Giant vacuum-field Rabi splitting of intersubband transitions

E. Dupont, J. A. Gupta and H. C. Liu

***Abstract*— A 42 meV vacuum-field Rabi splitting was observed between the upper and lower intersubband polariton branches of a moderately *n*-doped GaAs-AlGaAs multiple quantum well sample. For this structure, the Rabi energy represents 17% of the bare intersubband resonance. A new phenomenon is also demonstrated: the occurrence of a higher mode polariton.**

***Index Terms*— vacuum-field Rabi energy, intersubband transitions, cavity**

I. Introduction

In the present abstract, we show that, the vacuum Rabi frequency in QWIP structures scales as the square root of the doping density, as predicted by the classical model [1]. In the highest doped structure, we observe a vacuum Rabi splitting energy of 42 meV for an intersubband resonance at 123 meV. From the same structure, we report a strong absorption peak between the two polaritons branches, on the low energy side of the intersubband resonance. We show that this feature is related to the proximity of the $m = 1$ excited mode of the low quality factor and highly dispersive cavity. According to Ref. [2], the effect of ultrastrong coupling is already non-negligible in our moderately doped QWIP, i.e. the polariton state cannot be simply described by a linear combination of photon and intersubband excitations.

II. Experiments

The MQW structures of this study were designed as the core of a single-side surface plasmon waveguide similarly to those described in Ref. [3]. The number of periods was adjusted in order to overlap the intersubband resonance with the resonant mode of the waveguide at Brewster incidence on the cleaved facet. They consist of a 160-repeat MQW structure embedded between two n^+ GaAs contact layers. The wells are center delta-doped with Si to 2×10^{10} cm^{-2} (Wafer L) or 2×10^{11} cm^{-2} (Wafer M). The structural parameters of the two wafers (except for the delta-doping level) are similar, which suggests that the two cavities are identical. A mirror was deposited on the epilayers and 4 mm-long samples were cleaved. At a particular wavelength and internal incidence, the incoming beam can excite a slab waveguide mode and can subsequently be absorbed in the contacts and in the MQW.

The spectroscopic measurements are summarized in Fig. 1 and 2 respectively for Wafer L and M. From the Brewster transmittance and the 45° zigzag measurements, we derived the product between the oscillator strength f_{12} and free carrier concentration N_s. We get $N_s f_{12} = 1.68\times10^{10}$ and 1.92×10^{11} cm^{-2} for Wafer L and Wafer M respectively. From the topmost spectrum of Fig. 1, the absorption peak appears to consist of two Lorentzians centered at 950 and 965 cm^{-1} suggesting the occurrence of inhomogeneous broadening in Wafer L.

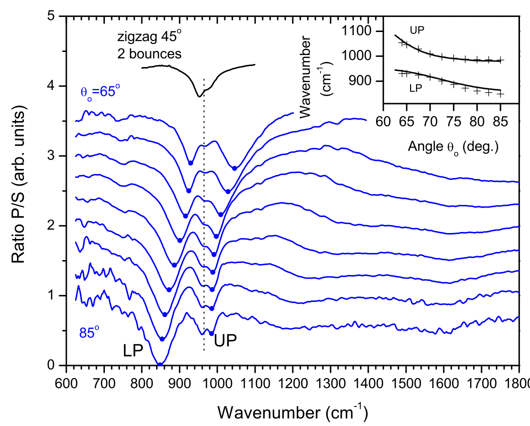

Fig. 1. Normalized ratios between *P*-polarized and *S*-polarized transmittance at 80 K of the waveguide sample made from Wafer L for different external angles θ_o. The top curve represents the *P/S* ratio for a two-bounces 45° zigzag waveguide. The vertical dashed line represents the centroid position of the absorption peak. The inset plot shows the resonance positions of the upper (UP), lower (LP) polaritons versus the external angle; the crosses (+) are experimental points and the solid line represents the theoretical calculation based on a semiclassical model.

The minimum separation between the lower and upper polariton branches is about 93 cm^{-1} at $\theta_o \sim 70°$ for Wafer L and 336 cm^{-1} (42 meV; $\Omega_R = 21$ meV) at $\theta_o \sim 80°$ for Wafer M. The ratio between the vacuum Rabi splitting of the two structures, 336 cm^{-1}/93 cm^{-1} = 3.61, is consistent with the square root dependance of vacuum-Rabi energy on the number of oscillators, i.e. $\sqrt{1.92\times10^{11}\ \text{cm}^{-2}/1.68\times10^{10}\ \text{cm}^{-2}} = 3.38$. The plots in the insets of Fig. 1 and 2 represent the experimental frequencies of the upper and lower polaritons as a function of the outside angle θ_o and the theoretical results of these resonances. One can see that the agreement between the experimental results and theory is very satisfactory.

Qualitatively, the full-width at half maximum of the polariton branches on both samples behaves normally. As the branches get closer to the bare intersubband frequency, the broadening of the polariton resonances decreases since the

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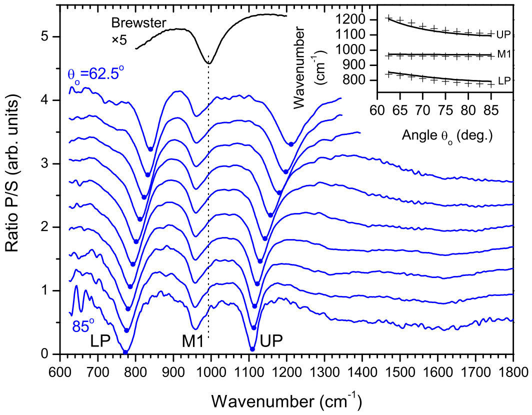

Fig. 2. Summary plot for Wafer M. The caption is similar to that of Fig. 1. Additionally, the inset plot shows the experimental (+) and predicted (solid line) frequencies of the higher mode (M1) polariton. The top curve is the P-transmission at Brewster angle with a five-fold expansion of the vertical scale.

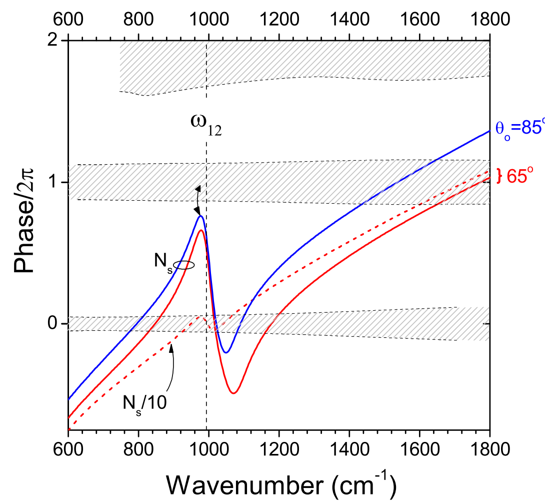

Fig. 3. Calculated phase versus wavenumber for TM-polarized light during a double-pass in the cavity for different external angles θ_o and doping concentrations. The parameters used for the simulations are : $N_s f_{12} = 1.92 \times 10^{11}$ cm^{-2}; $\omega_{12} = 993$ cm^{-1}; $\Delta\omega_{12} = 55$ cm^{-1}; n-contact layers doped to 2.24$\times 10^{18}$ cm^{-3} and mobility of 4240 cm^{2}V^{-1}s^{-1}. The gray horizontal regions represents the finesse of the cavity resonances. The vertical dashed line shows the position of the intersubband resonance. The double black arrow shows the proximity of the excitation of a $m = 1$ polariton.

quality factor of the intersubband oscillator (Q_{ISB} $\sim$20) is higher than the photon mode (Q_{cav} $\sim$16.5 (12) at 860 (1130) cm^{-1}). However, with the semiclassical model used in this work, an exact fitting of the broadening of the polariton resonances, could not be obtained. We used a Lorentzian intersubband dispersion in the dielectric function of the QWs. In Fig. 2, this resonance appears narrower ($\sim$33 cm^{-1} at $\theta_o = 85°$) than the bare intersubband oscillator ($\Delta\omega_{12} = 55$ cm^{-1}), while the Q_{cav} of an empty cavity corresponds to a large broadening ≥ 90 cm^{-1}. The narrowing of UP polariton branch when the frequency of the empty cavity $m = 0$ mode approaches the intersubband frequency suggests that the electronic excitation is strongly inhomogeneous [4].

The polariton tuning curves of Wafer L is very similar to what was reported in Ref. [3]. The observed central dip between the two polariton branches is associated with the low Q_{cav} of the cavity and the narrow intersubband resonance. However, the polariton tuning curves of Wafer M look different from those of Wafer L between the two main branches. One observes a peak between 958 and 962 cm^{-1}, called M1 in Fig. 2, which is fairly detuned from the intersubband resonance $\omega_{12} = 993$ cm^{-1}. Simple calculations indicate that the feature M1 is related to the occurrence of a higher mode polariton. We calculated the phase shift of a TM-polarized light during the propagation along a double-pass through the cavity. Provided the cavity is not strongly damped, cavity resonances occur when the phase is a multiple of 2π. The phase calculation is summarized in Fig. 3.

The finesse of the cavity is calculated for an empty cavity ($N_s = 0$) is represented as gray horizontal regions around $m = 0, 1, 2$. The phase spectra in Fig. 3 cross the $m = 0$ resonance at the polariton frequencies and near the intersubband resonance, this latter being strongly damped. For a N_s doping and for frequencies close to $\omega_{12} - \Delta\omega_{12}/2$, the intersubband dispersion is high enough to move the cavity close to next $m = 1$ mode. Because the finesse of our resonator is small, the coupling to the $m = 1$ mode is tolerated even though the phase does not reach 2π.

III. Conclusion

We have demonstrated a vacuum Rabi frequency of the order of the bare intersubband frequency in a moderately doped MQW structure. At 17% of the intersubband frequency, the cavity is expected to experience some effects due to the ultrastrong coupling regime. Additionally, we have demonstrated the square-root dependance of the vacuum Rabi energy versus the number of oscillators, the mixed photon-like and electron-like nature of the polaritons, the occurrence of a higher-mode polariton and finally, the inhomogeneous broadening of the intersubband excitations.

References

[1] Y. Zhu, D. J. Gauthier, S. E. Morin, Q. Wu, H. J. Carmichael, and T. W. Mossberg, “Vacuum Rabi splitting as a feature of linear-dispersion theory: Analysis and experimental observations,” *Phys. Rev. Lett.*, vol. 64, pp. 2499–2502, 1990.

[2] C. Ciuti, G. Bastard, and I. Carusotto, “Quantum vacuum properties of the intersubband cavity polariton field,” *Phys. Rev. B*, vol. 72, p. 115303, 2005.

[3] E. Dupont, H. C. Liu, A. J. SpringThorpe, W. Lai, and M. Extavour, “Vacuum-field Rabi splitting in quantum-well infrared photodetectors,” *Phys. Rev. B*, vol. 68, p. 245320, 2003.

[4] R. Houdré, R. P. Stanley, and M. Ilegems, “Vacuum-field Rabi splitting in the presence of inhomogeneous broadening: Resolution of a homogeneous linewidth in an inhomogeneously broadened system,” *Phys. Rev. A*, vol. 53, no. 4, pp. 2711–2715, 1996.