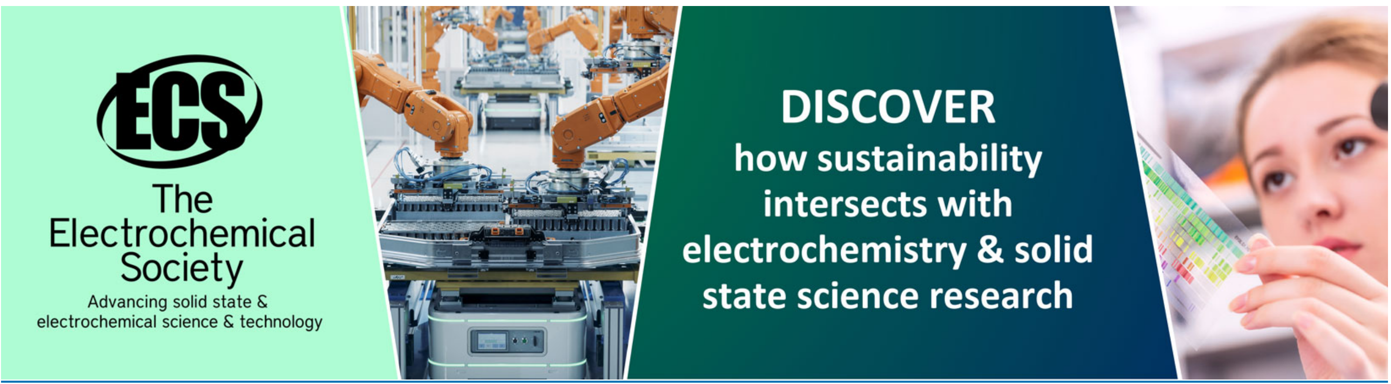
Journal of Physics: Conference Series

Influence of the sample design on the strong light-matter coupling in ZnSe-based periodic structures

To cite this article: K. Sebald *et al* 2017 *J. Phys.: Conf. Ser.* **864** 012020



IOP Conf. Series: Journal of Physics: Conf. Series **864** (2017) 012020 doi:10.1088/1742-6596/864/1/012020

Influence of sample design on the strong light-matter coupling in ZnSe-based periodic structures

K. Sebald[1], SK. S. Rahman[1], T. Kaya[1], J. Gutowski[1], T. Klein[2,3], S. Klembt[2,4], A. Gust[2], D. Hommel[2,5]

[1] Semiconductor Optics, [2] Semiconductor Epitaxy, Institute of Solid State Physics, University of Bremen, Germany

E-mail: `ksebald@ifp.uni-bremen.de`

Abstract. Cavity-exciton polaritons have attracted much interest because these light-matter quasiparticles are very promising for various optoelectronic applications. Bragg-polaritons have been discussed as new tools for tailoring light-matter interactions. These structures can be created by incorporating quantum wells (QWs) periodically into a distributed Bragg reflector (DBR). The advantage of this sample type is the high number of QWs which can be embedded into the sample in order to increase the Rabi-splitting energy. Calculations show, that the coverage of the sample with a thin metal layer results in an increase of the temperature stability of the strong coupling regime. In addition, this concept enables a specific spectral variation of the cavity resonance allowing for the manipulation of the light-matter interaction.

1. Introduction

The realization and manipulation of the strong coupling regime in microcavities (MCs) are one of the current research objectives, due to the unique properties of the generated exciton-polaritons for novel optical devices as well as for fundamental physics [1, 2]. Strong coupling in classical microcavities has been demonstrated for different material systems. In particular, the use of wide-bandgap semiconductor enabled polaritonic lasing at room temperature [3–5]. In recent years, Bragg-polariton samples, where the QWs are directly inserted into the DBR, have been discussed as a new tool for tailoring light-matter coupling [6, 7]. The advantage of this type of an unfolded MC sample is the simplification of the sample design and the large number of QWs which can be inserted into the structure without increasing the mode volume. In this case, the light-matter interaction occurs between the QW excitons and the Bragg-mirror modes forming a Bragg polariton. The first report on the realization of strong coupling for an unfolded MC concerned single InGaAs QWs embedded in a 30-periods distributed Bragg reflector (DBR) stack with a Rabi-splitting energy of 9.3 meV [6]. In order to control and manipulate the polariton eigenstate, as it is necessary for fundamental physics as well as for application, metal films can be utilized. This results in a local energy blueshift of the cavity mode which leads to a lower energy position of the polariton. In such a way potential barriers of about 200 μeV [8] can be created. An additional positive effect is the increase of the internal reflectivity of the device

[3] Present address:BIAS, Klagenfurter Str. 2, 28359 Bremen, Germany
[4] Technische Physik, University of Würzburg, Am Hubland, Germany
[5] Institute of Experimental Physics, University of Wroclaw and Wroclaw Research Center EIT, Poland

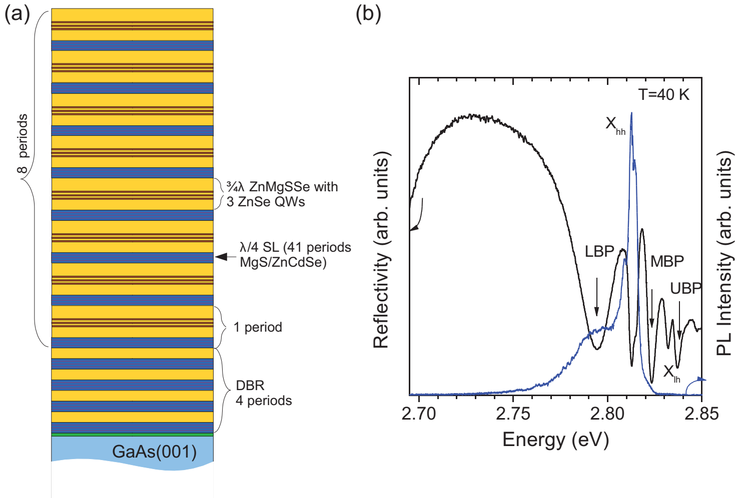


Figure 1. (a) Principle drawing of the sample setup of the unfolded cavity structure. (b) Reflectivity and photoluminescence spectra of the Bragg-polariton sample measured at T = 40 K (excitation energy 3.03 eV). The spectral position of the lower (LBP), middle (MBP) and upper Bragg-polariton (UBP) branch are indicated together with those of the X_{hh} and X_{lh} state.

improving its optical quality. In this contribution we will present investigations of the optical properties of a Bragg-polariton sample and discuss the possibility to achieve strong coupling at room temperature by the usage of metal films.

2. Experimental setup and results

The Bragg-polariton sample was grown by molecular beam epitaxy. For the Bragg-layers $Zn_{0.79}Mg_{0.21}S_{0.23}Se_{0.77}$ is chosen as the high-index material, while the low-index material consists of a superlattice of MgS and $Zn_{0.63}Cd_{0.37}Se$. Thus, a refractive index contrast in the order of $\Delta n = 0.4$ is obtained. Each three 8 nm thick ZnSe QWs are embedded in the center of any of the high-index material with a total thickness of $3\lambda/4$ (144 nm). The low-index material possesses a thickness of $\lambda/4$ (44.7 nm) (see Fig. 1 (a)). Eight of these Bragg-polariton layer combinations were grown on four plain DBR pairs, where the latter ensure a precise *in-situ* control of the respective $\lambda/4$-thickness. Micro-reflectivity and -photoluminescence (excitation energy 3.03 eV) measurements were performed and the experimental findings are compared to calculations using a transfer matrix (TM) method (CAMFR program [9]). Fig. 1 (b) shows the reflectivity of the sample in comparison to its photoluminescence at T = 40 K. The reflectivity exhibits five distinct minima. The second minimum centered at 2.812 eV originates from the ZnSe QW heavy-hole (X_{hh}) exciton, while the fourth minimum at 2.832 eV can be attributed to the absorption of light-hole exciton (X_{lh}). This classification is underscored by the PL spectrum showing a dominant contribution of the ZnSe QW X_{hh} together with a signature probably due to trionic recombination on the low-energy side. We have already shown earlier that the implementation of the QWs into the DBR structure results in the interaction of the first Bragg mode with the X_{hh} and X_{lh} states leading to the formation of three polariton states, the lower (LBP), middle (MBP) and upper Bragg-polariton (UBP) branch [10]. The strong indication for the existence of strong coupling is traceable up to a temperature of 200 K with Rabi-splitting energies of 24 meV and 13 meV between the Bragg-polaritons. In the reflectivity spectrum in Fig. 1 (b) the LBP, MBP and UBP can be identified at 2.7945 eV, 2.823 eV and 2.837 eV (first, third and fifth minimum). In Fig. 2 (a) the photoluminescence spectra are depicted in the temperature region between 40 K and 160 K. The emission of the X_{hh} and X_{lh} as well as the one at the position of LBP can be identified. The relative detuning of the LBP band with regard to the respective energy position of X_{hh} at any of the given temperatures can be easily derived if the appropriate energy position of X_{hh} is taken as zero. Besides the increasing spectral width of the excitonic components with growing temperature the spectral shift of the emission attributed to the LBP shows a decrement

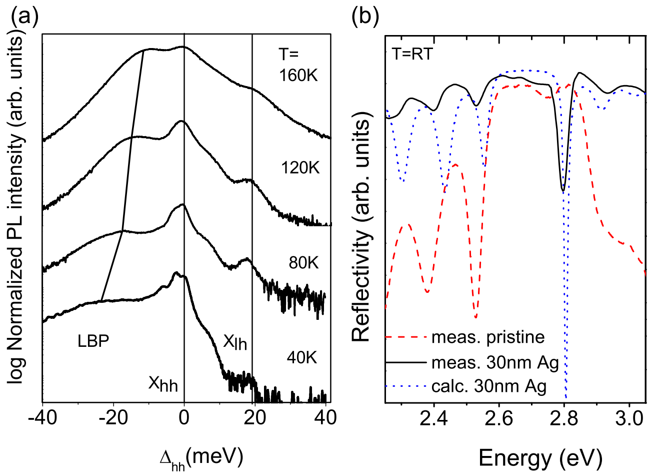


Figure 2. (a) PL spectra of the Bragg-polariton sample taken for temperatures between 40 and 160 K and vertically shifted for clarity. The relative energy position of the X_{hh} is taken as zero for the different temperatures. The spectral positions of the X_{hh} and X_{lh} are marked by a vertical lines while the relative shift of the emission at the position of the LBP is labeled by a line as guide to the eye. (b) Measured reflectivity of a pristine and a metal covered (30 nm Ag) microcavity (dashed and solid line) together with the calculated spectrum (dotted line).

for increasing temperatures. This is due to the anticrossing of the Bragg mode with the X_{hh}, which we have already reported to occur at T = 130 K [10]. For temperatures exceeding 200 K the strong-coupling regime is broken due to the spectral broadening of the excitonic components. These results have shown that a remarkably large Rabi-splitting energy can even be realized with eight Bragg-polariton stacks. The observed interaction strength is comparable to a complete MC structure consisting of an 18-fold bottom DBR, a λ cavity, and a 15-pair top DBR, for which a Rabi-splitting energy of 19 meV was reported at 70 K [11]. In order to fully exploit the promising properties of a Bragg-polariton sample one has to achieve the strong coupling regime near room temperature without scaling up the fabrication effort. One possibility is the usage of a thin metal layer which can drastically increase the optical quality of the structure, as already reported [12]. To emphasize this idea, we present a micro-reflectivity measurement at RT of a planar cavity sample which consists of a 12-pair bottom DBR, a $\lambda/2$ cavity, and a 1.5-pair top DBR, as shown in Figure 2 (b). The spectrum for the pristine sample (dashed line) possesses a cavity dip at $E_C = 2.742$ eV, and the reflectivity is close to 94 %. This relatively low value is due to the small number of top DBR layer pairs. When the MC is covered by a 30 nm thick Ag layer the reflectivity minimum shifts to higher energies what goes along with an enhancement of the transmission. The reflectivity minimum of that sample possesses a full width at half maximum of 33 meV. The measured spectrum is displayed along with the calculated one (dotted line) in which the band possesses a spectral width of 13 meV. The calculated blueshift of the reflectivity minimum amounts to 65 meV, being about a factor of 1.7 times larger than the experimental value. The maximal reflectivity is increased to 99.5%. These results indicate the large improvement of the optical properties of a microcavity achieved by applying a metal deposition. The deviation of the measurement relative to the calculation is due to an oxidation of the thin layer which is not completely reproduced by the calculation, although an oxidation degree of 15% was assumed. We have applied this concept theoretically to the Bragg-polariton sample by performing transfer matrix calculations. We have assumed that the sample is covered by a 30 nm thick Ag layer and as calculation parameters we have inserted the spectral width and position of the QWs excitonic components at room temperature. The spectral position of the Bragg mode can be tuned relative to X_{hh} by changing the thickness of the top layer by an appropriate factor as given in Fig. 3 (a). The resulting map of the gray-coded reflectivity shows

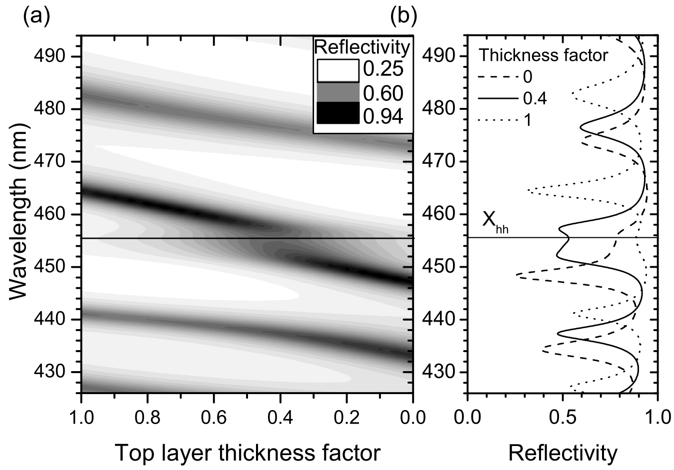


Figure 3. Calculated reflectivity for different top layer thicknesses of a Bragg-polariton sample covered with 30 nm of Ag. The parameter for the calculation matches the excitonic spectral position and spectral width of a ZnSe QW reference sample at room temperature. An anticrossing at the position of the X_{hh} (horizontal line) is observed. (b) shows the corresponding reflectivity spectra.

an anticrossing for a thickness factor of 0.4 at the position of the X_{hh}. The energy splitting can be deduced to 30 meV from the reflectivity spectra shown in Fig. 3 (b). This calculation indicates that a device operating at room temperature in the strong coupling regime can be achieved with a rather simple Bragg-polariton sample design by adding a thin metal layer.

3. Conclusion

The realization of strong coupling in an unfolded microcavity was verified by analyzing the photoluminescence for different temperatures. Calculations indicate that the application of a thin metal layer may help to achieve strong coupling at room temperature due to the improved reflectivity.

Acknowledgment: We gratefully acknowledge financial support from the Deutsche Forschungsgemeinschaft (Se 1846/1-2, Ho 1388/33-2).

References

[1] Kasprzak J, Richard M, Kundermann S, Baas A, Jeambrun P, Keeling J M J, Marchetti F M, Szymańska M H, André R, Staehli J L, Savona V, Littlewood P B, Deveaud B and Dang L S 2006 *Nature* **443** 409
[2] Amo A, Lefrére J, Pigeon S, Adrados C, Ciuti C, Carusotto I, Houdré R, Giacobino E and Bramati A 2009 *Nature Physics* **5** 805–810
[3] Christmann G, Butté R, Feltin E, Carlin J F and Grandjean N 2008 *Applied Physics Letters* **93** 051102
[4] Li F, Orosz L, Kamoun O, Bouchoule S, Brimont C, Disseix P, Guillet T, Lafosse X, Leroux M, Leymarie J, Malpuech G, Mexis M, Mihailovic M, Patriarche G, Réveret F, Solnyshkov D and Zuniga-Perez J 2013 *Applied Physics Letters* **102** 191118
[5] Klein T, Klembt S, Durupt E, Kruse C, Hommel D and Richard M 2015 *Applied Physics Letters* **107** 071101
[6] Askitopoulos A, Mouchliadis L, Iorsh I, Christmann G, Baumberg J J, Kaliteevski M A, Hatzopoulos Z and Savvidis P G 2011 *Phys. Rev. Lett.* **106** 076401
[7] Sedov E S, Iorsh I V, Arakelian S M, Alodjants A P and Kavokin A 2015 *Phys. Rev. Lett.* **114** 237402
[8] Lai C W, Kim N Y, Utsunomiya S, Roumpos G, Deng H, Fraser M D, Byrnes T, Recher P, Kumada N, Fujisawa T and Yamamoto Y 2007 *Nature* **450** 529
[9] Bienstmann P 2001 *Rigorous and efficient modeling of wavelength scale photonic components* (Universiteit Gent, Belgien)
[10] Sebald K, Rahman S, Cornelius M, Kaya T, Gutowski J, Klein T, Gust A, Hommel D and Klembt S 2016 *Applied Physics Letters* **108** 121105

[11] Sebald K, Seyfried M, Klembt S, Bley S, Rosenauer A, Hommel D and Kruse C 2012 *Applied Physics Letters* **100**

[12] Sebald K, Rahman S, Cornelius M, Gutowski J, Klein T, Klembt S, Kruse C and Hommel D 2015 *Applied Physics Letters* **107** 062101