Nanowire antennas embedding single quantum dots: towards the emission of indistinguishable photons

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***Abstract*—Nanowire antennas embedding a single semiconductor quantum dot (QD) represent an appealing solid-state platform for photonic quantum technologies. We present recent work aiming at generating indistinguishable photons with this system. We first investigate decoherence channels that spectrally broaden the QD emission, and discuss in particular the impact of nanowire thermal vibrations. We also develop nanowire optical nanocavities, which provide a large acceleration of the QD spontaneous emission, so that it becomes less sensitive to environmental noises.**

***Index Terms*—nanowire antenna, quantum dot, mechanical vibrations, nanocavity, Purcell effect, single photon source, quantum optics**

I. Introduction

In the last decade, tapered nanowire antennas embedding a single quantum dot (QD) have emerged as a versatile solid-state platform for photonic quantum technologies. These waveguide structures efficiently shape the QD spontaneous emission into a directive free-space beam [1], [2]. They find application in the realization of bright sources of quantum light [3], [4]. Their broad operation bandwidth is particularly interesting to realize wavelength-tunable single-photon sources [5], sources of entangled photon pairs [6] as well as sources of correlated photon triplets [7]. They can also enhance optical non-linearities down to single-photon levels, a first step towards the realization of photonic logical gates [8], [9]. Most applications to quantum technologies demand that the photons emitted by the QD are indistinguishable. In other words, their spectral linewidth should be solely defined by the QD radiative lifetime. Since the QD solid-state environment is home to a number of noise sources which cause additional spectral broadening, this represents a significant challenge.

We review here recent advances aiming at improving the spectral coherence of the photons emitted by a QD-nanowire antenna device. We tackle this challenge with a two-fold strategy. First, we investigate decoherence channels in this system, some of them being specific to the nanowire geometry. This is the case of spectral broadening induced by the nanowire thermal vibrations. In parallel, we also explore new nanowire photonic structures that accelerate the QD spontaneous emission, so that it becomes less sensitive to noise sources located in the QD environment.

II. Decoherence due to nanowire thermal vibrations: problem and solution

We first discus a previously overlooked decoherence channel for a QD embedded in a 'standard' nanowire antenna, such as the one shown in Fig. 1(a). The structure is 12 μm high, and the QDs are located close to the base, where the local wire diameter is 200 nm. Recent measurements, shown in Fig. 1(b), revealed that the thermal excitation of the first vibration modes of a nanowire antenna have a sizeable influence on the QD optical linewidth [10]. Indeed, a mechanical vibration induces stress fluctuations at the QD location, which in turn modulate the bandgap energy of the QD material. This modifies the spacing of the QD energy levels, and thus the color of the emitted photons. At cryogenic temperature (4K), the vibration amplitude is very small (10 pm r.m.s. for the fundamental flexural mode, which resonates at a frequency of 0.5MHz). Yet

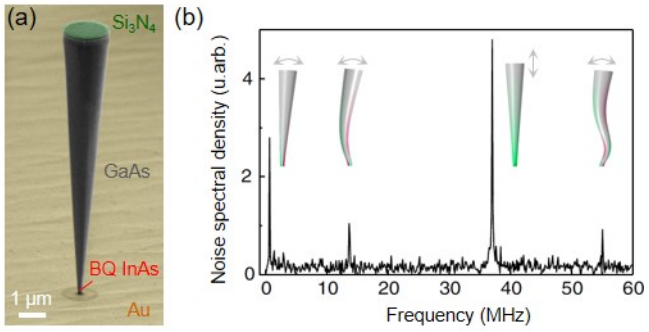

Fig. 1. (a) A 'photonic trumpet' nanowire antenna. (b) Spectroscopy of the noise acting on the QD emission energy. The sharp peaks correspond to nanowire vibration modes that are thermally excited at $T = 4$ K.

the QD is so sensitive to stress that this induces a significant spectral broadening. This initial experiment evidenced the impact of the first four vibration modes, up to $\sim$ 100 MHz (the experimental detection bandwidth). Of course, a nanowire supports an extended set of mechanical resonances, and these initial results naturally raise the question of their global impact on the QD emission.

This motivated a comprehensive theoretical analysis, based in particular on finite element simulations of the mechanical vibration modes [11]. Overall, we find that low-frequency thermal vibrations constitute a major source of decoherence in QD-nanowire antennas, even at liquid helium temperature. Our analysis reveals that, due to a cutoff mechanism, the QD spectral broadening is dominated by the contribution of a finite set of low-frequency mechanical modes. In addition, the spectral broadening strongly depends on the QD location within the nanowire section. This can be directly traced back to the highly inhomogeneous stress profile associated with flexural modes.

To overcome this fundamental limitation, we propose several designs based on the engineering of the mechanical properties of the nanowire. A first possible strategy is to design an antenna in which the QD is located in a zone experiencing minimal vibration-induced stress. A reduction of the nanowire height is also interesting: this shifts mechanical resonances to large frequencies (typically above 500 MHz), where their impact on the QD emission becomes perturbative. Overall, our work establishes such nanomechanical engineering as a crucial part of the design of high performance light-matter interfaces based on photonic nanostructures.

III. Nanowire optical nanocavities for broadband acceleration of spontaneous emission

Nanowire antennas offer a large operation bandwidth, but do not provide a significant acceleration of spontaneous emission. Indeed, the radiative lifetime of a QD embedded in the antenna is typically the same as the one of a QD embedded in bulk semiconductor ($\sim$ 1 ns). Defining a nanocavity around the QD represents an appealing strategy to accelerate its spontaneous emission, while preserving a broad operation bandwidth. Thanks to an ultrasmall mode volume (on the order of $(\lambda/n)^3$, with λ/n the wavelength in the material), one can reach a significant Purcell factor with a moderate optical quality factor, which directly translates into a large operation bandwidth.

We proposed several designs along these lines [12], [13], but focus here on a recent proposal and experimental demonstration [14]. As shown in Fig. 2(a), the proposed nanocavity simply consists of a segment of nanowire, which stands on a planar mirror. The predicted Purcell factor is as large as 6.3, and is maintained over a 30-nm broad operation bandwidth. Close-to-optimal collection efficiency is maintained over an equivalent bandwidth and reaches a predicted value of 0.54 at resonance for a first lens with a numerical aperture (NA) of 0.75. As a first experimental demonstration of this concept, we fabricate an Au-SiO_2-GaAs device embedding isolated InAs quantum dots (Fig. 2(b)). We measure a maximal acceleration of spontaneous emission by a factor as large as 5.6 and a bright quantum dot emission (collection efficiency of 0.35 into NA = 0.75). This nanowire cavity constitutes a promising building block to realize advanced sources of quantum light for a broad range of material systems.

Interestingly enough, we believe that there is still room for optimization, notably of the collection efficiency, which is currently limited by the divergence of the output beam. We first employed a single-mode approach to design the nanocavity (considering the reflections of the fundamental guided mode of the nanowire). While this approach is perfectly suited to model nanowire antennas, it is insufficient to accurately describe the nanocavity mode. An optimization that goes beyond the single-mode model is currently under progress.

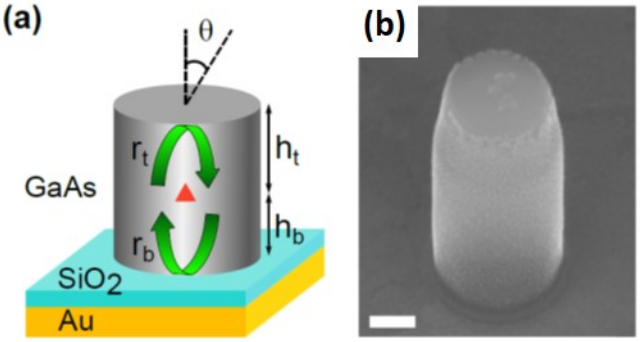

Fig. 2. (a) Schematics of the nanowire optical nanocavity. The triangle pictures a QD. (b) Tilted scanning electron microscope image of a fabricated device (scale bar: 100 nm).

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