Nonlinear emission dynamics of a GaAs microcavity with embedded quantum wells

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Abstract

The emission dynamics of a GaAs microcavity at different angles of observation with respect to the sample normal under conditions of nonresonant picosecond-pulse excitation is measured. At sufficiently high excitation densities, the decay time of the lower polariton emission increases with the polariton wavevector; at low excitation densities the decay time is independent of the wavevector. The effect of additional nonresonant continuous illumination on the emission originating from the bottom of the lower polariton branch is investigated. The additional illumination leads to a substantial increase in the emission intensity (considerably larger than the intensity of the photoluminescence excited by this illumination alone). This fact is explained in terms of acceleration of the polariton relaxation to the radiative states due to scattering by charge carriers created by the additional illumination. The results obtained show that, at large negative detunings between the photon and exciton modes, polariton–polariton and polariton–free carrier scattering are the main processes responsible for the filling of states near the bottom of the lower polariton branch.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

For almost two decades, the study of exciton polaritons in semiconductor microcavities (MC) [1] has attracted considerable attention inspired by a diversity of interesting features in this system: polariton Bose–Einstein condensation (BEC) [2–6], superfluidity [7, 8], stimulated polariton–polariton scattering [9–13], etc. (See the book [14] and references therein.)

MC polariton energy relaxation is of particular interest, because it has a profound effect on many properties of the polariton system. It is well known that relaxation of MC polaritons to the bottom of the lower polariton branch (LPB) is hampered by the bottleneck effect [15]. It is the bottleneck effect that together with the small polariton lifetime near the bottom of the LPB that lead to a decrease in the occupancy of states with low wavevectors $k$ with respect to the occupancy of high-$k$ states. This, in particular, hinders the polariton system from reaching BEC.

The most straightforward method to study MC polariton relaxation is measuring the dynamics of the MC emission under optical pumping by short pulses [16–30]. The dynamics of the MC emission at different angles of observation $\Theta$ with respect to the sample normal is of particular interest as it yields information about the filling of states corresponding to wavevectors $k = E(k) \sin \Theta / hc$, where $E(k)$ is the energy of observed photons and $c$ is the speed of light. The results of different studies on this issue are somewhat contradictory. In [17] it was shown for a CdTe MC that, at sufficiently large negative photon–exciton detunings $\Delta (\Delta = E_{ph}(k = 0) - E_{ex}(k = 0))$, where $E_{ph}(k = 0)$ and $E_{ex}(k = 0)$ are the energies at minima of the photon and exciton dispersion curves, respectively), the decay time $\tau$ of the emission from high-$k$ states is reduced considerably with respect to the decay time of the emission from the bottom of the LPB. These results were not confirmed in [18], also carried out with a CdTe MC; here, $\tau$ was observed to be independent of $\Theta$ within the accuracy of the experiment. In a study of a GaAs MC [20], it was found that the emission from $k \approx 0$ decays twice as fast as the emission from the high-$k$ states. The effect was explained under the assumption that relaxation to the states with $k \approx 0$ proceeds via polariton–polariton scattering and, thus, its rate depends quadratically on the occupancy of the reservoir of exciton-like states. On the other hand, the high-$k$ polariton states are close in energy to the reservoir and their occupancy directly reflects the reservoir depletion.
Qualitative disagreement between the results mentioned above indicates that the mechanism of filling of radiative MC states is not universal but depends on such factors as the excitation density, photon–exciton detuning, etc. In the present study, we measure the dynamics of the MC emission as a function of the angle of observation $\Theta$ and the excitation density at a large negative photon–exciton detuning. It is shown that at high excitation densities the decay time of the LPB emission increases with $\Theta$, in agreement with the results of [20]. At low excitation densities $\tau$ is almost independent of $\Theta$.

In order to obtain further information on the mechanism responsible for the population of states with $k \approx 0$, we also study the effect of additional continuous wave (CW) laser illumination on the MC emission dynamics. The additional illumination was used in a number of studies for creating free electrons [20, 31–33] (the polariton–electron scattering is believed to accelerate the relaxation substantially [34]) and heating up the exciton system [8]. The differential technique used in the present study enables us to measure changes in the MC emission dynamics caused by the additional CW illumination. As a result, it has been shown that the additional illumination leads to the acceleration of relaxation to the $k \approx 0$ states, which is associated with an increase in the electron–hole pair number; this process has a nonlinear character.

### 2. Experimental details

The sample under study was a $\frac{1}{2}\lambda$ MC with mirrors made of alternating AlAs and Al$_{0.12}$Ga$_{0.88}$As layers. Two stacks of three tunnel-isolated In$_{0.05}$Ga$_{0.95}$As quantum wells (QW) were embedded into the GaAs cavity at the positions of the two electric-field antinodes of the MC. The cavity was grown wedge-shaped, allowing us to change the photon-mode energy by moving the excitation spot along the sample surface while keeping the exciton-mode energy unchanged. The Rabi splitting for the sample was equal to 6 meV. The sample was mounted inside a variable-temperature helium cryostat. All the experiments were done at a temperature of 10 K and photon–exciton detuning $\Delta = -5$ meV.

The sample was excited by the emission of a mode-locked Ti:sapphire laser generating a periodic train of 2.5 ps long pulses at a repetition rate of 76 MHz. The excitation energy (1.595 eV; wavelength 776.6 nm) was larger than the GaAs bandgap (1.519 eV), which determines the height of the barriers for the QWs. The angle of incidence of the excitation laser beam was 60° with respect to the sample normal.

Spectrally resolved dynamics at different angles of observation was measured using a monochromator coupled to a Hamamatsu C5680 streak camera. The photoluminescence (PL) from the sample after passing through a diaphragm with an aperture of 2° was coupled by a lens into an optical fiber, whose opposite end was fixed at the monochromator slit. The end of the optical fiber to which the PL is collected was combined, together with the diaphragm and the lens, on a rotation rail allowing registration of the PL coming out at a given angle. The time and spectral resolution of this system were 30 ps and 0.3 meV, respectively.

In the second part of this study, the sample was illuminated by a CW 532 nm second-harmonic emission of an Nd:YVO$_4$ laser in addition to the pulsed excitation. The two laser beams were symmetric with respect to the sample normal and excited the same spot on the sample at an angle of 60°. The PL coming out at the normal direction with respect to the sample plane within a 2° aperture was registered.

In these experiments, the PL dynamics was measured using the picosecond up-conversion optical gating technique [35]. The up-converted (sum-frequency) emission, generated by mixing the PL with a delayed gate pulse (split from the excitation laser beam) in a nonlinear crystal, was analyzed by a double monochromator coupled to a PMT operating in the photon counting mode, and its intensity was recorded as a function of the delay between the excitation and the gate pulses. The additional CW illumination was modulated using a mechanical chopper operating at a frequency of 400 Hz and synchronized with the PMT control unit. With such a set-up, both the dynamics of the main signal (the PL caused by the pulse excitation only) and the dynamics of the differential signal (the difference between the PL excited by the pulse excitation with and without additional CW illumination) were measured. The time and spectral resolution of this set-up were 2.5 ps and 2 meV, respectively.

### 3. Microcavity emission dynamics: angular dependence

The time–spectral dynamics of the MC emission measured at different angles with respect to the sample normal are shown in figure 1. The intense low-energy line in the spectra corresponds to the LPB emission, while the high-energy line, which is much weaker but still recognizable in all spectra, corresponds to the UPB emission. Lines between the LPB and upper polariton branch (UPB) are attributed to localized excitons and to scattered LPB emission corresponding to other angles of observation.

In order to analyze the dispersion curves for the MC radiative states, spectra taken at different angles of observation were combined to yield a series of two-dimensional plots for different times after the excitation pulse (figure 2). Solid lines in figure 2 are polariton branches calculated to fit experimental data at large time delay from the excitation pulse ($t \approx 2000$ ps) and dashed lines are corresponding exciton and photon modes. At the very beginning of the relaxation process ($t \approx 50$ ps, left image), when the number of electron–hole pairs in the system is maximal, the LPB lines’ maxima are blueshifted by $\sim 0.3$ meV with respect to their position at longer times ($t \approx 2000$ ps, right image). Nevertheless, the exciton–photon system is strongly coupled at all times for the given excitation density $P = 25 \text{ W cm}^{-2}$.

It should be pointed out that, for $t \approx 2000$ ps (figure 2, right image), the bottleneck effect is pronounced: the low-energy states are considerably depleted with respect to the high-energy ones. On the other hand, for $t \approx 50$ ps, the emission intensity is larger for the low-energy states. This fact, however, does not mean a full bottleneck suppression, because the observed intensity from a given LPB state is related to its
filling factor \( f \) by the relation \( I = C^2 f / \tau_c \), where \( \tau_c \) is the photon lifetime inside the MC and \( C \) is the photon Hopfield coefficient (weight of the photon contribution in the polariton wavefunction), which decreases with the angle \( \Theta \) (the polariton becomes exciton-like).

It is seen from figure 1 that the LPB emission dynamics becomes slower with increasing angle of observation. The angle dependence of the LPB emission decay time \( \tau \) for different average excitation densities \( P \) is presented in figure 3. One can see that for \( P = 25 \text{ W cm}^{-2} \) \( \tau \) increases noticeably with the angle. A similar behavior was observed in [20], where the dynamics of the emission from the bottom of the LPB was compared to the dynamics of the emission registered at large \( \Theta \). For \( P = 8 \text{ W cm}^{-2} \) the dependence becomes flatter and for \( P = 3 \text{ W cm}^{-2} \) \( \tau \) no longer depends on \( \Theta \) within experimental accuracy.

To explain the experimental results we assume that the LPB emission dynamics is determined by the depletion rate of the reservoir of high-\( k \) exciton-like states. At sufficiently high excitation densities the exciton scattering to polariton...
states with $k \approx 0$ is assisted by collisions with other excitons and the remaining unbound free carriers, whereas the rate of polariton–acoustic phonon scattering is rather low due to the steep LPB dispersion in the low-$k$ region (which, for large negative detunings, results in a large energy difference between the initial and final states) [36]. The importance of the interparticle scattering in polariton relaxation towards the low-$k$ states, leading to the suppression of the bottleneck effect at high excitation densities, was previously demonstrated in the CW experiments [37, 38]. Owing to short polariton lifetimes at the bottom of the LPB in comparison to typical relaxation times, the emission intensity $I$ is proportional to the relaxation rate, which is quadratic in the total number of electron–hole pairs $n$ (in the case of the polariton–polariton and polariton–free carrier scattering, further referred to as interparticle scattering). Thus, $I(t) \sim n(t)^2$ (strictly speaking, $I(t) \sim w_{ex}(t)n_{ex}(t)^2 + w_{ch}(t)n_{ch}(t)n_c + w_{hp}(t)n_{ex}(t)n_0$), where $n_{ex}, n_{ch}$ and $n_c$ are respectively the exciton, electron and hole densities, $n_0 = n_0$, and $w_{ex}, w_{ch}$ and $w_{hp}$ are, respectively, the probabilities of the polariton–polariton, polariton–electron and polariton–hole scattering [20, 29]). Provided the reservoir depletion follows the law $n(t) = n_0 \exp(-t/\tau_s)$, the emission decays as $I(t) \sim n_0^2 \exp(-2t/\tau_s)$ and its lifetime equals $\tau_s/2$. With increasing angle of observation (polariton wavevector), scattering of polaritons by acoustic phonons becomes more efficient (because of a decrease in the energy difference between the final and initial states of scattered particles), and this process governs the LPB emission dynamics at sufficiently large angles. For the polariton–phonon scattering, $I(t) \sim n(t) = n_0 \exp(-t/\tau_s)$; thus, the emission decays with time $\tau_s$.

According to figure 3, for $P = 25$ W cm$^{-2}$ the decay time $\tau$ decreases from 840 ps at $\Theta = 21^\circ$ to 500 ps at $\Theta = 0^\circ$, which indicates a pronounced effect of interparticle scattering on state filling at the bottom of the LPB. It should be noted that $\tau$ was determined according to the emission decay rate in the time interval from 1000 to 2000 ps, when the number of electron–hole pairs is several times lower as compared to its initial value. Thus, at the beginning of the relaxation process, the interparticle scattering might be important even at low excitation densities.

Another factor contributing to an increase in $\tau$ for states corresponding to large $\Theta$ might be the scattering of polaritons back to the reservoir, which increases coupling of these states to the reservoir. Due to this process, $\tau$ becomes closer to $\tau_s$. The rate of backscattering associated with exciton-like polaritons and free carriers can be estimated from the linewidth dependence on the excitation density $P$. An increase in $P$ from 3 to 25 W cm$^{-2}$ leads to an increase in the LPB linewidth for $\Theta = 21^\circ$ and $t = 1000$ ps by $\Delta \gamma = 0.2$ meV. This value should be compared with the LPB line broadening associated with the photon escape from the cavity $\tilde{\gamma}_c = \gamma_c C^2$, where $\gamma_c$ is the broadening for a bare photon in the MC. For $\Theta = 21^\circ$, $\tilde{\gamma}_c = 0.5$ meV > $\Delta \gamma$, which indicates that states corresponding to $\Theta = 21^\circ$ are not fully coupled to the reservoir and polaritons mainly escape from these states via photon emission. Thus, for $P = 25$ W cm$^{-2}$, scattering of polaritons back to the reservoir caused by interparticle collisions cannot fully account for the observed nearly twofold increase in $\tau$, which means that the phonon scattering mechanism discussed above should be involved.

Thus, an increase in the emission decay time with the angle of observation is presumably related to the crossover of the polariton states’ filling mechanism from the interparticle scattering at small angles to the polariton–acoustic phonon scattering at large angles.

### 4. The effect of the additional illumination on the microcavity emission dynamics

In order to confirm that filling of states with $k \approx 0$ is controlled by the interparticle scattering mechanism, the effect of additional nonresonant CW laser illumination on the MC emission dynamics was studied. The kinetics of the differential signal was measured, which shows the effect of additional illumination on the relaxation dynamics of particles created by the laser pulse. If the additional illumination does not affect this dynamics, the differential signal simply corresponds to the MC emission created by the additional illumination alone and does not depend on time. The additional illumination power density $P_{cw}$ was comparable to the time-averaged pulse excitation density $P_{pulse}$. Note that, under these conditions, the density of electron–hole pairs created by the excitation pulse $n_{pulse} = P_{pulse}/(h\nu F)$ ($F = 76$ MHz is the pulse repetition rate and $h\nu$ is the excitation photon energy, which in our simple evaluation is assumed to be approximately the same for the CW illumination and pulse excitation) is considerably larger than the density of electron–hole pairs created by the CW illumination $n_{cw} = P_{cw}/(h\nu)$ (where the reservoir depletion time $\tau_s \approx 1$ ns):

$$\frac{n_{cw}}{n_{pulse}} = \frac{\tau_s F P_{cw}}{P_{pulse}},$$

(1)

which for $P_{cw} = P_{pulse}$ yields $n_{cw} = F \tau_s n_{pulse} \approx 0.08 n_{pulse}$. Thus, the additional illumination represents a small perturbation in the first 1–2 ns of the system relaxation.
We also note that the photon energy of the additional CW illumination (2.331 eV) was larger than the bandgaps for the MC-mirror materials (2.24 eV and 1.68 eV for AlAs and Al0.13Ga0.87As, respectively) and only the small portion of the original excitation would reach the cavity. Nevertheless, the time-integrated PL intensity created by the CW illumination and corresponding to the localized excitons (between the LPB and UPB), which is linear in the excitation power, was close to that created by the pulse excitation (with photon energy 1.595 eV) of the same time-averaged power density. Thus, the additional illumination excites the QWs inside the cavity presumably by the secondary emission created by the recombination of electrons and holes inside the MC mirrors with almost the same efficiency as the pulse excitation.

Figure 4 shows the kinetic dependences of the MC emission without additional CW illumination, further referred to as the main signal (dashed lines), and the differential signal (solid lines). The following features should be noted. (i) The intensity of the PL excited by the laser pulses increases under an additional CW illumination, and this increase (the differential signal (solid lines). The following features should be noted. (i) The intensity of the PL excited by the laser pulses increases under an additional CW illumination (2.331 eV) was larger than the bandgaps for the MC-mirror materials (2.24 eV and 1.68 eV for AlAs and Al0.13Ga0.87As, respectively) and only the small portion of the original excitation would reach the cavity. Nevertheless, the time-integrated PL intensity created by the CW illumination and corresponding to the localized excitons (between the LPB and UPB), which is linear in the excitation power, was close to that created by the pulse excitation (with photon energy 1.595 eV) of the same time-averaged power density. Thus, the additional illumination excites the QWs inside the cavity presumably by the secondary emission created by the recombination of electrons and holes inside the MC mirrors with almost the same efficiency as the pulse excitation.

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Features (i) and (ii) point at the nonlinear character of the emission from the bottom of the LPB, confirming that interparticle scattering is responsible for the filling of k ≈ 0 states. Under these conditions, the intensity of emission in the absence of CW illumination varies as

\[ I_{\text{pulse}}(t) = \alpha n_{\text{cw}}^2(t), \]  

where, for simplicity, the coefficient \( \alpha \) is assumed to be time-independent. The intensity of the differential signal equals approximately

\[ I_{\text{diff}}(t) = \alpha (n_{\text{pulse}}(t) + n_{\text{cw}}(t))^2 - \alpha n_{\text{pulse}}(t)^2 \approx 2\alpha n_{\text{cw}}(t)n_{\text{pulse}}(t). \]  

Assuming that the number of particles created by the CW illumination does not depend on time, we obtain for the intensity decay \( I_{\text{pulse}}(t) \sim n_{\text{cw}}^2(t) \exp(-2t/\tau_{x}) \) and \( I_{\text{diff}}(t) \sim 2n_{\text{cw}}(t)n_{\text{pulse}}(t) \). The above relations explain the twofold increase in the decay time of the differential signal as compared to the emission created by the pulse excitation alone.

The agreement between the description provided by formulae (2) and (3) and the experimental data is also demonstrated by the dependences of the peak intensities of the main signal (open squares in figure 5) and the differential signal (full squares in figure 5) on the time-averaged pulse excitation density \( P_{\text{pulse}} \). It follows from figure 5 that at low \( P_{\text{pulse}} \) the peak intensity of the main signal is proportional to \( P_{\text{pulse}}^2 \), while the peak intensity of the differential signal is proportional to \( P_{\text{pulse}} \) (because \( n_0 \sim P_{\text{pulse}} \)). As \( P_{\text{pulse}} \) is further increased, these dependences become steeper. For the peak intensity of the differential signal, deviation from a linear dependence, which is related to the fast component in the kinetics of \( I_{\text{diff}} \) (figure 4), becomes apparent at lower excitation densities \( P_{\text{pulse}} \) than the fast increase of the main signal peak intensity begins. That is, the onset of stimulated emission is more pronounced in the differential signal than in the main signal. For \( P_{\text{pulse}} \approx 60 \text{ W cm}^{-2} \), both intensities increase dramatically (figure 5) due to the onset of lasing in the weak coupling regime [29, 30].

Figure 6 shows the peak intensity of the differential signal (with respect to the differential signal intensity at \( t < 0 \)) as a function of time with two selected pulse excitation densities. The solid lines represent the calculated dependences based on formulae (2) and (3).
function of $P_{cw}$ for different values of $P_{pulse}$. To simplify the experimental data interpretation, the differential signal intensity was normalized by $I_{pulse}(I_{peak})/I_{pulse}$. Thus, the quantity plotted in figure 6 is $I_{diff} = I_{diff}(I_{peak})P_{pulse}/I_{pulse}(I_{peak})$. The data show that, for small CW illumination densities ($P_{cw} \leq 7$ W cm$^{-2}$), the differential signal intensity is close to zero or even negative for all pulse excitation levels. At higher $P_{cw}$, the dependence $I_{diff}(P_{cw})$ becomes linear and can be described by the following equation: $I_{diff} = \beta(P_{cw} - P_{0})$, where $P_{0} = 7$ W cm$^{-2}$.

The coefficient $\beta \approx 0.13$ for small pulse excitation densities $P_{pulse}$ and increases as $P_{pulse}$ approaches the lasing threshold value. Meanwhile, according to (1)–(3)

$$I_{diff} = I_{diff}(I_{peak}) - \frac{P_{pulse}}{I_{pulse}(I_{peak})} \approx 2\tau_s F P_{cw}.$$ (4)

This dependence is shown in figure 6 by a solid line for $\tau_s = 1$ ns. In general, a linear dependence $I_{diff} = \beta P_{cw}$ is a consequence of the condition $n_{cw} \ll n_{pulse}$, while the coefficient $\beta$ is determined by a particular dependence $I_{pulse}(n_{pulse})$. However, the threshold $P_{0}$ in the dependence of the differential signal on $P_{cw}$, the existence of which is evident in the data, does not appear in (4). The origin of this threshold is not understood at the moment.

Thus, under the given experimental conditions, the main effect of the additional CW illumination is related to the acceleration of the relaxation process due to an increase in the number of particles in the system. At the same time, the possible heating effect of the additional illumination on the non-equilibrium electron–hole system [8] seems to be irrelevant.

The above conclusions about the significance of the interparticle scattering in the filling of states at the bottom of the LPB is valid for the first 1–2 ns only. As the reservoir is depleted, the efficiency of the interparticle scattering mechanism decreases and the polariton–acoustic phonon scattering dominates the filling of $k \approx 0$ states. As a result, the time-integrated MC emission intensity increases more slowly with the pulse excitation density than the peak intensity shown in figure 5 with open squares.

In the experiments described above one cannot distinguish between the polariton–polariton and polariton–free carrier scattering mechanisms. This could be accomplished, for example, by applying an external magnetic field perpendicular to the MC plane [39]. Preliminary magnetic-field experiments have shown that, under a CW excitation, the contribution of the polariton–electron scattering to the total rate of polariton relaxation to the LPB bottom does not exceed 30% [40]. As for the results of the present study, it is reasonable to believe that, at the stage of the emission decay, the majority of charge carriers are already bound into excitons [41] and filling of $k \approx 0$ states is mainly accompanied by polariton–polariton scattering. We also note that free electrons possibly present in the system due to residual doping [32] do not contribute significantly to the polariton relaxation to the $k \approx 0$ states. Otherwise, the dependence $I_{pulse}(P_{pulse})$ would deviate from a quadratic one, since scattering by electrons released from impurities leads to a linear PL intensity dependence on the excitation power [20], similar to the case of polariton relaxation assisted by acoustic phonons.

5. Conclusions

The kinetic dependences of the GaAs MC emission from different states of the LPB have been studied as a function of the pulse excitation density. Also, the effect of the additional CW illumination on the MC emission dynamics has been investigated. It is shown that at low excitation densities the polariton emission decay rate is almost independent of the polariton wavevector. As the excitation density is increased, the decay rate of the LPB emission increases and becomes dependent on the polariton wavevector, so that it is highest for the emission from the bottom of the LPB and decreases with increasing polariton energy. The emission intensity from the bottom of the LPB is nonlinear in the excitation density and is increased noticeably under the additional CW illumination. On the basis of the results obtained we conclude that, for a large negative detuning, filling of states near the bottom of the LPB is mainly caused by the polariton scattering from the reservoir of exciton-like states assisted by other exciton-like polaritons and free charge carriers (except for fairly low excitation densities, when scattering by phonons becomes important).

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References

[1] Weisbuch C, Nishioka M, Ishikawa A and Arakawa Y 1992 Phys. Rev. Lett. 69 3314
[2] Kasprzak J et al 2006 Nature 443 409
[3] Balili R, Hartwell V, Snoke D, Pfeiffer L and West K 2007 Science 316 1007
[4] Christopoulos S et al 2007 Phys. Rev. Lett. 98 126405
[5] Wertz E, Ferrier L, Solnyshkov D, Sermellat P, Bajoni D, Miard A, Lemaitre A, Malpuech G and Bloch J 2009 Appl. Phys. Lett. 95 051108
[6] Rounpos G, Nitsche W H, Höfling S, Forchel A and Yamamoto Y 2010 Phys. Rev. Lett. 104 126403
[7] Amo A, Lefrère J, Pigeon S, Adrados C, Ciuti C, Carusotto I, Roumpos G, Nitsche W H, Höffling S, Forchel A and Yamamoto Y 2010 Phys. Rev. Lett. 104 126403
[8] Amo A, Sanvitto D and Viña L 2010 Semicond. Sci. Technol. 25 043001
[9] Savvidis P G, Baumberg J J, Stevenson R M, Skolnick M S, Whittaker D M and Roberts J S 2000 Phys. Rev. Lett. 84 1547
[10] Stevenson R M, Astratov V N, Skolnick M S, Whittaker D M, Emam-Ismael M, Tartakovskii A I, Savvidis P G, Baumberg J J and Roberts J S 2000 Phys. Rev. Lett. 85 3680
[11] Tartakovskii A I, Krizhanovskii D N and Kulakovskii V D 2000 Phys. Rev. B 62 R13298
[12] Krizhanovskii D N, Gavrilo S S, Love A P D, Sanvitto D, Gippius N A, Tikhodeev S G, Kulakovskii V D, Whittaker D M, Skolnick M S and Roberts J 2008 Phys. Rev. B 77 115336
[13] Kulakovskii V D, Krizhanovskii D N, Makhonin M N, Demenev A A, Gippius N A and Tikhodeev S G 2005 Phys.—Usp. 48 312
[14] Savvidis P G, Baumberg J J, Stevenson R M, Skolnick M S, Whittaker D M, Emam-Ismael M, Tartakovskii A I, Savvidis P G, Baumberg J J and Roberts J S 2000 Phys. Rev. Lett. 85 3680
[15] Tartakovskii A I, Krizhanovskii D N and Kulakovskii V D 2000 Phys. Rev. B 62 R13298
[16] Krizhanovskii D N, Gavrilo S S, Love A P D, Sanvitto D, Gippius N A, Tikhodeev S G, Kulakovskii V D, Whittaker D M, Skolnick M S and Roberts J 2008 Phys. Rev. B 77 115336
[17] Kulakovskii V D, Krizhanovskii D N, Makhonin M N, Demenev A A, Gippius N A and Tikhodeev S G 2005 Phys.—Usp. 48 312
[18] Kavokin A V, Baumberg J J, Malpuech G and Gaussy F P 2007 Microcavities (Series on Semiconductor Science and Technology) ed R J Nicholas and H Kamimura (Oxford: Oxford University Press)
[19] Tassone F, Piernarocci C, Savona V, Quattropani A and Schwendimann P 1997 Phys. Rev. B 56 7554
[20] Sermage B, Long S, Abram I, Marzin J Y, Bloch J, Planat R and Thierry-Mieg V 1996 Phys. Rev. B 53 16516
[21] Müller M, Bleuse J and André R 2000 Phys. Rev. B 62 16886
[22] Klopotowski L, Santos R, Amo A, Martín M D, Viña L and André R 2004 Acta Phys. Pol. A 106 443
[23] Renucci P, Amand T, Marie X, Sennellart P, Bloch J, Sermage B and Kavokin K V 2005 Phys. Rev. B 72 075317
[24] Bajoni D, Perrin M, Sennellart P, Lemaitre A, Sermage B and Bloch J 2006 Phys. Rev. B 73 205344
[25] Bloch J, Sermage B, Perrin M, Sennellart P, André R and Dang L S 2005 Phys. Rev. B 71 155311
[26] Martin M D, Aichmayr G, Amo A, Ballarini D, Klopotowski L and Viña L 2007 J. Phys.: Condens. Matter 19 295204
[27] Müller M, André R, Bleuse J, Romestain R, Dang L S, Huynh A, Tignon J, Roussignol Ph and Delalande C 2003 Semicond. Sci. Technol. 18 S319
[28] Alexandrou A, Bianchi G, Péronne E, Hallé B, Boeuf F, Andre R, Romestain R and Dang L S 2001 Phys. Rev. B 64 233138
[29] del Valle E, Sanvitto D, Amo A, Laussy F P, André R, Tejedor C and Viña L 2009 Phys. Rev. Lett. 103 096404
[30] Deng H, Press D, Gützinger S, Solomon G S, Hey R, Ploog K H and Yamamoto Y 2006 Phys. Rev. Lett. 97 146402
[31] Erland J, Mizeikis V, Langbein W, Jensen J R and Hvam J M 2001 Phys. Rev. Lett. 86 5791
[32] Ballarini D, Amo A, Viña L, Sanvitto D, Skolnick M S and Roberts J S 2007 Appl. Phys. Lett. 90 201905
[33] Bilykh V V, Nguyen M H, Sibeldin N N, Skorikov M L, Tsvetkov V A and Sharkov A V 2009 Sov. Phys.—JETP 109 472
[34] Bilykh V V, Nguyen M H, Sibeldin N N, Skorikov M L, Tsvetkov V A and Sharkov A V 2009 JETP Lett. 89 579
[35] Ramon G, Rapaport R, Querry A, Cohen E, Mann A, Ron A and Pfeiffer L N 2002 Phys. Rev. B 65 085323
[36] Tartakovskii A I, Krizhanovskii D N, Malpuech G, Emam-Ismail M, Chernenko A V, Kavokin A V, Kulakovskii V D, Skolnick M S and Roberts J S 2003 Phys. Rev. B 67 165302
[37] Perrin M, Sennellart P, Lemaitre A and Bloch J 2005 Phys. Rev. B 72 075340
[38] Malpuech G, Kavokin A, Di Carlo A and Baumberg J J 2002 Phys. Rev. B 65 153310
[39] Shah J 1988 IEEE J. Quantum Electron. 24 276
[40] Tassone F and Yamamoto Y 1999 Phys. Rev. B 59 10830
[41] Tartakovskii A I, Emam-Ismail M, Stevenson R M, Skolnick M S, Astratov V N, Whittaker D M, Baumberg J J and Roberts J S 2000 Phys. Rev. B 62 R2283
[42] Sennellart P, Bloch J, Sermage B and Marzin J Y 2000 Phys. Rev. B 62 R16263
[43] Bilykh V V 2007 Sov. Phys.—JETP 104 814
[44] Belykh V V 2009 PhD Thesis Moscow Institute of Physics and Technology
[45] Szczysko J, Kappei L, Berney J, Morier-Genoud F, Portella-Oberli M T and Deveaud B 2004 Phys. Rev. Lett. 93 137401