Strain couples a nano-mechanical oscillator and a quantum emitter

In theory, the strangeness of quantum mechanics is not solely restricted to the microscopic world but applies equally to macroscopic objects. However, in practice, to get a macroscopic object to behave quantum mechanically requires an exquisite degree of control over the object and its environment. Recently, a new class of experimental devices has emerged, where such a thing is possible. These devices consist of a micro-mechanical oscillator in strong interaction with an externally controllable quantum degree of freedom. We have fabricated such a hybrid device by exploiting the simplest possible mediator to provide the coupling, namely the strain field in the material.

In spite of the tremendous success of quantum mechanics, the frontier between the quantum and the classical world is not included in the theory and still remains poorly defined. Owing to recent progress in nanotechnology, it is now possible to achieve well controlled interaction between the motion of a macroscopic object, specifically a mechanical oscillator of micron size, and a genuinely quantum degree of freedom such as a superconducting quantum bit or a semiconductor quantum dot. A mechanical oscillator can be cooled down into its quantum mechanical ground state, and a non-classical motion (a phonon number state) can then be excited via external control over a single quantum object coupled to it. Such a hybrid device must exhibit the largest possible coupling strength, and allow maximal control over the macroscopic quantum object.

In a collaboration between NEEL Institute teams and the nanofabrication facility at CEA-Grenoble, we have fabricated a new, fully monolithic, hybrid device, where the coupling mechanism is provided by the internal strain field generated by the motion of the mechanical oscillator. This device consists of a deformable "nanowire" (diameter in the 200 nm range) embedding a small number of semiconductor quantum dots (nanometre-scale inclusions of a semiconductor material). The quantum dots behave like artificial atoms that can emit light of frequency ω.

To begin with, a layer of Indium Arsenide (InAs) quantum dots is grown by Molecular Beam Epitaxy on a GaAs substrate and capped by an 18 µm thick GaAs layer. Nanowires are etched through this layer by a combination of electron beam lithography and reactive ion etching. The resulting wires looks like the one shown in Fig.1(a), with the quantum dot layer situated close to the bottom. This specific conical shape is designed to maximize optical access to the quantum dots (75% light collection efficiency has been demonstrated), which is a key property for realization of a useful, quantum opto-mechanical hybrid device.

The nanowire has a well-defined fundamental mode of mechanical vibration corresponding to the lateral flexion of the wire. Its resonance frequency $\Omega/2\pi$ is around 500kHz, with a quality factor of 3000 at T = 5 K. As shown in Figs 1(b) and (c), with the wire clamped by the substrate at its bottom end, the wire flexion generates a strain field within the material at the height of the quantum dot layer. The strain has maximal amplitude on the edge of the wire. Quantum dots situated in this area experience a periodic lattice deformation which modulates (i.e. causes a periodic shift $\delta\omega(t)$ of) their optical transition frequency.

We characterized the strength of this coupling by mechanical and optical spectroscopy of the hybrid device. The motion of the wire is monitored via the spatially sensitive reflection of a laser beam detected with a split photodiode. The frequency $\omega_0+\delta\omega(t)$ of the optical transition between a *single* quantum dot's ground and excited states (g) and (e) (see Fig.1) is monitored by photoluminescence stroboscopic measurements. We found that when the top of the wire moves by δx = 1 nm, the photoluminescence frequency shifts by $\hbar\delta\omega$ =200 µeV. Calibrating using the wire's thermal Brownian motion, we were able to infer a coupling strength of $g_0/2\pi$ =450 kHz.

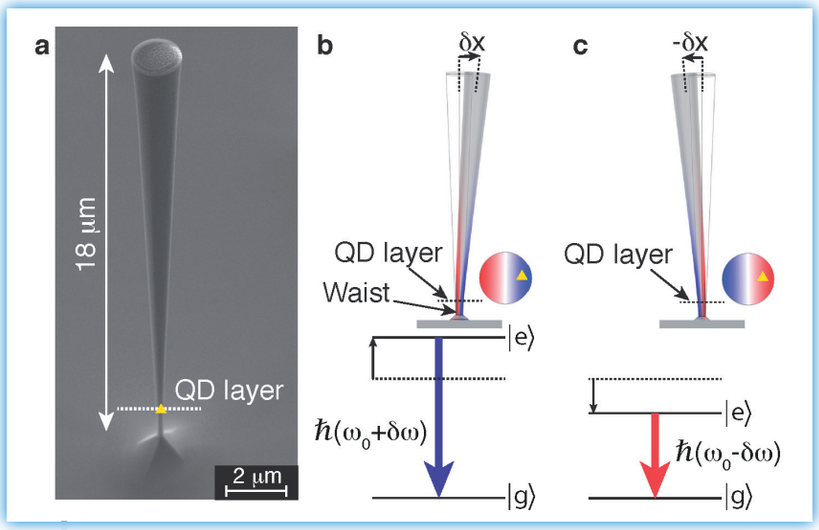

Fig. 1(a): Scanning Electronic Microscope image of the conical shaped GaAs nanowire embedding a layer of InAs Quantum Dots (QDs).
Fig. 1(b) and (c): When the top of the wire bends by +δx or -δx, the quantum dot depicted as a yellow triangle in the circular insets is under either compressive strain (blue) or tensile strain (red). The dot's optical transition energy ħω0 is either increased or decreased, by ħδω. Levels e and g represent the dot's excited and ground states, the dotted level represents the level e for δx=0.

This frequency can be understood as the spectral shift of the quantum dot induced by a single vibrational quantum in the nanowire. This coupling strength is very large as compared to state-of-the-art hybrid systems based on other strategies, and is even comparable with the mechanical frequency $\Omega/2\pi$. We are therefore close to the so-called strong-coupling regime where the spatial shift of the nanowire rest position caused by quantum dot excitation exceeds the nanowire's zero point fluctuation. In the future, the coupling strength could be still further enhanced by modifying the shape of the nanowire. This strain-based strategy is an important step towards the realization of an integrated, optically interfaced, external-field free, quantum hybrid system. It could be easily transferred to different materials such as the diamond nano-mechanical oscillator where Nitrogen-Vacancy colour centres constitute a quantum degree of freedom stable at room temperature.

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FURTHER READING

Strain-mediated coupling in a quantum dot–mechanical oscillator hybrid system
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
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