Spin-Dependent Strong- to Weak-Coupling Transition in Semiconductor Microcavities

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Abstract. We present a study of the transition from the strong- to the weak-coupling regime in InGaAs microcavities by means of time-resolved photoluminescence. We have found that under circularly-polarized excitation, with increasing excitation power, the co-polarized polaritons undergo a transition to bare modes (exciton + photons) at a power significantly lower than that of the cross-polarized polaritons. This demonstrates that the appearance of the weak coupling depends mainly on the excitonic population of a given spin orientation.

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Semiconductor microcavities are a very suitable systems to investigate the light-matter interaction in confined structures. In a microcavity, a quantum well (QW) excitonic state can be brought into resonance with a discrete Fabry-Perot mode (FP) of the cavity ($\delta=E_{FP}-E_{QW}=0$). If their interaction energy is greater than any homogeneous or inhomogeneous broadening of the bare photon or exciton mode, the system is in the strong-coupling regime (SC). In the SC regime, the eigenstates of the system are mixed states of light and matter, called polaritons, and the energy eigenvalues are modified with respect to those of the uncoupled particles. The normal-mode splitting breaks the degeneracy of photons and excitons into lower and upper polariton branches (LPB, UPB). The Rabi splitting Ω is a function of the exciton oscillator strength f_{osc}:[1]

$$\Omega \propto \sqrt{(f_{osc} - f_{th})}, \qquad (1)$$

where f_{th} is a threshold oscillator strength.

Saturation of the strong-coupling regime can be achieved, for example, by increasing the density of the electron-hole pairs, leading to a continuous transition to the weak-coupling regime (WC), where the light-matter interaction is well described by a perturbative approach: the energies of the coupled modes are very similar to those of the bare modes and Ω vanishes.

The SC regime has attracted great interest because of its importance from a fundamental point of view as well as for possible applications, in particular when the system is excited by non-resonant optical pumping.

To get a further understanding of the role of the spin in the polariton relaxation process and in the bleaching of the oscillator strength, we have analyzed the polarization properties of InGaAs microcavities under non-resonant optical excitation and have studied the transition from the strong- to the weak-coupling regime as a function of the excitation power.

The studied sample is a 3/2 λ GaAs microcavity with two stacks of three $In_{0.06}Ga_{0.94}As$ QWs, characterized by a Rabi splitting of 6 meV. Dielectric Bragg Reflectors confine the electromagnetic field in one dimension and are composed by 17 (top) and 20 (bottom) layers of $Al_{0.1}Ga_{0.9}As$ and AlAs. The photoluminescence (PL) is non-resonantly excited by circularly-polarized, 2 ps-long, pulses and analyzed into its co- (σ^+) and cross- (σ^-) polarized components. Excitation energy is 1.635 eV, just above the cavity stop-band. The PL emission at K~0 is time- and energy-resolved using a spectrograph and a streak camera (energy and time resolution of 0.2 meV and 10 ps, respectively).

Under low excitation power, the system is in the SC regime and at resonance the LPB energy is $\Omega/2$ lower than the energy of the bare cavity modes.

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Increasing the excitation power, the coupling of the QW excitons and cavity photons reduces, due to many-body effects, and the LPB emission is blue shifted towards the bare cavity mode energy.

Time-resolved PL shows that not-shifted and blue-shifted polaritons coexist (see Fig. 1: the streak at ~1.45 eV together with the comma-shaped image).

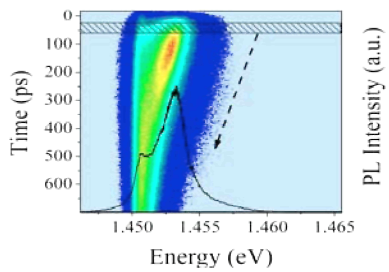

FIGURE 1. Streak-camera image of LPB-PL depicting its spectral and temporal behavior. Black line: PL-intensity spectrum at short time (selected shaded region in the figure) showing the coexistence of low- and high-energy components of the LPB.

The high-energy component, dominating the spectrum at short time, vanishes when a low carrier density is recovered. We have also studied the spatial distribution of the PL scanning the emission area (0.03 mm^2) with a resolution of 80 μm^2. We find that the two components are present on the whole emission area, ruling out inhomogeneities on the excitation spot as the origin of this coexistence.

An analysis of the polarized-PL spectra shows that σ^+ and σ^- polaritons have different energies at excitation powers near the strong- to weak-coupling transition, as shown in Fig. 2. With a direct calibration of our experimental setup it is possible to obtain from the intensity of the PL the number of polaritons, N_p, with momentum K~0. Selecting K~0 states by a pin-hole, a finite number, N_k, of K-states contribute to the PL. The occupation factor, f_p, is $f_p=N_p/N_k$ (see Ref. 2). As shown in Fig. 3, the dependence of the occupation factors with excitation power is very different for σ^+ and σ^- polaritons.

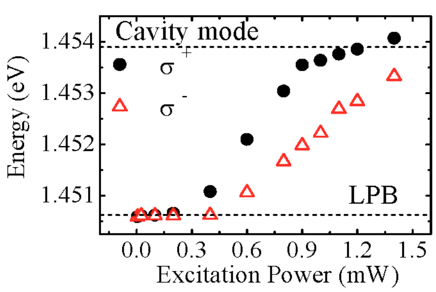

FIGURE 2. LPB-peak energies as a function of the excitation power for the two polarizations σ^+ (●) and σ^- (Δ).

Both $f_p^{\sigma+}$ and $f_p^{\sigma-}$ are smaller than one while the strong coupling dominates, hindering the possibility of stimulated polariton-polariton scattering[3, 4]. At an excitation power of ~1 mW, $f_p^{\sigma+}$ approaches unity, but the σ^+ polaritons are in the WC regime, as borne out by the values of their energies that approach the bare-cavity mode energy (see Fig. 2). However, at this excitation power, the σ^- polaritons are still in the SC regime, with $f_p^{\sigma-}$~0.2 and energies well below the bare-mode energy. The WC regime for σ^- polaritons is reached at P~1.4 mW. Cavity laser emission in the WC regime is obtained, for a given polarization, when its occupation factor is greater than one (in the WC regime the occupation factor is evaluated considering a polariton photon fraction of 100%).

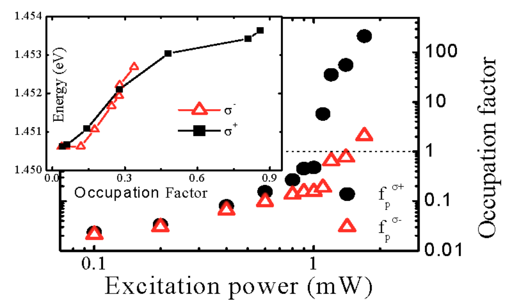

FIGURE 3. Occupation factor as a function of excitation power for the two polarizations σ^+ (●) and σ^- (Δ). Inset: LPB energies as a function of f_p.

In the inset of Fig. 3, a plot of the σ^+ and σ^- LPB-peak energies versus the respective occupation factors (while the system is in the SC regime) reveals that the energy shifts depend only on the number of polaritons with a given spin orientation. Therefore the loss of SC for a polariton population of a given spin is determined by the occupation factor of that population and not strongly influenced by the presence of opposite spin polaritons. Our findings suggest that not only screening but also exchange interactions and phase-space filling play a very important role on the strong- to weak-coupling regime transition.

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