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Ultrafast control of light emission from a quantum-well semiconductor microcavity using picosecond strain pulses

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A picosecond strain wave packet of subterahertz acoustic phonons is generated in a metal film by optical excitation with a femtosecond laser pulse and injected into a quantum well containing a GaAs-based planar microcavity in the strong-coupling regime. The strain pulse induces a dynamical energy shift of the quantum-well exciton resonance. This results in an ultrafast modulation of the photoluminescence spectrum from the lower polariton branch.

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High-frequency acoustics has been recently shown to be a prospective tool for manipulating light beams in nanophotonic devices such as photonic crystals and microcavities (MCs).[1–4] One of the currently challenging tasks of acousto-optics is to realize ultrafast intensity and frequency modulation of the spontaneous and stimulated light emission from nanophotonic emitters. Traditional ultrasonic experiments have been successfully performed on semiconductor MCs but there the modulation frequency is limited to the gigahertz frequency range.[1–4] The extension of the modulation frequencies to the terahertz range would provide significant progress in the ultrafast control of light emission from such cavities.

In the present work, we explore the potential of ultrafast acoustics, using picosecond strain pulses, for modulating the photon energy of the spontaneous photoluminescence (PL) from a MC with a quantum well (QW) as the optically active medium. The studied MC structure was grown without a wedge by metal-organic chemical-vapor deposition (MOCVD) on a GaAs substrate. It contained an 8-nm-wide $In_{0.04}Ga_{0.96}As$ QW in the middle of a GaAs barrier layer with a width $d=240$ nm, corresponding to the wavelength λ of the confined photon resonance. This λ-cavity layer was surrounded by Bragg mirrors made from 24 and 20 pairs of GaAs/AlAs $\lambda/4$ wave stacks at the bottom (toward substrate) and the top (toward vacuum), respectively. The finesse of the MC was $\sim 10^4$ and the exciton linewidth was 0.6 meV; this optical quality is good enough to reach the strong-coupling (polariton) regime between the QW exciton and the confined photon mode.[5]

The PL spectrum measured at normal incidence to the cavity at low temperature ($T=5$ K) for cw excitation is shown in Fig. 1(a) by the solid line. The spectrum consists of two emission lines with maxima at E_{LP} and E_{UP} which correspond to the lower and upper polariton states, respectively. The dashed vertical arrows labeled E_{MC} and E_{QW} indicate the energies of the uncoupled photon and exciton resonances of the MC and the QW. The value of 3.3 meV for the Rabi splitting was obtained from the dependence of the spectral position of the PL lines on temperature T (see inset).[6]

The calculated dependence of the polariton energies as a function of detuning $E_{QW}-E_{MC}$ is shown in Fig. 1(b). For further consideration it is convenient to present the curves in Fig. 1(b) such that E_{MC} shown by the dashed horizontal line is fixed while E_{QW} [oblique dashed line in Fig. 1(b)] could be tuned. The vertical dotted line in Fig. 1(b) corresponds to a detuning $E_{QW}-E_{MC}=2.7$ meV at $T=1.8$ K. Figure 1(c) shows the experimental dependence of the intensity of the lower polariton branch emission as a function of detuning measured by varying the temperature. This dependence qualitatively is similar to one that was measured at fixed temperature for different detunings in a wedge-shaped cavity.[7]

The experiments involving strain pulses were carried out in a helium cryostat with an inset for variable temperatures in the range of 1.8–120 K. The scheme of the ultrafast acoustics studies is shown in Fig. 2(a). A beam from a 150 fs Ti-sapphire laser pumping a regenerative amplifier (wavelength of 800 nm and repetition rate of 250 kHz) was used for generation of strain wave packets in a 100-nm-thick Al transducer deposited on the polished substrate opposite to the MC structure.[8] As a result of optical excitation with an energy density of 3 mJ/cm^2 on the metal film surface, a bipolar strain pulse with duration of about 40 ps and strain amplitude of $\sim 10^{-4}$ is injected into the GaAs substrate. The strain wave packet propagates through the 100 μm GaAs substrate with the velocity of longitudinal sound $s=4.8\times 10^3$ m/s, so that after about 20 ns it reaches the MC. Figure 2(b) shows the calculated temporal evolution of the pulse reaching the MC. Details of the calculations, which include the nonlinear elastic properties of the GaAs crystal, can be found elsewhere.[9]

A second beam split from the same laser excites nonresonantly the polariton PL through the top surface of the MC. The delay between the two pulses was set to about 20 ns so that the hypersound wave packet passes the GaAs substrate and reaches the MC when the PL is emitted. The effect of the strain pulse on the lower polariton emission was monitored by measuring the time-resolved PL spectrum with a single spectrometer followed by a streak camera. The temporal resolution was about 30 ps corresponding to a spectral resolution of 0.15 meV at a sufficient sensitivity level of the setup.

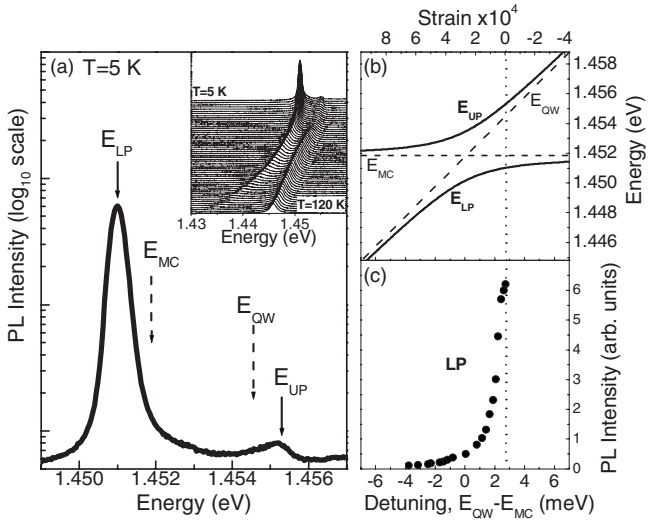

FIG. 1. (a) Photoluminescence spectra of the studied MC structure at $T=5$ K for cw–low power excitation ($\lambda_{las}=352$ nm; 100 W/cm^2). The dashed and solid vertical arrows indicate the energies of the uncoupled states (MC photon mode and QW exciton) and polariton resonances (LP and UP), respectively. The inset shows PL spectra for different temperatures $T=5-120$ K. At $T=50$ K the minimum-energy separation between the PL lines which is equal to 3.3 meV is reached corresponding to the Rabi splitting. (b) Calculated energies of low and upper polariton branches as a function of detuning between the photon mode and the QW exciton for a Rabi splitting of 3.3 meV at $T=1.8$ K. The dashed lines are the resonance energies of the MC photon mode and QW exciton. (c) Dependence of the lower polariton emission intensity on detuning determined from the temperature dependence of the PL spectra. Vertical dotted line in panels (b) and (c) shows the detuning at $T=1.8$ K in the absence of a strain pulse. The upper scale in panel (b) is given to show the correspondence between the strain in the QW and the strain-induced variation in detuning $E_{QW}-E_{MC}$.

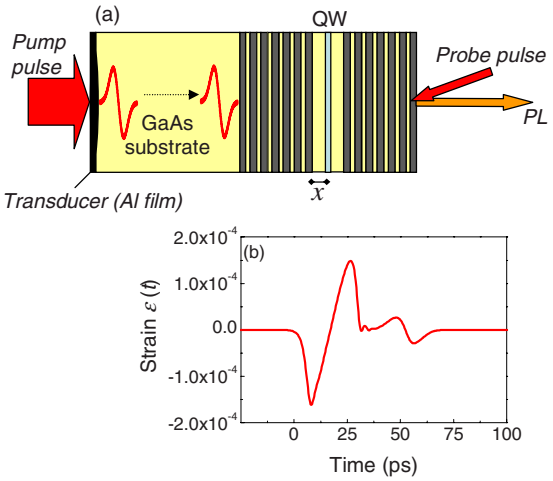

FIG. 2. (Color online) (a) Scheme of experiment with picosecond strain pulses. (b) Calculated temporal shape of a strain pulse at the interface between substrate and Bragg mirror.

Figure 3 shows the temporal and spectral streak camera images of the lower polariton PL intensity $I(E,t)$ measured at $T=1.8$ K in the absence (left) and in the presence (right) of the strain pulse. In the absence of the strain pulse [panel (a)] the PL line shifts to lower energies while decaying with a time constant of 350 ps. This behavior is governed by the dependence of the light-matter coupling parameter on the polariton density as discussed earlier for similar MC samples.[10] The image in Fig. 3(b) shows the PL decay when a strain wave packet has been injected into the MC. The delay Δt between the exciting PL laser pulse [shown by the big horizontal arrow in panel (a)] and the time moment when the strain pulse reaches the MC [shown by the big horizontal arrow in panel (b)] is 150 ps. Compared to the case without strain, a pronounced bump occurring at time $t\approx 100$ ps is clearly observed. The lower panels in Fig. 3 show emission spectra at different fixed delay times, t. One can see in panel (d) that the strain wave packet induces both a shift and a broadening of the PL spectra.

Figure 4 shows the time evolutions of the energy of the PL maximum [panel (a)], of the spectral width of the emission [panel (b)], and of the PL intensity integrated over the emission line [panel (c)]. The energy shift induced by the strain pulse reaches a maximum value of $\Delta E_{LP}\approx 0.2$ meV [panel (a)]. Further, the shift is almost independent of the delay between the strain and the PL excitation pulses (see inset). The width of the spectrum increases in the presence of the strain pulse [panel (b)]. The integrated PL intensity of the lower polariton branch decreases [panel (c)] when the PL linewidth starts to increase ($t=0$), then rapidly increases simultaneously with the shift of the emission line, and thereafter decreases again. From the comparison of the leading edge of the energy shift with those of spectral width and intensity, it is seen that this shift starts with a delay with respect to the two other quantities.

In the analysis of the strain-induced effect on the PL spectrum of the MC two effects have to be considered: (i) the strain-induced change in the length and the refractive index of the MC and (ii) the strain-induced change in the exciton resonance energy E_{QW} in the QW.[11] First we discuss the separate contributions of (i) and (ii) to the strain-induced energy shift of the PL line [Figs. 3(b) and 4(a)]. Both effects modulate the detuning $E_{QW}-E_{MC}$ and, therefore, the energies of the two polariton branches, as can be seen from Fig. 1(b). The first contribution (i) is equivalent to modulating the horizontal dashed line by moving it up or down. The second contribution (ii) corresponds to moving along the oblique dashed line. To estimate the two contributions we use the temporal profile $\varepsilon(t)$ of the strain pulse in Fig. 2(b). We ignore the modification of its shape by the multilayered Bragg mirrors.[12] The change in the MC length Δd at time t can be estimated by the integral over the strain pulse $|\Delta d| = \int_0^t s\varepsilon(t')dt'$. We obtain a maximum MC length change $|\Delta d^{max}|\sim 10^{-11}$ m corresponding to a change in the photon resonance energy of $\Delta E_{MC}^{max}\approx 0.05$ meV. The value of ΔE_{MC}^{max} due to the strain-induced change in the refractive index (i.e., due to the photoelastic effect) is significantly smaller. The second contribution (ii) gives a maximum strain-induced change in the exciton resonance energy by $\Delta E_{QW}^{max}\approx 1$ meV. This can be evaluated from measurements under similar experimental conditions for a GaAs/(Al,Ga)As QW without a surrounding cavity.[11] Inserting the estimated values of ΔE_{QW}^{max}

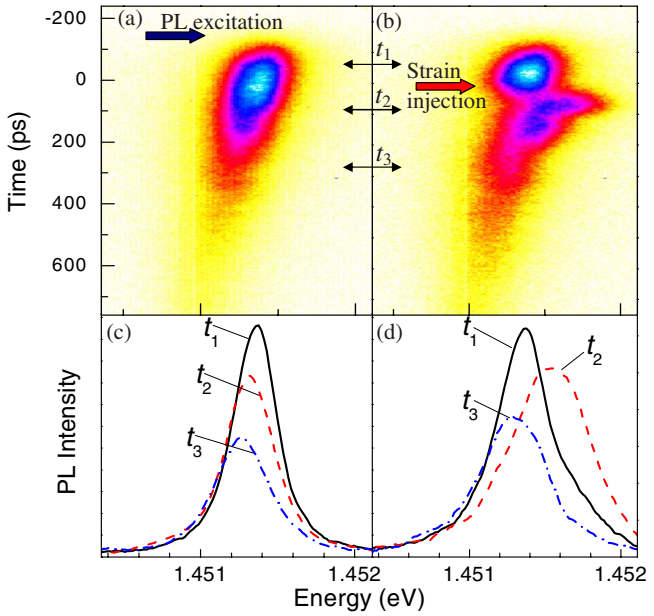

FIG. 3. (Color online) Streak-camera images of the temporal (vertical direction) and spectral (horizontal direction) PL evolutions in the (a) absence and (b) presence of a strain pulse at $T=1.8$ K. The big horizontal arrows show times, which correspond to the pulse excitation of the PL [panel (a)] and injection of a strain pulse into MC [panel (b)]. Panels (c) and (d) demonstrate spectral profiles at time delays shown in (a) and (b) by numbered arrows in (c) absence and (d) presence of a strain pulse.

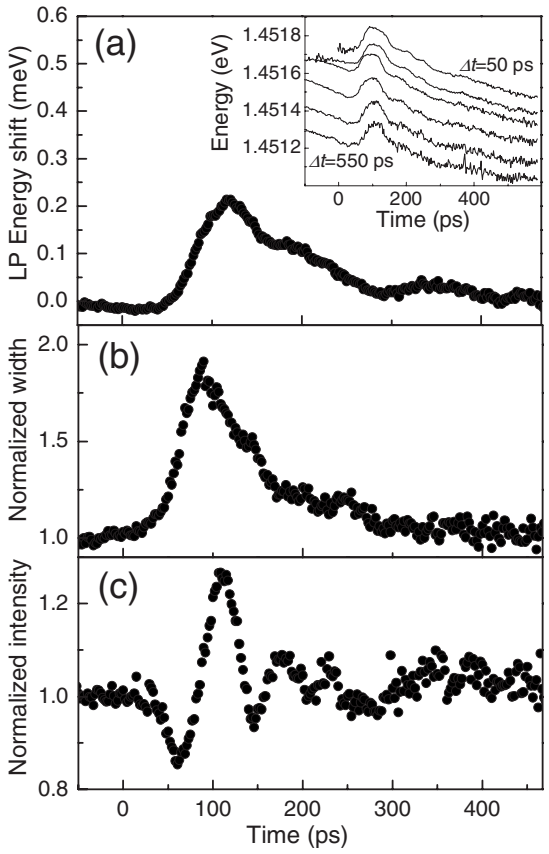

FIG. 4. Temporal evolution of the LP line at $T=1.8$ K: (a) energy shift, (b) spectral width, and (c) integral PL intensity of LP line normalized to the spectral width and integral intensity in the absence of a strain pulse. The inset shows the temporal evolution of the PL energy measured for various time delays Δt, between the pulses for PL excitation and strain pulse injection. The step between the delays is 100 ps. The upper curve corresponds to the shortest delay when the arrival of the strain pulse at the QW coincides with the maximum PL intensity. For better comparison the time scales have been shifted by the corresponding delay so that the curves lie on top of each other.

and $\Delta E_{\mathrm{MC}}^{\mathrm{max}}$ into the dependence of the lower polariton energy on $E_{\mathrm{QW}}-E_{\mathrm{MC}}$ [Fig. 1(b)] it can be easily seen that contribution (ii) dominates over contribution (i) in the net strain-induced PL energy shift, giving $\Delta E_{\mathrm{LP}}\approx 0.17$ meV for our MC. This value is in good agreement with the experimentally measured lower polariton energy shift $\Delta E_{\mathrm{LP}}\approx 0.2$ meV [shown in Fig. 4(a)].

The strain wave packet acts on the MC as a bipolar strain pulse [Fig. 2(b)]. The compression part of the pulse [$\varepsilon(t)<0$] is followed by a tensile perturbation [$\varepsilon(t)>0$]. Thus ΔE_{QW} is expected to change sign from positive for $\varepsilon(t)<0$ to negative for $\varepsilon(t)>0$.[11] Therefore also ΔE_{LP} should change sign in phase with ΔE_{QW}. However, this is not observed experimentally where only $\Delta E_{\mathrm{LP}}>0$ is detected [Fig. 3(b)]. Qualitatively this can be explained by the strong quenching of the lower polariton branch PL for decreasing detuning [see Fig. 1(c) and Ref. 7]. Consequently the PL signal during compression will give a much greater contribution than the PL signal during the tensile part to the signal $I(E,t)$ recorded with a limited time resolution. As a result $\Delta E_{\mathrm{LP}}<0$ is not observed in Fig. 3(b).

The observation of the lower polariton PL energy shift due to the modulation of E_{QW} is possible only due to the strong coupling between the photon mode and the exciton resonance. An increase in the optical excitation density reduces this coupling (i.e., decreases the Rabi splitting). This explains the observed shift of the lower polariton PL peak up to 1.4515 eV at early delays in Fig. 3(a) from its energy position $E_{\mathrm{LP}}=1.4510$ eV measured for cw–low power optical excitation [Fig. 1(a)]. The dependence of the coupling strength on excitation density also results in a decrease in E_{LP} during the PL decay after pulsed excitation [Fig. 3(a) and Ref. 9]. However, the strain-induced shift $\Delta E_{\mathrm{LP}}\approx 0.2$ meV does not depend on the polariton density in our experiments. This is demonstrated in the inset of Fig. 4(a) where ΔE_{LP} is almost independent of the delay between the pulsed optical excitation of the MC and the arrival of the strain pulse. Therefore in our case the density dependent effects can be neglected in the analysis of the strain-induced PL energy shift. However, for other experimental conditions than the ones realized here excitation density dependent effects in the light-matter coupling might become important for the strain-induced PL changes.

The start of the strain-induced effect on the spectral width [Fig. 4(b)] and PL intensity [Fig. 4(c)] is shifted by 30 ± 10 ps to earlier times compared to the PL energy shift [Fig. 4(a)]. This value agrees very well with the time for a distance of 120 nm, which a strain pulse travels during its motion from the edge of the Bragg mirror to the QW, as

shown by the horizontal bar in Fig. 2(a). In fact, the strain pulse reaches first the internal edge of the Bragg mirror and induces broadening and intensity decrease in the PL emission without a strong change in the photon resonance energy E_{MC}. Apparently the explanation of these observations can be strain-induced changes in the MC finesse. The strain-induced changes in the finesse of the cavity and the energy shift of the exciton in the QW give different signs for PL changes. Together with different arrival times of the strain pulse to the Bragg mirrors and the QW this results in the pseudo-oscillations observed in Fig. 4(c).

The PL energy and intensity modulation obviously depend on the initial detuning $E_{QW}-E_{MC}$. In the present work this value is chosen positive and not too far from the Rabi splitting value. In this case we get a considerable energy modulation without strong changes in the PL intensity. From Figs. 1(b) and 1(c) it is clear that having a detuning closer to the resonance ($E_{QW}-E_{MC}=0$) the energy modulation will have higher amplitude but the intensity of PL will be lower. Therefore values $E_{QW}-E_{MC}<0$ appear to be not useful because of the low PL intensity.

In conclusion we have obtained the subterahertz modulation of the light-emission spectrum from a semiconductor quantum well embedded in a planar microcavity with high finesse, so that strong coupling between the exciton and photon occurs. The modulation is achieved by injecting a picosecond strain pulse into the microcavity. The experiments open the way for ultrafast control of light in photonic devices using monochromatic hypersound, strain wave packets, and acoustic solitons. Further, experiments in which the strain pulse controls optically stimulated processes in a cavity or manipulates a polariton condensate may become feasible. At higher temperatures the proposed idea could be realized with semiconductor lasers where the modulation of the gain spectrum relative to the optical mode spectrum might result in ultrafast switching on and off of the lasing. Also other materials such as GaN based nanostructures may be of interest where the strain pulse leads to a stronger shift of the exciton.

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