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Strong coupling in a quantum dot micropillar system under electrical current injection

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Integrating $In_{0.3}Ga_{0.7}As$ quantum dots (QDs) featuring a high oscillator strength into a high quality electrically contacted micropillar cavity enabled us to realize strong coupling under electrical carrier injection. In the micropillar cavity with a quality factor of 10 000 and a diameter of 1.9 μm, a vacuum Rabi splitting of 108 μeV was observed when an electrically excited QD exciton was tuned through resonance with the fundamental cavity mode by varying the temperature. © *2010 American Institute of Physics*. [doi:10.1063/1.3442912]

Since the initial demonstrations of strong coupling in optically pumped semiconductor quantum dot (QD) microcavity systems,[1–3] there have been tremendous efforts to explore and exploit the properties of such nanosystems and microsystems (e.g., Refs. 4–9). This intense interest originates from a number of possible applications of coherent light matter interaction in quantum information science. For instance, a strongly coupled quantum dot microcavity system can act as a quantum mechanical interface to couple a localized qubit to a propagating flying qubit which represents a fundamental building block for the realization of future quantum communication systems.[10] In this respect electrically driven solid state devices operating in the strong coupling regime are of upmost importance since they pave the way to practical and chip-based quantum technology. Nevertheless, electrically driven, coherent light-matter interfaces have not been achieved up till now which can be explained by the stringent requirements on the involved semiconductor technology in order to overcome the threshold for strong coupling.[11] While it is very challenging to reach the strong coupling regime in optically pumped systems, it is even more demanding to demonstrate it in electrically driven counterparts since this requires a precise contacting and suitable doping of these delicate objects. Some progress in this field has been achieved recently when electrically contacted QD microcavities have been used to demonstrate the strong coupling regime under optical excitation by utilizing the quantum confined Stark effect.[12,13]

In this paper, we report on a significant milestone in the field of solid-state cavity quantum electrodynamics (cQED). We have fabricated electrically contacted high-Q micropillar cavities with large oscillator strength 30% InGaAs QDs in the active cavity layer, which are suitable to enter the strong coupling regime under electrical current injection. The strong coupling regime was realized at cryogenic temperature for a micropillar cavity with a diameter of 1.9 μm at an injection current of 260 nA. The underlying coherent exchange of energy between light and matter is reflected in a vacuum Rabi splitting of 108 μeV. Our results go far beyond the state-of-the-art of electrically contacted small mode volume microcavities and represent an important step toward practical quantum photonic devices. In particular, the generation of single photons within the regime of strong coupling enables diverse capabilities, including the reversible transfer of quantum states between two-level quantum emitters and photons, thus serving as a practical building block for the realization of solid-state based quantum networks.[14–16]

Enormous technological efforts were required to achieve the strong coupling regime under optical pumping. In the case of micropillar cavities, not only the quality of the microcavity itself is important but also the QD properties need to be optimized.[1] In fact, the realization of strong coupling under electrical pumping is even more demanding since it further requires doped cavity structures and precisely aligned contacts to locally inject charge carriers into the active layer. While electrical contacting has also been achieved in photonic crystal based microcavities, they suffer from inefficient carrier injection into the QDs that interact with the cavity mode—a drawback that can be circumvented by a central post at the cost of a reduced Q-factor.[17] Micropillar cavities, on the other hand, are very suitable for current injection and due to the recently developed peripheral current injection scheme, in combination with an optimized doping profile, we now introduce an important breakthrough regime of strong coupling under electrical injection.

The micropillar cavities under study are based on a planar high quality doped QD-microcavity structure, grown by molecular beam epitaxy. The planar sample consists of 27 (23) doped GaAs/AlAs mirror pairs in the bottom (top) distributed Bragg-reflector (DBR). As the active material, a layer of low density ($\approx 5\times10^{9}$ cm^{-2}) InGaAs QDs was integrated into the center of the undoped one-λ thick cavity sandwiched between the upper and lower DBR. In order to achieve an efficient current injection and simultaneously keeping detrimental influences on the Q-factor at a minimum an optimized doping profile was developed. A rather high doping concentration of $p=2\times10^{19}$ cm^{-3} was applied in the top two mirror pairs of the p-doped upper DBR where the current is injected while the doping concentration was gradually reduced from $n,p=3\times10^{18}$ cm^{-3} toward $n,p=1\times10^{18}$ cm^{-3} near the intrinsic cavity. In addition, δ-doped layers ($n,p=1\times10^{12}$ cm^{-2}) were embedded at the nodes of

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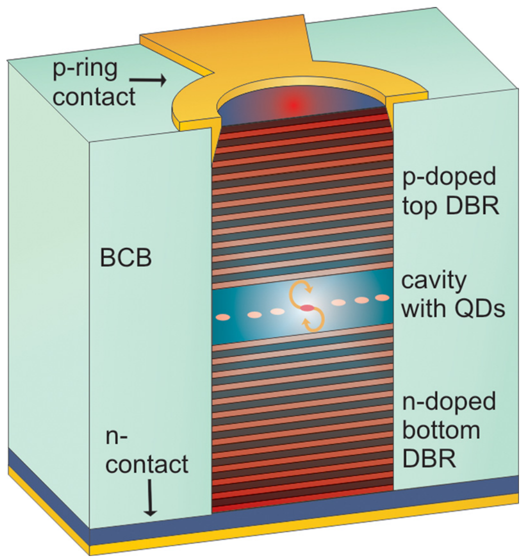

FIG. 1. (Color online) Schematic of the electrically contacted micropillar cavity. The micropillar is embedded into BCB which mechanically supports the upper ring shaped contact. Electrical excitation of the QDs in the active layer is realized via carrier injection through the p (n) doped upper (lower) DBR.

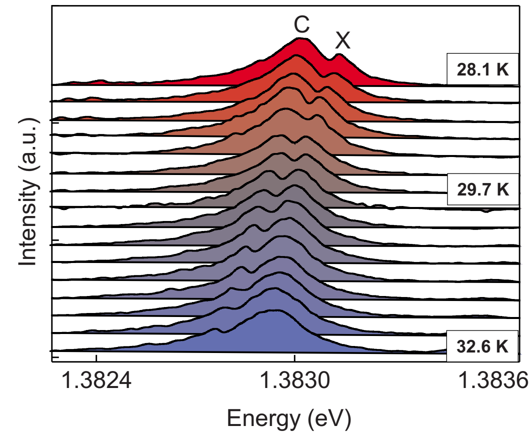

FIG. 2. (Color online) Demonstration of the strong coupling regime under electrical pumping. Series of μ-EL spectra for temperatures between 28.1 and 32.6 K obtained from a micropillar cavity with 1.9 μm in diameter. The avoided crossing of the cavity mode C and the QD exciton line X are a clear signature of the strong coupling regime. At resonance (29.7 K) a vacuum Rabi-splitting of 108 μeV is observed.

the electrical field, i.e., at the GaAs/AlAs interfaces in the DBRs, to decrease the resistivity of the DBRs. The nanoprocessing of the electrically contacted devices includes the definition of micropillars with diameters down to 1 μm via high resolution electron beam lithography and a subsequent reactive ion etching step. Afterwards, the sample is planarized by the use of benzocyclobutene (BCB) which acts as an isolator. It also mechanically supports the ring shaped upper contact which is realized by a second electron beam lithography step. For details on the fabrication process we refer to Ref. 18. In contrast to that work,[18] in which standard $In_{0.6}Ga_{0.4}As$ QDs allowed for the observation of pronounced cQED effects in the weak coupling regime, we have chosen larger $In_{0.3}Ga_{0.7}As$ QDs with enhanced oscillator strength in the present work to facilitate the demonstration of strong coupling.[1] A schematic of the targeted device is shown in Fig. 1. All experiments were carried out with a high resolution microelectroluminescence (μ-EL) setup. The signal is collected with a microscope objective with a numerical aperture of 0.42 and then dispersed with a 1 m double monochromator equipped with a charge coupled device camera resulting in an overall resolution of 16 μeV. The sample was kept at cryogenic temperatures (10–40 K) inside a helium-flow cryostat with electrical throughputs and precise temperature control.

Figure 2 shows a series of μ-EL spectra taken at different temperatures. At 28.1 K the QD exciton X is located at 1.38315 eV and the fundamental cavity mode C is centered at 1.38302 eV. A low excitation current of 260 nA, i.e., well below the saturation of the QD exciton, was chosen for this series to ensure that nonlinearities such as second photon effects or lasing can be neglected for this study. Due to a slight asymmetry of the micropillar, the fundamental mode is split into two mode components with a splitting of 200 μeV. This explains the shoulder related to the low component of the fundamental mode which could not be fully suppressed by a linear polarizer. The splitting of the fundamental cavity mode exceeds values of 10–20 μeV observed typically for optically pumped high-Q micropillars in the same diameter range[19] and is attributed to an asymmetry of the ring contact. As the temperature is increased, the exciton line tunes through resonance with the cavity mode and both lines show a distinct anticrossing, the clear signature of a system in the strong coupling regime in the framework of cQED. The avoided crossing is also evident from a Lorentzian line-shape analysis of the two lines when the two peak positions are plotted versus temperature [Fig. 3(a)]. At resonance, a vacuum Rabi-splitting (ΔE_{VRS}) of 108 μeV is observed. Figure 3(b) shows the evolution of the linewidth of both the exciton line and the cavity mode with temperature. Starting from a value of 70 μeV for X and 139 μeV for C, the values become equal when the system is tuned into resonance because two identical eigenstates are formed and then

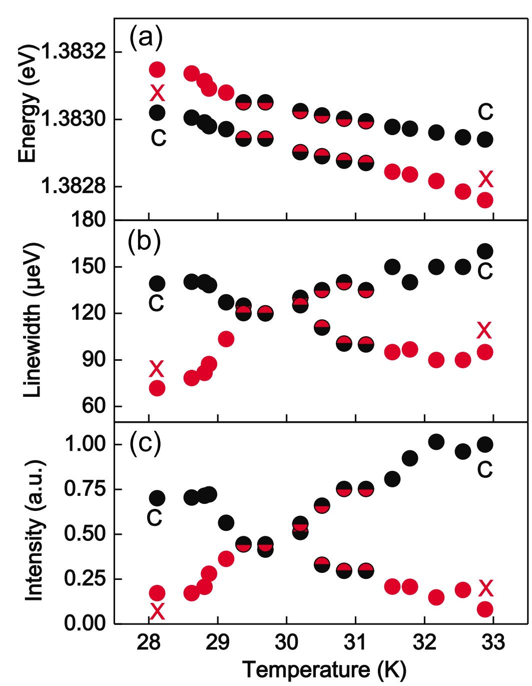

FIG. 3. (Color online) Analysis of the EL spectra. Energy dispersion (a) of the cavity C and the exciton X as well as the evolution of the linewidth (b) and the integrated intensity (c) of the two emission lines vs temperature.

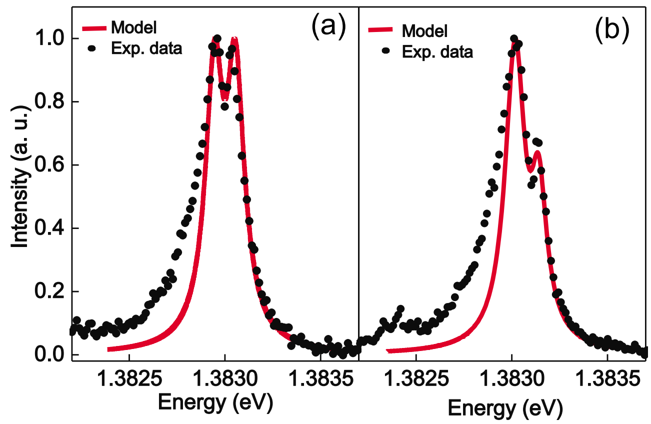

FIG. 4. (Color online) Comparison of computed spectra and the experimental data. (a) for zero detuning at 29.7 K and (b) for positive detuning at 28.1 K. The deviation from the model originates form the split cavity mode which broadens the spectrum at the low energy side.

they separate again as the system is tuned away from resonance. The formation of two equal eigenstates is also manifest in the temperature dependence of the integrated intensities of the two lines. As the system approaches resonance the intensity of X and C become similar which is shown in Fig. 3(c).

In order to obtain deeper insight into the fundamental light matter interactions, and to extract the physical parameters of the system, we employ a recently developed theory from Yao *et al.*[20] to model our experimental spectra. The model is based on a quantum master equation technique that takes into account the incoherent pumping, stimulated emission, pure dephasing of the exciton, and the fermionic nature of the system. Best agreement with our data was obtained for a coupling strength g of 53 μeV, an exciton pump rate $P_X = 0.0021$ g and a cavity pump rate of $P_C = 1.7 P_X$. Figure 4 displays two experimental spectra and the corresponding model data for zero detuning at 29.7 K and positive detuning at 28.1 K which are in good agreement with each other. The deviation of the experimental data from the model in Fig. 4 is mainly attributed to the second cavity mode which broadens the spectrum at the low energy side. While in principle, we could include this second cavity mode as well, its overall effect is not qualitatively important for the present purpose of basic understanding. The usual threshold condition for the occurrence of strong coupling $g > \gamma_C/4 = 35$ μeV is thus clearly fulfilled. From g, an estimate of the oscillator strength $f = (g^2 \epsilon_0 \epsilon_r V m_0 / e^2) \approx 50$ for the QD exciton can be obtained, where ϵ_0 denotes the vacuum permittivity, ϵ_r the relative dielectric constant of GaAs, m_0 the free electron mass, V the effective mode volume, and e the electron charge. This magnitude is typical for these elongated QDs with an In content of 30% (Ref. 1) and crucial for reaching the strong coupling regime in these electrically pumped devices.

In conclusion, we have demonstrated a micropillar-QD light emitting diode operating in the strong coupling regime under electrical injection, displaying a vacuum Rabi-splitting of 108 μeV. Our work shows that these electrically driven micropillar structures are promising devices for future quantum communication relying on the coherent photon-matter interactions. Moreover, it represents an important step toward an electrically pumped single QD laser operating in the strong coupling regime.

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