PHYSICAL REVIEW B VOLUME 56, NUMBER 16 15 OCTOBER 1997-II

Polarization-dependent phenomena in the reflectivity spectra of semiconductor quantum microcavities

D. Baxter, M. S. Skolnick, and A. Armitage
Department of Physics, University of Sheffield, Sheffield S3 7RH, United Kingdom

V. N. Astratov
Department of Physics, University of Sheffield, Sheffield S3 7RH, United Kingdom
and A. F. Ioffe Physico-Technical Institute, 194021 St. Petersburg, Russia

D. M. Whittaker
Toshiba Cambridge Research Centre, Cambridge CB4 4WE, United Kingdom

T. A. Fisher*
Department of Physics, University of Sheffield, Sheffield S3 7RH, United Kingdom

J. S. Roberts
Department of Electronic and Electrical Engineering, University of Sheffield, Sheffield S1 3JD, United Kingdom

D. J. Mowbray
Department of Physics, University of Sheffield, Sheffield S3 7RH, United Kingdom

M. A. Kaliteevski
A. F. Ioffe Physico-Technical Institute, 194021 St. Petersburg, Russia
(Received 12 May 1997; revised manuscript received 7 August 1997)

Angular-dependent reflectivity techniques are employed to probe the exciton-polariton states of a semiconductor quantum microcavity. The spectra exhibit marked polarization dependence, with the energies, line widths, and intensities all differing between transverse-electric and transverse-magnetic polarizations, consistent with the predictions of transfer-matrix simulations. In addition, anomalous narrowing of the spectra on resonance, broadening of the cavity mode by interaction with exciton continuum states and interaction of the cavity mode with quantum-well excited-state transitions are reported. [S0163-1829(97)52040-6]

Cavity polaritons are the coupled exciton-photon eigenstates of semiconductor quantum microcavities (QMC's).[1–3] In the strong-coupling regime the excitations of the system oscillate between the two polariton modes, before decay occurs through leakage of the photon mode from the cavity. In the present paper angular-dependent reflectivity is employed to investigate polarization-dependent properties of cavity polaritons. The reflectivity spectra are found to exhibit marked polarization dependence, with clear differences in dip energy, line width, and intensity being found between transverse electric (TE) and transverse magnetic (TM) incident polarizations. In addition motional narrowing of the spectra on resonance, interaction with excited quantum well (QW) levels and broadening of the cavity mode due to absorption from exciton continuum states are reported. Angular-dependent studies of QMC's have been reported previously, but with focus on photoluminescence processes,[2,4] and on enhancements of Raman cross sections and the role of polaritons in Raman scattering.[5]

QMC's are designed such that their optical length is an integer or half-integer multiple of the wavelength of QW excitons in the cavity. The lowest-order photon mode has quantized wave vector along the cavity axis given by $k_z = 2\pi/L$, where L is the length of the cavity. The in-plane photon dispersion, by contrast, is not quantized. As a result the energy of a photon with $k_z = 2\pi/L$ and in-plane wave vector $k_\parallel$ in the medium is given by

$$E(k_\parallel) = \frac{\hbar c}{n}\left[\left(\frac{2\pi}{L}\right)^2 + k_\parallel^2\right]^{1/2} = E_0\left(1 + \frac{\hbar^2 c^2 k_\parallel^2}{E_0^2 n^2}\right)^{1/2}, \quad (1)$$

where n is the effective refractive index of the QMC and E_0 is the photon energy for $k_\parallel = 0$. Equation (1) corresponds to strong in-plane dispersion, which can be characterized by a very small in-plane ''mass'' of $3\times10^{-5} m_0^3$. Each in-plane photon mode couples only with an exciton state with the same $k_\parallel$. The resulting cavity polaritons also have strong in-plane dispersion, with the dominant contribution arising from Eq. (1), but with marked perturbation in the region of strong interaction between the photon and exciton modes.[2,3] $k_\parallel$ is related to the external angle of incidence θ via $k_\parallel = (E/\hbar c)\sin\theta$ and so a particular $k_\parallel$ can be selected by varying θ.[6] The polariton dispersion and associated phenomena can thus be studied in angular-dependent experiments. In addition at finite angle, TE (electric vector perpendicular to the plane of incidence) and TM (electric vector in the plane of incidence) optical polarizations experience different reflection coefficients and phase delays,[7] leading to polarization-

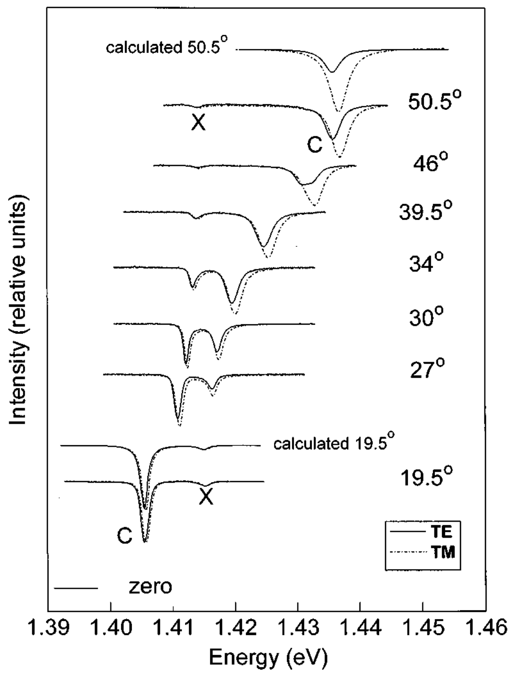

FIG. 1. Reflectivity spectra at 10 K as a function of angle of incidence for TE (full lines) and TM (dashed lines) polarizations of the incident light. Away from resonance the predominantly cavity and exciton modes are labeled *C* and *X*, respectively. All spectra are on the same vertical scale, with reflectivity values away from the resonant dips all ~100%. The zero of reflectivity is indicated for the 19° spectra. Calculated spectra are shown for 19.5°, 50.5°.

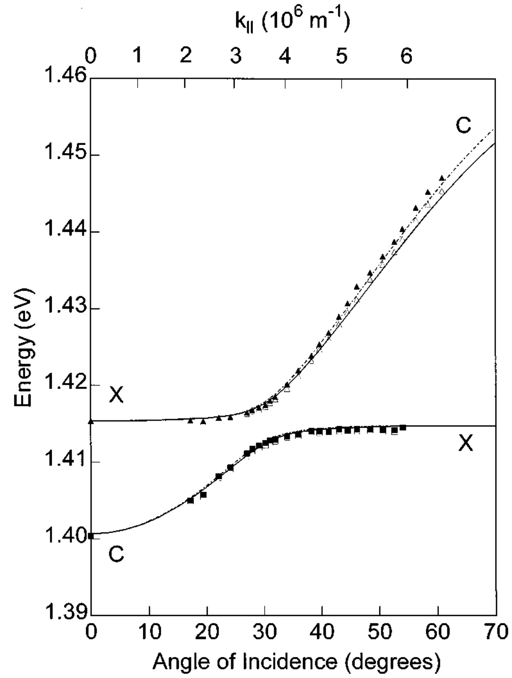

FIG. 2. Energy positions of reflectivity dips of Fig. 1 as a function of θ and $k_{\|}$. Open symbols, TE; closed symbols, TM polarization. The full (TE) and dashed (TM) lines are transfer matrix model fits. Triangles, upper branch; squares, lower branch.

dependent polariton energies, intensities, and line widths in the reflectivity spectra, as reported here.

The experiments were carried out on a QMC (Refs. 3, 8, and 9) consisting of a one wavelength (λ) GaAs cavity sandwiched between 20 period $\lambda/4$ $Al_{0.13}Ga_{0.87}As$-AlAs Bragg reflectors. The upper and lower Bragg mirrors were *p* and *n* doped, respectively. The cavity contains three 100-Å wide $In_{0.13}Ga_{0.87}As$ QW's in its central region. White light illumination from a projector lamp, with angular spread $<1°$, was employed. The reflected light was dispersed by a grating spectrometer, and detected by a Ge photodiode.

A series of reflectivity spectra at 10 K is presented in Fig. 1 as a function of θ, for both TE (full lines) and TM (dashed lines) polarizations. The overall features for the two polarizations are very similar. At low θ the cavity mode is observed strongly (labeled C), with a very weak exciton feature (X) to higher energy. With increasing θ (and hence $k_{\|}$) the cavity dip moves to higher energy as expected from Eq. (1). As it moves towards the exciton feature, the exciton gains in intensity due to mixing with the cavity mode, until at resonance[10] at ~30°, the two features have equal integrated intensity.[9] Increasing θ further leads to additional shift of the cavity to higher energy with consequent weakening of the exciton dip. It is notable that with increasing θ, the spectra exhibit increasingly polarization dependent properties: the TM dips are observed to higher energy than in TE, with splitting between the two of 1.5 meV at 60°, the TE dips become progressively weaker (by a factor of 1.5 relative to TM at 60°), and the TM dips become broader than those in TE (by 0.3 meV at 50°).

The peak positions are plotted in Fig. 2 as a function of θ (TE open symbols, TM filled symbols). The strong shift to higher energy of the cavity features with θ is clearly visible, together with characteristic anticrossing between the two modes.[1,8,9] The full (TE) and dashed (TM) lines are the results of transfer matrix reflectivity (TMR) simulations[7] as a function of θ. A very good fit to experiment is found. In the fits the excitons are modeled as Lorentz oscillators, with the cavity length, the unperturbed exciton energy and the exciton oscillator strength varied to give the best agreement with experiment.[11] The TE-TM splitting for $\theta>0$ arises from the slightly different phase shifts and penetration of the optical modes into the Bragg mirrors for the two polarizations. For cavity and mirror layers of width exactly λ and $\lambda/4$, respectively, the calculated TE-TM splitting is only 0.2 meV at 60°. However, adjusting the mirror lengths to be $0.99(\lambda/4)$ gives TE-TM splittings in good agreement with experiment over the whole range of θ (Fig. 2).

The reduction of the intensity of the cavity dips in TE polarization with increasing θ, relative to those in TM, is also reproduced well by the TMR simulations, as seen in Fig. 1, where calculated spectra are compared to the experimental data at 19.5° and 50.5°.[12] The physical origin of the TE reduction can be understood from an analytical model that takes into account multiple reflections from the distributed Bragg reflector (DBR) mirrors. Under resonance conditions, neglecting absorption, the reflection coefficient from a Fabry-Perot cavity is given by $R=[(r_1-r_2)/(1-r_1r_2)]^2$, where r_1 and r_2 are amplitude reflection coefficients from the upper and lower mirrors, respectively.[13] This expression shows that the reflectivity on-resonance is governed by the degree of balancing of the upper and lower mirror reflectivities, with the minimum R (zero) occurring when $r_1=r_2$.

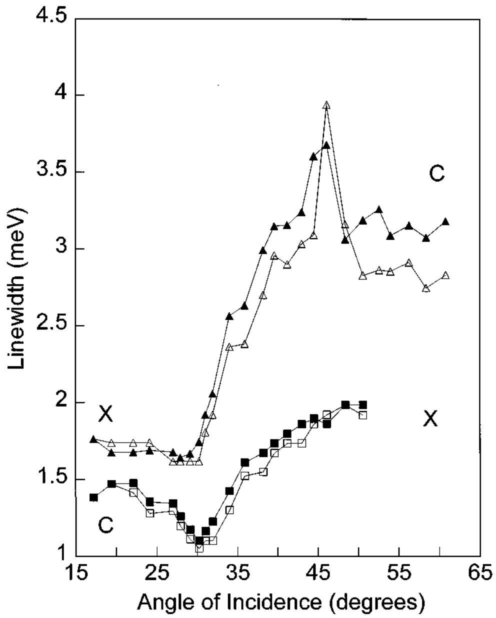

FIG. 3. Polariton line widths as a function of θ. Triangles, upper branch; squares, lower branch; open symbols, TE; filled symbols, TM polarization. The decrease in lower branch line width from 18 to 30° arises from motional narrowing as resonance is approached. The increase of upper branch line width beyond resonance at $\sim$39° is due to absorption by exciton continuum states and the peak at 43–47° arises from interaction between the cavity mode and the $E1$-HH2 exciton state.

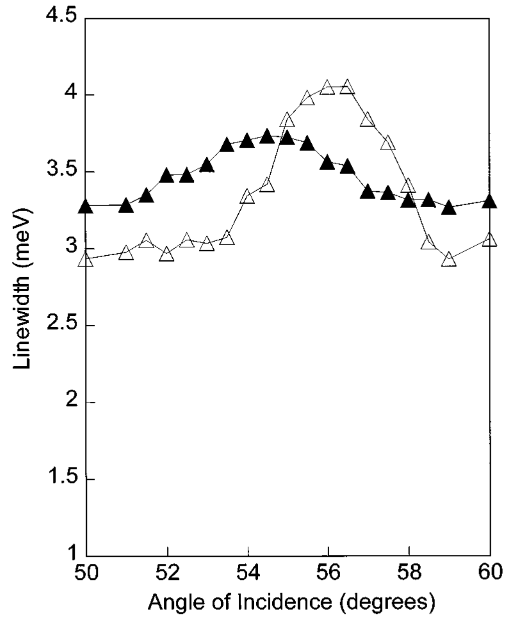

FIG. 4. As Fig. 3, but for separate spot showing resonance between the cavity mode and the $E1$-HH2 transition at 54°(TM), 56°(TE).

Even though the upper and lower DBR's have the same number of pair repeats, they are unbalanced at $\theta=0$ ($r_1 \approx 98\%$, $r_2 \approx 96\%$ from TMR calculations), since the first interface (air-GaAs) of the top mirror has a higher reflection coefficient than the first interface (GaAs-$Al_{0.13}Ga_{0.87}As$) of the bottom mirror. With increasing θ, r_1 increases to 99% at 50.5° for TE polarization, whilst for TM r_1 decreases to 97% at 50.5°, the variations being governed mainly by the increase (decrease) of reflection coefficient at the first interface in TE (TM) polarization, as predicted by the Fresnel relations of classical optics.[7] By contrast r_2 shows a much weaker dependence on the external angle θ since light is incident on its first interface at a much lower angle due to refraction at the first air-QMC interface. The increase of r_1 for TE polarization thus leads to further unbalancing of the cavity for finite θ, whereas TM moves closer to balance, explaining qualitatively the reduction of the intensity of the TE dip relative to that in TM with increasing θ.

The line widths (full width at half maximum) of the polariton dips are plotted as a function of θ in Fig. 3. The data are presented for the upper branch as triangles and for the lower branch as squares for both TE and TM polarizations (open and filled symbols, respectively). At low angle the lower (upper) branch is predominantly cavity (exciton)like, while at high angle the reverse holds with the lower (upper) branch being mainly exciton (cavity)like. It is notable that the lower branch linewidth decreases from 1.4–1.5 meV at 17–20° to only 1.05 meV at resonance at $\sim$30°. The value on-resonance is below the line widths of either the cavity (1.4 meV) or exciton (2 meV) off-resonance. This narrowing cannot be accounted for within the TMR model, where on-resonance linewidths are expected to be the average of off-resonance line widths.[3]

The motional narrowing theory of polariton line widths, described in Ref. 3, by contrast, provides a natural explanation for the narrow on-resonance linewidth. The essential point is that on-resonance polaritons have strong dispersion in k space as discussed in the Introduction and seen in Fig. 2. The marked dispersion corresponds to a very extended wave function in real space, which averages strongly over the disorder potential in the QW. As a result, the normally dominant disorder broadening of the exciton component of the polariton is strongly reduced on resonance, thus explaining the reduction of the observed line width below both of the off-resonance linewidths. The upper branch line width in the 18–30° range shows a small decrease as resonance is approached. However, on resonance its line width is $\sim$1.5 times greater than that of the lower branch, as observed previously, the extra broadening usually being attributed to additional interaction with exciton excited states.[14,3,8,9]

The importance of exciton excited and continuum states in determining polariton line widths is demonstrated conclusively by the line-width behavior of the upper branch for $\theta > 30°$, which increases strongly to a value of $\sim$3 meV at $\theta \approx 40°$. This is followed by a peak in line width at $\theta \approx 45°$, after which the width returns to the approximately constant value of $\sim$3 meV, very much greater than the unperturbed cavity width of 1.4 meV. In addition, the TM line width is greater than that for TE, except in the region of the peak at $\sim$45°, by an amount that increases with angle to $\sim$0.3 meV at 55°.

The marked increase in line width from 30 to 40°, followed by saturation at 40° arises from increasing absorption at the increasingly cavitylike upper branch when the cavity mode moves into the excited and continuum states of the excitonlike lower mode.[15] Such additional absorption leads to a decrease of cavity finesse and broadening of the cavity mode. Indeed, we are able to explain the increased average line width of the ''cavity'' mode[16] for $\theta > 40°$ compared to its value at $\theta = 18°$ if we include a QW absorption coefficient of 6×10^3 cm^{-1} in the TMR simulations, close to that expected for the continuum absorption of a 100 Å wide QW.[17] The greater line width of the TM spectra compared to those for TE has been predicted previously[18] and is reproduced by our TMR simulations.[19] It arises from the decreasing reflectivity of the Bragg mirrors in TM polarization as θ is increased, as discussed in the analysis of the relative intensities. The decreasing reflectivity leads to reduction of cavity finesse and hence additional broadening at high angle.

Finally we explain the peak in line width at $\sim 46°$. The TE spectrum at 46° in Fig. 1 shows that the peak is due to the presence of a poorly resolved additional feature. The energy separation between the modes at 45–47° is 18 meV. The observations are supported by the data in Fig. 4 for a separate spot with cavity 8 meV to lower energy than for Figs. 1–3; the peak in line width is again observed, but now in the range from 50 to 60° corresponding again to a separation between modes of ~ 18 meV. This energy is very close to the calculated separation of 17.6 meV of the $n=1$ heavy hole to $n=1$ electron ($E1$-HH1) and $n=2$ heavy hole to $n=1$ electron ($E1$-HH2) transitions of the QW. We thus ascribe the increased line width at 46° to interaction of the cavity mode with $E1$-HH2, the normally forbidden $E1$-HH2 being made weakly allowed by electric fields (F) from the p-n doped Bragg mirrors.[20]

In conclusion, polariton spectra from QMC's have been shown to exhibit marked polarization dependence. Clear differences between polariton energies, intensities, and line widths in TE relative to TM polarization have been found, and are well accounted for by transfer matrix simulations. In addition, motional narrowing of the polariton spectra, and interaction of the cavity mode with exciton continuum states, and with QW excited state transitions, have been demonstrated.

We thank L. C. Andreani and A. V. Kavokin for very helpful discussions.

---

*Present address: Department of Electrical and Electronic Engineering, University of Western Australia, Nedlands WA6907, Australia.

[1] C. Weisbuch, M. Nishioka, A. Ishikawa, and Y. Arakawa, Phys. Rev. Lett. **69**, 3314 (1992).

[2] R. Houdré, C. Weisbuch, R. P. Stanley, U. Oesterle, P. Pellandini, and M. Ilegems, Phys. Rev. Lett. **73**, 2043 (1994).

[3] D. M. Whittaker, P. Kinsler, T. A. Fisher, M. S. Skolnick, A. Armitage, A. M. Afshar, and J. S. Roberts, Phys. Rev. Lett. **77**, 4792 (1996).

[4] S. Pau, G. Bjork, H. Cao, F. Tassone, R. Huang, Y. Yamomoto, and R. P. Stanley, Phys. Rev. B **55**, R1942 (1997).

[5] A. Fainstein, B. Jusserand, and V. Thierry-Mieg, Phys. Rev. Lett. **75**, 3764 (1995); **78**, 1576 (1997).

[6] Substituting $k_{\parallel} = E/\hbar c \sin\theta$ into Eq. (1) leads to the expression $E(\theta) = E_0[1 - (\sin^2\theta/n^2)]^{-1/2}$ for cavity mode energy as a function of θ. $\theta = 60°$ corresponds to an increase of cavity energy of ~ 45 meV, thus permitting polariton phenomena to be studied over a wide tuning range.

[7] See, e.g., M. Born and E. Wolf, *Principles of Optics* (Pergamon, New York, 1964).

[8] T. A. Fisher *et al.*, Phys. Rev. B **51**, 2600 (1995); Solid-State Electron. **40**, 493 (1996).

[9] A. Armitage, T. A. Fisher, M. S. Skolnick, D. M. Whittaker, P. Kinsler, and J. S. Roberts, Phys. Rev. B **55**, 16 395 (1997).

[10] Resonance occurs at 29° for TM and 30° for TE, the TM resonance occurring at slightly lower angle since the TM cavity mode is shifted slightly to higher energy.

[11] The refractive indices used in the fits were taken from the 300 K data of J. T. Boyd, IEEE J. Quantum Electron. **8**, 788 (1972), decreased by 1.3% for use at 10 K. The 1.3% decrease is obtained from the 1.3% decrease of cavity wavelength from 300 to 10 K. The good fit we obtain to the angular dependence of the energies as compared to some earlier work, e.g., S. Jorda, Phys. Rev. B **51**, 10 185 (1995) may be related to our better choice of refractive indices.

[12] Uniform background absorption is included to decrease the cavity finesse and to fit the observed cavity mode linewidth at 19.5°. The ratio of the TE to TM depths at 50.5° is calculated to be 2.8 as compared to the experimental value of 1.5. We consider this agreement to be very reasonable since the calculated value is very sensitive to the precise reflectivities of the top and bottom mirrors.

[13] M. A. Kaliteevski and A. V. Kavokin, Phys. Solid State **37**, 3074 (1995).

[14] R. Houdré, R. P. Stanley, U. Oesterle, M. Ilegems, and C. Weisbuch, Phys. Rev. B **49**, 16 761 (1994).

[15] J. Tignon *et al.* Phys. Rev. Lett. **74**, 3967 (1995).

[16] Inspection of the spectra of Fig. 1 shows that the cavity fraction of the upper branch is $>90\%$ for $\theta > 40°$.

[17] W. T. Masselink *et al.*, Phys. Rev. B **32**, 8027 (1985).

[18] A. V. Kavokin and M. A. Kaliteevski, Solid State Commun. **95**, 859 (1995).

[19] We predict TM to be broader than TE by 0.2 meV, in reasonable agreement with the 0.3 meV observed.

[20] A good fit to the barely resolved splitting of 1.2 meV of the 46° spectrum is obtained for an $E1$-HH2 oscillator strength 0.04 times that of $E1$-HH1. We calculate such an oscillator strength ratio at $F = 3 \times 10^3$ V/cm, a very reasonable value in a p-i-n junction under open circuit conditions. The peak in linewidth due to interaction with $E1$-HH2 is of greater magnitude in TE than in TM polarization in Figs. 3 and 4, probably due at least in part to the forbidden character of E-HH transitions for pure TM polarization.