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Angular switching of the linear polarization of the emission in InGaAs microcavities

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The angular dependence of the degree of linear polarization of the emission is presented for an InGaAs microcavity at several detunings. For emission angles (φ) close to the growth direction, polarizations as high as + 80 % for lower branch polaritons at negative detuning are found. This polarization degree abruptly switches to negative values (up to – 90 %) for emission angles outside a narrow cone of about ±2º. A similar behaviour, with smaller values of the polarization, is found at 0 and positive detunings. The relation between these effects and cavity birefringence is discussed.

1 Introduction Polarization properties of polaritons in semiconductor microcavities in the strong coupling regime have attracted a lot of attention in the last five years. Specifically, linear polarization features of lower branch polaritons at zero and negative exciton-cavity detunings have been recently reported in pump-probe and pulsed photoluminescence (PL) experiments. In pump-probe experiments in III-V microcavities, after a linear polarized pump at the angle of inflexion of the lower polariton branch dispersion, it has been found that the gain for zero momentum lower branch polaritons is maximum when the probe is linearly polarized with a plane of polarization rotated 45° with respect to that of the pump [1]. On the other hand, pulsed photoluminescence experiments with non-resonant excitation at negative detuning in II-VI microcavities, yield rotations of the plane of linear polarization of the emission, of zero momentum polaritons, of 90° with respect to that of the pump [2, 3]. Theoretical simulations [4] have proposed that the linear polarization of the emitting zero momentum polaritons is dominated by spin dependent polariton-polariton interactions in the relaxation bottleneck of the lower branch dispersion, and these interactions are responsible for these polarization plane rotations in the emission. In this paper we present results on the angular dependence of the linear polarization of the emission from lower and upper branch polaritons, and conclude that effects such as cavity birefringence can be important in the polarization characteristics of the emission in microcavities.

2 Sample description and experimental setup The samples used for these studies were $3\lambda/2$ wedged microcavities with two sets of three $In_{0.06}Ga_{0.94}As$ quantum wells at the antinodes of the electromagnetic field. The quantum wells are embedded in a GaAs spacer which is wedged, allowing the selection of the exciton-cavity energy detuning (δ) by exciting in different points in the sample. The sample was grown by metalorganic vapor-phase epitaxy. The results presented in this paper will concentrate on

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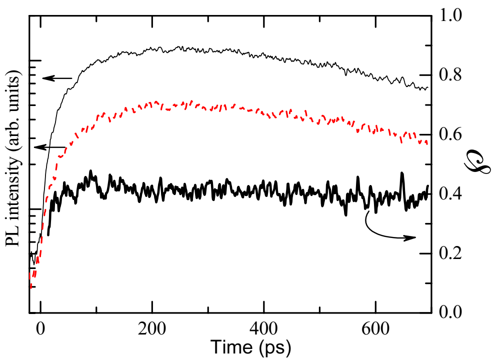

Fig. 1 Time evolution of the PL intensity for $k_{//} = 0$ emission of lower branch polaritons at $\delta = -3$ after TM polarized excitation at 2.5 mW (left axis); thin (dashed) line: TM (TE) polarized emission; thick line: degree of linear polarization (right axis).

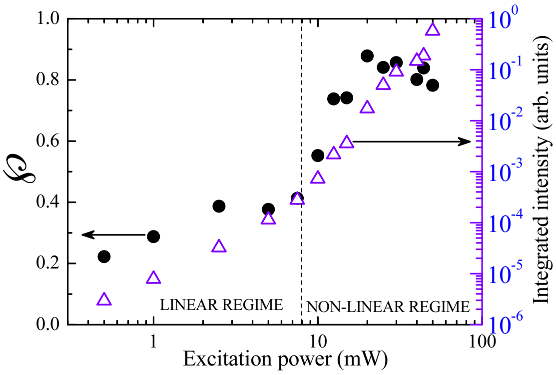

Fig. 2 Power dependence of the emitted integrated intensity (open triangles, right axis) and of the maximum degree of linear polarization (solid dots, left axis) for the lower polariton branch at $k_{//} = 0$ and $\delta = -3$ meV.

three detunings: $\delta = -3$, 0 and +3 meV. Above and below the cavity spacer, $Al_{0.1}Ga_{0.9}As$/GaAs distributed Bragg reflectors were grown. A Rabi splitting of 6.6 meV between the upper and lower polariton branches (UPB and LPB, respectively) was measured in a low-power cw characterization at 5 K. In the time resolved experiments, the sample, kept at 5 K, was excited with 2 ps-long pulses from a Ti:Al_2O_3 laser at an angle of ~ 2º respect to the growth direction. The excitation energy (1.608 eV) was well above the first reflectivity minimum of the cavity stop band. The luminescence was energy- and time-resolved using a spectrograph in conjunction with a streak camera, with an overall time resolution below 10 ps. The emission angle, φ, was selected by means of a pinhole. Thus, light emitted with different in-plane momentum $k_{//}$ ($\propto \cos\varphi$) could be accessed. Polarization optics were used in order to prepare the polarization degree of the exciting pulse and to analyze the linear polarization of the emission. The polarization characteristics of the emission are studied through the degree of linear polarization, $\wp$, defined as $\wp = (I_{CO} - I_{CROSS})/(I_{CO} + I_{CROSS})$, where $I_{CO/CROSS}$ is the intensity of the linearly polarized components of the emission with polarization plane parallel/perpendicular to the polarization of excitation.

3 Experimental results and discussion For low power excitation, excitons and cavity photons are strongly coupled and the upper and lower polariton branches can be well identified in the luminescence emitted by the samples. Figure 1 shows the time evolution of the co- and cross-linearly polarized components of the LPB emission at $k_{//} = 0$ after horizontal (TM) excitation at $\delta = -3$ meV, in this low power regime. The co-polarized component (TM emission) is more intense than the cross-polarized one at all times, yielding a degree of linear polarization with an initial value of about 45% and a very long decay time (~ 4 ns). If the excitation power is increased up to a critical value of 8 mW, the luminescence dynamics slightly accelerates and the degree of linear polarization steadily increases. This excitation power range (0 to 8 mW) is the so-called linear regime, as the integrated luminescence intensity linearly increases with excitation power (Fig. 2). A further increase in excitation power leads to a regime where the LPB luminescence intensity increases superlinearly. In this non-linear regime, the PL dynamics drastically accelerate and the value of $\wp$ also increases superlinearly with excitation power up to a saturation level, at $\wp$ ~ 0.8-0.9, for powers above 20 mW. Nonetheless, the decay time of $\wp$ remains very long (~ 4 ns; much longer than the lifetime of the emission) for all the investigated excitation powers.

An analogous behaviour in the linear polarization dependence with excitation power, and similar long $\wp$ decay times, have been observed at negative detuning in II-VI microcavities [2]. In that case, these effects were attributed to the manifestation of the anisotropic spin dependent polariton-polariton interac-

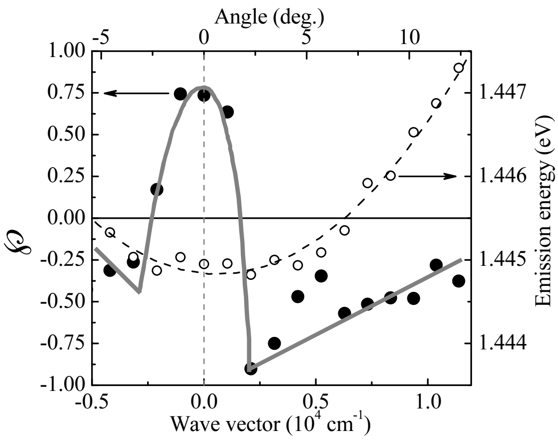

Fig. 3 Maximum degree of polarization (black points, left scale) as a function of wavevector (angle) for the LPB at δ = -3 meV. The dispersion of the LPB is shown by open points (right scale).Excitation power: 40 mW. The line is a guide to the eye.

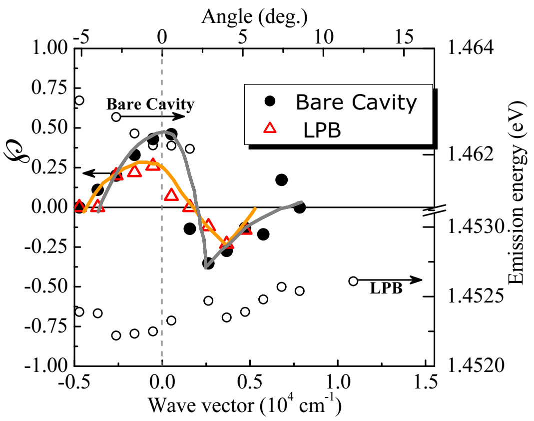

Fig. 4 Maximum degree of polarization (black points, left scale) as a function of wavevector (angle) for the LPB at δ = +3 meV. The dispersions of the LPB and bare cavity mode are shown by open points (right scale).Excitation power: 40 mW. The line is a guide to the eye.

tion in the bottleneck of the LPB [3, 4]. However, the above mentioned ℘ dependence on excitation power is also present for δ = 0 and +3 meV (results not shown here) for the sample used in the present study. For these two detunings, and specifically at δ = +3 meV, any effect of the bottleneck in the dynamics is greatly reduced as the curvature of the LPB is smoother. Thus, the origin of such high values of ℘ may not be sought in spin dependent polariton-polariton interaction at the bottleneck, but in cavity birefringence as we shall discuss below.

More striking than the time evolution of ℘ at $k_{//}$ = 0, is the dependence of ℘ with the angle of emission φ ($k_{//} \neq 0$). Figure 3 depicts the maximum value of ℘ as a function of φ for the LPB at δ = -3 meV and high excitation power (40 mW; non-linear regime). The point at φ = 0 ($k_{//}$ = 0) shows the high value of ℘ described above (Fig. 2) for high power excitation. ℘ remains approximately constant for angles ~ ±2º around the $k_{//}$ = 0 emission. However, a small increase in the emission angle beyond φ = ±2º results in an abrupt switching in the degree of linear polarization from ~ + 0.8 to ~ – 0.9. A further increase of φ leads to a monotonic reduction of |℘| towards 0. Thus, the polarization plane of the emission changes from TM (co-polarized with the excitation) in a narrow cone around $k_{//}$ = 0 ($|\varphi| \leq$ 2º), to TE outside this narrow cone. The values of the polarization for negative wave vectors in Fig. 3 are not as accurate as those for positive wave vectors due to specific details in the experimental setup.

A similar polarization switching, but with opposite sign, is observed when the plane of the polarization of excitation is changed to TE. In that case, at $k_{//}$ = 0 the emission is still TM and thus yields a net polarization value which is negative (℘ ~ - 0.8). Right outside a narrow cone of ~ ±2º there is a switching in the plane of polarization leading to ℘ values as high as ~ + 0.9, just in an analogous way as in the case of TM excitation (Fig. 1). The opposite behaviours of the degree of polarization observed for TM and TE excitations reflect the fact that at $k_{//}$ = 0 the polarization of the emission is always TM (outside the aforementioned narrow cone, TE) regardless the polarization of the excitation.

Analogous experiments have been performed at δ = 0 and +3 meV, for TM polarized excitation. For δ = +3 meV and low excitation power, LPB and UPB dispersions in the strong coupling regime are obtained. However, at high powers (non-linear regime) a coexistence of polariton emission and bare cavity mode emission (red shifted ~ 1 meV with respect to the UPB) is observed. In this case of high power, the angular dependence of $\wp$ has been obtained for LPB and bare cavity modes (the UPB emission having been overcome by the much more intense bare cavity luminescence), as depicted in Fig. 4. For the LPB a switching of $\wp$ from positive to negative values is observed when φ is increased beyond the ±2° cone, but with absolute $\wp$ values (up to 0.26) much lower than for δ = -3 meV. The bare cavity mode emission presents the same features in the degree of linear polarization as the LPB, with greater values of $|\wp|$ (up to 0.47), but still below those found in the negative detuning case.

For δ = 0 and high excitation power, a coexistence between polariton and bare cavity modes is also observed. The polarization angular characteristics are alike those at positive detuning: an angular switching of $\wp$, and higher polarization degrees for the bare cavity mode than for the LPB. Now the absolute values of $\wp$ lay in an intermediate range between those obtained at positive and negative detunings.

From the preceding described experimental results, some general features can be extracted. The main one is that the angular switching of the polarization for emission angles in the vicinity of ±2° takes place at all investigated detunings. In each detuning, the absolute values of the polarization are higher for the polaritons with a higher photonic component (LPB for δ <0, UPB for δ >0), or for the photonic bare cavity mode. This indicates that these effects are related to the dynamics of the photonic component of the polaritons in the microcavity and its origin may be in the presence of birefringence in the system. Birefringence effects are known to control the linear polarization characteristics of the fundamental mode emission in Vertical Cavity Surface Emitting Lasers (VCSELs), which are devices that contain *just the photonic part* of a usual microcavity (absence of quantum well excitons). Birefringence in VCSELs can be originated by the crystallographic orientation of the samples, or may be induced by electron injection, optical pumping [5] or strain induced in the cavities [6]. The fact that, in the experiments shown here, the TM emission is dominant at $k_{//}$ = 0 regardless the polarization of the excitation, points to the existence of a privileged axis in the sample, which can be responsible for birefringence effects observed in the emission. This privileged axis may arise from strain induced in the cavity during the growth of distributed Bragg reflectors, or from the direction of the wedge in the cavity. The determination of the direction of the cavity wedge is not trivial in the studied samples, as they were grown by grown by metalorganic vapor-phase epitaxy. Further experiments are in progress in order to find conclusive evidences for the relation between orientation of the polarization and the wedge direction.

4 Conclusions In summary, we have demonstrated an abrupt angular switching in the degree of linear polarization in the emission of non-resonantly excited microcavities. We have also shown that the degree of linear polarization decays very slowly (~ 4 ns) indicating that the eigenmodes of the cavity correspond to linearly polarized states. Furthermore, the fact that TM-polarized emission is the dominant one, for any polarization of the excitation, indicates that some geometrical asymmetry is responsible for a cavity birefringence.

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