phys. stat. sol. (b) **221**, 151 (2000)

Subject classification: 71.35.–y; 71.36.+c; 78.20.Bh

Gigantic Photon–Photon Coupling in Biased Semiconductor Microcavities: A Step toward Single-Photon Blockade

M. RÜFENACHT

Quantum Institute, University of California, Santa Barbara, CA 93106, USA
e-mail: mathilde@qi.ucsb.edu

(Received April 10, 2000)

We discuss optical nonlinearities in biased semiconductor microcavities. Optical nonlinearities arise from field screening by spatially separated electron–hole pairs in biased quantum wells (QWs). However, in wide QWs where the spatial separation is large, biasing is accompanied by a drastic decrease of oscillator strength, and has a negative impact on the optical nonlinearity. We show here that in an exciton polariton microcavity in the strong coupling regime, a decrease in oscillator strength only weakly affects the optical nonlinearity. Gigantic enhancement of photon–photon interaction is then realized by biasing, and the single-photon blockade limit can be reached.

The principal obstacle to the realization of few-photon optical devices is the usual weakness of photon–photon interaction. Photon–photon interaction can be increased in semiconductor nanostructures by designing large optical nonlinearities, but those are usually achieved at the cost of a strong absorption and sometimes at the cost of speed. Atomic dark resonances were proposed in atomic systems as a mean to obtain giant nonlinearities without loss and to achieve photon blockade, i.e. a system allowing the transit of only a single photon at a time, in analogy with Coulomb blockade [1, 2]. Unfortunately, a similar scheme cannot be adapted to semiconductor structures, due to the short dephasing times inherent to them. It is however highly desirable to realize photon blockade in semiconductors, as well for device applications as for the extreme adaptability of these systems.

We demonstrate in this article that huge absorption-free optical nonlinearities can be obtained in biased exciton polariton microcavities. These nonlinearities could lead to few-photon or single-photon blockade.

Biasing quantum well (QW) as a mean of enhancing optical nonlinearities has already been proposed more than ten years ago [3 to 6]. The nonlinearity arises from the field screening by the electron–hole dipole induced by the biasing. This process was found however practically of little use. A gain of nonlinearity arises only at small bias and in narrow QWs, where carrier separation is relatively small. The strongest optical nonlinearity was found for 7 nm wide QWs and with an electric field of 150 kV cm^{-1}. In wider QWs, the carrier separation is enhanced, but the gain due to increased screening is injured by the decrease of oscillator strength.

The situation is very different in exciton polariton microcavities. In the strong coupling regime, which usually prevails in QW microcavities, photon–exciton coupling is saturated and is not injured, in first-order approximation, by decrease in oscillator strength. We will show in the following that we can use wider QWs to increase the field screening effect by several orders of magnitude at no detriment of the photon–exciton interaction.

A semiconductor microcavity is typically formed of a semiconductor layer a wavelength thick, clad by two distributed Bragg reflectors (DBR), see e.g. [7]. A DBR is made of alternative dielectric materials of different refraction indexes and of quarter-wavelength thicknesses. The microcavity is highly reflective on a wide wavelength range and has a sharp transparency line at its resonance frequency. The width Γ_c of this resonance depends on the quality and number of periods of the DBRs, and practically can be nearly as sharp as $\Gamma_c \approx 0.1$ meV. A photon coupled to the resonance will penetrate in the cavity and stay there for a finite time τ_c given by $\tau_c = \hbar/\Gamma_c$, where $\hbar$ is the Planck constant. In 1992, it was demonstrated that cavity photons couple very strongly to QW excitons at resonance, creating exciton polaritons, a quantum combination of a photon and an exciton [8]. Coupling energies as large as $\Omega_{cx} = 20$ meV were observed in multi-QW microcavities. Those polaritons give rise to a splitting of the cavity resonance, called the vacuum field Rabi splitting, and is observed as two peaks separated by the coupling energy Ω_{cx} in the transmission characteristic of the microcavity. The coupling energy is related to the exciton oscillator strength and cavity parameters as

$$\Omega_{cx} = 2\sqrt{\frac{\hbar^2 e^2 f_{HH}}{2n_c^2 \epsilon_0 m_0 L_{eff}}}, \tag{1}$$

where e is the electric charge, f_{HH} is the heavy-hole excitonic oscillator strength, n_c is the refraction index of the cavity, ϵ_0 is the vacuum dielectric constant, m_0 is the electron mass, and L_{eff} is the effective length of the microcavity [9].

Such exciton polariton systems are virtually absorption-free, as an external photon can only couple to the exciton through the cavity mode and then can only relax back into the cavity mode. Also, contrary to usual QW excitons, polariton lineshape is limited by the cavity photon lifetime, and they exhibit typically much sharper features.

The energy of the polaritons is given by

$$\epsilon_{\pm} = \epsilon_c + \frac{\Delta}{2} \pm \frac{1}{2}\sqrt{\Delta^2 + \Omega_{cx}^2}, \tag{2}$$

where $\Delta = \epsilon_x - \epsilon_c$ is the detuning between excitonic energy ϵ_x and cavity photon energy ϵ_c. The energy ϵ_+ designates the upper polariton and ϵ_- designates the lower one (Fig. 1).

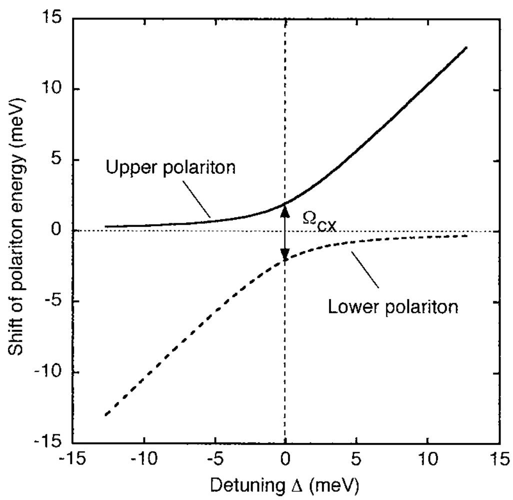

Fig. 1. Shift of polariton energies as a function of the detuning $\Delta = \epsilon_x - \epsilon_c$ between the exciton and the cavity polariton

In the following, we discuss an optical switching of a microcavity from a transparent mode to a reflective mode by shifting the excitonic resonance. In order to switch the microcavity for an incoming photon initially resonant with a polariton line, we need to shift the polariton energy by an amount larger than its width. In a microcavity initially at resonance with the exciton ($\epsilon_{\rm x} = \epsilon_{\rm c}$), this can be achieved by shifting the excitonic energy by at least an energy σ given by

$$\sigma_\pm = \Gamma_{\rm c} \frac{1 \pm \gamma}{1 \pm \dfrac{\gamma}{2}} \,, \tag{3}$$

where σ_+ and σ_- are the minimum excitonic shifts to detune the upper and lower polaritons, respectively. γ is given by $\gamma = \Omega_{\rm cx}/\Gamma_{\rm c}$.

In order to realize a photon blockade, we need a large nonlinear excitonic shift and, for the upper polariton case, a small Rabi splitting. These two conditions can be realized simultaneously in a microcavity with an electrically biased QW. Electron–hole pairs in a biased QW are spatially separated. The effect of the spatial separation is twofold. First, carrier separation enhances the nonlinear response of the excitonic system, as an exciton creates an electric field that screens the applied field, shifting the energy level by an amount proportional to the electron–hole separation as illustrated in Fig. 2. Second, the reduction of excitonic oscillator strength results in a decrease of $\Omega_{\rm cx}$ [10, 11]. Let us emphasize that contrary to pure excitonic system, this is the only consequence of the decrease of excitonic oscillator strength, as long as we stay in the strong coupling regime ($\gamma > 2$), and that it barely affects the optical nonlinearities. As a result, large bias and wide QWs can be used, where large screening effects occur, yielding huge nonlinearities.

We note that the key point to improve the optical nonlinearity is the spatial separation of the electron–hole pairs. This separation can be obtained by other means than applying external bias. For example, built-in bias can be obtained by adequate doping. Also, step QWs and type-I–type-II structures present spatial separation and should exhibit enhanced photon–photon interactions.

Figure 3 shows the shift in excitonic energy induced by screening by an exciton population $N_{\rm X}$ of 10^8 cm^{-2} as a function of applied electric field and for different QW widths. The shift was obtained by solving the one-dimensional Schrödinger equation self-consistently for a uniform electron–hole population in a biased GaAs–AlAs QW. As expected, the screening effect is larger in wider QWs.

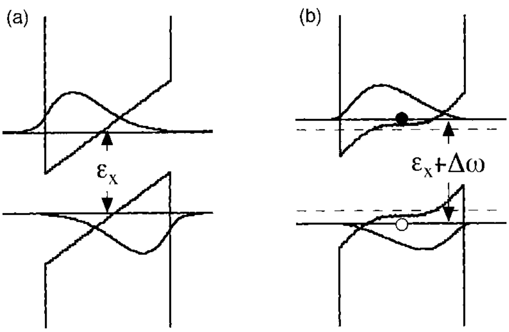

Fig. 2. Effect of biasing with finite population on excitonic energy. a) Excitonic energy in an empty biased quantum well. b) Change of excitonic energy when applied electric field is screened by excitons

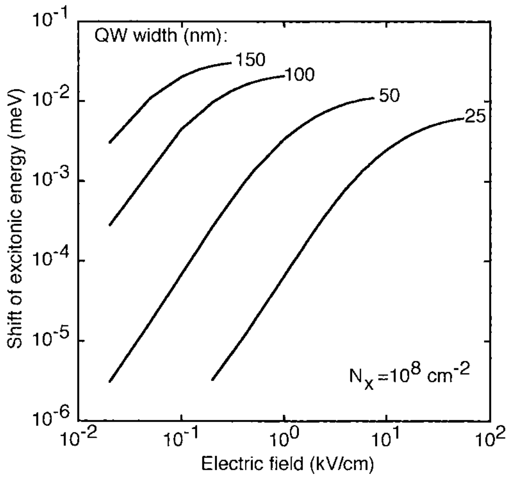

Fig. 3. Screening-induced excitonic shift for an excitonic population of $N_X = 10^8$ cm^{-2} as a function of applied electric field and for several QW widths

Figure 4 shows the optical energy density penetrating the cavity, required to shift the polariton energies by their linewidths, as a function of electric field and for several QW widths. The Rabi splitting at finite electric field was estimated by scaling zero-field values taken from literature by the overlap integral of electron–hole wave functions perpendicular to the QW. We neglected the contribution of the in-plane excitonic wavefunction.

The calculations were performed for a cavity linewidth of $\Gamma_c = 0.1$ meV, which corresponds to a photon lifetime of $\tau_c = 7$ ps. Solid lines are for the upper polariton branch, and dashed lines for the lower one. Each curve is traced for electric fields F satisfying the condition $\Omega_{cx}(F) > 2\Gamma_c$. When F is larger than that, the cavity leaves the strong coupling regime and switching is suppressed. In Fig. 4, the shadowed region corresponds to a single photon penetrating a microcavity pillar of 0.3 μm diameter. In this region, the microcavity could theoretically be switched between a transparent and a reflective mode by a single photon. This region is reached in both polariton branches with a 100 nm thick QW and an applied field of 0.5 kV cm^{-1}. We note that in narrow microcavity pillars, the lateral confinement of the light field should also be taken into account, and is expected to yield a further increase of the screening effect.

Concerning the Rabi splitting Ω_{cx}, as long as we have $\gamma \geq 4$, its value only weakly affects the shift of the lower polariton. For the upper polariton branch, a small Ω_{cx} is advantageous for larger nonlinearity. On the other hand, Ω_{cx} should be larger than $2\Gamma_c$ ($\gamma > 2$) so that the two polaritons are decoupled. Practically, the upper polariton requires a

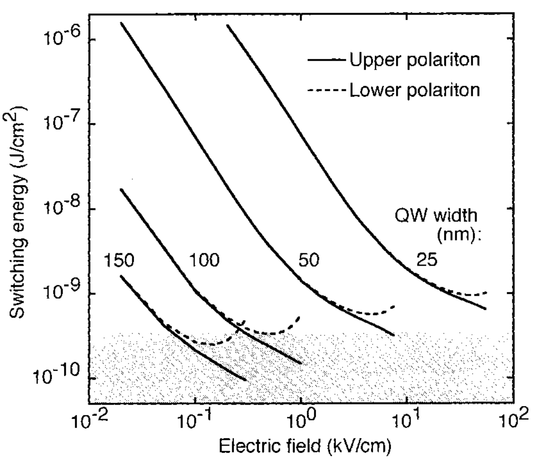

Fig. 4. Light pulse energy penetrating the cavity, necessary to switch it from a transparent to a reflective mode. The hatched region shows the single-photon switching limit for a microcavity pillar of 0.3 μm diameter

smaller excitonic shift than the lower polariton ($\sigma_+ < \sigma_-$), in order to be detuned from the incident light. However, upper polariton branch suffers from scattering and presents typically a larger linewidth than the lower polariton. For lossless operation, the lower polariton line should be used.

In order to minimize the size of the switching intensity, we want a small Γ_c and small diameter microcavity pillar. It is however a technological challenge to realize a micropillar that presents a small diameter and a high Q-factor simultaneously.

Applications of this switching process are numerous. For example, a wavelength converter can be realized with the input light tuned on the lower polariton energy. A cw light resonant with the cavity photon energy should reproduce the temporal dependence of the input light at the exit of the device, as the polariton energy is switched in and out of resonance. In the same configuration, an all-optical on/off switch can be realized with the control light tuned to the polariton energy, and the signal light resonant with the cavity line. Another application is a saturable mirror. A light incident on the cavity line will be reflected as long as the polariton is out of resonance. The light will couple weakly to the polariton through the tail of its lineshape. When the power of the incident light is large, it will shift the polariton line toward the cavity line and the cavity will become transparent.

In the single-photon blockade limit, strong photon anti-bunching is expected. Also, by driving the cavity with a 100 fs pulsed laser, we can realize a single-photon turnstile device. The highly non-classical light that exits a photon turnstile has an intensity noise well under the classical shot noise limit and is of particular interest for optical communications.

In summary, we discussed the optical nonlinearity of electrically biased exciton polariton microcavities. We found that improvements of several orders of magnitude can be obtained over their unbiased counterpart, which allows to approach the limit of single-photon blockade. More detailed calculation, including the full excitonic wavefunction and the effect of lateral confinement of polaritons in microcavity pillars should be carried out to determine if this limit could actually be reached experimentally.

References

[1] H. Schmidt and A. Imamoglu, Opt. Lett. **21**, 1936 (1996).
[2] A. Imamoglu et al., Phys. Rev. Lett. **79**, 1467 (1997).
[3] D.S. Chemla, D.A.B. Miller, and S. Schmitt-Rink, Phys. Rev. Lett. **59**, 1018 (1987).
[4] M. Yamanishi, Phys. Rev. Lett. **59**, 1014 (1987).
[5] A. Shimizu, Phys. Rev. Lett. **61**, 613 (1988).
[6] H. Kuwatsuka and H. Ishikawa, Phys. Rev. B **50**, 5323 (1994).
[7] E. Burstein and C. Weisbuch (Eds.), Confined Electrons and Photons, NATO ASI ser. B, Vol. 340, Plenum Press, New York 1995.
[8] C. Weisbuch et al., Phys. Rev. Lett. **69**, 3314 (1992).
[9] E. Goobar, R. J. Ram, J. Ko, G. Bork, M. Oestreich, and A. Imamoglu, Appl. Phys. Lett. **69**, 3465 (1996).
[10] Y. Kadoya et al., Appl. Phys. Lett. **68**, 281 (1996).
[11] T.A. Fisher et al., Phys. Rev. B **51**, 2600 (1995).