Transition from the strong- to the weak-coupling regime in semiconductor microcavities: Polarization dependence

D. Ballarini,[a)] A. Amo, and L. Viña
SEMICUAM, Departamento de Física de Materiales, Universidad Autónoma de Madrid, E-28049 Madrid, Spain

D. Sanvitto and M. S. Skolnick
Department of Physics and Astronomy, University of Sheffield, S3 7RH Sheffield, United Kingdom

J. S. Roberts
Department of Electronic and Electrical Engineering, University of Sheffield, S1 3JD Sheffield, United Kingdom

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The dependence on the polariton spin orientation of the transition from the strong- to the weak-coupling regime in InGaAs semiconductor microcavities is experimentally studied by means of time-resolved photoluminescence. Polaritons are nonresonantly excited by circularly polarized pulses and the photoluminescence of the $K_{\parallel}\sim 0$ states is analyzed into its co- and cross-polarized components. The loss of strong coupling with increasing excitation intensity takes place at different powers for polaritons with opposite spin orientation and it is determined by the polariton population of each spin. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2739370]

A semiconductor planar microcavity is a structure formed by high reflecting dielectric mirrors (distributed Bragg reflectors) on the two sides of a spacer layer, of length L_C, with embedded quantum wells (QWs). If L_C is tuned in such a way that a confined photon mode of the cavity couples with a QW exciton, new eigenstates of the system result, called exciton polaritons, which are mixed states of excitons and photons.[1,2] Semiconductor microcavities, and its optical properties, have been intensively investigated, due to its fundamental interest and possible applications as optical devices.[3–6] Light-matter interaction in such structures is usually described in the framework of the weak-coupling (WC) and strong-coupling (SC) regimes.[7] If the cavity-mirror reflectivity is large and the exciton linewidth sufficiently small, exciton and photon are strongly coupled and a coherent energy transfer between them occurs with the so-called Rabi frequency. In the SC regime, if the cavity mode (CM) is chosen at resonance with the exciton transition [i.e., detuning $\delta=E_{\mathrm{CM}}-E_{\mathrm{ex}}=0$, with $E_{\mathrm{CM(ex)}}$ the cavity mode (exciton) energy], the degeneracy of the exciton and photon levels breaks into the lower polariton branch (LPB) and upper polariton branch, which are separated by a Rabi splitting $\hbar\Omega$

$$\hbar\Omega = 2\sqrt{|V|^2 - 1/4(\gamma_c - \gamma)^2}, \quad (1)$$

where V is the light-matter coupling parameter, proportional to the exciton oscillator strength, $f_{\mathrm{osc}}^{\mathrm{ex}}$; γ_c and γ are the cavity linewidth and the nonradiative exciton linewidth, respectively.[7] Furthermore, the dispersion relations of the polaritons are strongly modified with respect to those of the bare modes and present a deep minimum at the bottom of the LPB. The small density of states near the ground state allows polaritons to form a Bose condensate out of equilibrium at relatively high temperature, and a polariton laser that does not require population inversion could be possible.[8,9] On the contrary, in the WC regime 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.

When the carrier density is increased, for example, by raising the optical excitation power, $f_{\mathrm{osc}}^{\mathrm{ex}}$ is renormalized due to the presence of an electron-hole (e-h) plasma. As a result, a reduction of the coupling parameter V and a continuous transition from the SC to the WC regime occur.[10–13] Two processes are responsible for the change of $f_{\mathrm{osc}}^{\mathrm{ex}}$ at high carrier density: the blocking mechanism due to the Pauli exclusion principle (phase space filling) and the modification of the e-h interaction in the presence of other e-h pairs.[14] Both the exchange effect, another consequence of the exclusion principle, and the long-range Coulomb interaction contribute to the latter process. These effects have been profusely studied and it is well known how they affect the exciton properties and, in particular, $f_{\mathrm{osc}}^{\mathrm{ex}}$.[15] However, only few works deal with polarized interacting exciton in QWs.[16,17] In order to understand and control the emission properties of a polariton laser, it is important to study the role of the spin in the polariton interactions.[18,19] In this letter, we demonstrate that the transition from the SC to the WC regime takes place at different powers for polaritons with opposite spin orientation and that it is governed by the occupation factor of each spin population.

The studied sample is a $3/2\ \lambda$ GaAs microcavity with two stacks of three $In_{0.06}Ga_{0.94}As$ QWs, with $\hbar\Omega=6$ meV at 5 K; e-h pairs are nonresonantly excited by 2 ps long circularly polarized (σ^+) pulses of a Ti:Al_2O_3 laser (at an energy $E_{\mathrm{PUMP}}=1.63$ eV and repetition rate of 80 Mhz). Polaritons with a large wave vector $K_{\parallel}$ ($K_{\parallel}$ is the momentum in the QW plane) are formed and relax towards the bottom of the LPB. Photoluminescence (PL) from states with $K_{\parallel}\sim 0$ is selected by a diaphragm and analyzed into its copolarized (σ^+) and cross-polarized (σ^-) components by a combination of a $\lambda/4$ plate and a linear polarizer. The PL is energy resolved and time resolved by a spectrograph coupled with a streak camera (resolution of 0.2 meV and 10 ps, respectively). All the

a)Electronic mail: dario.ballarini@uam.es

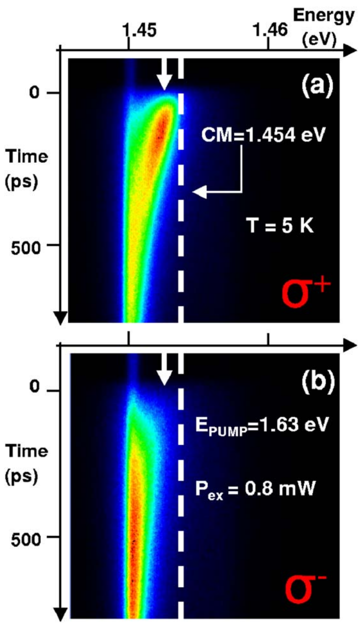

FIG. 1. (Color online) Streak-camera images of the microcavity emission under σ^+ excitation. The horizontal axis represents energy and the vertical one the time scale. (a) σ^+ emission and (b) σ^- emission. The dashed line indicates the energy of the bare cavity mode and the arrows indicate the energy position of the σ^+ shifted emission.

experiments are carried out at $\delta=0$ and $T=5$ K.

Figures 1(a) and 1(b) illustrate the streak-camera images of the LPB emission with polarization σ^+ and σ^-, respectively, for an excitation power $P_{ex}=0.8$ mW. In Fig. 1(a), the σ^+-LPB emission energy is blueshifted at short times (as indicated by the arrow), when a high carrier density is present. At longer time, as the carrier density decreases, the shift of the σ^+-LPB emission energy vanishes. The σ^--LPB emission [Fig. 1(b)] presents the same behavior as that described for the σ^+ case, but the energy shift at short time is smaller, as evidenced by the arrow, which marks the short-time energies of the σ^+ emission. It should be stated that the false-color intensity scales of Figs. 1(a) and 1(b) are different. Actually, the σ^+ signal is much stronger than the σ^- one, yielding a time-integrated polarization degree $P=0.5$, where P is defined as $P=(I^{\sigma+}-I^{\sigma-})/(I^{\sigma+}+I^{\sigma-})$, with $I^{\sigma+(\sigma-)}$ as the σ^+ (σ^-) time-integrated PL intensity.

In Fig. 2(a), the LPB peak energies at short time[20] are plotted as a function of P_{ex} for the two polarizations. Under low excitation power the system is in the SC regime and the LPB, for both polarizations, lies at an energy ~3.5 meV below the bare CM. With increasing P_{ex}, both polarized branches of the LP blueshift: the Rabi splitting $\hbar\Omega$, given by twice the energy separation between the CM and the LP, is effectively reduced due to the aforementioned decrease of f_{osc}^{ex}. Strikingly, at a given P_{ex}, the energy shift of the σ^+ polaritons is larger than that of the σ^- polaritons and an energy splitting between them is obtained. Eventually, for $P>1$ mW, σ^+ polaritons (spin up) reach the energy of the CM and are in the WC regime, while σ^- polaritons (spin down) are still in the SC regime, as can be inferred by their energy positions [see Fig. 2(a)]. A transition from the SC regime to the WC regime has taken place only for the copolarized polaritons.

Figure 2(b) shows the dependence on P_{ex} of the time-integrated PL intensity for both polarizations and its corresponding polarization degree. At low P_{ex}, the PL intensity is similar for both polarizations, yielding $P\approx 0$. At powers higher than ~0.6 mW, when the transition from the SC to the WC regime starts, the intensity of σ^+ polaritons grows superlinearly with P_{ex} and the polarization degree increases rapidly reaching $P\approx 0.95$ at 1.2 mW.[21,22] At this power, the σ^+ emission corresponds to laser action from the bare cavity mode in the WC regime.[13,23]

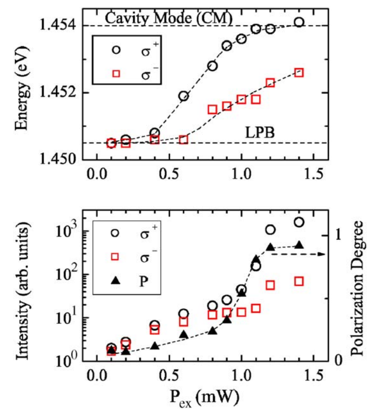

FIG. 2. (Color online) (a) LPB peak energies for σ^+- and σ^- polaritons at short times as a function of the excitation power P_{ex}. (b) LPB time-integrated (0–700 ps) PL intensity for both polarizations (left scale) and polarization degree (right scale, ▲) vs P_{ex}. ○ (□) denotes σ^+ (σ^-) polarization.

To have a deeper understanding of the energy shifts for both polarizations, we analyze their dependence on the occupation factors of each of the polariton populations with a given spin. Indeed, with a direct calibration of the experimental setup, measuring the absolute PL intensity, it is possible to obtain the occupation factors $\eta_{occ}^{\sigma+}$ and $\eta_{occ}^{\sigma-}$ of polariton states with $K_{\parallel}\sim 0$. We relate the number of polaritons N ($K_{\parallel}\sim 0$) to the PL intensity I_{PL} (in watt) by

$$N(K_{\parallel}\sim 0)=\frac{I_{PL}\times\tau}{\alpha\times E}, \tag{2}$$

where $\tau=2$ ps is the cavity photon escape time, α is the LP photon weight, and E is its energy. Selecting $K\sim 0$ states by a pinhole, a finite number, N_k, of K states contribute to the PL: the occupation factor[24] is $\eta_{occ}=N/N_K$. Figure 3(a) shows the occupation factors for both spin populations, $\eta_{occ}^{\sigma+}$ and

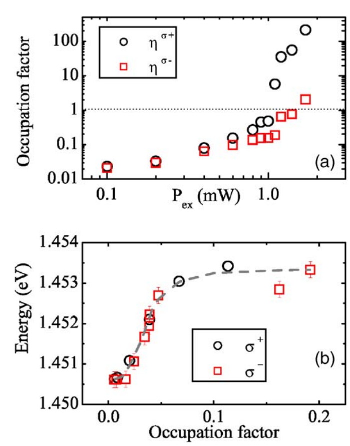

FIG. 3. (Color online) (a) Occupation factors of σ^+ (○) and σ^- (□) polaritons as a function of the excitation power P_{ex}. (b) LPB peak energies for both polarizations as a function of the respective occupation factor.

$\eta_{occ}^{\sigma-}$, versus the excitation power. This analysis now makes clear that the difference in the energy shifts for both polarizations is directly linked to their respective occupation factors: the energy splitting between σ^+ and σ^- emissions appears at $P_{ex} \geqslant 0.6$ mW [Fig. 2(a)], the same power for which a noticeable difference in the occupation factors is obtained [Fig. 3(a)]. Since in the WC regime the emission behaves as that from photons in a vertical-cavity surface-emitting laser, in the following we will restrict our analysis of σ^+ polarization to polariton occupation factors corresponding to values of P_{ex} at which the polaritons are still in the SC regime ($P_{ex} < 1.1$ mW).

Plotting now the σ^+ and σ^- LPB peak energies versus the respective occupation factors, as in Fig. 3(b), the same behavior is observed for both polarizations with the two curves exactly superimposed. The emission energies of the polarized polaritons and, consequently, their coupling regime are determined by the occupation factor of the polaritons with a given spin. It is quite remarkable that the combined effect of the total carrier density and of the spin orientation of the polaritons on the screening of the exciton (i.e., on the collapse of the Rabi splitting) yields an identical dependence on the occupation factors. In fact, it has been noted that phase space filling plays a dominant role in determining the exciton properties in the presence of high carrier densities: the wave function of a bound electron-hole pair can be represented as a linear combination of the eigenfunctions of all free-electron states; if the states with small $k_{\parallel}^{e,h}$ are occupied by free carriers and subject to the Pauli exclusion principle, the allowed electron/hole states that contribute to the exciton wave function are those with large momentum $k_{\parallel}^{e,h}$ and the shape of the exciton wave function is strongly modified. Bigenwald *et al.* have shown that in this case the binding energy and the oscillator strength of the exciton depend on the distribution rather than on the total density of electrons and holes.[25] One could argue that the different distributions of carriers with opposite spins, together with the fact that *e-h* interactions include exchange, which depends strongly on spin, may explain why the f_{osc}^{ex} of majority (σ^+)-spin excitons becomes smaller than that of minority (σ^-)-spin excitons at a given carrier density (i.e., excitation power) and that the transition from the SC to the WC regime for polaritons with a given spin orientation is mainly determined by its own occupation factor. It should be mentioned that the splitting between polarized exciton[16] can be ruled out as the origin of the results presented in Fig. 2(a), in fact, the splitting is absent for the LPB at large positive detunings, where LPB is mostly excitonic, and it is also absent in an identical sample without cavity mirrors.

In order to exclude possible spatial inhomogeneities present in these samples,[9,26,27] which could lead to spatially separated regions containing different populations of σ^+ and σ^- polaritons, we have performed confocal scanning of the polariton emission with a resolution of 10 μm. In a region of 50 μm close to the laser spot center we have observed the coexistence of both the weakly coupled σ^+ emission and the strongly coupled σ^- polaritons, confirming that the two populations with opposite spins do not originate from different regions within the excitation spot.

In summary, we have observed that under nonresonant circularly polarized excitation the transition from the SC to the WC regime of the copolarized polaritons occurs at an excitation power lower than that of the cross-polarized polaritons. This is attributed to the different carrier distributions for each spin orientation and to phase space filling effects, which obtain a transition that depends only on the polariton population of a given spin.

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