HAL
open science

Static strain tuning of quantum dots embedded in a photonic wire

D. Tumanov, N. Vaish, H.-A. Nguyen, Y. Curé, J.-M Gérard, J. Claudon, F. Donatini, J.-P. Poizat

To cite this version:

D. Tumanov, N. Vaish, H.-A. Nguyen, Y. Curé, J.-M Gérard, et al.. Static strain tuning of quantum dots embedded in a photonic wire. Applied Physics Letters, 2018, 112 (12), pp.123102. 10.1063/1.5025313 . hal-01740323

HAL Id: hal-01740323

https://hal.science/hal-01740323

Submitted on 21 Mar 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Static strain tuning of quantum dots embedded in a photonic wire

D. Tumanov[1,2], N. Vaish[1,2], H.A. Nguyen[1,2], Y. Curé[3], J.-M. Gérard[3], J. Claudon[3], F. Donatini[1], and J.-Ph. Poizat[1,2,*]

[1] *Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut NEEL, F-38000 Grenoble, France*

[2] *Univ. Grenoble Alpes, CNRS, Grenoble INP, Institut NEEL, "Nanophysique et semiconducteurs" group, 38000 Grenoble, France*

[3] *Univ. Grenoble Alpes, CEA, INAC, PHELIQS, "Nanophysique et semiconducteurs" group, F-38000 Grenoble, France*

* *Corresponding author : jean-philippe.poizat@neel.cnrs.fr*

(Dated: March 6, 2018)

We use strain to statically tune the semiconductor band gap of individual InAs quantum dots (QDs) embedded in a GaAs photonic wire featuring very efficient single photon collection efficiency. Thanks to the geometry of the structure, we are able to shift the QD excitonic transition by more than 20 meV by using nano-manipulators to apply the stress. Moreover, owing to the strong transverse strain gradient generated in the structure, we can relatively tune two QDs located in the wire waveguide and bring them in resonance, opening the way to the observation of collective effects such as superradiance.

Epitaxial semiconductor quantum dots (QDs) embedded in nanophotonic structures are very efficient single photon sources (see [1–3] and [4] for a review). However their use in quantum information protocols involving more than two sources has been hindered by the dispersion in energy of different QDs. This dispersion is due to their intrinsically random self-assembly fabrication process [5], so that two QDs are never alike. QD energy tuning can be achieved using temperature [6], electric field [7–9], or material strain [10–14]. Temperature tuning is limited to fine tuning. Electrical control is also suitable for fine tuning and can reach shifts up to 25 meV [9]. Strain tuning can be used for fine tuning [10, 11, 13, 14] (see [15] for a review) and, as temperature and electrical tuning, can enable two-photon interferences with two different QDs [6, 8, 11]. Interestingly, it offers the additional possibility to generate ultra-large shifts up to 500 meV as demonstrated by Wu *et al* [12] using a diamond anvil cell. Such cells are however limited to bulk systems and are unsuitable to QDs embedded in photonic environments. Fine strain tuning is usually realized by bonding the bulk QD structure on piezoelectric actuators [10–12, 14, 15], imposing limitations on the structure geometry. Remarkably, Kremer *et al* [13] managed to achieve up to 1.2 meV strain tuning for a QD embedded in a nanowire antenna using this bonding technique.

In this paper, we demonstrate large static strain tuning (up to 25 meV) of QDs embedded in a photonic waveguide allowing efficient light extraction [1]. Four years ago, these photonic structures were used by some of us as mechanical oscillator to demonstrate strain-mediated optomechanical coupling [16] (see also [17]). In the present work, the strain is produced *statically* using a nanomanipulator enabling the realization of bright and broadly tunable quantum light sources. In addition, since the generated strain field features a very large gradient across the wire diameter [18], our method allows us to bring in mutual resonance two QDs contained in a waveguide and opens interesting perspective for the observation of collective spontaneous emission effects such as superradiance [19].

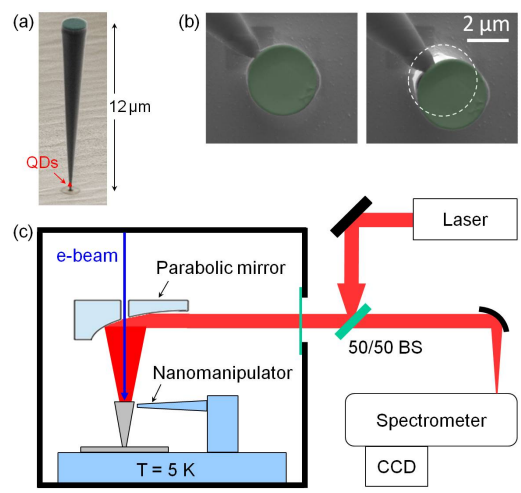

Figure 1. (a) Tilted scanning electron microscope (SEM) view of the GaAs photonic tapered waveguide from sample S1. The QDs (red triangle) are located 110 nm above the basis. The top facet is covered by an anti-reflection coating (false, green color). (b) SEM top view showing the top facet of a waveguide and the tip of the nanomanipulator. Between the left and right image, the tip has moved and pushed the top of the waveguide by 1 μm. (c) Experimental set-up based on a modified cathodoluminescence set-up: a laser excites the QDs photoluminescence and we use SEM imaging to monitor the position of the tip with respect to the top facet.

Our system is based on the GaAs tapered waveguide shown in Fig.1(a) and described in detail in [1]. The waveguide from sample S1 that we have used for the first experiment (see Fig.2) is 12 μm high. The top diameter has been measured to 1.69 μm, and the bottom diameter to 350 nm. Self-assembled InAs QDs (around 10) are located at random lateral positions in a plane at

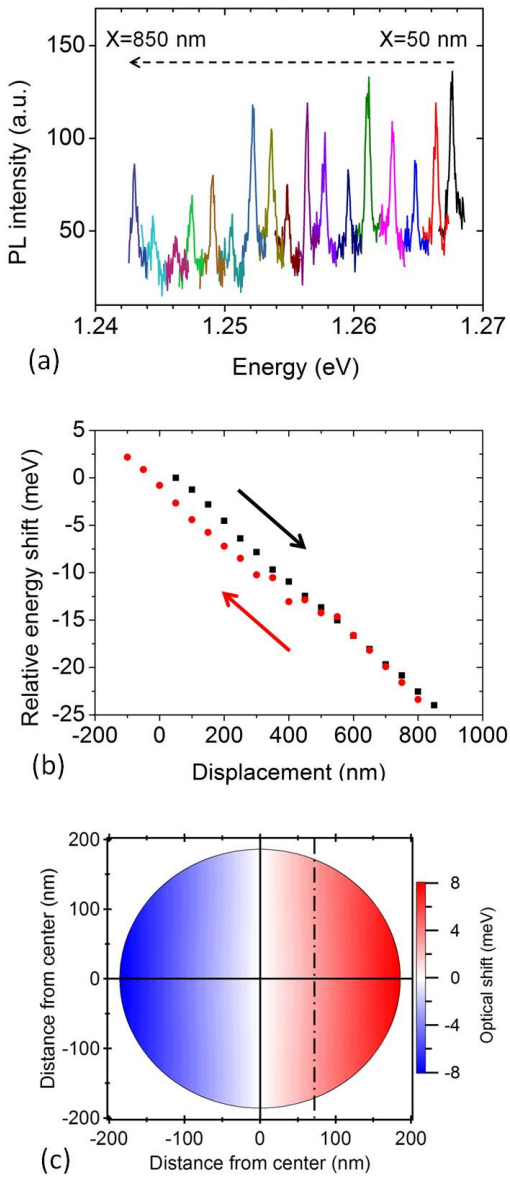

Figure 2. Energy shift as a function of the displacement X of nanomanipulator tip obtained from a QD embedded in the waveguide from sample S1. (a) Photoluminescence spectrum of a single QD for varying nanomanipulator positions X. The right most peak corresponds to $X = 50$ nm and the left most to $X = 850$ nm. The increment between two consecutive peaks is 50 nm. (b) Relative energy shift as a function of the displacement of nanomanipulator tip corresponding to the data shown in (a). The black square are for increasing displacement, and the red circles correspond to the way back. The slight kink on the way back is attributed to the slippage of the tip. (c) Map of the calculated energy shift caused by the strain gradient across the QD plane for a top facet displacement of 100 nm along the horizontal axis. The slope of 31 μeV/nm of (b) corresponds to a QD located on the dash-dotted line at 70 nm from the zero strain line.

110 nm above the basis of the structure, which stands on a planar gold mirror to redirect all the light to the top. This photonic structure has been designed for efficient collection of the single photons emitted by the QDs [1] as well as for the efficient optical addressing of the QD [20, 21]. This inverted cone geometry also features a very strong optomechanical coupling: the mechanical displacement of the top facet induces a large strain in the lower part of the structure affecting the energy of the fundamental excitonic QD transition [16]. In [16], the top facet motion was caused by the mechanical oscillation of the fundamental flexural mode. In the present work, the displacement is induced statically by a tungsten tip mounted on a nanomanipulator pushing the structure top (see Fig.1(b),(c)). We then excite the QD photoluminescence (PL) to determine the effect of this static stress on the excitonic line energy.

To perform these experiments, we have adapted a cathodoluminescence set-up to benefit from a scanning electron microscope (SEM) operating at cryogenic temperature and equipped with a window for optical access (see Fig.1(c)). This allowed us to use SEM imaging to monitor the relative position of the nanomanipulator tip with respect to the waveguide (see Fig.1(b)) while exploiting the optical access to carry out PL experiments at a temperature $T = 5$ K. The PL is excited by a continuous laser tuned to $\lambda = 830$ nm, below the energy band gap of GaAs. The laser beam is focused on the device with an aluminum parabolic mirror and generates charge carriers in the QDs wetting layer. The QDs PL is collected with the same mirror, and is sent to a grating spectrometer equipped with a CCD camera for spectral analysis. The alignment of the optical part of the setup is relatively delicate. The device is first aligned on the focal point of the parabola in cathodoluminescence mode (luminescence excitation by the e-beam). The laser beam is then shaped and aligned to be mode-matched with the cathodoluminescence beam. In order to insure a sufficient signal on noise ratio in our in-situ SEM PL experiment, the input slit of the spectrometer has to be opened, limiting the spectral resolution to about 300 μeV as can be noticed in the experimental spectra below. With a high-resolution PL set-up, the line-widths of QDs embedded in these waveguides are typically on the order of a few tens of μeV [22], and can be as low as a few μeV in the case of strictly resonant excitation [20, 21].

The closed-loop nanomanipulator features a stick and slip coarse mode that we use for the approach, and a fine mode using an analog piezoelectric scanner with a position noise of about 1 nm and an amplitude of 1 μm that we use for pushing on the structure. The nanomanipulator tip is electrically grounded and thermalized using wires connected to the cold plate at a temperature $T = 5$ K. The SEM depth of focus allows us to control the tip height within a few hundreds of nm accuracy so that the tip contact point is a few hundreds of nanometers below the top facet. Note that the QDs lines are often redistributed when the tip enters into contact with

the waveguide, likely caused by the rearrangement of the electrostatic and thermal environment. As discussed in the end of the paper, the position noise of the tip can affect the QD optical line-width.

Once the tip is in contact with the waveguide, the PL spectrum is recorded as a function of the position of the nanomanipulator tip as given by the calibrated closed loop analog piezoelectric driver as shown in Fig.2(a),(b). Depending on its location within the waveguide, each QD experiences a different spectral strain-induced shift, owing to the strain gradient existing in the QD plane as shown in Fig.2(c). For QDs located far from the zero stress line, the spectral shift can be as large as 25 meV for a top facet displacement of 0.8 μm as shown in Fig.2(b). Note that we are here only limited by the scanning range of the nanomanipulator and that we could probably push further before the waveguide breaks.

For quantitative analysis, we used a finite element commercial software to compute the stress tensor in the QD plane. The main stress component, σ_{zz}, is oriented along the vertical z direction. It depends linearly on the top facet displacement. For this locally uniaxial stress configuration, the energy shift ΔE of a heavy-hole exciton trapped in the QD is dominated by the shift of the QD bandgap [23, 24]. We assume in the following that the QD is composed of an $In_{0.5}Ga_{0.5}As$ alloy, characterized by the deformation potentials $a = -7.2$ eV and $b = -1.9$ eV. ΔE is then given by:

$$\Delta E = \sigma_{zz} \left[a(S_{11} + 2S_{12}) + b(S_{11} - S_{12}) \right], \qquad (1)$$

with $S_{11} = 1.14 \times 10^{-5}$ MPa^{-1}, and $S_{12} = -0.35 \times 10^{-5}$ MPa^{-1} the compliance parameters of GaAs (the wire material governs the mechanical response). From this simple model, we infer that the QD featuring a shift $\Delta E = 25$ meV for a top facet displacement of 0.8 μm undergoes a $\sigma_{zz} = 420$ MPa stress and is located at a distance of 70 nm from the zero strain line (see Fig.2(c)).

Since two QDs located on either sides of the zero-stress line undergo energy shifts of different signs, our technique can be exploited to easily bring two QDs in resonance. We demonstrate this possibility with a different waveguide sample, named S2. It features a slightly different geometry (see [16] for a complete description). As shown in Fig.3, two QDs whose emission energies initially differ by 2 meV are brought in resonance for a displacement of the top facet of 70 nm. We have also been able to use two independent nanomanipulator tips pushing along two different arbitrary directions. This allowed us to choose and tune the direction of the applied stress gradient. The additional degree of freedom brought by a second nanomanipulator would make it possible to bring three QDs on resonance in the same waveguide.

Relative tuning of two QDs has already been obtained using strain gradient in different structures [25, 26]. In our work, the two QDs brought in resonance are embedded in a one-dimensional single mode waveguide, which opens up interesting perspective to investigate collective effects in light-matter coupling [19]. If g is the coupling of a two level system to a single optical mode, the constructive coherent coupling of N such two-level systems to a single optical mode gives rise to an enhanced light-matter coupling of $g\sqrt{N}$ of this collective state leading to a spontaneous emission rate accelerated by a factor N [19]. This property can be beneficial for implementing quantum memories as mentioned in the landmark paper by Duan *et al* [27].

We close the paper with practical considerations regarding the observation of such collective effects. As previously mentioned, the position noise of the tip translates into a spectral broadening of the QD emission lines, which is obviously detrimental for coherent effects. In our proof-of-principle experiment, the tip position noise is 1 nm. For the QD investigated in Fig.2 (70 nm away from the neutral strain line), this leads to a spectral noise of 30 μeV. State-of-the-art piezo scanners feature a position noise below 0.1 nm, allowing to gain one order of magnitude on the QD linewidth. In addition, considering QDs closer to the neutral line ($\sim$ 10 nm) leads to spectral fluctuations smaller than the natural QD linewidth (0.5 μeV for a 1 ns excitonic lifetime). In the same time, the tuning range remains acceptable ($\pm$4 meV for a 1 μm top facet displacement). From an optical point of view, these slightly off-axis QDs remains very well coupled to the fundamental guided mode. For a wire diameter below 300 nm, the spontaneous emission coupling factor is larger than 90% for QDs 10 nm away from the wire axis [28].

In summary, we have achieved a large static strain tuning of up to 25 meV for a semi-conductor QD embedded in an optically engineered environment using an original set-up based on photonic wires stressed by nanomanipulators. Thanks to the strong gradient generated within the structure, we have demonstrated differential tuning of two QDs coupled to the same single mode waveguide. This opens interesting perspectives for the demonstration of collective effects such as superradiance.

ACKNOWLEDGMENTS

Sample fabrication was carried out in the "Upstream Nanofabrication Facility" (PTA) and CEA LETI MINATEC/DOPT clean rooms. We thank Nitin S. Malik for his contribution to the sample fabrication. D.T. was supported by a PhD scholarship from the Rhône-Alpes Region, N.V by a PhD scholarship from Fondation Nanosciences, and H.A.N. by a PhD scholarship from Vietnamese government. This work was supported by ANR project QDOT (ANR-16-CE09-0010-01) and by the CEA DRF-Impulsion project SOUPAPE.

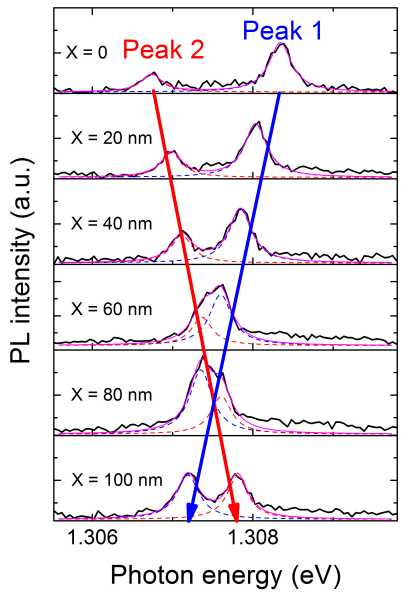

Figure 3. PL spectra for different nanomanipulator positions ranging from $X = 0$ nm to $X = 100$ nm, measured on sample S2. The two peaks correspond to two QDs that are located on either side of the neutral strain line, and therefore undergo energy shifts of different signs. The two QDs are brought in resonance for $X \simeq 70$ nm.

[1] M. Munsch, N. S. Malik, E. Dupuy, A. Delga, J. Bleuse, J. M. Gérard, J. Claudon, N. Gregersen, and J. Mørk, Phys. Rev. Lett. **110**, 177402 (2013).

[2] X. Ding, Y. He, Z.-C. Duan, N. Gregersen, M.-C. Chen, S. Unsleber, S. Maier, C. Schneider, M. Kamp, S. Höfling, C.-Y. Lu, and J.-W. Pan, Phys. Rev. Lett. **116**, 020401 (2016).

[3] N. Somaschi, V. Giesz, L. De Santis, J.C. Loredo, M.P. Almeida, G. Hornecker, S. L. Portalupi, T. Grange, C. Antón, J. Demory, C. Gómez, I. Sagnes, N.D. Lanzillotti-Kimura, A. Lemaître, A. Auffèves, A. G. White, L. Lanco and P. Senellart, Nat. Photon. **10**, 340 (2016).

[4] P. Senellart, G. Solomon, and A. White, Nat. Nanotech. **12**, 1026 (2017)

[5] J.-Y. Marzin, J.-M. Gérard, A. Izraël, D. Barrier, and G. Bastard, Phys. Rev. Lett. **73**, 716 (1994).

[6] P. Gold, A. Thoma, S. Maier, S. Reitzenstein, C. Schneider, S. Höfling, and M. Kamp, Phys. Rev. B **89**, 035313 (2014).

[7] J. J. Finley, M. Sabathil, P. Vogl, G. Abstreiter, R. Oulton, A. I. Tartakovskii, D. J. Mowbray, M. S. Skolnick, S. L. Liew, A. G. Cullis, and M. Hopkinson, Phys. Rev. B **70**, 201308 (2004).

[8] R. B. Patel, A. J. Bennett, I. Farrer, C. A. Nicoll, D. A. Ritchie and A. J. Shields, Nat. Photon. **4**, 632 (2010).

[9] A. J. Bennett, R. B. Patel, J. Skiba-Szymanska, C. A. Nicoll, I. Farrer, D. A. Ritchie, and A. J. Shields, Appl. Phys. Lett. **97**, 031104 (2010).

[10] S. Seidl, M. Kroner, A. Högele, K. Karrai, R. J. Warburton, A. Badolato and P. M. Petroff, Appl. Phys. Lett. **88**, 203113 (2006).

[11] E. B. Flagg, A. Muller, S. V. Polyakov, A. Ling, A. Migdall, and G. S. Solomon, Phys. Rev. Lett. **104**, 137401 (2010).

[12] X. Wu, X. Dou, K. Ding, P. Zhou, H. Ni, Z. Niu, D. Jiang, and B. Sun, Appl. Phys. Lett. **103**, 252108 (2013).

[13] P. E. Kremer, A. C. Dada, P. Kumar, Y. Ma, S. Kumar, E. Clarke, and B. D. Gerardot, Phys. Rev. B *90*, 201408(R) (2014).

[14] R. Trotta, J. Martín-Sánchez, I. Daruka, C. Ortix, and A. Rastelli, Phys. Rev. Lett. **114**, 150502 (2015).

[15] J. Martín-Sánchez, R. Trotta, A. Mariscal, R. Serna, G. Piredda, S. Stroj, J. Edlinger, C. Schimpf, J. Aberl, T. Lettner, J. Wildmann, H. Huang, X. Yuan, D. Ziss, J. Stangl, and A. Rastelli, arXiv:1710.07374 (2017).

[16] I. Yeo, P-L. de Assis, A. Gloppe, E. Dupont-Ferrier, P. Verlot, N. S. Malik, E. Dupuy, J. Claudon, J.-M. Gérard, A. Auffèves, G. Nogues, S. Seidelin, J-Ph. Poizat, O. Arcizet and M. Richard, Nat. Nanotech. **9**, 106 (2014).

[17] M. Montinaro, G. Wüst, M. Munsch, Y. Fontana, E. Russo-Averchi, M. Heiss, A. Fontcuberta i Morral, R. J.

Warburton, and M. Poggio, Nano Lett. **14**, 4454 (2014).

[18] P.-L. de Assis, I. Yeo, A. Gloppe, H. A. Nguyen, D. Tumanov, E. Dupont-Ferrier, N. S. Malik, E. Dupuy, J. Claudon, J.-M. Gérard, A. Auffèves, O. Arcizet, M. Richard, and J.-Ph. Poizat, Phys. Rev. Lett. **118**, 117401 (2017).

[19] A. Goban, C.-L. Hung, J.D. Hood, S.-P. Yu, J.A. Muniz, O. Painter, and H.J. Kimble, Phys. Rev. Lett. **115**, 063601 (2015).

[20] H.A. Nguyen, T. Grange, B. Reznychenko, I. Yeo, P.-L. de Assis, D. Tumanov, F. Fratini, N. S. Malik, E. Dupuy, N. Gregersen, A. Auffèves, J.-M. Gérard, J. Claudon, and J.-Ph. Poizat, arXiv:1705.04056.

[21] M. Munsch, A. V. Kuhlmann, D. Cadeddu, J.-M. Gérard, J. Claudon, M. Poggio, and R. J. Warburton, Nat. Commun. **8**, 76 (2017).

[22] H. A. Nguyen, PhD thesis, Université Grenoble Alpes (2016), https://tel.archives-ouvertes.fr/tel-01360549

[23] P.Y. Yu, and M. Cardona, *Fundamentals of semiconductors*, Springer ed. (2010).

[24] P. Stepanov, M. Elzo-Aizarna, J. Bleuse, N.S. Malik, Y. Curé, E. Gautier, V. Favre-Nicolin, J.-M. Gérard, and J. Claudon, Nano Lett. **16**, 3215 (2016).

[25] S. Mendach, S. Kiravittaya, A. Rastelli, M. Benyoucef, R. Songmuang, and O. G. Schmidt, Phys. Rev. B **78**, 035317 (2008).

[26] T. Zander, A. Herklotz, S. Kiravittaya, M. Benyoucef, F. Ding, P. Atkinson, S. Kumar, J. D. Plumhof, K. Dörr, A. Rastelli, and O. G. Schmidt, Opt. Express **17**, 22452 (2009) .

[27] L.-M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, Nature **414**, 413 (2001).

[28] J. Bleuse, J. Claudon, M. Creasey, N. S. Malik, J.-M. Gérard, I. Maksymov, J.-P. Hugonin, and P. Lalanne, Phys. Rev. Lett. **106**, 103601 (2011).