Resonant Subband Landau Level Coupling in Symmetric Quantum Well

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Subband structure and depolarization shifts in an ultra-high mobility GaAs/Al0.24Ga0.76As quantum well are studied using magneto-infrared spectroscopy via resonant subband Landau level coupling. Resonant couplings between the 1st and up to the 4th subbands are identified by well-separated anti-level-crossing split resonance, while the hy-lying subbands were identified by the cyclotron resonance linewidth broadening in the literature. In addition, a forbidden intersubband transition (1st to 3rd) has been observed. With the precise determination of the subband structure, we find that the depolarization shift can be well described by the semiclassical slab plasma model, and the possible origins for the forbidden transition are discussed.

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Many terahertz (THz) radiation applications involve detecting or generating THz radiation using intersubband (ISB) transitions in a quasi-two dimensional electron system (2DES). Designing the 2D heterostructure optimized for desired THz applications demands a comprehensive understanding of the subband structure and ISB couplings. Many intended applications involves optical absorptions in their operations, which can be affected by the depolarization of the radiation. Subband structure and depolarization effect were extensively studied in the past, but the understanding of these subjects are more qualitative than quantitative and sometimes controversial. It is believed that depolarization shifts the absorption energies of the ISB transitions, but the magnitude of the depolarization shift has been calculated using various methods. The depolarization shift can be calculated numerically in the self-consistent calculation by calculating induced changes of the charge densities, but it is not always available and sometimes impossible given the circumstance of the system.

In the past, two of the analytical models have been developed for calculating the depolarization shifts. A semiclassical approach is to calculate the depolarization shift by approximating the 2DES as a slab plasma of thickness d filled with electrons. The depolarization-shifted ISB transition energy ˜ω10 is related to the classical plasma frequency ωp and ISB transition energy ω10 as ˜ω10 = ω10 + ωp2 where the effective plasma frequency ωp = (f10ωp2)1/2 and f10 is the oscillator strength of the optical transition. On the other hand, the depolarization shift was described by a microscopic model, in which the overlap of the subband wavefunctions has to be calculated. The shifted ISB transition energy is represented as ˜ω10 = ω10 + α10 + β10 where β10 represents the exchange interaction. The depolarization shift is represented by α10 and α10 is related to the overlap of the subband wavefunction φi(z) via S11 = ∫ −∞ ∞ dz [∫ −∞ ∞ d′z′ φi(z′)φj(z)]2. Both of the models have been used to calculate the depolarization shift and agree fairly well with the experimental results. Due to the uncertainty in the function form of the subband wavefunctions in many 2DES systems, it is not yet clear whether the depolarization shift is better described by the microscopic model that considers the wavefunction overlaps, or the semiclassical model that approximates the 2DES as a three dimensional plasma.

To evaluate the magnitude of the depolarization shift, one should first measure the ISB transition energies. ISB transitions have been investigated using optical intersubband-resonance (ISR) and mostly resonant subband Landau level coupling (RSLC). RSLC measures the ISB transition energies by coupling the in-plane cyclotron resonance (CR) orbital motion to the motion along the confinement axes with the presence of a magnetic field parallel to the 2DES. When the CR energy is brought close to the ISB transition energy, CR splits into two modes due to the resonant anti-level crossing of the Landau levels (LLs) belonging to different subbands. It was used to investigate subband structure in heterojunctions and parabolic quantum wells and (asymmetric) quantum wells. All of these works focused on the ISB transition between the two lowest subbands and the hy-lying subbands were identified by CR linewidth broadening. A symmetric QW eases the uncertainties arising from the gradient of the confining potential, the presence of the depletion charges, and subband’s diamagnetic shifts and offsets in k-space. We have selected an ultra-clean, 500 Å

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symmetrically doped Al$_{0.24}$Ga$_{0.76}$As/GaAs/Al$_{0.24}$Ga$_{0.76}$As QW ($n_s = 1.1 \times 10^{11}\text{cm}^{-2}$) and investigated its subband energies via RSLC by magneto-infrared (IR) spectroscopy at tilt angles from $10^\circ$ to $35^\circ$. In the symmetric QW, the subband wavefunction are better known, and thus the depolarization shift can be estimated more accurately using both of the analytical models. We find that the depolarization shift can be better described by the semiclassical slab plasma model and have observed a resonant coupling forbidden in the first order perturbation.

A set of magneto-IR spectra ($\theta = 25^\circ$) are displayed in Fig. 1 (b)-(d) and a schematic energy diagram is displayed in Fig. 1 (a). It is plotted in scale using the subband energies obtained from the self-consistent calculation, which excludes the depolarization shift. Since the 2DES enters the extreme quantum limit at around 2.2T, only the $n=0$ and $n=1$ LLs of the first subband need to be considered. At the resonance of the LL and ISB transitions, i.e. when the CR energy matches the ISB transition energy, split resonances result from the anti-level crossing between the $n=1$ LL of the first subband and the $n=0$ LLs of the higher subbands. With increasing magnetic field, the lower-energy mode transfers its integrated intensity to the higher-energy mode, as shown in Fig. 1 (b)-(d). RSLC to the hy-lying subbands are observed by the well-separated split resonance and the energies of the split resonance can be precisely extracted to study the ISB transitions to the hy-lying subbands.

The energies of the split resonance as a function of the magnetic fields at five different angles are plotted in Fig. 2. The dotted lines show the expected CR energies that scale with $\cos \theta$. We will refer the anticrossings as the first, second and third, ordered by their energies in ascending order. The energies of the split resonance around the first anticrossing can be well described by the coupled oscillator mode$^{26,27}$ with $m^* = 0.069m_e$, and $\tilde{\omega}_{10} = 57\text{cm}^{-1}$.

To get a picture of the transitions particularly for those resulting from the resonant coupling to the hy-lying subbands, coupled Schrödinger and Poisson equations are solved self-consistently in order to obtain the subband
FIG. 2. The energies of the split resonance as a function of magnetic field for different angles: (b) 10°, (c) 15°, (d) 25°, (e) 30° and (f) 35°. The solid lines are results of the self-consistent calculation including the depolarization shift. The dotted lines represent the expected CR energies that scale with \( \cos \theta \). The pinning energies extracted from the measurements are shown in open symbols, while the ones extracted from the self-consistent calculation are shown in solid symbols.
are listed in Table 1.

| $\omega_{10}$ | Exp. (cm$^{-1}$) | Theo. (depol.) | ex. depol. |
|--------------|-----------------|---------------|------------|
| $\omega_{20}$ | 116             | 116           | 110        |
| $\omega_{30}$ | 216             | 212           | 218        |

TABLE I. Measured subband energies: One column lists the experimental values for the anticrossings, while the other list the theoretical values when the depolarization effect is included (depol.) or excluded (ex. depol.).
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