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Large room temperature Rabi-splitting in II–VI semiconductor microcavity quantum structures

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Abstract

Due to their large oscillator strength, ZnSe microcavities with (Zn,Cd)Se quantum wells are particularly suited to investigate the photon–exciton coupling behaviour in semiconductors. We have observed a strong coupling between the excitonic and photonic mode in a ZnSe microcavity with four (Zn,Cd)Se quantum wells and distributed Bragg-mirrors of ZnS and YF_3. A very large Rabi-splitting $\Omega > 40$ meV was observed at $T = 300$ K in reflection measurements as well as in photoluminescence investigations.

Keywords: Rabi-splitting; Microcavity structure; Bragg-mirrors

1. Introduction

Semiconductor quantum wells as part of microcavities allow to study the interconversion between excitons and photons, which in the strong coupling regime is manifested as a Rabi-splitting into two resonance features of the optical spectrum.

The coupling between excitons and photons generate quasi-particles known as polaritons. These particles have some extraordinary properties which open the possibility to develop new types of efficient light emitters or quantum processors [1,2].

For room temperature applications, the Rabi-splitting must exceed the thermal energy of about 25 meV. Since the Rabi-splitting is proportional to the oscillator strength, this condition is excellently satisfied with ZnSe-based quantum structures.

After the first observation of a polariton splitting in a Fabry–Perot microcavity [3,4], the strong coupling regime of quantum well excitons was studied by various spectroscopy methods of III–V and II–VI semiconductor microcavities [5–8]. Kelkar et al. [9] reported a Rabi-splitting of 17.5 meV at 70 K and 10 meV at 175 K in a (Zn,Mg)(S,Se) microcavity with three (Zn,Cd)Se quantum wells as the resonant medium and dielectric Bragg-mirrors of SiO_2/TiO_2 in 1995. André et al. [10] have investigated CdTe multi quantum well (MQW) structures enclosed in (Cd,Mg)Te/(Cd,Mn)Te semiconductor Bragg-mirrors, showing Rabi-splitting energies between 12 and 30 meV at room temperature as a function of the number of quantum wells.

Recently Saba et al. [11,12] have measured parametric polariton amplification up to 220 K in CdTe-based MQW microcavity structures. The experimental observations demonstrate that the polariton amplification cut-off temperature is directly related to the exciton binding energy. In ZnSe, a large Rabi-splitting energy and high exciton binding energy of about 40 meV is combined. Therefore, this material is particularly suited for microcavity applications such as polariton amplification devices.

In this paper, we report large Rabi-splitting at room temperature, which was realized in a ZnSe microcavity containing four strained (Zn,Cd)Se quantum wells as the resonant medium. We used dielectric ZnS and YF_3 distributed Bragg-mirrors (DBRs).

Measurements of the reflectivity and the photoluminescence reveal clear evidence of the strong coupling between the photonic (PM) and the excitonic mode (EM) in our microcavities yielding a Rabi-splitting of 44 meV at room temperature.

2. Experimental setup

ZnSe/(Zn,Cd)Se MQW structures were grown on (001)GaAs by molecular beam epitaxy (MBE) at

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$T = 310$ °C. The nominal layer thickness of the sample was about 195 nm, which is identical to the optical length of the 528 nm emission in ZnSe. A cavity layer thickness gradient across the sample of about 2 nm per mm sample length was realized by placing the substrate in an appropriate angle with respect to the effusion cells. Four (Zn,Cd)Se quantum wells with a cadmium content of $x = 0.34 \pm 0.02$ and a thickness of $d = 7$ nm were placed near the antinodes of the standing wave in the microcavity. After the growth of the microcavity, an eightfold stack of ZnS and YF_3 DBRs was deposited by thermal evaporation on top of the MQW structures. Then the GaAs substrate was removed by wet etching and the microcavity structure was completed by a sixfold stack of DBRs on the backside.

The sample structure was characterized by high resolution X-ray diffraction (HRXRD) in triple axis mode and simulation of the X-ray data by dynamic diffraction theory [13].

For the reflection measurements, we used a tungsten lamp and a spot of about 100 μm diameter focused on the sample. The photoluminescence was measured using a HeCd laser at $\lambda = 325$ nm with an excitation density of approximately 1 W cm^{-2}. The reflectivity and photoluminescence spectra were measured on different sites on the sample in order to obtain data as a function of the cavity length.

3. Results and discussion

Fig. 1 shows a cross-section drawing of our microcavity structure. Four (Zn,Cd)Se quantum wells enclosed in ZnSe barriers represent the resonant medium. The cadmium content of $x = 0.34$ and the well size of $d = 7$ nm were obtained by HRXRD. During MBE growth, the sample was placed in an appropriate angle with respect to the effusion cells to generate a layer thickness gradient in the structure which is schematically indicated in Fig. 1. The analysis of the strain status of the microcavity structures was carried out, measuring the $(-2-24)$ reflection reciprocal space map. It was found that the quantum wells are fully strained, whereas the barriers are partially relaxed.

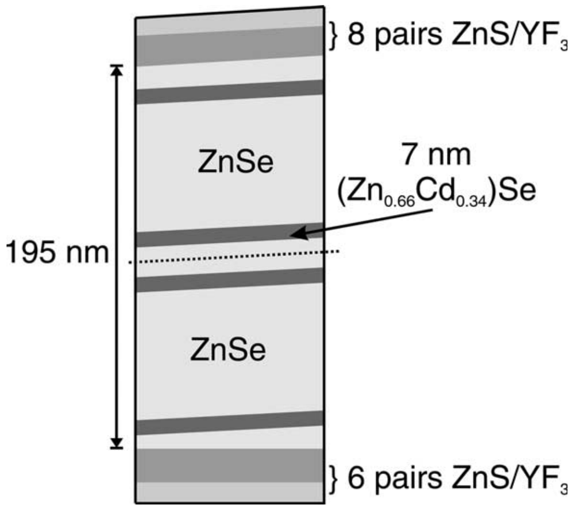

Fig. 1. Cross-section drawing of the microcavity structure. Four (Zn,Cd)Se quantum wells embedded in ZnSe barriers represent the resonant medium. Cadmium content $x = 0.34$ and well width $d = 7$ nm were obtained by X-ray measurements. The cavity thickness gradient allows the tuning of the cavity length.

Fig. 2 depicts the photoluminescence spectra of the MQWs before deposition of the DBRs measured at 5 and 300 K, respectively. In both cases, the luminescence was fitted by Lorentzian functions. At low temperature, a full width at a half maximum (FWHM) of $\Delta E = 11$ meV was measured revealing the excellent interface quality in the MQW structure. The FWHM at 300 K is about 27 meV. The peak is shifted by 94 meV to lower energies according to the bandgap shift.

Fig. 3 shows the room temperature reflectivity spectra of the microcavity obtained at different sample positions. The dots depict the experimental data and the curves represent Lorentzian fits. The respective cavity length values, which are also indicated in Fig. 3, were calculated from the shift of the PM (cavity mode), which is caused by the layer thickness gradient. In dependence on the cavity length, the PM shifts to higher energies, which is indicated in Fig. 3. At $L_c = 200.5$ nm, the PM approaches the luminescence energy and a splitting of the reflectivity spectrum into two

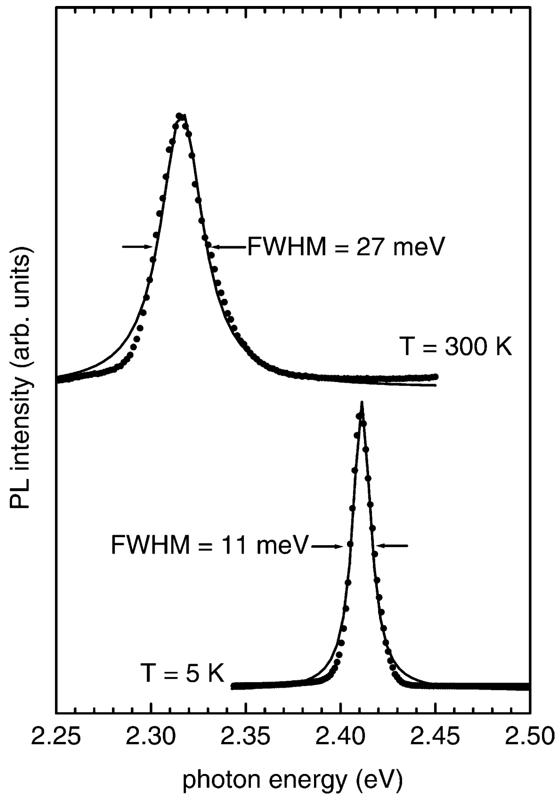

Fig. 2. Photoluminescence measurements of the quantum wells before mirror deposition at 5 K and at room temperature (dots). The lines were fitted with Lorentzian functions. The FWHM at 5 K is 11 meV and 27 meV at room temperature, respectively.

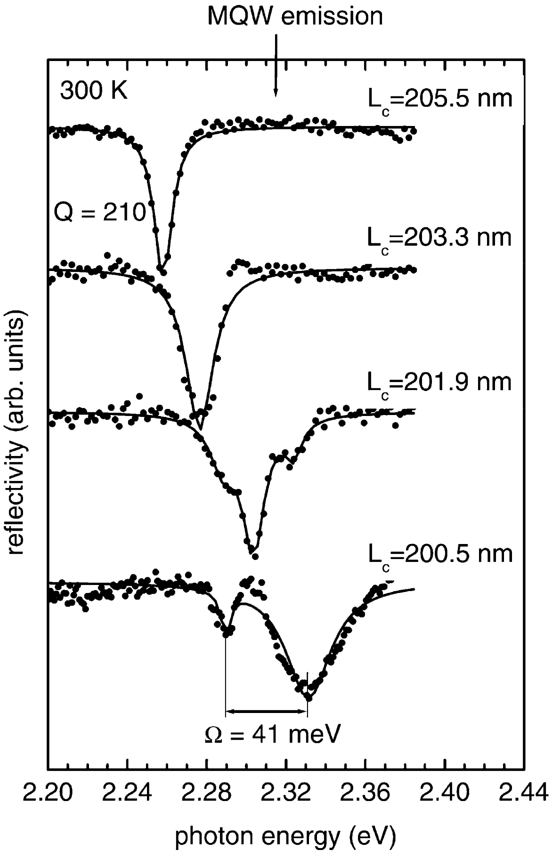

Fig. 3. Reflection measurements of the microcavity structure at different sample positions at room temperature (dots). The curves represent Lorentzian fits. The respective cavity length values (L_c) were calculated from the shift of the PM which is caused by the layer thickness gradient. At $L_c = 200.5$ nm, a splitting into two absorption peaks is observed revealing an energy difference of $\Omega = 41$ meV.

peaks at 2.290 and 2.331 eV is observed. The energy difference between both peaks is $\Omega = 41$ meV.

The square of the Rabi-splitting energy Ω^2_{Rabi} in a microcavity is proportional to the number of quantum wells N_{QW}, the oscillator strength f_{osz} and the inverse of the cavity length L_c [14]. Kelkar et al. [9] measured the low temperature Rabi-splitting of a 4λ-cavity containing three $(Zn_{0.76}Cd_{0.24})Se/ZnSe$ quantum wells. Using their value of 17.5 meV, we obtain $\Omega_{Rabi} = 40$ meV for our structure. From the excellent agreement of this value with the splitting obtained in the reflectivity spectrum of Fig. 3, we conclude that the observed splitting is due to polariton effects.

Fig. 4 shows photoluminescence spectra of a complete microcavity structure at temperatures between 270 and 330 K. The variation of the temperature leads to a shift of the quantum well luminescence energy according to the bandgap shift. Therefore, the EM approaches the PM at a constant cavity length of $L_c = 200.5$ nm. It is evident from Fig. 4 that the luminescence peaks show a clear anticrossing behaviour.

The experimental values of these PL peaks are plotted as a function of the temperature in Fig. 5. The curves in Fig. 5 are a fit of the experimental data using a model of the

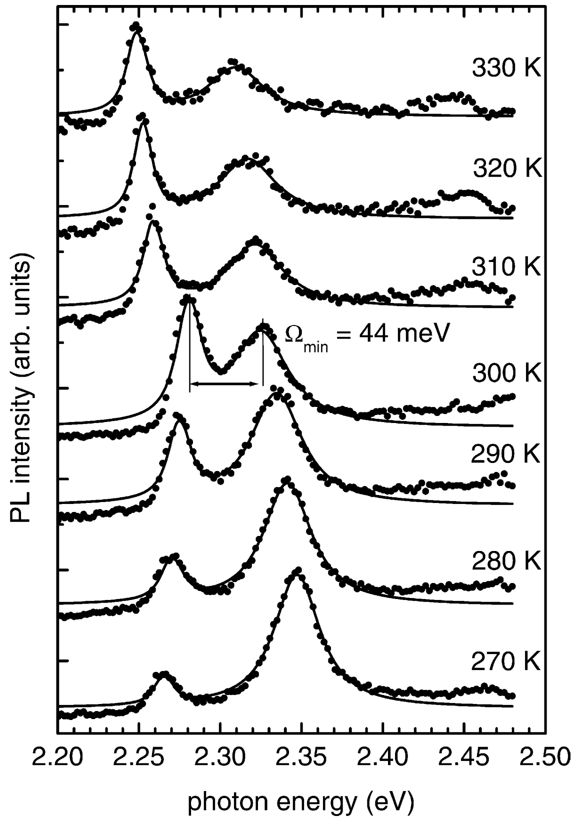

Fig. 4. Temperature-dependent photoluminescence measurements of the microcavity between 270 and 330 K (dots). The curves represent Lorentzian fits. The variation of the temperature leads to a redshift of the quantum well emission, while the cavity mode is constant at $L_c = 200.5$ nm. The experimental data show a clear anticrossing behaviour. The minimum splitting $\Omega_{min} = 44$ meV was detected at $T = 300$ K.

polariton dispersion. After André et al. [10], the polariton dispersion E_{pol} is calculated by using $E_{pol\pm} = 1/2(E_x + E_p) \pm 1/2(\Omega^2_{Rabi} + (E_x - E_p)^2)^{1/2}$, where E_x is the exciton dispersion, E_p, the cavity photon dispersion and Ω_{Rabi}, the Rabi-splitting energy.

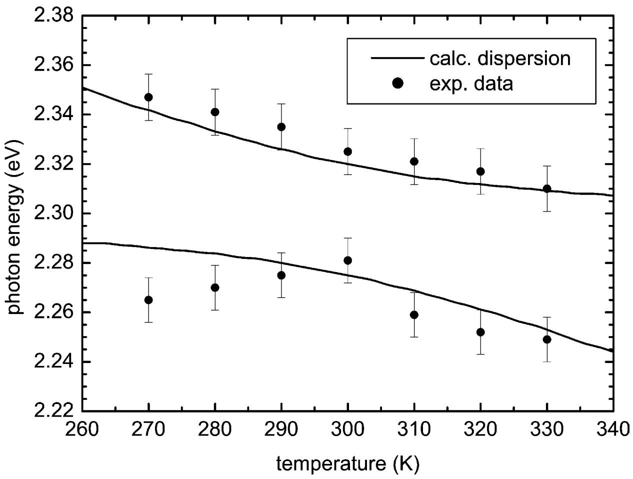

Fig. 5. The peak energies, which were fitted in Fig. 4 with Lorentzian functions are plotted as a function of the temperature (dots). The curves depict the calculated polariton dispersion branches. From this calculation, a Rabi-splitting energy $\Omega_{Rabi} = 45$ meV is determined.

In our calculation, we used $E_x = 2.627 - 1.1 \times 10^{-3}$ T (eV) for the temperature dependence of our quantum well luminescence and $E_p = 2.298$ eV as the constant cavity mode energy, yielding $\Omega_{Rabi} = 45$ meV. This value is in good agreement to the experimental data of the reflection measurements and confirms in addition, the existence of the strong coupling regime. The slight difference of the Rabi-splitting in reflectivity and PL is due to the higher exciton density in the photoluminescence experiments [14].

4. Conclusion

ZnSe/($Zn_{0.7}Cd_{0.3}$)Se MQW cavity structures, which were covered by eight pairs of ZnS and YF_3 DBRs on top and six pairs of the same material on the backside were grown.

PL measurements at 5 and 300 K show a good quality of the interfaces in the structures. The polariton luminescence of the microcavity was investigated by cavity detuning. By the variation of cavity length, the PM was shifted into resonance with the EM. By variation of the temperature, the EM was shifted into resonance with the PM. In the reflection measurements, two absorption peaks with a Rabi-splitting of $\Omega = 41$ meV were detected.

The anticrossing behaviour of the polariton luminescence was verified in temperature-dependent photoluminescence investigations. The Rabi-Splitting of $\Omega = 44$ meV at 300 K is in a good agreement with the other experimental results and is consistent to the theoretical calculation of the polariton dispersion curves. To our knowledge, this is the largest room temperature Rabi-splitting value reported so far in semiconductor MQWs.

Acknowledgements

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