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Striking dynamics of II-VI microcavity polaritons after linearly polarized excitation

M. D. Martín[*1], **D. Ballarini**[1], **A. Amo**[1], **Ł. Kłopotowsi**[1], **L. Viña**[1], **A. V. Kavokin**[2], and **R. André**[3]

[1] Grupo de Semiconductores (SEMICUAM), Departamento de Física de Materiales, Universidad Autónoma de Madrid, C/ Francisco Tomás y Valiente 7, 28049 Cantoblanco, Madrid, Spain
[2] Laboratoire des Sciences et Matériaux pour l'Electronique, et d'Automatique, Université Blaise Pascal - Clermont-Ferrand II, 63177 Aubière Cedex, France
[3] Laboratoire de Spectrométrie Physique (CNRS UMR5588), Université Joseph Fourier, 38042 Grenoble, France

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We present a detailed study of the polariton spin dynamics in a II-VI microcavity after linearly polarized excitation. We have found that the vertically polarized (i.e. TE) emission is systematically larger than the horizontally polarized one (i.e. TM) for both, vertically and horizontally polarized excitation. Furthermore, a persistent difference between the two components of the emission is observed, leading to a *net* and *constant* (within the duration of the emission) linear polarization degree. Additionally, we have observed marked oscillations of the linear polarization degree once the excitation power is raised above the polariton-polariton stimulated scattering threshold.

1 Introduction In recent years, the spin of microcavity polaritons has elicited a lot of interest. The seminal experimental works under both resonant [1] and non-resonant excitation [2] stimulated many fruitful discussions about the role of polariton-polariton interactions on the spin dynamics. Shortly after comprehensive theoretical descriptions of these phenomena were published [3]. The case of non-resonant excitation is of particular interest as an intermediate step in the fabrication of potential spintronics devices. However, there is a major disadvantage for non-resonant excitation: a bottleneck in the relaxation of polaritons towards $\boldsymbol{k} = 0$ states ($\boldsymbol{k}$ being the in-plane momentum). For small polariton populations, the non-resonantly created polaritons accumulate in the bottleneck region, hindering the energy relaxation. However, for large enough populations, strong polariton-polariton interactions trigger the stimulated relaxation to $\boldsymbol{k} = 0$. This polariton final-state stimulated scattering has proven to be very efficient in overcoming the bottleneck, allowing the observation of very interesting non-linear effects, such as polariton stimulated emission [4], optical gain [5] and very recently a condensation [6].

2 Sample description and experimental setup In this paper we will concentrate our studies on the polariton spin relaxation after linearly-polarized non-resonant excitation. The sample under study is a $Cd_{0.4}Mg_{0.6}Te$ λ-microcavity with embedded CdTe quantum wells, with a Rabi splitting of 10 meV. The measurements are performed at a point of the sample characterized by an exciton-cavity detuning of ~ -15 meV and at 5 K (Fig. 1). The optical excitation is done using 2-ps long pulses tuned to the first reflectivity minimum above the mirror's stop band and arrives to the sample almost at normal incidence.

* Corresponding author: e-mail: dolores.martin@uam.es, Phone: +34 91 497 5025, Fax: +34 91 497 8579

The photoluminescence (PL) is spectrally- and time-resolved by means of a streak camera coupled to a spectrograph with a time resolution of 10 ps. After linearly polarized excitation, either vertical (TE) or horizontal (TM), the PL is analysed into its two linearly polarized components by means of a linear polarizer [7]. The degree of linear polarization is defined as $\wp = (I_{CO} - I_{CROSS})/(I_{CO} + I_{CROSS})$, where $I_{CO/CROSS}$ denote the intensity of the PL component co/cross polarized with the excitation, respectively. We will concentrate here on the dynamics of the lower polariton branch (LPB) population at $\boldsymbol{k}$ = 0, i.e. at zero degrees (angular resolution ±1°).

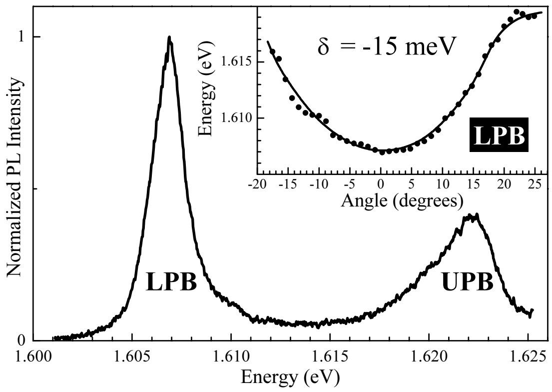

Fig. 1 Time-integrated PL spectrum for an excitation power of 0.5 mW at $\boldsymbol{k}$ = 0. Inset: Lower polariton branch dispersion relation, obtained varying the detection angle.

3 Results and discussion In the linear emission regime (excitation power < 10 mW) the integrated emission from the LPB displays a linear dependence on excitation and excitons and photons are strongly coupled. Figure 2(a) displays the time evolution of the LPB emission after horizontally polarized excitation. For the large negative detuning considered here, the LPB has a predominant photonic character and the emission dynamics should be governed by the photon lifetime (escape from the cavity in a few picoseconds). However, due to the bottleneck, the relaxation is considerably slowed, with decay times of ~ 150 ps. In this linear regime there is no efficient mechanism available for polaritons to quickly surpass the bottleneck as polariton-phonon interaction is drastically reduced beyond the bottleneck. However it is still possible to observe remarkable spin effects at $\boldsymbol{k}$ = 0. In Fig. 2(a) a large difference between the two linearly polarized PLs can be clearly observed, with the vertically polarized emission (orthogonal to the excitation!) being larger than the horizontal one. This difference is present all through the duration of the emission, leading to a negative linear polarization degree (depicted in Fig. 2(b)): $\wp$ remains constant (~ -0.3), with a decay time of ~ 1 ns (much longer than the radiative lifetime!).

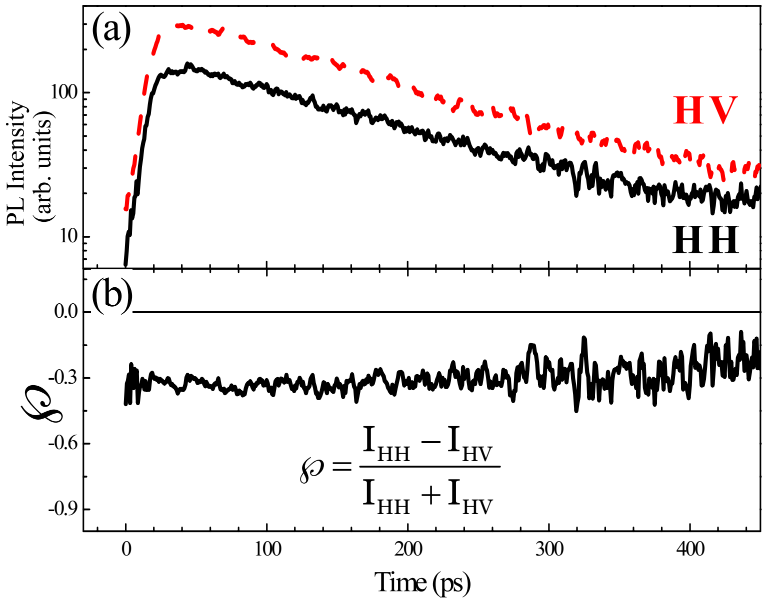

Fig. 2 (a) Time evolution of the LPB emission at $\boldsymbol{k}$ = 0 for an excitation power of 0.5 mW after horizontally polarized excitation. Solid/dashed lines depict the horizontally (H)/ vertically (V) polarized PL component. (b) Time evolution of the degree of linear polarization $\wp$, (see text). Same conditions as above.

Raising a bit further the excitation power (10 mW < excitation power < 20 mW) changes drastically the recombination dynamics and the integrated emission from the LPB displays a super linear dependence on power. Even though the polariton branches appear slightly shifted, excitons and photons are still strongly coupled. Figure 3(a) displays the time evolution of the two linearly polarized components of the non-linear emission from the LPB. The decay time has shortened to about 40 ps (as compared to the 150 ps of the linear emission regime). This acceleration of the recombination dynamics is directly related with the activation of polariton-polariton stimulated scattering, which helps polaritons to efficiently overcome the relaxation bottleneck. We observe that the intensity of the vertically polarized PL is still much larger than the horizontally polarized one all along the duration of the emission. This difference between the intensities of the two linearly polarized components of the PL is enhanced with increasing the excitation power and $\wp$ in the non-linear regime (Fig. 3(b), - 0.5) is larger than in the linear emission regime (Fig. 2(b), - 0.3). The decay time of $\wp$ remains ~ 1 ns. On the other hand, marked oscillations of $\wp$ can be seen after reaching the maximum linear polarization degree (- 0.7) for $t \neq 0$. These oscillations suggest that the spin eigenstates of the polaritons are not purely TE/TM states but elliptically polarized. The spin effects described above (*freezing* and oscillations of $\wp$) have been described theoretically using a pseudospin model [8], which considers the interplay between two different mechanisms: (i) a suppression of the spin relaxation (through exchange interaction as described in [9]) for linearly polarized polaritons and (ii) an anisotropy of polariton-polariton stimulated scattering. The model also accounts for the 90º rotation of the polarization plane.

To gain deeper insight into this polarization plane rotation we rotated by 90º the polarization of the excitation, from horizontal to vertical, and repeated the experiments. The experimental results are equivalent to those described above for horizontally polarized excitation. From the recombination dynamics we have extracted decay times comparable to those deduced from Figs 2(a) and 3(a) and a comparable excitation power threshold for the transition to the non-linear emission regime. However, there is a significant difference between the two sets of data: the *vertically polarized emission is always stronger* than the horizontally polarized one, regardless of the excitation polarization. Under vertically polarized excitation the linear polarization degree is positive and constant as long as there is any measurable signal (see Fig. 4). The values of $\wp$ are of the same order of magnitude for either excitation polarization ($|\wp| \approx 0.3$ in the linear regime and $|\wp| \approx 0.5$ in the non-linear regime) and even the oscillations of the linear polarization degree are reproduced after vertically polarized excitation (Fig. 4(b)). Current theories cannot explain this preferential orientation of the LPB emission and further experiments are underway to test whether this effect is related with the crystalographic directions of the sample or eventually the direction of the cavity's wedge.

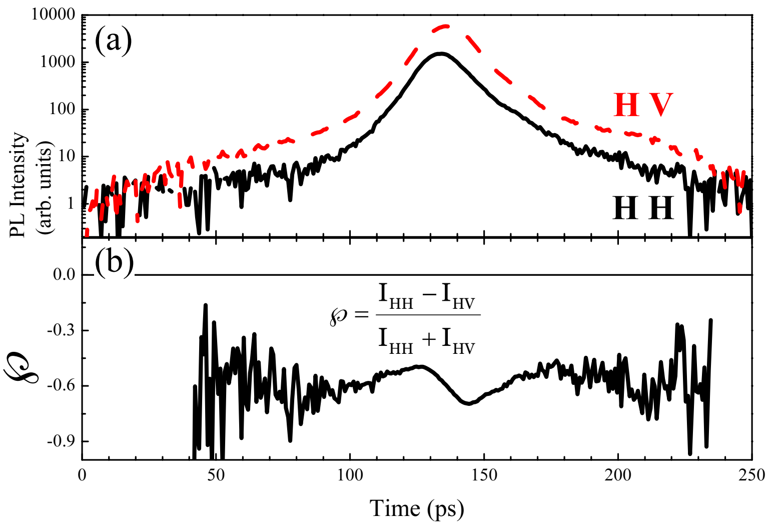

Fig. 3 (a) Time evolution of the LPB emission at $\boldsymbol{k} = 0$ for an excitation power of 10 mW, after horizontally polarized excitation. Solid/dashed lines depict the horizontally (H)/ vertically (V) polarized PL component. (b) Time evolution of the degree of linear polarization $\wp$. Same conditions as above.

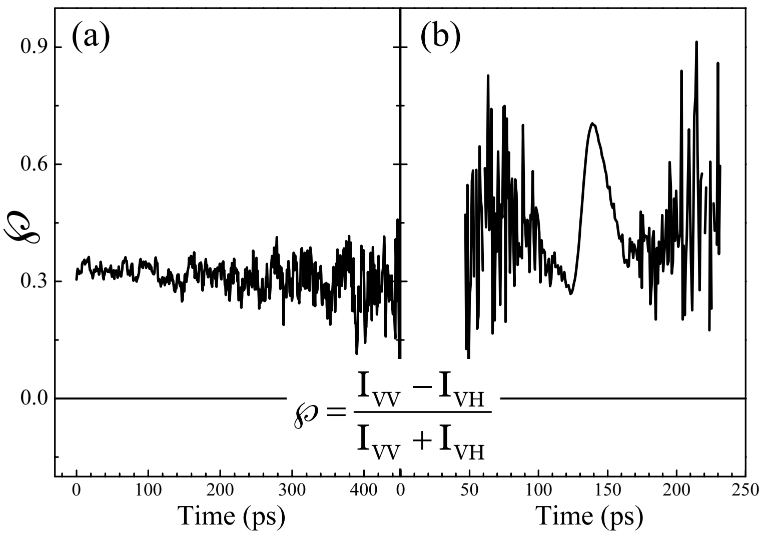

Fig. 4 Time evolution of the degree of linear polarization of the emission ($\wp$) from the LPB at $\boldsymbol{k} = 0$ for an excitation power of (a) 1 mW and (b) 15 mW after vertically polarized excitation.

Further increase of the excitation power, beyond 20 mW, weakens the coupling of excitons and photons, the integrated emission intensity from $\boldsymbol{k} = 0$ LPB states displays a linear dependence with power and the non-linear effects observed in this regime are mainly due to the photonic part of the polaritons. However, very similar features can still be observed: the vertically polarized emission being systematically larger than the horizontally polarized one even though the experimental values of $\wp$ are smaller than those obtained in the non-linear emission regime.

4 Conclusions We have reported the predominance of the vertically (TE) polarized emission from $\boldsymbol{k} = 0$ LPB states after linearly polarized excitation, regardless of the orientation of the linearly polarized excitation. Furthermore, we have found that this effect lasts much longer than the polariton recombination process, leading to a freezing of the degree of linear polarization. A recent theoretical proposal describes the rotation of the plane of polarization after linearly polarized excitation but we observe such rotation *only* under horizontally (TM) polarized excitation. This dominance of the TE emission could be linked with the existence of a privileged direction in the microcavity such as crystalographic axis or cavity wedge. We have also observed marked oscillations of the degree of linear polarization in the non-linear emission regime, which suggest that the spin eigenstates of the polaritons are not purely TE or TM states but elliptically polarized. Our experimental results provide evidences of the anisotropy of the spin dependent polariton interaction and indicate that TE and TM polarized pumping is not equivalent.

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References

[1] P. G. Savvidis et al., Phys. Rev. Lett. **84**, 1547 (2000); P. G. Lagoudakis et al., Phys. Rev. B **65**, 161310(R) (2002); P. Renucci, T. Amand, and X. Marie, Semicond. Sci. & Technol. **18**, S361 (2003).
[2] M. D. Martín et al., Phys. Rev. Lett. **89**, 077402 (2002).
[3] K. V. Kavokin et al., Phys. Rev. Lett. **92**, 017401 (2004); I. Shelykh et al., Phys. Rev. B **70**, 115301 (2004).
[4] P. Senellart et al., Phys. Rev. B **62**, R16263 (2000); A. Alexandrou et al., Phys. Rev. B **64**, 233318 (2001).
[5] M. Saba et al., Nature **414**, 731 (2001).
[6] M. Richard et al., Phys. Rev. Lett. **94**, 187401 (2005).
[7] A λ/4- plate is placed after the linear polarizer to avoid the polarization sensitivity of the grating.
[8] Ł. Kłopotowski et al., Phys. Rev. B (submitted).
[9] M. Z. Maialle, E. A. de Andrada e Silva, and L. J. Sham, Phys. Rev. B **47**, 15776 (1993).

