Vacuum Rabi coupling enhancement and Zeeman splitting in semiconductor quantum microcavity structures in a high magnetic field

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Reflectivity spectra of high-quality quantum microcavity structures are investigated in high magnetic fields from 0 to 14 T. Over this field range we observe an increase in the vacuum Rabi splitting by a factor of 1.4, due to the magnetic-field-induced increase of exciton oscillator strength. In addition, exciton Zeeman splitting is seen. We demonstrate that this splitting arises from the independent interaction of each exciton spin component with the corresponding circularly polarized cavity photon mode. We also report anomalous broadening of the higher-energy polariton feature in high magnetic field, raising doubts that the same broadening seen at zero magnetic field is due to coupling of the cavity mode with higher discrete and continuum exciton states. [S0163-1829(96)52216-2]

In this paper we discuss the effects of magnetic field on exciton-photon vacuum Rabi coupling in semiconductor quantum microcavity (QMC) structures. The photon properties are controlled by the Fabry-Pérot mode of the cavity and the exciton by quantum wells (QW's) embedded in the cavity. In our high-quality structure the exciton and cavity modes have linewidths significantly narrower than the vacuum Rabi splitting, so that on resonance the resulting polariton modes are observed as two well-resolved peaks of equal intensity. The coupling strength and hence the vacuum Rabi splitting has an approximately square-root dependence on the exciton oscillator strength when the splitting is significantly greater than the exciton and cavity linewidths, as is the case in this paper.

The first observation and study of vacuum Rabi splitting was by Weisbuch *et al.*,[1] followed by further studies by Stanley and co-workers.[2–4] In these studies and others[5,6] the cavity is tuned through the exciton by changing the probe spot of the exciting source. In our previous work we have used both temperature[7] and electric field[7,8] for tuning the exciton through the cavity mode. By using temperature to keep the exciton and photon on resonance we have shown how the reduction in exciton oscillator strength, due to electric field, reduces the vacuum Rabi coupling strength.[7–9]

In the present paper we discuss several magnetic-field effects on the coupled polariton state. In this case increasing magnetic field increases the exciton oscillator strength. Again, using temperature to keep the polariton on resonance we find that an increase in field from 0 to 14 T increases the splitting by a factor of 1.4. Interestingly, for fields, $B \geqslant 6.6$ T clearly resolved Zeeman splitting is seen on the lower-energy branch of the polariton. Transfer matrix reflectivity (TMR) simulations and circular polarization measurements show that the spin components of the exciton are fully decoupled, with each exciton spin component interacting with the appropriate circularly polarized component of the photon mode. Using the TMR simulations we deduce the increase in exciton oscillator strength and Zeeman splitting in the field range 0 to 14 T. In previous magnetic-field work on microcavities Tignon *et al.*[10] reported tuning of the cavity mode through several higher-energy Landau levels. They also inferred the effects of increased exciton oscillator strength on the vacuum Rabi splitting from the study of spectra near resonance.

The QMC structure discussed in this paper consists of a λ GaAs cavity, sandwiched by two distributed Bragg reflectors (DBR's). The DBR's each consist of 20 periods of quarter-wavelength layers of AlAs (low refractive index) and $Al_{0.13}Ga_{0.87}As$ (high refractive index). Three 100-Å-wide $In_{0.13}Ga_{0.87}As$ QW's are located centrally in the cavity at the antinode of the cavity photon mode. The structure is designed so that the wavelength of the lowest-energy heavy-hole exciton (HH_x) transition is the same as that of the cavity length. Since the QW is strained only the lowest-energy heavy-hole exciton is observed. The reflectivity spectra are measured using white light illumination.

With increasing magnetic field the exciton is expected to increase in oscillator strength due to shrinkage of the exciton wave function. In addition, there is an upshift in the excitonic transition energy. To study the effect of magnetic field on the on-resonance polariton, resonance is maintained at each field by varying the temperature; temperature decreases the transition energy without altering the oscillator strength.[7] The exciton linewidth does not vary significantly over the temperature range used, up to 100 K.[11] Therefore the observed changes in the spectra are due only to magnetic-field-induced effects.

Figure 1(A) shows the on-resonance vacuum Rabi coupled reflectivity spectra at various magnetic fields. At $B = 0$ T the polariton is on resonance at a temperature of 27 K, and at the highest field of 14 T it is on resonance at $T = 95$ K.[12] At $B = 0$ T the polariton is observed as two well-resolved coupled peaks with linewidths (full width at half maximum) of 0.95 and 1.25 meV, much narrower than the vacuum Rabi splitting (Ω_{HH_x}) of 5.1 meV. The higher-energy peak is broader than the lower-energy peak. We return to this point later in the paper.

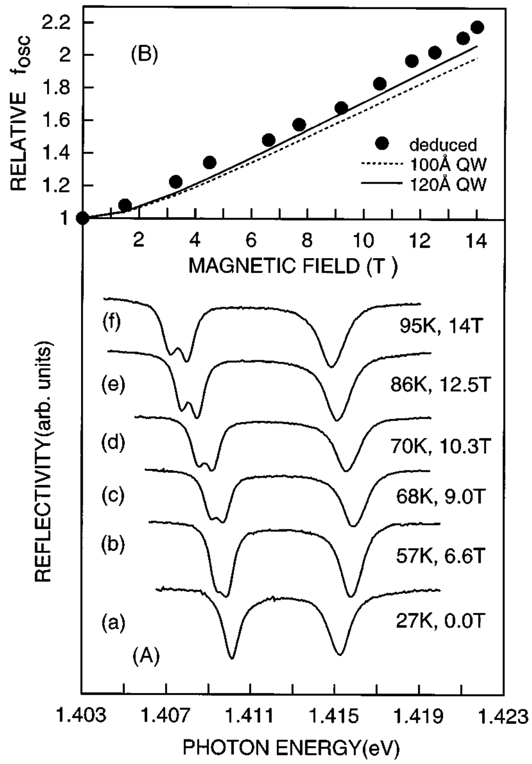

FIG. 1. (A) On-resonance reflectivity spectra, shown from $B=(a)$ 0 T to (f) 14 T. The spectra are kept on-resonance by increasing the temperature with increasing magnetic field. (B) Exciton oscillator strengths deduced from the experimental reflectivity spectra, using the transfer matrix reflectivity model (solid circles). These are in good agreement with predicted oscillator strengths from QW exciton calculations for a 120-Å QW (solid line). The prediction for a 100-Å QW is also shown (dashed line).

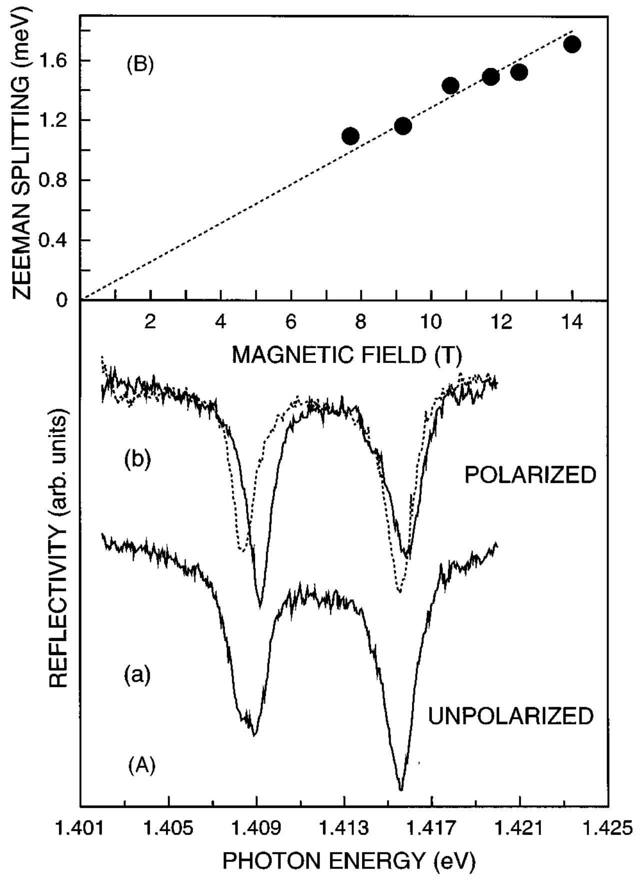

FIG. 2. (A) Curve (a): unpolarized spectra close to resonance at $B=12$ T, $T=85$ K. Curve (b): circularly polarized σ^+ (solid line) and σ^- (dashed line) spectra. (B) Deduced exciton Zeeman splitting as a function of magnetic field, from transfer matrix reflectivity simulations of the spectra in Fig. 1(A). The dashed line is a guide to the eye.

As the field is increased Fig. 1(A) clearly shows an increase in Ω_{HH_x} from 5.1 meV at $B=0$ T to an average of 7.2 meV at 14 T, with the features becoming even better resolved. In addition, at $B=6.6$ T an additional weak splitting is observed on the low-energy peak, becoming very clearly resolved at $B=14$ T. This splitting, attributed to exciton Zeeman splitting, increases from 0.4 meV at 6.6 T to 0.8 meV at 14 T. To confirm this attribution, circular polarization measurements were performed. Figure 2(A), curve (a) shows unpolarized spectra close to resonance, taken at $B=12$ T and $T=85$ K. The circularly polarized σ^+ (full line) and σ^- (dashed line) excited reflectivity spectra are shown in Fig. 2(A), curve (b). The spectra are seen to be very strongly polarized, supporting the Zeeman splitting interpretation.

To simulate the observed reflectivity spectra with the TMR model it is necessary to assume each spin component of the exciton interacts only with the appropriate circularly polarized component of the photon mode. The spectrum is calculated for each spin, using the whole inhomogeneous linewidth of the exciton spin component, and then added to reproduce the full unpolarized spectrum. We term this the independent exciton model. The exciton oscillator strength (f_{osc}) at each field is deduced from the simulations, by varying f_{osc} in the simulations until the simulated vacuum Rabi splitting agrees with the observed value. The exciton Zeeman splitting is deduced by varying the separation of the unperturbed σ^+ and σ^- excitons, until the simulated splitting on the low-energy peak is the same as the observed value on the unpolarized spectra. The value for the unperturbed cavity linewidth is obtained from experimental spectra where the cavity is not strongly coupled with the exciton. The exciton linewidth is adjusted in the simulated spectra until the resolution of the Zeeman split polariton peaks is the same as the low-energy polariton peak in the experimental spectra.

The deduced values of the exciton oscillator strength as a function of magnetic field are plotted in Fig. 1(B) as circles. Increasing the magnetic field from 0 to 14 T increases the oscillator strength by a factor of 2.2, corresponding to the increase in vacuum Rabi splitting of 1.4. QW exciton calculations were performed, which use a numerical solution of Schrödinger's equation for a finite QW with decoupled heavy- and light-hole bands.[13] The predicted changes in oscillator strength, normalized to unity at $B=0$, are shown in Fig. 1(B) for 100-Å (dashed line) and 120-Å (solid line) QW's. Very reasonable agreement is found between the deduced change in f_{osc} and the calculated values for a 120-Å QW.[14]

Our on-resonance ($B=12$ T, $T=85$ K) experimental [Fig. 3, curve (a)] and simulated [Fig. 3, curve (b)—solid line] spectra are in very reasonable agreement.[15] If, however, the two spin components of the exciton are treated as

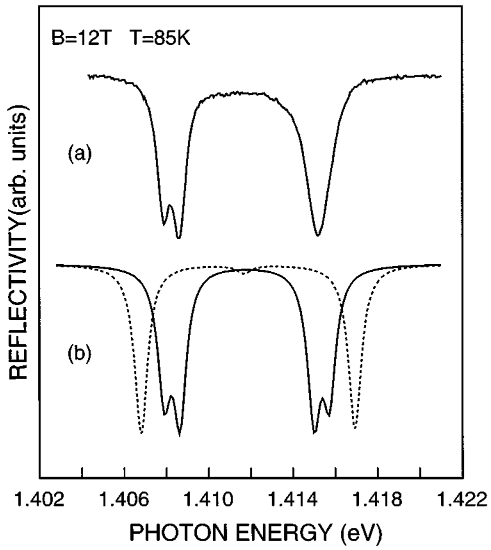

FIG. 3. On-resonance reflectivity spectra at 12 T showing (a) the experimental spectra at 85 K and (b) the corresponding simulated spectra (solid line). The overall agreement between the experiment and simulations is very good. The dashed line shows a simulation assuming the Zeeman split excitons interact with the same photon mode (dashed line), which does not agree with the observed spectra.

both interacting with the same cavity mode three peaks are predicted [dashed line in Fig. 3, curve (b)] with the two strong outer peaks having a greater vacuum Rabi splitting than the original simulation. To reproduce the experimental vacuum Rabi splitting it is necessary to use an oscillator strength of half the value used in the independent exciton model. That is, if two excitons interact with the same cavity mode their oscillator strengths both contribute to the vacuum Rabi splitting. However, the Zeeman-related splitting observed experimentally on the low-energy peak is not seen in these simulations. These results add strong support to the independent exciton model, in agreement with the conclusions of the circular polarization measurements.

The exciton Zeeman splittings deduced with the independent exciton model, for fields where the observed splitting is well resolved, are plotted in Fig. 2(B). The Zeeman splitting increases from 1.0 meV at 6.6 T to 1.7 meV at 14 T. These values are approximately twice that of the observed unperturbed splitting on the low-energy peak at resonance (0.4–0.8 meV), as expected from perturbation theory arguments.[16] We compare our value of the Zeeman splitting at 11 T of 1.4 meV to the value of 2.3 meV at 11 T for a 100-Å QW, reported by Wimbauer *et al.*[17] but for indium composition, $x=0.18$ (in our structure $x=0.13$). However, Traynor *et al.*[18] have reported strong dependence of the Zeeman splitting on x (and well width), with an approximately factor of 2 increase between $x=0.075$ and $x=0.11$. In view of this strong dependence on x we regard our deduced value of spin splitting as being in reasonable agreement with the result of Ref. 17.

We now discuss some interesting points raised by the simulations. Figure 3, curve (a) shows the $B=12$ T, $T=85$ K on-resonance experimental spectra, with the clearly resolved Zeeman-related splitting on the low-energy peak, but not the high-energy peak. The TMR simulations of the same spectra [Fig. 3, curve (b)—solid line] show four

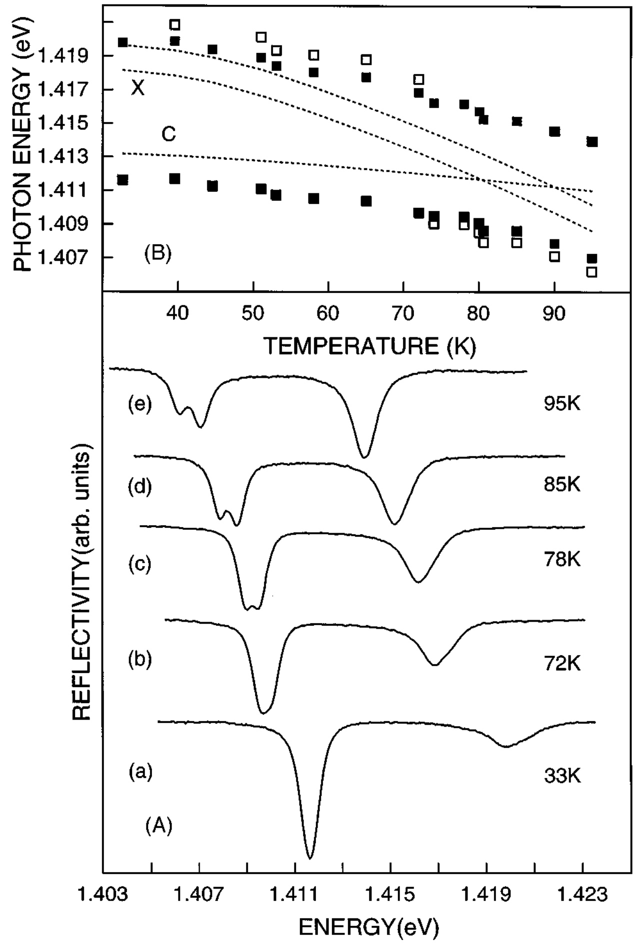

FIG. 4. (A) Experimental reflectivity spectra at $B=12$ T showing tuning of the exciton through the cavity mode by temperature. The exciton Zeeman-related splitting is only clearly resolved close to resonance. (B) Plot of the peak positions versus temperature. Dashed lines show the unperturbed Zeeman split exciton and cavity mode energies.

clearly resolved states, as expected. The polarization spectra of Fig. 2(A), curve (a) show there are two reasons why the Zeeman-related splitting is not resolved on the high-energy peak. First the higher-energy polariton peak is broader in both polarizations, but, in addition, the splitting between the two high-energy polarized peaks (0.25 meV) is less than that of the low-energy peaks (0.85 meV). Neither feature is understood at present. In particular, the broadening on the high-energy peak at zero field has been suggested as being due to coupling with higher discrete and continuum exciton states.[2] At high fields the same broadening is seen. However the splitting between the $1s$ state and all higher-energy exciton states will be significantly increased in magnetic field. For example, at 12 T the first Landau level, which derives from the zero-field $2s$ state, is expected to be ~35 meV higher in energy than the $1s$ state,[19] and thus is not expected to contribute to the coupling of the lowest $1s$ exciton state with the photon mode. This clearly raises doubts as to whether the original suggestion as to the origin of the high-energy broadening at zero field is correct.[2]

Tuning of the exciton feature through the cavity mode at 12 T by variation of the temperature from 32 to 95 K is shown in Fig. 4(A). At $T=32$ K, the predominantly exciton feature is at higher energy than the cavity mode, and is relatively weak. The exciton Zeeman splitting can only be seen as a weak shoulder. As the temperature is increased the energy of the predominantly exciton feature decreases and approaches that of the cavity mode. The intensity of this feature increases until at $T=85$ K, the on-resonance polariton is formed and two main features of equal intensity are seen. At temperatures higher than this the exciton moves to lower energy and the predominantly exciton feature weakens. The peak positions are plotted in Fig. 4(B). The dashed lines are the estimated positions of the unperturbed Zeeman split excitons and cavity mode with temperature, following the procedure described in Ref. 7.

For low temperatures where the exciton is at higher energy than the cavity the Zeeman splitting is not well resolved, and is only seen as a shoulder on the predominantly exciton high-energy feature. The exciton couples more strongly as resonance is approached and the Zeeman related splitting becomes more strongly resolved on the low-energy peak [for example, Fig. 4(A), curve (c) at $T=78$ K]. It should be noted that the Zeeman-related splitting off resonance (0.9 meV at $T=95$ K) is greater than that for the on-resonance spectra (0.7 meV at $T=85$ K). As discussed previously, on resonance the observed splitting on resonance will be approximately half that of the actual Zeeman splitting.[16] As the exciton moves further off resonance the splitting approaches that of the actual Zeeman splitting [1.5 meV at 12 T, taken from Fig. 2(B)], as observed in the $T=95$ K spectra [Fig. 4(A), curve (e)].

In conclusion, we have reported the effects of magnetic field on the reflectivity spectra of high-quality quantum microcavity structures. The effects of magnetic-field-enhanced oscillator strength and of Zeeman splitting have been clearly demonstrated. We show that each spin component of the exciton interacts independently with only the appropriate circularly polarized photon mode. Broadening seen on the high-energy polariton peak at high magnetic fields raises serious doubt as to whether the same broadening seen at zero magnetic field can be due to coupling with higher discrete and continuum exciton states.

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[12] It should be noted that in zero-magnetic-field experiments in Ref. 8 there was no discernible difference between on-resonance spectra at 95 or 6 K.

[13] Values of the input parameters used for the QW exciton calculations are indium concentration ($x=0.13$) and in-plane electron and hole masses ($In_{0.13}Ga_{0.87}As$, $m_e=0.07m_0$, $m_h=0.13m_0$; GaAs, $m_e=0.07m_0$, $m_e=0.35m_0$).

[14] In the electro-optic tuning experiments of the same sample (Ref. 8) a well width of 120 Å was required to reproduce the unperturbed exciton shift rate with electric field.

[15] The off-resonance cavity linewidth of 0.95 meV, and σ^+ and σ^- exciton linewidths of 0.7 meV were used in the simulations of Fig. 3(b), and for the simulations which lead to the deductions of oscillator strength and Zeeman splittings of Figs. 1(B) and 2(B).

[16] This result is obtained from degenerate perturbation theory from the solution of the 2×2 matrix for one spin component of the exciton and the appropriate circularly polarized cavity mode interacting via a potential $\Omega_{HH_x}/2$. For the exciton component Zeeman shifted by an energy $\delta \ll \Omega_{HHx}$ from its uncoupled on-resonance position, the eigenvalue equation is $E=[\delta \pm(\Omega_{HH_x}^2+\delta^2)^{1/2}]/2$, with solutions $(\delta\pm\Omega_{HH_x})/2$. Thus the two coupled mode peaks derived from one sense of electron spin are shifted by $\delta/2$ from the position without spin splitting. The Zeeman splitting observed on resonance is therefore expected to be one-half the actual exciton Zeeman splitting.

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