel spin states at the two subbands, respectively, ($|1,\uparrow\rangle\to|2,\uparrow\rangle$ and $|1,\downarrow\rangle\to|2,\downarrow\rangle$).[33] It is thus expected that for circularly polarized light, the transition between the two antiparallel spin states at the two subbands, respectively ($|1,\uparrow\rangle\to|2,\downarrow\rangle$ or $|1,\downarrow\rangle\to|2,\uparrow\rangle$), presents as single peak in the infrared absorption spectra, which is energy shifted from the peak in the previous case. The amount of the energy shift is equal to the spin-splitting energy. In the case of quantum wells, similar absorption spectra due to the spin-orbit interaction are expected, although no theoretical or experimental study has been reported. In our case, the influence of the spin-orbit interaction is negligible in the infrared absorption spectra with linearly polarized light, because the two parallel spin states at the two subbands, respectively, are shifted almost equally under the influence of the spin-orbit interaction. In contrast, the absorption peaks for circularly polarized light corresponding to the Rabi splitting are, however, influenced by the spin-orbit interaction effect. A comparison study between the absorption spectra with the two polarization schemes should help to resolve the Rabi splitting and the spin-splitting effects.

IV. CONCLUSIONS

In conclusion, we have predicted that the intersubband transition in the quantum well of a polar semiconductor can reveal Rabi splitting in absorption spectra without additional resonator and without coupling to any waveguide mode of the film. The value of Rabi splitting is increased with the electron concentration, which is similar to the resonator case. The absorption coefficient of the intersubband transition in polar quantum well is enhanced as compared to the one of the corresponding nonpolar semiconductor film. The enhancement depends on the splitting value. We also show that the Rabi splitting in our case depends on the dielectric function, as expected. Finally, the influence of the spin-orbit interaction effect in our case has been discussed.

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