Polaron Effects on Cyclotron Mass due to Interface and Slab Phonons in GaAs/AlGaAs Quantum Wells

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The effects of interface optical-phonon and confined slab LO-phonon modes on the polaron cyclotron resonance mass are investigated with considering the band non-parabolicity for a GaAs/$Al_xGa_{1-x}As$ quantum well. The polaron cyclotron frequency has been obtained from the peak positions in the magneto-optical absorption spectrum. The results of our calculation are in good agreement with the experimental results of the cyclotron mass.

In the last decade, polaron effects in two-dimensional (2D) semiconductor systems have received considerable attention[1−9]. Theoretical studies have shown that, only considering the confinement to the electrons and using bulk LO-phonon modes[1−6], the behavior of polaron Landau levels and cyclotron resonance (CR) mass in a 2D system is qualitatively similar to the 3D case. Recent studies[7−9] indicated that in narrow GaAs/AlAs quantum wells (QW) the electrons couple substantially to interface phonons and the magneto-polaron resonance is influenced considerably near the LO- and TO-phonon frequencies of GaAs and AlAs.

As far as we know, a detailed comparison of the theoretical calculations with the experimental results has not been reported in the literature even though a large amount of theoretical work has been done on the polaron effects due to the interface phonons in 2D semiconductor systems. In a previous work[8], we investigated the effects of interface optical-phonon and confined slab LO-phonon modes on the polaron cyclotron resonance (CR) frequency for a GaAs/AlAs QW. Our study focused on the magnetopolaron resonance effects due to the interface modes and the calculation based on a parabolic conduction band structure. In this paper, we calculate the polaron cyclotron mass obtained from the magneto-optical absorption spectra. Our calculation is improved by taking into account the band nonparabolicity of the 2D electron system and extended to GaAs/$Al_xGa_{1-x}As$ QW structures by considering the effective TO and LO phonon modes[7] in $Al_xGa_{1-x}As$ for $x \neq 1$. In the present work, for the first time, theoretical calculations of the polaron effects coming from the interface-optical- phonon modes are compared with the experimental results of the CR mass. Our results show that the polaron cyclotron mass obtained from the interface and the slab phonon modes is in good agreement with the experimental results in GaAs/$Al_xGa_{1-x}As$ QW.

In the presence of a magnetic field **B** applied in the z-direction perpendicular to the interface, the energy level of an electron is given by

$$E^0_{n,l} = E^z_l + \hbar\omega_c(n + 1/2) , \tag{1}$$

where E^z_l is the electric level ($l = 1, 2, ...$) corresponding to the motion in the z-direction, $\omega_c = eB/m_\parallel$ is the unperturbed cyclotron frequency, n is the Landau level index, and $m_\parallel$ is the electron band mass in the xy-plane. To compare theoretical results of the cyclotron mass with experiments, it is necessary to include the nonparabolicity of the conduction band in the calculation. Within three band **k.p** theory, the Landau level of the present system is given by[4,5]

$$E_{n,1} = -\frac{E_g}{2} + \frac{E_g}{2}\left(1 + 4\frac{E^0_{n,1}}{E_g}\right)^{1/2} \tag{2}$$

where $E_g = 1.52$ eV is the energy gap of GaAs. The cyclotron frequency with the correction of the nonparabolicity is given by

$$\omega_c^{np} = (E_{1,1} - E_{0,1})/\hbar \ . \tag{3}$$

Theoretically there are two different ways in calculating the polaron CR frequency. One, which is the most often used because of its simplicity, is by starting from the position of the polaron Landau levels, and the CR frequency is given by the difference between the Landau levels. The other is by calculating the magneto-optical absorption spectrum itself, and the CR frequency is determined by the position of the peaks in the absorption spectrum which is the quantity experimentally measured. Although the later procedure turns the numerical calculations more difficult, it is closer to the experimental situation. The advantage of this approach is that shows the relative importance of the different absorption peaks. Also, the Landau level broadening can be easily introduced. By considering the band nonparabolicity, the calculation of the magneto-optical absorption spectrum follows similar to that described in Ref. [8]. We introduce ω_c^{np} as the unperturbed CR frequency. Within the linear response theory, the polaron magneto-optical absorption is proportional to

$$\frac{-Im\Sigma(\omega)}{[\omega - \omega_c^{np} - Re\Sigma(\omega)]^2 + [Im\Sigma(\omega)]^2} \ , \tag{4}$$

where $\Sigma(\omega)$ is the so-called memory function. The memory function with the contributions of interface and slab phonon modes as well as the effect of band nonparabolicity is written as

$$\Sigma(\omega) = \frac{1}{\omega}\int_0^\infty dt(1 - e^{i\omega t})ImF(t) \tag{5}$$

with

$$F(t) = -\sum_j \sum_{\vec{q}_\parallel} \frac{q_\parallel^2}{\hbar m_\parallel} |<1|\Gamma_j(\vec{q}_\parallel, z)|1>|^2 \exp\left(-\frac{\Gamma^2 t^2}{4} - \frac{\hbar^2 q_\parallel^2}{2m_\parallel \omega_c^{np}}(1 - e^{-i\omega_c^{np} t} - i\omega_j(q_\parallel)t\right) \ , \tag{6}$$

where $\Gamma_j(q_\parallel, z)$ is the coupling function (see Ref. [7]) which describes the strength of the coupling of a single electron at the position z with the j-th optical-phonon mode with the dispersion relation $\omega_j(q_\parallel)$. There are four types of optical-phonon modes interacting with the electrons[7] in the present system, *i.e.,* symmetric and antisymmetric interface modes, confined slab modes in the well, and half-space modes in the barrier layers. We have found that, similarly to the case of the GaAs/AlAs QW with a parabolic band, only the symmetric interface modes and the confined slab modes are important for the polaron CR. The contribution coming from the other modes can be neglected.

The memory function has been calculated including the Landau level broadening Γ. In the calculation, we take $\Gamma = 1.8$ meV which is a typical level broadening width in GaAs QW. Fig. 1 shows the magneto-optical absorption spectrum at different magnetic fields for a 100 Å GaAs/AlAs QW. In order to see the effect of the nonparabolicity on the polaron absorption spectrum, we depict the results with and without the nonparabolicity effect represented by the thick and thin curves, respectively. It is seen that, for a fixed magnetic field, there are three different absorption peaks. The first one is located below the LO-phonon frequency ω_{LO} of GaAs, The second one is between the LO-phonon frequencies of GaAs and AlAs. And the third is above ω_{LO} of AlAs. This result is very different from the previous results by using 3D LO-phonon modes where only two absorption peaks are found around ω_{LO} of GaAs. The dashed upward arrow indicates the cyclotron resonance peak for $\omega_c = 0.8\omega_{LO}$ which has zero linewidth. We also observe that, due to the effect of the band nonparabolicity, all the three absorption peaks shift to lower frequencies. However the absorption strength of the first peak is enhanced while the other two become weaker.

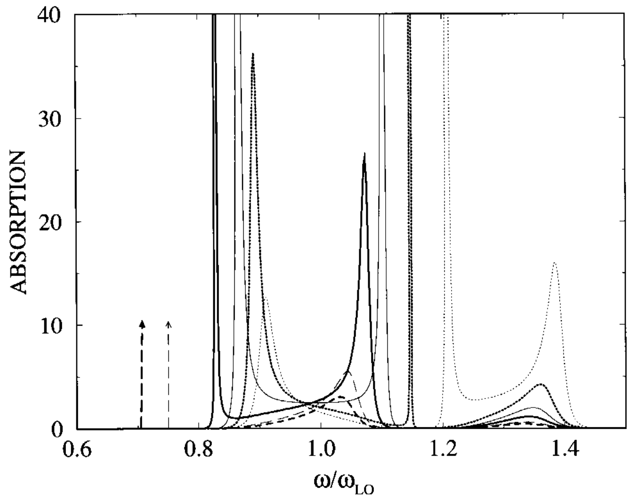

Figure 1. The magneto-optical absorption spectrum for a 100 Å GaAs/AlAs QW at different magnetic fields. The thick and thin curves present the results with and without the band non- parabolicity effect, respectively. The dashed, solid and dotted curves refer to $\omega/\omega_{LO} = 0.8, 1.0$ and 1.2, respectively.

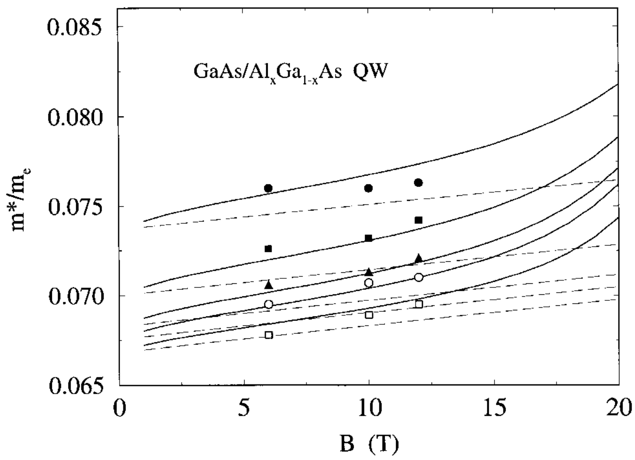

Figure 2. The magnetic field dependence of the CR mass in GaAs/$Al_x Ga_{1-x}$As QW. Experimental results[10] for different QW are indicated by solid circles (W=58 Å, x=0.25), solid squares (W=95 Å, x=0.26), solid triangles (W=144 Å, x=0.23), open circles (W=194 Å, 2=0.26), and open squares (W=373 Å, x=0.26). The corresponding calculated results are given by the thin dashed curves (with non-parabolicity only) and solid curves (with polaron effects).

In a cyclotron resonance experiment, the CR frequency ω^* is related to the transition between $E_{0,1}$ and $E_{1,1}$. Consequently, the polaron CR mass m^* is defined by

$$\frac{m^*}{m_{\|}} = \frac{\omega_c}{\omega^*} \tag{7}$$

The CR frequency ω^* is determined by the peak position in the absorption spectrum.

Fig. 2 shows the CR mass as a function of magnetic field for different GaAs/$Al_x Ga_{1-x}$As QW. The corresponding CR frequency is obtained from the position of the absorption peak with lowest frequency. Our calculation demonstrates that, by including the band non-parabolicity, the calculated polaron CR mass by taking the interface and slab modes into account is in quite good agreement with experimental results[10].

In summary, the polaron cyclotron mass has been obtained from the absorption spectrum taking into account the interface and confined slab phonon modes for GaAs/$Al_x Ga_{1-x}$As QW. The effect of the band nonparabolicity was also included in the study of the polaron effects due to the interface and slab phonon modes. We showed that in order to compare the calculated CR mass with experimental results, the polaron as well as the band nonparabolicity effects have to be considered on equal footing. Our calculation results are in good agreement with experimental measured cyclotron mass.

Acknowledgments

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