Proceedings of the 42th "Jaszowiec" International School and Conference on the Physics of Semiconductors, Wisła 2013

GaAs-Based Quantum Well Exciton-Polaritons beyond 1 μm

M. Pieczarka[a], P. Podemski[a], A. Musiał[a], K. Ryczko[a], G. Sęk[a], J. Misiewicz[a], F. Langer[b], S. Höfling[b], M. Kamp[b] and A. Forchel[b]

[a]Institute of Physics, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland

[b]Technische Physik, University of Würzburg and Wilhelm-Conrad-Röntgen-Research Center for Complex Material Systems (RCCM), Am Hubland, D-97074 Würzburg, Germany

Realization of the Bose–Einstein condensate can provide a way for creation of an inversion-free coherent light emitter with ultra-low threshold power. The currently considered solutions provide polaritonic emitters in a spectral range far below 1 μm limiting their application potential. Hereby, we present optical studies of InGaAs/GaAs based quantum well in a cavity structure exhibiting polaritonic eigenmodes from 5 to 160 K at a record wavelength exceeding 1 μm. The obtained Rabi splitting of 7 meV was almost constant with temperature, and the resulting coupling constant is close to the calculated QW exciton binding energy. This indicates the very strong coupling conditions explaining the observation of polaritons at temperatures where the exciton dissociation is already expected, and allows predicting that room temperature polaritons could still be formed in this kind of a system.

DOI: 10.12693/APhysPolA.124.817

PACS: 73.21.−b, 78.67.−n, 78.67.Pt

1. Introduction

Light–matter interaction in semiconductor systems has attracted much attention in recent years [1–3]. A specific reason is the strong coupling of the excitonic states in one (or more) quantum well(s) with a photonic cavity mode (CM), forming a new class of quasi-particles called exciton-polaritons [3–6]. Like excitons, these exciton-polaritons have a bosonic character allowing for intriguing fundamental phenomena like the Bose–Einstein condensation (BEC) [4, 5]. At the same time, unique physical properties of exciton-polaritons made them also an interesting candidate for device applications. Since the exciton-polariton is formed as a superposition of excitonic and photonic states, the effective mass of exciton-polaritons is much smaller than that of bare excitons and several orders of magnitude smaller than the hydrogen atomic mass [7]. This allows for high-temperature BEC in this kind of a system.

Due to the condensation of exciton-polaritons, microcavity structure emits coherent light making it interesting for laser applications [7, 8]. The main advantage of exciton-polariton lasing is that the population inversion, necessary in photon laser structures (e.g. diode lasers), is no longer required [7, 8]. This results in a threshold carrier density which can be 2 orders of magnitude smaller than in the case of pure photonic laser emission, building up a future for ultra-low-power-consuming coherent light sources [7]. So far, exciton-polariton lasers have been realized based on CdTe, GaN and GaAs substrates with emission wavelength far below 1 μm [5, 9–12], typically even below 900 nm.

The main challenge to move these devices out of the lab into the real world is to make them compatible to application standards. One of the biggest optoelectronic markets nowadays is the telecommunication, where lasers are used as light sources for data transmission based on optical fibers. The interesting wavelengths are dictated by the fiber characteristics like absorption and dispersion which are most advantageous in the near infrared range above 1 μm. Realizing exciton-polariton lasers at longer wavelengths will bring these devices much closer to application, but no experimental attempts in this direction have been published so far. In this case, GaAs-based structures are of high interest since they offer important advantages as e.g. compatibility to the GaAs/AlAs-distributed Bragg reflectors (DBRs), which easily allows for high quality semiconductor microcavities needed to reach the strong coupling of the exciton to a photonic cavity mode [2, 13], and ability for electrical pumping of such structures [14, 15].

In this report we present optical studies of GaAs-based quantum wells placed in a planar Bragg reflector microcavity. The structure features a gradually changing layers thickness across the wafer, providing easy tuning of the QW-microcavity system at any chosen temperature. The measurements were performed in a form of temperature dependent reflectance along the wafer radius and demonstrated formation of exciton-polaritons above 1 μm at temperatures up to 160 K.

2. Experiment

The examined structures were grown by molecular beam epitaxy on (001) GaAs substrate. The $\lambda/2$ GaAs cavity has been formed between two AlGaAs/GaAs DBRs (16 mirror pairs at the bottom and 12 at the top) with the emitter constituted of 8 $In_{0.3}Ga_{0.7}As$ QWs (7 nm thick). Stripes of the wafer cleaved along its radius have been used for the optical measurements which allows for the cavity mode energy tuning due to the growth rate gradient along the wafer. This enabled easy spectral matching between the energy of the QW exciton and the optical mode.

The optical measurements have been performed using a standard reflectivity configuration with a tungsten halogen lamp as a broadband source. The detection has been realized by using InGaAs CCD linear detector combined with 0.3 m focal length monochromator. The sample was mounted in a continuous-flow liquid helium cryostat allowing for temperature tuning.

3. Results and discussion

Figure 1a shows reflectivity spectra measured at 4 K in a function of a position on the wafer (along its radius). It means in fact tuning the energy of the cavity mode with respect to the QW exciton energy, as the latter remains almost constant in a broad range of the positions on the wafer. The exciton-related reflectivity feature is rather weakly pronounced in the spectra far from the resonance but can be seen at about 1.262 eV (Fig. 1). The cavity mode shifts by more than 20 meV while travelling 6 mm over the radius (along the whole wafer radius the cavity mode energy is a nonlinear but smooth function of the position change). There is clearly seen an anticrossing behavior, a characteristic feature confirming the formation of Exciton-Polaritons with the Rabi splitting of about 7 meV. For each spectrum, a fitting by double Gaussian peak has been performed and the energy positions have been extracted.

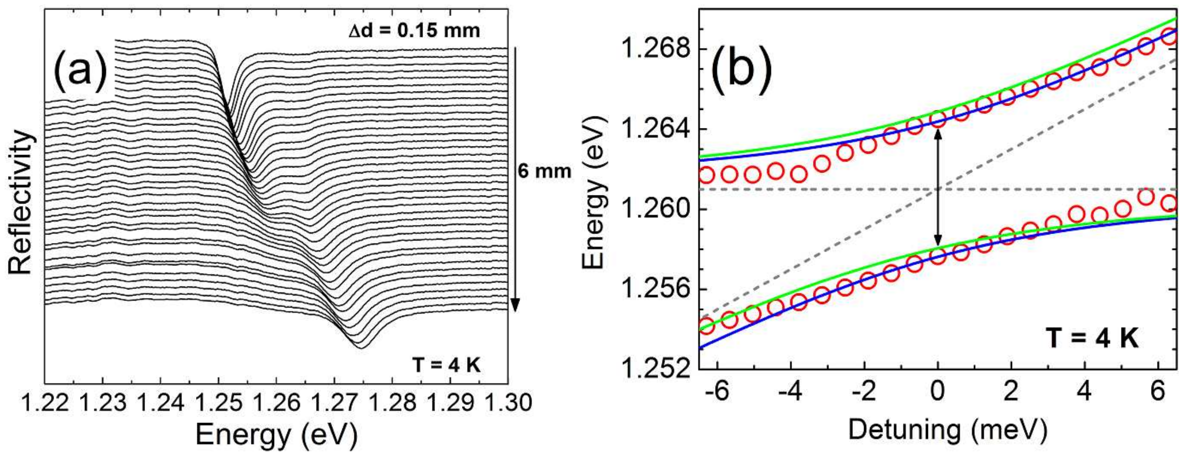

Fig. 1. (a) Reflectivity spectra (at 4 K) vs. the position on the wafer along its radius. Typical anticrossing is observed as a fingerprint of the exciton-optical mode strong coupling with the Rabi splitting of about 7 meV. (b) Polariton branches plotted as a function of the detuning parameter; open symbols — experiment, solid blue lines — theoretical curves according to Eq. (1); solid green lines — theoretical dependence calculated from the model of two coupled oscillators, dashed grey lines — expected energies of uncoupled exciton and CM (guides to the eye).

Figure 1b summarizes the spectra evaluation and shows the corresponding peak energies of both the branches in the vicinity of the resonance vs the detuning energy ($\delta = E_{\text{CM}} - E_{\text{X}}$). The solid blue curves correspond to the theoretical dependence describing the coupled modes according to the following formula:

$$E_{\pm} = \frac{1}{2}\Big(E_{\text{X}} + E_{\text{CM}}(P) \pm \sqrt{(\text{RS})^2 + (E_{\text{CM}}(P) - E_{\text{X}})^2}\Big), \quad (1)$$

where E_{X} and E_{CM} are the exciton and cavity mode energies, respectively, RS is the value of the Rabi splitting and P means the position on the wafer along the radius. The fitting procedure of the polariton branches has been done, taking the rough values of RS and the anticrossing energy from the experiment as the starting point. We assumed a constant value of the uncoupled exciton transition energy E_{X} and an approximately linear dependence of the mode energy E_{CM} on the position P, which is a sufficient approximation due to the short distance travelled on the sample compared to the total wafer radius (6 mm vs. 25 mm). The dashed grey lines in Fig. 1b indicate the expected energies of the uncoupled exciton and CM, and are just guides to the eye.

The investigated coupled system has also been simulated using a quantum-mechanical model of two coupled harmonic oscillators [16], result of which is shown by the green lines in Fig. 1b. They fit the experiment very well, for all the realistic parameters taken into account in this calculation, i.e. the Q-factor of the mode out of the resonance (about 1000) and the linewidth of the QW emission taken from the experiment (approximately 10 meV from PL spectra out of the resonance — not shown here). The only remaining relevant fitting parameter was the coupling strength (or the Rabi splitting), which allows deriving the averaged exciton oscillator strength per QW which was obtained to be approximately 0.8×10^{-3} per unit volume.

The same kind of tuning of the CM through the resonance with the QW exciton has been performed at several higher temperatures and an anticrossing with a pronounced Rabi splitting could still be recorded up to 160 K. The respective reflectivity spectra are shown in Fig. 2a, whereas the plot of the energies of both the polariton branches vs. the detuning energy is presented in Fig. 2b. The resulting tuning range is significantly narrower now, because, due to the temperature change the resonance occurred at quite different position on the wafer. Unfortunately, we have been limited with further tuning and going into the higher temperatures due to the physical limit of the sample, but the effect at 160 K was still well pronounced, predicting the existence of polaritons at even higher temperatures.

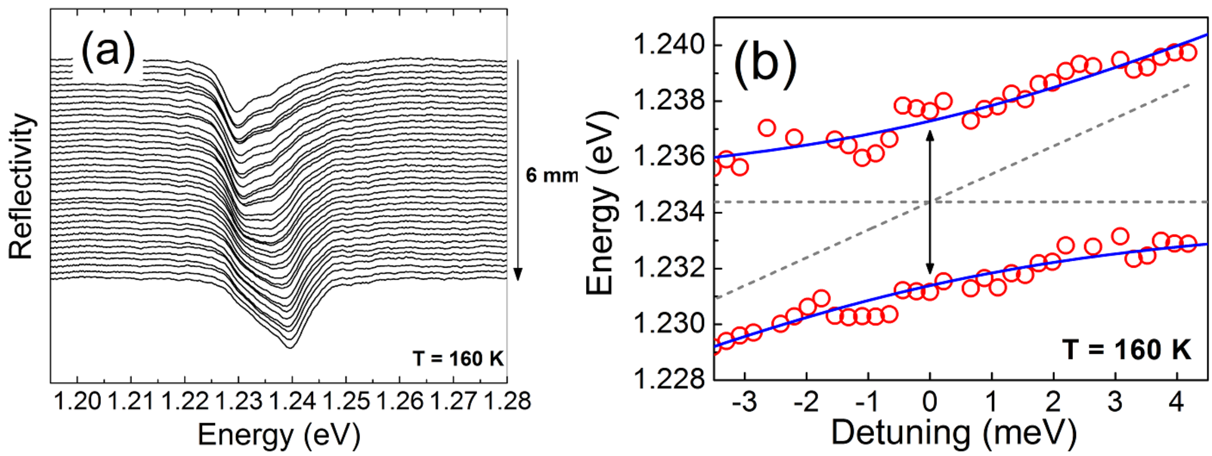

Fig. 2. (a) Reflectivity spectra (at 160 K) vs. the position on the wafer along its radius. Typical anticrossing of both spectral lines, as at low temperature, is observed with approximately the same value of the Rabi splitting equal to 7 meV. (b) Polariton branches plotted as a function of the detuning parameter; open symbols — experiment, solid blue lines — theoretical curves according to Eq. (1), dashed grey lines — expected energies of uncoupled exciton and CM (guides to the eye).

In order to follow the temperature dependence of both the eigenmodes and the related Rabi splitting we measured the respective reflectivity spectra as a function of temperature shifting the position on the wafer so that the "on-resonance" conditions were kept. The result is shown in Fig. 3. It can be seen that one can indeed preserve the strong coupling conditions in a broad range of temperatures, and the splitting energy is almost constant. Generally, a decrease of the coupling strength would be expected with temperature (due to, e.g., carrier losses and less efficient formation of excitons), but this is not the case here as the position on the wafer has to be changed accordingly at each temperature to follow the resonance. Therefore, the Q-factor of the cavity is also altered, namely slightly different for each of the spectra in Fig. 3. It increases in that direction which corresponds to the decrease of the CM energy, which in our case improves the cavity finesse. This agrees with the shift direction, compensating the possible temperature dependence and the unfavorable effect on the coupling. Therefore, the deteriorating influence of the temperature is not observed.

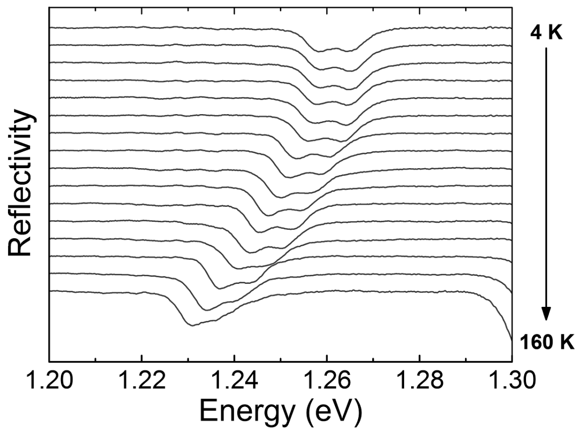

Fig. 3. Temperature dependence of the reflectivity spectra at the zero detuning between the excitonic and photonic modes. The resonance condition is kept by the compensation of the thermally induced spectral shift with the correction of the light spot position along the radius of the wafer.

Another effect is the value of the Rabi splitting which is relatively large compared to the exciton binding energy in this kind of quantum wells. We have calculated the exciton binding energy by a variational envelope function procedure including strain and the dielectric constants contrast between the well and the barrier material. The model is described more in detail in Ref. [17]. The obtained binding energy (E_{B}) value is 5.9 meV, which must be compared to the coupling constant $g = \frac{1}{2}$RS, which in our case is about 3.5 meV. As the coupling constant is not much smaller than the exciton binding energy, the system approaches the conditions for the so-

-called very strong coupling [18–20]. The system enters clearly into that regime when the coupling constant exceeds E_{B}, but as shown in the previous papers [18–20] the effect itself becomes observable for $g/E_{\mathrm{B}} = 0.5$, or even less. In our case this ratio is approximately 0.6, and this is why the exciton-polaritons could survive at temperatures for which the thermal energy kT is significantly larger than the exciton binding energy ($kT \approx 14$ meV versus $E_{\mathrm{B}} = 5.9$ meV), and where in the case of a QW out of a cavity an efficient dissociation of excitons should already occur. Normally, this would prevent the exciton-polaritons formation, which is apparently not the case.

The very strong coupling of the exciton and the CM leads to a photon-mediated renormalization of the optically allowed (i.e., s-like) exciton internal states. Thus, the new eigenstates of the microcavity system may possess electron–hole relative motion probability density (spatial correlation) whose spatial extents may differ strongly from the otherwise dominant $1s$ states, i.e., from the two-dimensional exciton Bohr radius. In particular, for a near-resonant case in which half of the Rabi splitting exceeds the binding energy of the $1s$ exciton, the exciton-polaritons of the lower branch may have a spatial extent significantly smaller than the half of the nominal exciton Bohr radius. This makes the system more robust to the collisions with phonons and allows for the existence of exciton-polaritons at much higher temperatures than could be expected when based just on the value of the exciton binding energy of a QW out of the cavity.

4. Conclusions

We have investigated the formation of exciton-polaritons in the InGaAs/GaAs QW placed inside a Bragg mirror monolithic GaAs-based cavity. By selecting the proper QW content and width it was possible to achieve strong coupling conditions between the QW exciton and the photonic mode for a moderate planar cavity quality factors and to push it to the spectral range above 1 μm at temperatures as high as 160 K. The obtained results indicate some of the existing limitations, and the necessity of further development on the material side, concerning mainly the further wavelength extension via for instance introducing nitrogen and antimony atoms into the InGaAs QW. However, this is already a crucial step toward room temperature polaritons in GaAs material system and the practical exploitation of the condensation of these quasiparticles in optoelectronic devices at telecommunication wavelengths.

Acknowledgments

The authors acknowledge the financial support from the bilateral project of Deutsche Forschungsgemeinschaft (project named LIEPOLATE) and Polish Ministry of Science and Higher Education (project No. DPN/N99/DFG/2010), and the COPERNICUS Award of the Foundation for Polish Science and Deutsche Forschungsgemeinschaft.

References

[1] K. Hennessy, A. Badolato, M. Winger, D. Gerace, M. Atatüre, S. Gulde, S. Fält, E.L. Hu, A. Imamoğlu, *Nature* **445**, 896 (2007).

[2] J.P. Reithmaier, G. Sęk, A. Loeffler, C. Hofmann, S. Kuhn, S. Reitzenstein, L.V. Keldysh, V.D. Kulakovskii, T.L. Reinecke, A. Forchel, *Nature* **432**, 197 (2004).

[3] L.S. Dang, D. Heger, R. André, F. Bœuf, R. Romestain, *Phys. Rev. Lett.* **81**, 3920 (1998).

[4] R. Balili, V. Hartwell, D. Snoke, L. Pfeiffer, K. West, *Science* **316**, 1007 (2007).

[5] J. Kasprzak, M. Richard, S. Kundermann, A. Baas, P. Jeambrun, J.M.J. Keeling, F.M. Marchetti, M.H. Szymaska, R. André, J.L. Staehli, V. Savona, P.B. Littlewood, B. Deveaud, Le Si Dang, *Nature* **443**, 409 (2006).

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

[7] H. Deng, G. Weihs, D. Snoke, J. Bloch, Y. Yamamoto, *Proc. Natl. Acad. Sci.* **100**, 15318 (2003).

[8] A. Imamoglu, R.J. Ram, S. Pau, Y. Yamamoto, *Phys. Rev. A* **53**, 4250 (1996).

[9] S. Christopoulos, G. Baldassarri, H. von Högersthal, A.J.D. Grundy, P.G. Lagoudakis, A.V. Kavokin, J.J. Baumberg, G. Christmann, R. Butté, E. Feltin, J.-F. Carlin, N. Grandjean, *Phys. Rev. Lett.* **98**, 126405 (2007).

[10] G. Christmann, R. Butté, E. Feltin, J.F. Carlin, N. Grandjean, *Appl. Phys. Lett.* **93**, 051102 (2008).

[11] H. Deng, G. Weihs, C. Santori, J. Bloch, Y. Yamamoto, *Science* **298**, 199 (2002).

[12] D. Bajoni, P. Senellart, E. Wertz, I. Sagnes, A. Miard, A. Lemaître, J. Bloch, *Phys. Rev. Lett.* **100**, 047401 (2008).

[13] S. Reitzenstein, C. Hofmann, A. Gorbunov, M. Strauß, S.H. Kwon, C. Schneider, A. Löffler, S. Höfling, M. Kamp, A. Forchel, *Appl. Phys. Lett.* **90**, 251109 (2007).

[14] S.I. Tsintzos, N.T. Pelekanos, G. Konstantinidis, Z. Hatzopoulos, P.G. Savvidis, *Nature* **453**, 372 (2008).

[15] C. Schneider, A. Rahimi-Iman, N.Y. Kim, J. Fischer, I.G. Savenko, M. Amthor, M. Lermer, A. Wolf, L. Worschech, V.D. Kulakovskii, I.A. Shelykh, M. Kamp, S. Reitzenstein, A. Forchel, Y. Yamamoto, S. Höfling, *Nature* **497**, 348 (2013).

[16] S. Pau, G. Björk, J. Jacobson, H. Tsao, Y. Yamamoto, *Phys. Rev. B* **51**, 14437 (1995).

[17] K. Ryczko, G. Sęk, J. Misiewicz, *Solid State Commun.* **122**, 323 (2002).

[18] J.B. Khurgin, *Solid State Commun.* **117**, 307 (2001).

[19] D.S. Citrin, J.B. Khurgin, *Phys. Rev. B* **68**, 205325 (2003).

[20] H. Zhang, N.Y. Kim, Y. Yamamoto, N. Na, *Phys. Rev. B* **87**, 115303 (2013).