Observation of strong exciton–photon coupling at temperatures up to 410 K

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Abstract. We report on the observation of strong exciton–photon coupling in a ZnO-based microresonator consisting of a half medium wavelength ZnO cavity embedded between two dielectric Bragg reflectors made of 10.5 layer pairs of yttria stabilized zirconia and Al2O3. The microresonator was investigated by photoluminescence and reflectivity measurements in a wide temperature range between 10 and 550 K. With both techniques a lower polariton branch (LPB) was observable. As expected no signal from an upper polariton branch could be detected caused by the strong absorption of ZnO in this spectral range. The dispersion behaviour of the LPB (in both energy and broadening) is well described by a model that takes into account the coupling between one exciton mode and one cavity-photon mode. From this analysis we can conclude that the microresonator is in the strong coupling regime up to 410 K. Maximum values of the coupling strength at 10 K of 51 meV, respectively 55 meV, could be derived from the photoluminescence and from the reflectivity. These results demonstrate the high potential of ZnO microresonators for the realization of a Bose–Einstein condensation at room temperature and above.

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1. Introduction

The strong coupling of light and matter in microresonators has been intensively investigated in the last few decades since it forms new bosonic quasi-particles, so-called exciton–polaritons [1]–[9]. These particles are characterized by dispersion branches, in the simplest way an upper and a lower polariton branch (UPB and LPB). Near the centre of the Brillouin zone, the dispersion of the polariton modes is steep, resulting in a very low effective polariton mass in the range $10^{-5}$–$10^{-4}$ times the free electron mass. As exciton–polaritons are bosons, they can occupy the same quantum state and therefore can undergo Bose–Einstein condensation (BEC) at temperatures even above room temperature (RT) due to their low effective mass, which is about nine orders of magnitude smaller than the atomic mass of diluted atom gases. BEC of exciton–polaritons was for the first time observed by Kasprzak et al [5] in a CdTe-based microresonator at 19 K, and Christopoulos et al [7] presented the realization of a BEC at RT in a GaN-based microresonator. The emission from such a macroscopic exciton–polariton quantum state provides the basis for a multitude of new applications, e.g. optical amplifiers and ultra-low threshold lasers. The advantage of these devices is that they can operate at much lower power in comparison to their conventional counterparts. The main obstacle so far is the limited temperature range for the formation of exciton–polaritons and up to now, microcavity exciton–polaritons were observed at temperatures up to RT only. By using a ZnO-based resonator we are able to overcome this limited temperature range, due to the large exciton binding energy of 60 meV in ZnO.

The first observations of exciton–polaritons in microresonators were reported for GaAs- and CdTe-based resonators at low temperatures ($T < 30$ K) [1, 2, 8]. In these materials, the exciton binding energy is smaller than the thermal energy at RT and excitons are not stable at RT. Therefore, many efforts have been made to obtain microresonators with gain media that reveal an exciton binding energy larger than the thermal energy at RT, such as organic semiconductors [10, 11], or GaN [7, 12, 13] and ZnO [14]–[16]. The advantage of organic semiconductors is their huge exciton oscillator strength resulting in a large coupling strength between the excitons and the cavity photons. However, often the low crystal quality of such materials leads to emission spectra that are superposed from the emission from localized and delocalized states. In contrast, inorganic semiconductors reveal high crystal qualities with an emission from well-defined exciton states. Here, GaN and ZnO are the most prominent candidates that are considered for high temperature applications. ZnO offers some
advantages, since it reveals the largest exciton oscillator strength of the technologically relevant semiconductors, about three times larger than that of GaN [9, 17], and its exciton binding energy is about twice the thermal energy at RT.

In this paper, we present the observation of exciton–polaritons in a ZnO-based microresonator up to 410 K, which is the first observation of exciton–polaritons well above RT. A model analysis of the experimentally observed dispersion behaviour of the resonator modes shows that the microresonator is in the strong coupling regime up to this temperature. This is the highest reported temperature for strong exciton–photon coupling up to now.

2. Exciton–polariton dispersion

As mentioned in the introduction, the strong coupling between excitons and cavity-photons forms new mixed states that are called exciton–polaritons. In the simplest case of coupling between only one cavity-photon mode and one exciton mode, the exciton–polariton dispersion exhibits a LPB and an UPB (figure 1). Since exciton–polaritons are mixed states, their lifetime and dispersion depend on the properties of both the uncoupled exciton mode and the uncoupled cavity-photon mode. An important quantity, which depends on the in-plane wavevector $k_\parallel$, is the difference $\delta(k_\parallel)$ between the energy of the exciton mode $E_X$ and the cavity-photon mode $E_C$, $\delta(k_\parallel) = E_C(k_\parallel) - E_X(k_\parallel)$. It is a measure of the character, that means the dominance of the excitonic or photonic properties, of the LP and UP which are complementary to each other. In the case of $\delta = 0$ both the excitonic and the photonic properties contribute equally to the LP and UP, whereas for $\delta < 0$ or $\delta > 0$ the photonic part dominates the LP and the excitonic one the UP or vice versa, respectively. Since $\delta$ depends on the in-plane wavevector, the fraction of the excitonic and the photonic properties depends on the in-plane wavevector and so the dispersion behaviour of the exciton–polariton branches depends also on $\delta$. For zero in-plane wavevector $k_\parallel$, $\delta$ is known as detuning $\Delta = \delta(k_\parallel = 0)$. The exciton–polariton dispersion for the case of negative, zero and positive detuning is shown in figure 1.

The dispersion of exciton–polaritons can be described semiclassically by using a coupling Hamiltonian for the exciton–photon coupling and taking into account complex energies $\tilde{E} = E_r - i\gamma$ for the uncoupled exciton and cavity-photon modes. Thereby, the real part represents
the mode energy position $E_r$ and the imaginary part represents the broadening $\gamma$ which is related to the lifetime by $\tau = \hbar/\gamma$. In the case of coupling between one exciton and one cavity-photon mode the coupling Hamiltonian is represented by a $2 \times 2$ matrix. The exciton–polariton energies are given by the eigenvalues of this matrix:

$$
\tilde{E}_{LP,UP}(\varphi) = \frac{1}{2} \left[ (\tilde{E}_X + \tilde{E}_C(\varphi)) \pm \sqrt{(\tilde{E}_X - \tilde{E}_C(\varphi))^2 + 4V^2} \right].
$$

(1)

$\tilde{E}_X$ denotes the complex energy of the uncoupled exciton mode, $\tilde{E}_C$ the complex energy of the uncoupled cavity-photon mode, $V$ the coupling strength, and $\varphi$ the angle of incidence or rather the emission angle. Since the exciton mode shows a nearly flat dispersion for small $k$-values, its energy can be assumed to be constant for all angles. However, the energy of the uncoupled cavity-photon mode depends strongly on the angle due to its parabolic dispersion behaviour. It is controlled by the optical thickness of the cavity as well as by the penetration depth of the photons into the mirrors. Therefore, the uncoupled cavity-photon mode can be described following the approach suggested by Panzarini et al [18] so that the cavity-photon mode energy ($E_C$) and the corresponding broadening ($\gamma_C$) is given by:

$$
E_C(\varphi) = \frac{\pi + \Lambda_B(E, \varphi)E_s(E, \varphi)}{\Lambda_B(E, \varphi) + n_Cd_C \cos(\varphi_C)/\hbar c},
$$

(2)

$$
\gamma_C(\varphi) = -\frac{\ln \sqrt{R_tR_b}}{2(\Lambda_B(E, \varphi) + n_Cd_C \cos(\varphi_C)/\hbar c)}.
$$

(3)

with the thickness of the cavity $d_C$, the refractive index of the cavity material $n_C$, the propagation angle of the light inside the cavity material $\varphi_C$, the energy of the stop band centre $E_s$, the pseudo penetration depth $\Lambda_B$ and the reflectivity of the top and bottom Bragg reflector (BR) ($R_t$ and $R_b$, respectively). $\Lambda_B$ and $E_s$ depend on the optical thickness of each layer, this means on the geometrical thickness as well as on the refractive index. Therefore, the knowledge of the refractive index and the thickness of each layer is important in order to describe the dispersion of the cavity-photon mode of a resonator. The symbols $\hbar$ and $c$ represent the reduced Planck constant and the vacuum velocity of light, respectively.

3. Refractive index

In order to reach a controlled growth of the resonator structure with well-defined properties and finally to design and model the resonator, we have determined the dielectric function (DF) spectra of each resonator constituent and the growth rate of each of the layers by means of spectroscopic ellipsometry with a subsequent layer-stack model analysis. Since it is difficult to determine these properties for each layer within a complete microresonator, we use for this purpose a set of adequate single- and multilayer structures. These structures were grown under the same conditions as used for the whole resonator. We assume that all $i$th layers within each of the structures possess equal optical constants and growth rates. For the determination of the optical constants, we have applied the so-called multi-sample-fit technique. In doing so, layers of the same material but with different layer thickness or with differences in the overall structure of the sample are fitted simultaneously with the same optical constants.
Table 1. Parameters for the dispersion of the refraction index of the Bragg materials.

| Material          | A (10^{-2} \mu m^{-2}) | B (10^{-2} \mu m^{-2}) | C (10^{-4} \mu m^{-2}) |
|-------------------|--------------------------|--------------------------|--------------------------|
| Al_{2}O_{3}       | 1.70                     | 0.57                     | 0.00                     |
| YSZ               | 2.14                     | 1.48                     | 6.16                     |
| YSZ (2nd layer)   | 2.13                     | 1.45                     | 6.24                     |

In the case of the Bragg materials (yttria stabilized zirconia (YSZ) and Al_{2}O_{3}) we have found that the refractive index of the first and second YSZ layers (first layer on top of the substrate and third layer of the structure, respectively) are different, whereas all following YSZ layers reveal the same refractive index as that of the second YSZ layer. For the refractive index of the Al_{2}O_{3} layers, no dependence on the layer number was observed. For both materials, the refractive index $n$ was described by a Cauchy ansatz

$$n = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4}$$

with the adjustable parameters $A$, $B$ and $C$ and the wavelength of the light $\lambda$. The obtained Cauchy parameters for YSZ and Al_{2}O_{3} are summarized in table 1.

The optical properties of the ZnO cavity were determined on a ZnO film deposited on a multilayer structure made of 2.5 layer pairs of YSZ and Al_{2}O_{3} since we have found that such a structure reveals similar crystallographic structure and surface texture properties compared to a complete bottom BR. The optical properties of the ZnO film were described by a model DF approach suggested by Yoshikawa et al [19] taking into account the contribution for the band–band transitions, discrete excitons and the unbound exciton states. For the further calculation of the uncoupled cavity-photon mode, the contributions of the excitons have been removed from the DF in order to avoid coupling effects. By doing this we assume that the unbound excitons couple only partially with the cavity-photon modes, that means, we removed only the contributions from the unbound exciton states near the band edge. Figure 2 shows the DF of ZnO with and without excitons.

4. Sample structure and experimental setup

Based on the preliminary work presented in section 3, we realized the strong exciton–photon coupling way above RT by using a ZnO-based microresonator deposited by pulsed laser deposition. The resonator consists of a half wavelength ZnO cavity that acts simultaneously as active medium, embedded between dielectric BR. Each BR was made of YSZ and Al_{2}O_{3} with 10.5 layer pairs [20]. Scanning transmission electron microscopy (STEM) and atomic force microscopy (AFM) of this microresonator (figure 3) yield smooth interfaces, layers without inclusion or droplets, and a smooth surface (average roughness $R_{a} \sim 1.0$ nm determined on a $1 \times 2 \mu m^2$ area).

We have investigated the mode structure of our microresonator by photoluminescence (PL) and reflection (R) experiments in the temperature range 10–550 K for emission angles or rather angles of incidence of 0°–76° (6°–76° in R). Thereby the light was focussed on the sample with a spot size of about 200 µm and the emitted or rather the reflected light was collected and

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Figure 2. DF of ZnO at 290 K with (dashed lines) and without (solid lines) excitonic contributions.

Figure 3. STEM image of the resonator. The bright layers represent the Al$_2$O$_3$ layers and the dark layers represent the YSZ layers. The ZnO cavity also appears dark.

 injected into an optical fibre that guided the light to a spectrometer with a CCD camera. For the PL measurements, we use a cw-HeCd laser with a wavelength of 325 nm for the excitation and in the reflection experiments, we use a 30 W deuterium lamp as probe beam. To realize investigations in the wide temperature range of 10–550 K, two experimental setups were used (cryostat for 10–290 K and hot plate for 290–550 K). We note that the position of the light spot on the sample was different in these two temperature ranges and we observed slightly different energies and broadening values of the LPB ($\Delta E \sim 9$ meV and $\Delta\gamma \sim 4$ meV) which can be attributed to lateral inhomogeneities of our microresonator.
5. Results and discussion

For selected temperatures, the experimental PL and reflectivity spectra are shown in figure 4. Instead of a pure exciton dispersion and a pure cavity-photon dispersion, an LPB is observable clearly up to 410 K. For small angles, the dispersion shows an increasing mode energy with increasing angle. This behaviour changes for an angle between 30° and 40° and the mode energy converges to an energy that is close to that of the ZnO A-exciton. The UPB is not observable, as expected, due to the strong absorption of ZnO in this spectral range [21].

For the determination of the coupling strength, we assume for simplification the coupling of only one exciton mode (that with the lowest ground state energy in ZnO [16]) with the cavity-photon mode and apply the model described in section 2. Thereby we use the refractive indices that we have determined by spectroscopic ellipsometry as described in section 3. Since non-idealities like rough interfaces cause lower reflectivity values of the BR and therefore a lower cavity-photon lifetime compared to the ideal case we introduce a non ideality factor $\alpha$ (typically $\alpha \sim 0.98$) in equation (3):

$$\gamma_c \sim \ln \sqrt{\alpha R_t R_b}.$$  

By applying this model, the fitting parameters are the exciton energy as well as its broadening, the coupling strength $V$ as a function of the temperature, the thickness of each material within a certain confidentiality limit and the non-ideality parameter $\alpha$. The last two parameters, the layer

![Figure 4](http://www.njp.org/)

**Figure 4.** Dispersion of the observed LPB for selected temperatures. (a)–(c) PL spectra in a false colour scale for 10 K (a), 290 K (b) and 410 K (c), respectively. The calculated LPB and the UPB are shown as solid lines whereas the corresponding uncoupled exciton mode (X) and cavity-photon mode (Cav) are indicated by dashed lines. (d)–(f) The same as in (a)–(c) but for the reflectivity spectra.
thicknesses and the non-ideality parameter, are considered to be constant for all temperatures. All parameters are fitted simultaneously for all temperatures up to 410 K, allowing different values of the coupling strength $V$ for the PL and for the R experiment.

The calculated dispersion of the LP is shown in figure 5 for all temperatures. It is obvious that the model describes the experimentally found dispersion, or rather the angular evolution, of the LPB in energy and broadening very well for all temperatures. For the coupling strength $V$, we obtain a maximum value of about 51 meV (in PL) and 55 meV (in R) at 10 K, which is among the largest ones reported for inorganic microresonators. Only for CuCl-based microresonators was a larger coupling strength of about 80 meV maximum at 10 K reported [22]. The difference between the values found in the PL and R experiments can be attributed to the different formation processes of the excitons in these experiments that lead to a different exciton density and therefore different occupation of the polariton branches. With increasing temperature we observe a slight decrease of the coupling strength. We attribute this finding to a decrease of the exciton oscillator strength with increasing temperature due to the reduction of the static dielectric constant. For 410 K we obtain a value $V = 43$ meV (in PL) and 35 meV (in R). This is the highest temperature for which exciton–polariton formation is reported. For large angles, the difference between the experimental data and the model calculated broadening values can be attributed to uncertainties in the determination of the broadening from the experimental data. Here, the LPB peak exhibits an asymmetric line-shape. We attribute this finding on the one hand to the incipient overlap of the LPB with the Bragg band edge (BBE) mode at large angles and on the other hand to the energy splitting between the TE and TM polarizations, which increases with increasing angle. A strong coupling between the LPB and the BBE as reported in [14] is not observable.

With increasing temperature, the cavity-photon energy decreases due to the temperature dependence of the refractive index. Also the exciton energy decreases caused by a reduction of the band-gap energy (figure 6). This can be well described by a Bose–Einstein model proposed by Viña et al [23]. The amount of the redshift of both energies is different, since the exciton energy is much more strongly affected by the temperature change than the cavity resonance energy. Therefore, the detuning $\Delta$ of the resonator changes with temperature. For low temperatures, our microresonator exhibits a negative detuning with $\Delta = -65$ meV, which causes a strong bottleneck effect. This large negative detuning is prejudicial for the formation

Figure 5. (a) Experimentally observed (symbols) and model calculated (lines) LP energy as a function of the emission angle for all investigated temperatures. (b) The same as (a) but for the broadening.
of a macroscopic quantum ground state [24] in our resonator since the scattering rate of bottleneck polaritons into the ground state is very low. On the other hand, high occupation of exciton–polaritons in the bottleneck region can be used for investigations of relaxation mechanisms. The detuning increases with increasing temperature and becomes zero at about 380 K. For 410 K, we obtain a slightly positive detuning value of about $\Delta = 7$ meV. In this temperature range, the short exciton lifetime in our actual resonator is prejudicial for the realization of a condensate.

The temperature behaviour of the broadening, which corresponds to the inverse lifetime, is shown in figure 7. In contrast to the cavity-photon, whose lifetime is marginally affected by the temperature, the increasing temperature leads to a dephasing of the excitons (increase of the broadening) mainly caused by the scattering with phonons (homogeneous broadening). This homogeneous broadening dominates the exciton broadening for temperatures larger than 130 K. For 410 K, the broadening of the exciton mode ($\Gamma_X$) amounts to 76 meV. Below 130 K, the broadening is mainly affected by the inhomogeneous contributions. The temperature dependence of the entire broadening (containing the inhomogeneous one and the homogeneous contributions) can be described by the model proposed by Makino et al [25]. We have found an inhomogeneous broadening of about 13 meV. This agrees very well with the value of 15 meV (of the donor bound exciton) determined on a ZnO film on a multilayer structure made of YSZ and Al$_2$O$_3$, grown under similar conditions. For the broadening of the cavity-photon ($\gamma_C$), we obtain for the low and high temperature ranges values of about 9 and 4.4 meV, respectively.
Figure 7. (a) Temperature evolution of the uncoupled exciton (X) and cavity-photon (Cav) energy as well as of the LP and UP energy (at $k_{\parallel} = 0$) as obtained from the model. The two temperature ranges are indicated by filled (10–290 K) and open (290–410 K) symbols. (b) Temperature evolution of the exciton ($\Gamma_X$) and cavity-photon ($\gamma_C$) broadening. The red solid line shows the temperature dependence of the exciton broadening according to the model proposed by Makino et al [25]. The fourfold of the coupling strength ($V$) is shown by the triangles so that it is easy to see that the condition for the strong coupling $|\gamma_C - \Gamma_X| < 4V$ [26] is fulfilled for all temperatures. The filled symbols represent the low temperature range whereas the open symbols represent the high temperature range.

Accordingly, the quality factor amounts to 380 and 740, respectively. The lateral inhomogeneity of the microresonator is responsible for the different values as mentioned above.

On the basis of the values found for the coupling strength, the broadening and the energetic positions of the polariton branches we conclude that the resonator is in the strong coupling regime for temperatures up to 410 K. The condition for strong coupling, $|\gamma_C - \Gamma_X| < 4V$ at the anti-crossing point ($\delta = 0$ eV) [26] is fulfilled for all temperatures since the energetic mode splitting between the LPB and the modelled UPB is larger than their broadening values (cf figure 7). This demonstrates for the first time the observation of strong coupling between light and excitons at temperatures well above RT and opens the way for real devices based on the emission from macroscopic light–matter quantum states.

Above 410 K, a slight blue shift of the LPB ground state energy with increasing temperature can be observed up to 450 K (figure 6). However, the presence of a strong coupling regime for these temperatures cannot be definitely confirmed. On the one hand, the quantum efficiency is very low at these temperatures that leads to a low peak intensity and so the observed peak disappears already at small angles. Furthermore, the uncertainty of the determined peak energy is very large. On the other hand, using the determined temperature behaviour of the exciton–polaritons, the splitting between these two branches is smaller than their broadening. Therefore, we state that the resonator for this temperature range operates in the intermediate coupling regime. Above 450 K, no further energy shift is observable and the resonator is in the weak coupling regime. We attribute the observed collapse of the strong coupling to the strong exciton broadening and the very small exciton oscillator strength at these temperatures. In order to maintain the strong coupling up to the predicted maximum temperature of 610 K [27], which
we consider to be a realistic aim, the exciton oscillator strength has to be increased by improving the ZnO cavity material. Furthermore, ZnO quantum wells (QW) can be used as active medium. This would increase the oscillator strength further and, at elevated temperatures, reduce the exciton broadening. Additionally, the usage of QW reduces the absorption of the cavity and therefore the UPB should become observable in such a structure.

6. Summary

We have observed the formation of exciton–polaritons in a ZnO-based resonator at temperatures up to 410 K by PL and reflectivity measurements. Only the LPB could be investigated since observation of an UPB is not possible due to the strong absorption of ZnO in this spectral range. The dispersion of this LPB could be modelled very well for all temperatures, taking into account the coupling between one exciton and one cavity-photon mode. From this analysis we can conclude that we are in the strong coupling regime up to 410 K with a maximal coupling strength of 51 meV in the PL and 55 meV in the reflectivity measurement at 10 K. Above 410 K the calculated mode splitting is similar to the broadening of the observed LPB and the system is in the intermediate coupling regime.

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References

[1] Weisbuch C, Nishioka M, Ishikawa A and Arakawa Y 1992 *Phys. Rev. Lett.* **69** 3314
[2] Kavokin A, Baumberg J J, Malpuech G and Laussy F P 2008 *Microcavities (Semiconductor Science and Technology)* (Oxford: Oxford University Press)
[3] Deng H, Weihs G, Snake D, Bloch J and Yamamoto Y 2003 *Proc. Natl Acad. Sci. USA* **100** 15318
[4] Saba M *et al.* 2001 *Nature* **414** 731
[5] Kasprzak J *et al.* 2006 *Nature* **443** 409
[6] Tsintzos S I, Pelekanos N T, Konstantinidis G, Hatzopoulos Z and Savvidis P G 2008 *Nature* **453** 372
[7] Christophoulou S *et al.* 2007 *Phys. Rev. Lett.* **98** 126405
[8] Dang L S, Heger D, André R, Beuf F and Romestain R 1998 *Phys. Rev. Lett.* **81** 3920
[9] Zamfirescu M, Kavokin A, Gil B, Malpuech G and Kaliteevski M 2002 *Phys. Rev. B* **65** 161205
[10] Oulton R F, Takada N, Koe J, Stavrinou P N and Bradley D D C 2003 *Semicond. Sci. Technol.* **18** S419
[11] Hobson P A, Barnes W L, Lidzey D G, Gehring G A, Whittaker D M, Skolnick M S and Walker S 2002 *Appl. Phys. Lett.* **81** 3519
[12] Christmann G, Butté R, Feltin E, Mouti A, Stadelmann P A, Castiglia A, Carlin J-F and Grandjean N 2008 *Phys. Rev. B* **77** 085310
[13] Antoine-Vincent N, Natali F, Byrne D, Vasson A, Disseix P, Leymarie J, Leroux M, Semon M and Massies J 2003 *Phys. Rev. B* **68** 153313
[14] Schmidt-Grund R, Rheinländer B, Czekalla C, Benndorf G, Hochmuth H, Lorenz M and Grundmann M 2008 *Appl. Phys. B* **93** 331
[15] Shimada R, Xie J, Avrutin V, Özgür Ü and Morkoč H 2008 *Appl. Phys. Lett.* **92** 011127

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[16] Médard F et al 2009 Phys. Rev. B 79 125302
[17] Kavokin A and Gil B 1998 Appl. Phys. Lett. 72 2880
[18] Panzarini G, Andreani L C, Armitage A, Baxter D, Skolnick M S, Astratov V N, Roberts J S, Kavokin A V, Vladimirova M R and Kaliteevski M A 1999 Phys. Rev. B 59 5082
[19] Yoshikawa H and Adachi S 1997 Japan. J. Appl. Phys. 36 6237
[20] Hilmer H, Sellmann J, Sturm Ch, Schmidt-Grund R, Reinländer B, Hochmuth H, Lenzner J, Lorenz M and Grundmann M 2009 AIP Conf. Proc. at press
[21] Faure S, Guillet T, Lefebvre P, Bretagnon T and Gil B 2008 Phys. Rev. B 78 235323
[22] Oohata G, Nishioka T, Kim D, Ishihara H and Nakayama M 2008 Phys. Rev. B 78 233304
[23] Viña L, Logothetidis S and Cardona M 1984 Phys. Rev. B 30 1979
[24] Johne R, Solnyshkov D D and Malpuech G 2008 Appl. Phys. Lett. 93 211105
[25] Makino T, Chia C H, Tuan N T, Segawa Y, Kawasaki M, Ohtomo A, Tamura K and Koinuma H 2000 Appl. Phys. Lett. 76 3549
[26] Savona V, Andreani L C, Schwendimann P and Quattropani A 1995 Solid State Commun. 93 733
[27] Chichibu S F et al 2005 Semicond. Sci. Technol. 20 S67

New Journal of Physics 11 (2009) 073044 (http://www.njp.org/)