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Andrei Faraon, Dirk Englund, Ilya Fushman, Jelena Vučković, Nick Stoltz et al.

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## Local quantum dot tuning on photonic crystal chips

Andrei Faraon,<sup>a)</sup> Dirk Englund, Ilya Fushman, and Jelena Vučković  
*E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305*

Nick Stoltz and Pierre Petroff

*Department of Electrical and Computer Engineering, University of California,  
 Santa Barbara, California 93106*

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Quantum networks based on InAs quantum dots embedded in photonic crystal devices rely on quantum dots being in resonance with each other and with the cavities they are embedded in. The authors developed a technique based on temperature tuning to spectrally align different quantum dots located on the same chip. The technique allows for up to 1.8 nm reversible on-chip quantum dot tuning. © 2007 American Institute of Physics. [DOI: 10.1063/1.2742789]

Solid-state approaches to quantum information have generated tremendous interest over the past decade. Recent schemes often employ cavity quantum electrodynamics to manipulate qubits, with many using quantum dots (QDs) coupled to optical cavities. Cavities in photonic crystals (PCs) are particularly attractive due to their small mode volume and high quality factor ( $Q$ ).<sup>1,2</sup> In addition, photonic crystals are ideal for integrating devices into an on-chip network for information processing.<sup>3,4</sup> A major problem facing such proposals, however, is spatial and spectral matching of distinct inhomogeneously broadened quantum dots. Spatial alignment can be achieved either by positioning the PC cavity on an already identified QD<sup>5,6</sup> or by relying on chance. For spectral alignment, there are a few techniques that can be used to modify the emission wavelength of InAs quantum dots: Stark shift,<sup>7</sup> Zeeman shift,<sup>8</sup> temperature tuning,<sup>9</sup> and strain tuning.<sup>10</sup> In this letter, we demonstrate a technique for independent control of QDs, employing structures with high- $Q$  cavities whose temperature is controlled by laser beams. We discuss the thermal and optical designs, device fabrication, and testing. Our *in situ* technique allows extremely precise spectral tuning of InAs quantum dots by up to 1.8 nm and of cavities of up to 0.4 nm (four cavity linewidths). The technique is crucial for spectrally aligning distinct quantum dots on a photonic crystal chip and forms an essential step toward creating on-chip quantum information processing devices.

To achieve independent on-chip tuning, distinct regions containing the quantum dots of interest must be kept at different temperatures. Since GaAs is a good thermal conductor, on-chip local thermal insulation must be provided to achieve significant local heating. For this reason, we fabricated suspended PC structures with minimal thermal contact to the rest of the chip (Fig. 1). The suspended PC structures were fabricated on a quantum dot wafer grown by molecular beam epitaxy on a Si  $n$ -doped GaAs (100) substrate with a 0.1  $\mu\text{m}$  buffer layer. To increase quantum dot collection efficiency, a ten period distributed Bragg reflector (DBR) mirror underneath the QDs is included, consisting of alternating layers of AlAs/GaAs with thicknesses of 80.2/67.6 nm, respectively. A 918 nm sacrificial layer of  $\text{Al}_{0.8}\text{Ga}_{0.2}\text{As}$  is located above the DBR mirror. The active region consists of a

150 nm thick GaAs region with a centered InGaAs/GaAs QD layer. QDs self-assemble during epitaxy operating in the Stranski-Krastanov growth mode. InAs islands are partially covered with GaAs and annealed before completely capping with GaAs. During the annealing step, Ga diffuses into the InAs islands. This procedure blueshifts the QD emission wavelengths toward the spectral region where Si-based detectors are more efficient.

The fabricated structures (12  $\mu\text{m}$  long, 4  $\mu\text{m}$  wide, and 150 nm thick) consist of a PC cavity and a heating pad (Fig. 1). To provide the thermal insulation needed for efficient device heating, the structure was connected to the rest of the chip by only six narrow bridges. The thermal conductivity of narrow ( $\approx 100$  nm), cold (4–10 K) GaAs bridges is reduced by up to four orders of magnitude with respect to the bulk GaAs,<sup>11</sup> thus improving the thermal insulation. We tested two devices with connection bridges of the same length (2  $\mu\text{m}$ ) but different widths:  $w=320$  nm and  $w=800$  nm. The temperature of the device was controlled by using a focused laser beam to heat up the pad next to the photonic crystal cavity. To minimize background photoluminescence in single quantum dot measurements, the heating laser is tuned below the QD absorption frequency. A metal layer (20 nm Cr/15 nm Au) was deposited on the heating pad to increase heat absorption. The thermal conductivity of GaAs beams with cross sections on the order of 100/100 nm and the absorption coefficient of the metal layer are not

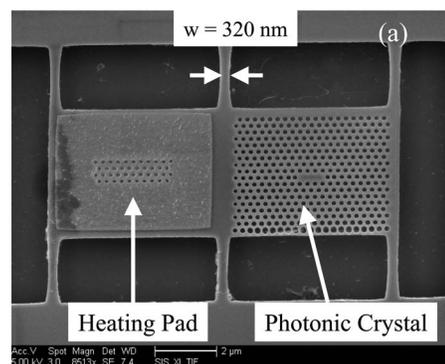


FIG. 1. Scanning electron microscope image of the fabricated structure showing the PC cavity, the heating pad, and the connection bridges. The temperature of the structure was controlled with a laser beam (960 nm) focused on the heating pad.

<sup>a)</sup>Electronic mail: faraon@stanford.edu

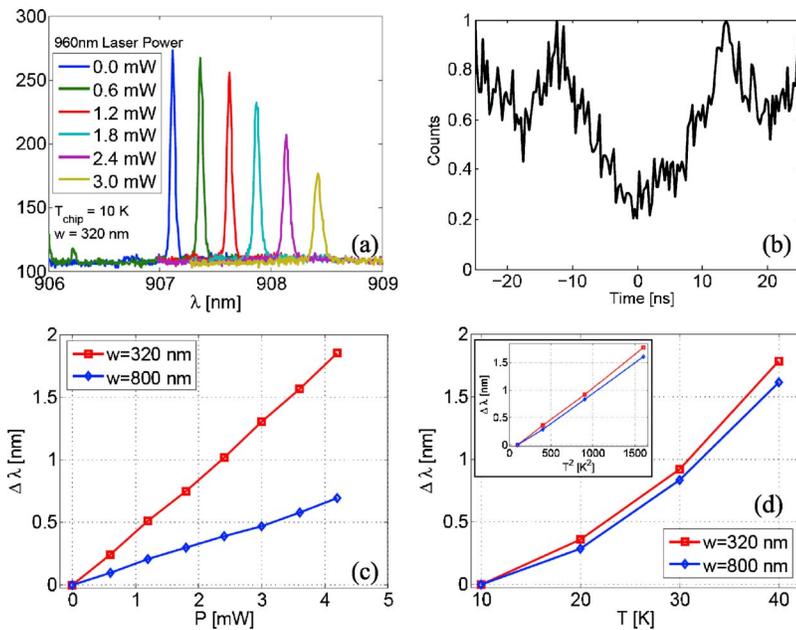


FIG. 2. (Color online) (a) Quantum dot tuning vs heating pump power. The structure is connected to the substrate by bridges measuring 320 nm in width. The quantum dot emission shifts by 1.4 nm while increasing the heating laser power to 3 mW. Only a small fraction of the heating laser power is absorbed in the metal pad. (b) Autocorrelation measurement showing single photon antibunching while the QD was detuned by 0.8 nm using the local tuning technique. (c) Dependence of the QD detuning on the heating laser power. The two data sets correspond to structures with different thermal contacts to the substrate (320 and 800 nm bridges). (d) QD temperature tuning by changing the temperature of the entire chip by heating the cryostat. The inset shows that the detuning is linear in  $T^2$ .

well known. As measured by Fon *et al.*,<sup>11</sup> the thermal conductivity of GaAs beams with dimensions of 100 nm/200 nm/6  $\mu\text{m}$  is about  $3 \times 10^{-2} \text{ W K}^{-1} \text{ cm}^{-1}$  at 10 K, three orders of magnitude lower than the bulk value. Because of the size similarity, we assume that the connection bridges from our device have a similar thermal conductivity. Assuming that  $10^{-2}$  mW of heat is absorbed in the heating pad and considering that the device has the same thermal conductivity as the bridges, we expect the temperature of the membrane to increase by a few tens of kelvins.

The local quantum dot tuning measurements were performed in a continuous flow liquid helium cryostat maintained at 10 K. A Ti:sapphire laser tuned at 855 nm was used to excite the quantum dots, while a 960 nm laser diode acted as the heating laser. Using a pinhole we collected photoluminescence from a quantum dot located inside the photonic crystal slab. By increasing the power of the heating laser, QD emission was observed to redshift [Fig. 2(a)]. The QD linewidth broadens with increasing heating pump power, as expected from experiments where the full sample is heated. We were able to tune the quantum dot by 1.4 nm, while the linewidth broadened from 0.04 to 0.08 nm. The quantum dot could be further shifted by 1.8 nm but the PL intensity dropped rapidly. To show the compatibility of this local tuning technique with single photon measurements and quantum information processing, we proved antibunched single photon emission from an exciton transition using a Hanbury-

Brown-Twiss interferometer while the emission line was shifted by 0.8 nm [Fig. 2(b)]. Antibunching can be measured as long as the thermal energy is not larger than the confining energy of the QD, which in our case corresponds to a detuning of  $\approx 1.4$  nm.

To investigate the thermal properties of the fabricated devices, we compared the shift of quantum dots located on structures with different bridge widths,  $w=320$  nm and  $w=800$  nm. The thermal conductance of the bridges is proportional to their width  $w$ . Under the same pump conditions, the temperature of the structure is inversely proportional to  $w$ , so we would expect the QD to shift 2.5 (i.e., 800/320) times further for the structure with thinner bridges. The QD shift observed on the two structures is plotted in Fig. 2(c). For the same pump power, the QD shifts 2.65 times further for  $w=320$  nm than for  $w=800$  nm, in good agreement with the expected result.

The temperature dependence of the QD shift was determined by changing the temperature of the entire chip by heating the cryostat. The results are plotted in a Fig. 2(d) and indicate that a shift of 1.8 nm corresponds to a temperature of 40 K. This implies that during the local temperature tuning experiment the structure was also heated up to 40 K. The QD shift shows a quadratic dependence with temperature [Fig. 2(d) inset], which is expected since the band gaps of GaAs/InAs have a quadratic temperature dependence in this temperature interval.<sup>12</sup> Our experimental data show a linear dependence of the QD shift with the heating laser power [Fig. 2(c)], which implies a linear relation between the power of the heating laser and  $T^2$ . The local temperature gradient also induces strain which can be responsible for shifting the QD emission. To release the strain in the suspended membrane, we used a focused laser beam to cut some of the connection bridges next to the QD. After the strain release we still observed the same shift of the QD with the heating power which indicates that the shift is mainly due to temperature.

Not only the QDs but also the PC cavities shift their resonant frequency with temperature. The local heating technique was used to shift a PC cavity located on the  $w=320$  nm structure. Using the same heating power as for

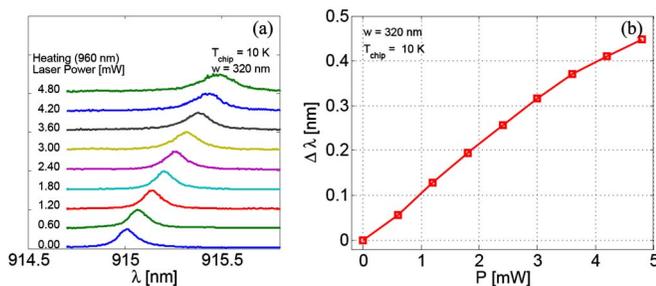


FIG. 3. (Color online) (a) Detuning of the PC cavity resonance with increasing temperature due to local heating. (b) Dependence of the PC cavity resonance wavelength on the local heating power.

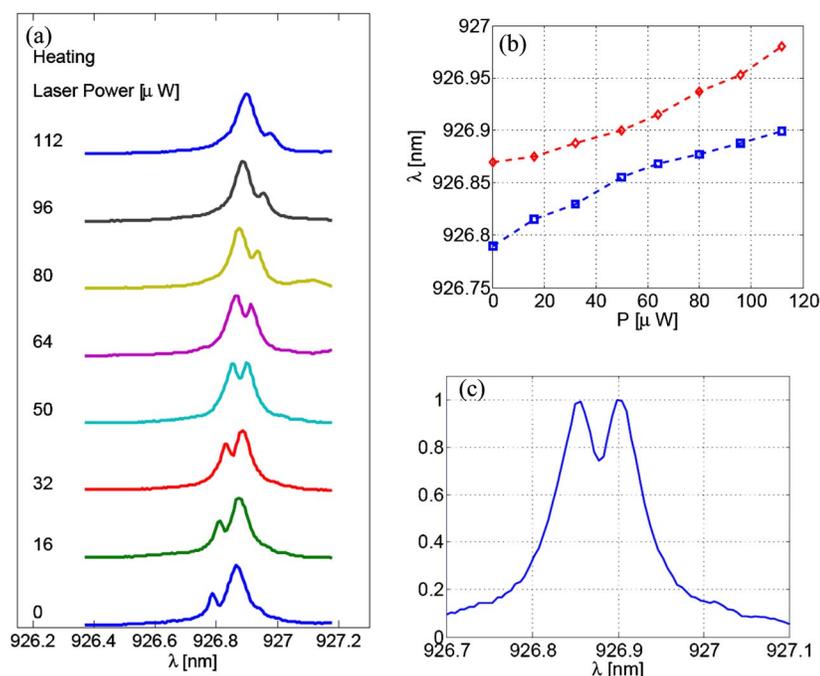


FIG. 4. (Color online) (a) Spectra showing the tuning of a single QD into resonance with the cavity mode using the local heating technique. (b) Anticrossing between the polariton lines of the strongly coupled PC cavity-QD system. (c) Spectrum showing the 0.05 nm splitting of the polaritons. Note that the data in this figure were taken on a different chip than the data in Figs. 1–3.

the QD tuning, we observed the cavity resonance redshift by up to 0.48 nm [Figs. 3(a) and 3(b)], about three times less than the QD shift. The quality factor of the cavity dropped from 7600 to 4900. Beside temperature tuning, photonic crystal cavities can be tuned using chemical digital etching<sup>13</sup> or by deposition of molecular layers on top of the PC membrane.<sup>14</sup>

A problem of immediate concern in cavity-QED experiments is spectral tuning of the QD onto the cavity resonance. We used our technique to locally tune a QD into resonance with a PC cavity mode with  $Q=10\,000$ , as shown in Fig. 4(a). We observe splitting and anticrossing of the polariton states, the signature of strong coupling regime, as the QD is tuned into resonance with the cavity [Figs. 4(a) and 4(b)]. A polariton splitting of 0.05 nm is observed [Fig. 4(c)].

The proof of concept experiment presented in our letter shows the local tuning of PC cavities and QDs that are not integrated into a PC circuit. However, it is only a matter of design to build PC circuits with integrated local heaters that could enable the independent tuning of different components of the same circuit. Moreover, this technique can be slightly modified by changing the heating method from optical to electrical by connecting electrical wires to the metal pads.

Our local temperature tuning technique is completely reversible and does not affect the structure of the PC cavities or the QDs. Another tuning technique that relies on locally heating microcavities to permanently change the structure of the resonator and the QDs has been reported by Rastelli *et al.*<sup>15</sup>

In conclusion, we have demonstrated a technique for *in situ* tuning of QDs by up to 1.4 nm without significant deterioration in the QD emission. This method works locally and reversibly, making it a useful tool for a range of solid-state studies, from local thermometry to quantum information science. In particular, the method is compatible with photonic crystal structures and forms a crucial step toward building an on-chip quantum network involving resonant QDs.

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