Electric-field and temperature tuning of exciton-photon coupling in quantum microcavity structures

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Temperature and electric-field tuning of the vacuum Rabi splitting of the coupled exciton-photon state in a semiconductor microcavity is reported. A very good fit to the coupling of the heavy- and light-hole excitons to the cavity photon mode, as a function of temperature, is obtained from a theoretical model for the reflectivity spectra. In addition, the variation of Rabi splitting with an applied electric field is well accounted for by the calculated variation of exciton oscillator strength with the electric field. Electro-optic control of the vacuum Rabi splitting is demonstrated.

Semiconductor quantum microcavity (QMC) structures have been shown to be an excellent means to control separately the properties of both excitons and photons. The initial interest in these structures was for the control of spontaneous emission,[1,2] in particular to increase the coupling efficiency of spontaneous emission into the lasing mode for surface emitting lasers.[3] More recently Weisbuch *et al.*[4–7] investigated the coupling between the cavity photon mode and the quantum-well exciton. In these experiments the authors relied on the variation of cavity thickness across the wafer to control the tuning. In our experiments we demonstrate control of the coupling between the cavity photon field and the exciton by varying either an applied electric field or temperature. By doing this, the photon-exciton coupling is studied on a particular device, unaffected by possible exciton linewidth or cavity finesse variations across the sample.

Tuning by temperature is achieved since the exciton energy decreases rapidly with increasing temperature, while there is only a small decrease in energy of the cavity photon mode. Tuning by electric field is realized by sweeping the exciton energy through the cavity energy by the quantum-confined Stark effect.[9] The strength of the cavity photon-exciton coupling, or vacuum Rabi splitting in the coupled mode language of atomic physics,[8] depends principally on exciton oscillator strength and cavity length.[4,8] By contrast to temperature,[10] electric field causes a change in exciton oscillator strength[9,11] and hence cavity photon-exciton coupling strength. Utilizing temperature to vary the position of the exciton relative to the cavity mode at zero electric field, we have investigated the effect that different electric fields, from 0 to 38 kV/cm, have on the cavity photon-exciton coupling. The results of these experiments are in good agreement with the results of quantum-well exciton oscillator-strength calculations as a function of electric field. As a result of this work, electro-optic control of the vacuum Rabi splitting is demonstrated in a semiconductor QMC.

The QMC structure investigated here consists of an $Al_{0.2}Ga_{0.8}As$ cavity in the intrinsic region of a *p-i-n* junction where the *p* (3×10^{18} cm^{-3} Zn) and *n* (1.5×10^{18} cm^{3} Si) regions consist of 20 period Bragg reflectors, each period containing $Al_{0.46}Ga_{0.54}As$, AlAs, $Al_{0.46}Ga_{0.54}As$, and $Al_{0.14}Ga_{0.86}As$ layers.[12] Three GaAs quantum wells (QW's), with nominal well widths of 100 Å and barrier widths of 80 Å, are placed at the center of the cavity, at the antinode of the cavity photon field. The optical length of the cavity is designed to match at 4 K, the wavelength of the lowest energy heavy-hole exciton $(HH)_x$ transition involving the first heavy hole and electron states. X-ray measurements on one piece of the structure showed the cavity width to be 2375 Å, close to the designed length of 2308 Å. The mirror widths were also close to the designed values with widths of 157, 553, 157, and 340 Å for the $Al_{0.46}Ga_{0.54}As$, AlAs, $Al_{0.46}Ga_{0.54}As$, and $Al_{0.14}Ga_{0.86}As$ layers, respectively, being measured. The unperturbed exciton peak position, exciton shift rate and changes of oscillator strength with electric field, discussed later, suggest the actual well width is closer to 110 Å.

The sample used for the electric-field measurements was processed into 400-μm-diameter mesas with optical access of 200 μm, and contacted for electrical measurements. Reflectivity measurements were carried out at normal incidence at temperatures from 5 to 240 K, with broadband light from a tungsten-halogen lamp incident on the sample. The reflected signal was dispersed with a grating spectrometer and detected with a Ge photodiode.

Reflectivity spectra, obtained from the unprocessed QMC structure at various temperatures are shown in Fig. 1. At $T=5$ K, a strong cavity resonance is observed at 1.5362 eV, with a reflectivity depth of 73%. The cavity resonance linewidth of 2.9 meV corresponds to a finesse of 250. The lowest energy heavy-hole exciton and light-hole exciton (LH_x) peaks are observed at 6.5 and 15.0 meV, respectively, to higher energy. HH_x and LH_x are relatively weak since at these energies they are only weakly coupled to the cavity mode. The HH_x linewidth is 2.4 meV in this relatively unperturbed position.

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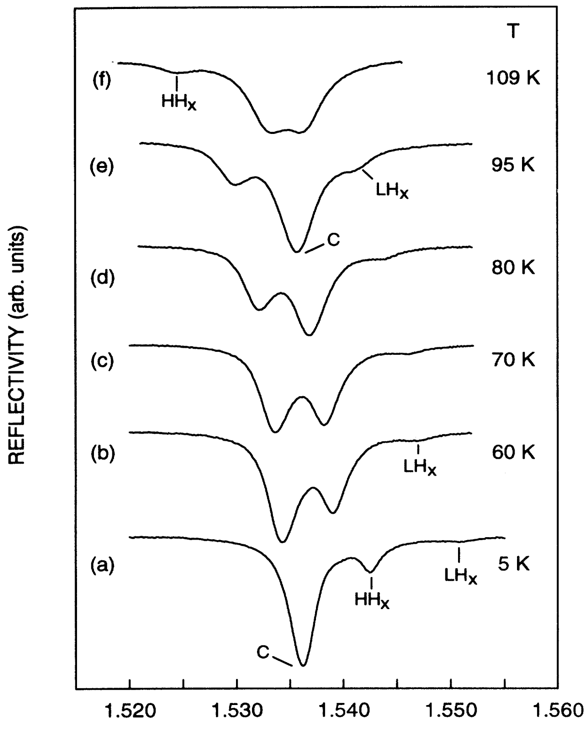

FIG. 1. Reflectivity spectra at temperatures (a) 5 K, (b) 60 K, (c) 70 K, (d) 80 K, (e) 95 K, and (f) 109 K. Heavy-hole exciton (HH_x)-cavity resonance is seen at (c) 70 K, with a splitting 1.7 times bigger than that of the light-hole exciton-cavity resonance at (f) 109 K.

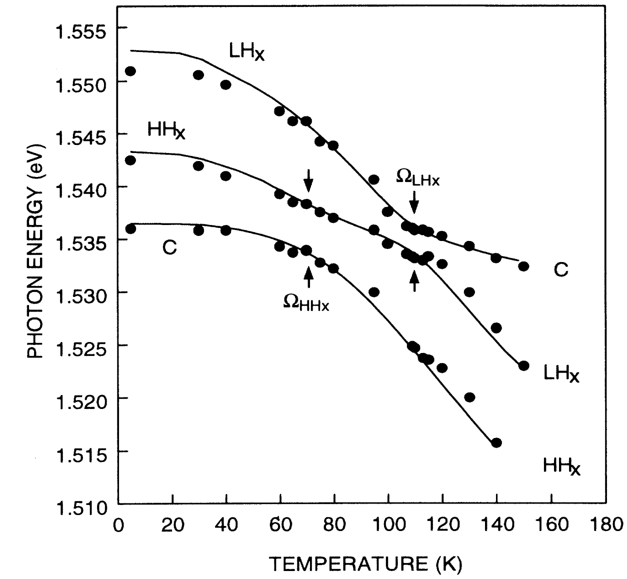

FIG. 2. Reflectivity peak positions as a function of temperature (circles). The fit to the data calculated using the reflectivity model, which incorporates HH_x and LH_x as two broadened Lorentz oscillators, is plotted as full lines. The splittings Ω_{HHx} and Ω_{LHx} at resonance are marked.

Reflectivity measurements of the unperturbed cavity peak position as a function of temperature on this and similar samples show the cavity resonance shifts down in energy by only $(1.3\pm0.1)\%$ between 5 and 300 K. On the other hand, the exciton energy that follows the band-gap variation,[13] shifts by 6.5% over the same range.

As the temperature (T) is raised, the HH_x and LH_x peaks move closer in energy to the cavity mode feature. Resonant exchange of intensity between HH_x and the cavity peak is seen from 5 to 70 K [Fig. 1(a)–1(c)] as HH_x increases in intensity, until at $T=70$ K [Fig. 1(c)] two features of equal intensity are seen. Beyond $T=70$ K [Fig. 1(d) and 1(e)], HH_x has moved through the resonance and weakens. Anticrossing behavior is clearly seen in Fig. 2 where the observed peak positions are plotted (circles) as a function of temperature. By increasing the temperature further, tuning of LH_x through the cavity peak is achieved. Maximum cavity-LH_x coupling occurs at $T=109$ K and is shown in Fig. 1(f). The cavity-LH_x anticrossing is seen clearly in Fig. 2. Of particular interest is that the splitting at resonance of the coupled cavity-HH_x peaks (Ω_{HHx}) is 4.6 meV, 1.7 times greater than that of the cavity-LH_x splitting (Ω_{LHx}) of 2.7 meV [see Figs. 1(c), 1(f), and 2].

The experimental results are modeled using a calculation of cavity reflectivity based on the multibeam interference analysis of Zhu *et al.*[8] and Born and Wolf,[14] which allows the experimental linewidths of the cavity and exciton features to be included as input parameters. A similar analysis was used by Weisbuch *et al.*,[4] where the transmission function, incorporating a broadened exciton line, was used to fit the reflectivity spectra. The multibeam interference analysis gives the cavity reflectivity function,[14] as a function of frequency ν for axial propagation as

$$R_c(\nu)=\frac{(1-e^{-\alpha L})^2+4e^{-\alpha L}\sin^2\varepsilon/2}{(1-\mathrm{R}e^{-\alpha L})^2+4\,\mathrm{R}e^{-\alpha L}\sin^2\varepsilon/2}\,, \tag{1}$$

where R is the intensity reflection coefficient of a single mirror and αL the single-pass absorption. ε is the round-trip phase shift, which depends on the refractive index, n, and the cavity free spectral range Δ_{FSR} according to $\varepsilon=2\pi(\nu-\nu_c)/\Delta_{FSR}+4\pi(n-1)L\nu/c$. Δ_{FSR} is determined from the optical length of the cavity D_c using $\Delta_{FSR}=c/(2D_c)$.[8] It is related to the empty cavity resonance width δ_c and the finesse $F=\pi\sqrt{R}/(1-R)$ by $\Delta_{FSR}=F\delta_c$. The heavy- and light-hole exciton states are treated as two independent Lorentz oscillators. The real part of the Lorentz oscillator affects the refractive index n, and the imaginary part affects the absorption coefficient α. In this classical analysis, solution of Eq. (1) leads to coupling between the two exciton oscillators and the cavity mode, and anticrossing behavior, in the resonance region.[4,8]

When the widths of the cavity and exciton lines δ_c and δ^i are small in comparison to the splitting Ω_i and $\delta_c\approx\delta^i$, the vacuum Rabi splittings at resonance are, to a good approximation, given by $\Omega_i=(\Delta_{FSR}\alpha_0^i L\delta^i/\pi)^{1/2}$, where α_0^i is the peak absorption of the ith exciton line[4] and L is the width of the quantum wells. However, when the broadening becomes comparable in magnitude to Ω_i, as in the present spectra, the measured splitting is reduced.[15]

In order to fit the experimental variation of reflectivity with temperature, the HH_x oscillator strength (f_{HHx}, proportional to $\alpha_0^{HH} L \delta^{HH}$) was varied in the reflectivity calculation until the calculated splitting (Ω_{HHx}) for the HH_x-cavity resonance agreed with the observed value of 4.6 meV at $T=70$ K. Similarly the LH_x oscillator strength (f_{LHx}) was varied until it agreed with the observed LH_x-cavity resonance splitting ($\Omega_{LHx}=2.7$ meV) at $T=109$ K.[16] As discussed above and in Ref. 15, the vacuum Rabi splitting is weakly dependent on δ_c and the exciton linewidth. However, the variations in these linewidths is negligible up to 120 K,[16] so no significant variation in Ω_i is expected in the temperature range indicated. The best fit to the vacuum Rabi splittings at $T=70$ K and $T=109$ K was obtained with a $f_{HHx}:f_{LHx}$ ratio of 2.6:1[17] and HH_x-LH_x energy separation of 9.9 meV. The deduced ratio f_{HHx}/f_{LHx} is in good agreement with measured value of 2.5 of Masselink *et al.*[18] and the theoretical value of 2.4 of Andreani and Pasquarello[19] for QW's of similar width.

The variation in peak positions over the whole temperature range was calculated with the deduced values of f_{HHx}, f_{LHx}, and HH_x-LH_x separation, using the known variation of the unperturbed exciton[13] and the experimentally measured unperturbed cavity peak positions with temperature. A good fit to the experimental results was obtained[20] and is shown in Fig. 2 by the solid lines.

Very similar tuning is achieved by electric field where the quantum confined stark effect (QCSE) lowers the exciton transition energy with increasing electric field.[9] However, in contrast to its behavior with increasing temperature the lowest energy exciton HH_x transition is expected to reduce in oscillator strength with increasing electric field due to a reduction in the overlap of the wave functions of the first electron and first heavy-hole states,[11] and to a reduction in the strength of the excitonic interaction. Electric-field tuning was performed by varying the applied bias, V_{appl} across the intrinsic region of the p-i-n junction. At $V_{appl}=1.5$ V there is zero electric field across the intrinsic region, and flat band conditions in the QW's are expected. The electric field across the sample is then given by $\mathbf{E}=(1.5V-V_{appl})/L_{in}$ where $L_{in}=2375$ Å is the length of the intrinsic region.

Electric-field tuning was carried out at various temperatures. At the lowest temperature of $T=5$ K a high electric field of 38 kV/cm was required to bring HH_x and the cavity mode into resonance. As the temperature was raised HH_x is brought closer in energy to the cavity at zero electric field. Therefore, a lower electric field is needed for the cavity mode and HH_x to couple. As discussed previously, temperature has a negligible effect on the exciton oscillator strength, f_{HHx}.[10] The reflectivity spectra at resonance are shown for various electric fields (and hence temperatures) in Fig. 3 [I]. At $T=95$ K, $\mathbf{E}=0$ kV/cm the splitting at resonance is $\Omega_{HHx}=4.5$ meV {Fig. 3 [I] (a)]}. As the temperature is reduced, and

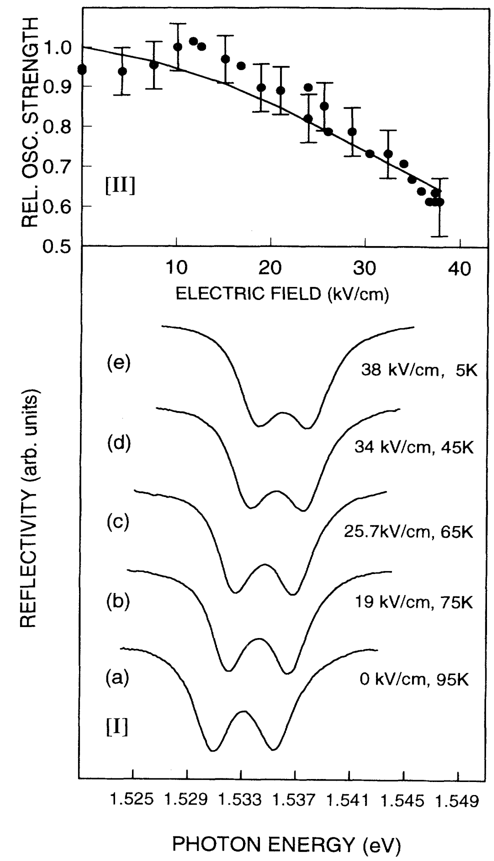

FIG. 3. [I] Reflectivity spectra showing resonant coupling of the cavity photon mode and HH_x at electric fields $\mathbf{E}=$ (a) 0, (b) 19 kV/cm, (c) 25.7 kV/cm, (d) 34.1 kV/cm, and (e) 37.9 kV/cm. The Rabi splitting decreases as the electric field is increased. [II] Relative change of the HH_x oscillator strength (f_{HHx}) as a function of electric field deduced from the Rabi splitting (Ω_{HHx})-circles-and the expected change in f_{HHx} for a 110-Å QW, from exciton calculations-full line.

hence the electric field required to achieve resonance is increased, the splitting Ω_{HHx} decreases so that at $T=5$ K, $\mathbf{E}=38$ kV/cm {Fig. 3 [I] (e)} a splitting of 3.6 meV is seen.

The relative change in splitting, Ω_{HHx} from $\mathbf{E}=0$ to 38 kV/cm is 1 to 0.78. The corresponding decrease in HH_x oscillator strength (f_{HHx}), deduced from the reflectivity model for Ω_{HHx}, is 1 to 0.60 and is plotted in Fig. 3 [II] as circles. The changes in exciton oscillator strength deduced from the experiment using the reflectivity model are compared to calculated changes using a standard approach for quantum-well excitons.[21] Including the effect of the electric field on both the wave function overlap and the excitonic interaction, good agreement is obtained between the calculated variation of excitonic oscillator strength with electric field for a 110-Å QW (solid line, Fig. 3 [II]) and the deduced experimental variation[22] [circles, Fig. 3(b)], in both cases the variations being normalized to give the same maximum value. From measurements of the HH_x peak, as a function of electric field, on a different part of the sample, where it is only weakly perturbed by the cavity, the HH_x linewidth is found to increase at most from 2.0 to 2.8 meV from 0 to 38 kV/cm. This linewidth increase at 38 kV/cm is expected to decrease the observed vacuum Rabi splitting by only 2.9% (0.14 meV) and thus does not affect the comparison between theory and experiment in Fig. 3 [II].

At $\mathbf{E}=0$ the observed vacuum Rabi splitting, Ω_{HHx}, of 4.5 meV is fitted for unperturbed exciton and cavity linewidths of 2.0 and 2.6 meV, respectively, with a value of $\alpha_0^{HH} L \delta^{HH}=0.0962$ meV [note that $\Omega_{HHx} \approx (\Delta_{FSR} \alpha_0^{HH} L \delta^{HH}/\pi)^{1/2}$]. Δ_{FSR} is taken as $[c/(2\times$ actual cavity length $\times$ refractive index$)]$ = 723 meV. From the $\alpha_0^{HH} L \delta^{HH}$ value, we deduce $\alpha_0^{HH}\delta^{HH} = 2.92\times 10^4$ meV cm^{-1} ($\alpha_0^{HH}=1.46\times 10^4$ cm^{-1}) per QW for the three QW structure. The deduced $\alpha_0^{HH}\delta^{HH}$ is ~ 4 times smaller than that reported by Masselink *et al.*[18] per QW from absorption measurements on a 116-A QW.[23] The small value of absorption arises because of the distributed nature of the Bragg reflectors, which leads to the optical length of the cavity (D_c) being longer than the actual length [$L_c=$ (refractive index) $\times$ (physical length)]. As a result the free spectral range using L_c is too large, with the result that the $\alpha_0^{HH}\delta^{HH}$ product obtained above is too small.[23] However, it should be noted that good fitting to the vacuum Rabi splitting was obtained by Houdré *et al.*[7] using standard values of absorption coefficient in a transfer-matrix model, which includes the different layers of the Bragg reflectors.[24]

To conclude, electro-optic tuning and control of the Rabi splitting in semiconductor quantum microcavities has been demonstrated by the variation of temperature and electric field. Temperature tuning is achieved due to the rapid decrease of band gap and hence exciton energy with temperature. On the other hand, the electric field provides a method for varying the exciton oscillator strength, and hence the cavity-exciton coupling strength, due to the change in the electron-hole wave-function overlap with electric field. We have shown that increasing the electric field at which coupling occurs from 0 to 38 kV/cm reduces the cavity-HH_x Rabi splitting by a factor of 0.78, in good agreement with quantum-well exciton calculations.

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[12] Each period has four layers of the composition described, to minimize the resistance across the structure.

[13] *Semiconductors. Physics of Group IV Elements and III-V Compounds,* edited by O. Madelung, Landölt-Bornstein, New Series, Group III, Vol. 17, Pt. a (Springer-Verlag, Berlin, 1982), pp. 218 and 513.

[14] See, M. Born and E. Wolf, *Principles of Optics,* 6th ed. (Pergamon, Oxford, 1986).

[15] It is essential to use the appropriate function for modeling the reflectivity spectra. To obtain the observed HH_x vacuum Rabi splitting (Ω_{HHx}) of 4.6 meV using the reflectivity function and the δ_C (2.9 meV) and δ^{HH} (2.4 meV) value away from resonance, a value of $\alpha_0^{HH} L\delta^{HH}=0.1026$ meV) is required. However, if the transmission function is employed using the above value of $\alpha_0^{HH} L\delta^{HH}$ a larger splitting of 5.2 meV is expected. A similar point is made by Houdré *et al.* in Ref. 7.

[16] The cavity linewidth as a function of temperature, measured on a piece of the sample where no perturbation by the exciton occurs, does not vary over the temperature range 4 to 240 K. Up to 120 K, the exciton linewidth is expected to increase by only 0.15 meV, D. S. Chemla, D. A. B. Miller, P. W. Smith, A. C. Gossard, and W. Wiegmann, IEEE J. Quantum Electron. **20**, 265 (1984).

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