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Controlling light emission from single-photon sources using photonic nanowires

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Abstract—**The photonic nanowire has recently emerged as an promising alternative to microcavity-based single-photon source designs. In this simple structure, a geometrical effect ensures a strong coupling between an embedded emitter and the optical mode of interest and a combination of tapers and mirrors are used to tailor the far-field emission pattern. This non-resonant approach relaxes the demands to fabrication perfection, allowing for record-high measured efficiency of fabricated nanowire single-photon sources. We review recent progress in photonic nanowire technology and present next generation designs allowing for electrical contacting, polarization control, improved efficiency and simplified fabrication.**

Keywords-photonic nanowire, single-photon source, single photons, electrical pumping, polarization control

I. INTRODUCTION

A major challenge for the realization of future quantum photonic applications is the development of solid-state light-emitting devices capable of emitting single photons on demand. [1] The semiconductor quantum dot (QD) embedded in a engineered microstructure appears as a promising platform for such a single-photon source (SPS). The self-assembled QD features a high radiative yield without bleaching or blinking. For practical applications, it is desirable to trigger the photon using an electrical pulse, and this can be achieved by integrating the QD into a *p-i-n* structure to realize a single-photon LED.

For the quantum communication and quantum information applications, a near-unity efficiency ε, defined as the number of detected photons by the collection optics per trigger, is desired. The fabrication of self-assembled QDs allowing for a nearly perfect conversion of excitons to emitted photons is well-established, however to obtain a high efficiency the photonic environment must be engineered such that all the emitted light couples to the collection optics.

For an InAs QD embedded in GaAs, the large refractive index of GaAs limits the photon extraction efficiency to a few percent. This extraction efficiency can be improved by placing the emitter inside a high quality (Q) microcavity [2] and taking advantage of cavity quantum electrodynamics. The relevant figures of merit are the β factor describing the spontaneous emission rate into the fundamental cavity mode over the emission total rate and the probability γ describing the ratio of the power collected by the collection optics and that of the fundamental mode. Assuming a perfect radiative yield, the total efficiency ε is then given by the product $\beta\gamma$. In high-Q microcavities, a β close to 100 % is achieved using the Purcell effect, however fabrication-induced imperfections limit the γ leading to efficiencies of microcavity-based SPSs $\leq$ 44 %. [2] Furthermore, these devices feature an autocorrelation function at zero time delay $g^{(2)}(\tau=0)$ generally much larger than 0, most likely due to cavity-feeding effects, and these resonant systems only operate over the limited bandwidth of the cavity resonance.

As alternative we have explored the photonic nanowire geometry which is better adapted to efficient collection of light. In this geometry, a geometrical effect ensures a β close to unity, [3] and the combination of a top conical tapering [4] and a metal mirror [5] allows for control of the far-field radiation pattern. This has lead to the proposal of optically [6] and electrically [7] pumped designs with predicted efficiencies of ~ 90 % and to the experimental demonstrated of an optically pumped device with an efficiency of 72 %. [8]

II. PHOTONIC NANOWIRE SPS DESIGNS

The photonic nanowire SPS designs considered in this work are illustrated in Fig. 1. The nanowire is simply a GaAs cylinder placed on a substrate. Single photons are emitted by an InAs QD and they couple to the fundamental mode of the nanowire with a probability which can be optimized by choosing the correct nanowire radius. At an emission wavelength of λ = 950 nm, a β of 96 % is obtained for an optimum radius R_{nw} of 120 nm. [3] This high β is the result of a geometrical screening effect dampening the electric field strength of radiation modes inside the nanowire. [9] For even smaller radii, the guided mode is no longer supported and the same screening effect results in strong inhibition of the spontaneous emission [9] realized without the presence of a bandgap.
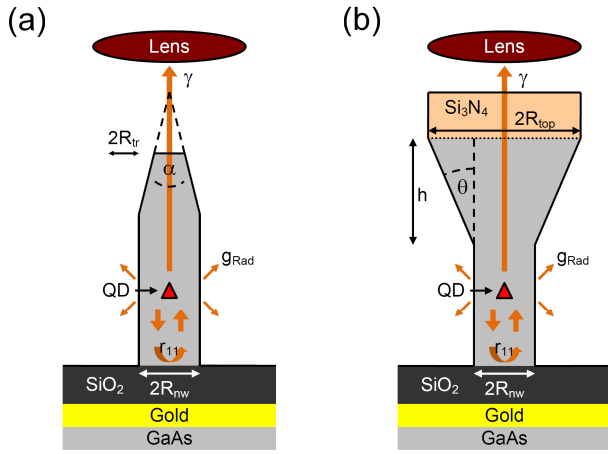
Figure 1. Optically pumped photonic nanowire designs based on a regular tapering (a) and an inverted taper (b).

Figure 2. Scanning electron micrographs of nanowires implementing a regular conical tapering (a) and an inverted conical tapering (b).

Due to symmetry, half of the photons in the fundamental mode will be propagating towards the substrate and it is necessary to implement a bottom metal mirror [5] reflecting these photons back towards the top. We include a thin dielectric layer of thickness ~ 10 nm to suppress coupling to surface plasmons resulting in a reflection coefficient $R_{11} = |r_{11}|^2$ of 91 %.

Using the mirror we ensure that the emitted photons in the fundamental mode propagate towards the top of the nanowire, however for a nanowire radius R_{nw} of 120 nm, the fundamental mode waist is narrow leading to a wide far-field radiation pattern and a poor coupling to the objective lens. To improve this coupling it is thus necessary to expand the mode waist such that the resulting output beam divergence is reduced. [4] The two designs presented in Fig. 1. represent two different strategies for achieving this mode expansion.

The design in Fig. 1(a) features a regular conical tapering of opening angle α. As the fundamental mode propagates forward, the radius of the nanowire decreases. For R_{nw} below ~ 100 nm, the nanowire can no longer support a guided mode, and the fundamental mode expands rapidly. For sufficient small values of α, the taper thus allows for an adiabatic expansion of the fundamental mode, [4] resulting in a large mode waist and a narrow far field profile. Furthermore, the mode is adiabatically expanded into the surrounding air leading to a strong reduction of the reflection at the semiconductor-air interface. The adiabatic expansion primarily takes part in the lower part of the taper, and thus a truncated taper with truncation radius of $R_{tr} = 60$ nm gives the same performance as the perfectly sharp tip.

The top part of the photonic nanowire is engineered to suppress reflection. There is thus no cavity meaning that the emitted photons escape immediately and are thus much less subject to scattering from fabrication imperfections than they are in e.g. the high-Q micropillar cavity. A scanning electron micrograph (SEM) of a full device based on the regular conical tapering is illustrated in Fig. 2(a). Indeed, this device features a measured efficiency 72 % combined with a very clean single photon emission with $g^{(2)}(\tau = 0)$ below 0.8 %. [8]
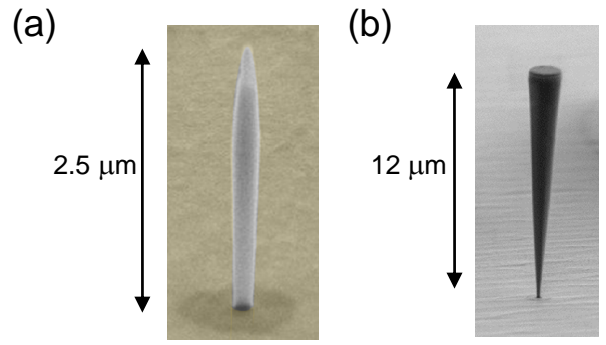
However, the design in Fig. 1(a) suffers from several weaknesses. The fabrication of the regular conical tapering with opening angles ≤ 5° is quite challenging using our top-down approach. [8] Furthermore, due to the large part of the mode extending into the surrounding air, the implementation of a top metal contact which does not perturb the optical field profile is not immediate. For this reason we have investigated a photonic nanowire design implementing an inverted conical tapering [7] with side angle θ. The design is illustrated in Fig. 1(b). The bottom part of the design is identical to that in Fig. 1(a), however the top part features an inverted conical tapering and an anti-reflection coating. Here, the fundamental mode is adiabatically expanded not outside the nanowire as it is the case for the regular tapering, but inside the photonic nanowire. Since the mode stays inside the nanowire, we introduce an anti-reflection coating to eliminate the reflection occurring at the semiconductor-air interface.

We compute the efficiency of these devices using a single mode model based on an elements-splitting approach. [6] Assuming an emitter placed in an antinode of the field, the efficiency in this model is given by

$$\varepsilon = \beta\gamma \frac{\left(1 + |r_{11}|\right)^2}{2\left(1 + \beta|r_{11}|\right)}, \qquad (1)$$

where the fraction on the RHS of (1) represents a correction due to the reflection of the downwards propagating light by the metal mirror.

The predicted efficiencies for the two designs are given in Fig. 3 as function of α and θ. For a 0.8 NA objective lens, the regular design features a maximum predicted efficiency of 95 % for $\alpha \leq 2°$, however we note that an efficiency of 85 % requires an opening angle below 5°. In comparison, the maximum efficiency for the inverted taper design is 92 % and a high efficiency above 85 % is maintained for a side wall angle θ up to 10°. Furthermore, the maximum efficiency of 92 % is achievable for a taper height h of only 12 μm. A SEM image of such an inverted taper is shown in Fig. 2(b). While opening angles for regular conical taperings below 2° may be achievable using a bottom-up fabrication method, these results show that the inverted taper approach is less demanding in
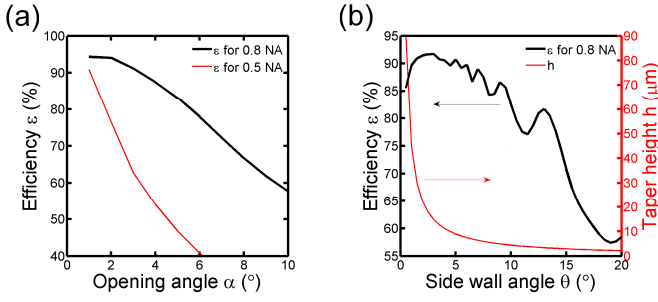
Figure 3. Predicted efficiency ε for the regular taper design (a) as function of opening angle α. Predicted efficiency and taper height for the inverted taper design (b) as function of side wall angle θ for R_{top} = 900 nm.

terms of side wall angle and thus represents an attractive alternative well adapted to our top-down fabrication technique.

III. POLARIZATION CONTROL

The photonic nanowire designs considered so far feature rotational symmetry and thus support two degenerate optical modes with orthogonal polarization states. In standard semiconductor QDs the emitter is not strongly polarized in one direction, and the emitter thus couples to the two modes with equal probability. For such emitters one approach to achieving polarization control is to lift the degeneracy of the optical modes by introducing an elliptical cross-section. [10]

The computed fundamental modes in a photonic nanowire PW$_0$ featuring an elliptical cross-section with diameters $d_\parallel$ = 280 nm and $d_\perp$ = 130 nm are shown in Fig. 4. We observe that the moderate degree of anisotropy leads to a dramatic contrast in mode amplitudes. The fundamental mode $M_\parallel$ with dominating electric field component aligned parallel to the major semi-axis remains well confined to the elliptical nanowire, while the orthogonal mode $M_\perp$ is subject to strong selective deconfinement.

We have fabricated elliptical nanowires with dimensions similar to PW$_0$ and with various orientations of the major semi-axis with respect to the crystal [110] axis. A SEM image of such a device is shown in Fig. 5(a). To quantify the control of the polarization we have measured the intensities $I_\parallel$ and $I_\perp$ along the two axes using a polarization filter. For each device we
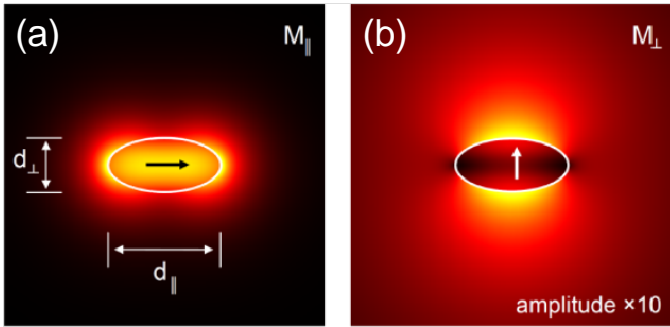

Figure 4. Field amplitude of the fundamental modes $M_\parallel$ (a) and $M_\perp$ (b) with dominating field component oriented parallel and perpendicular respectively to the large semi-axis. The white line illustrates the nanowire boundary. From [10].
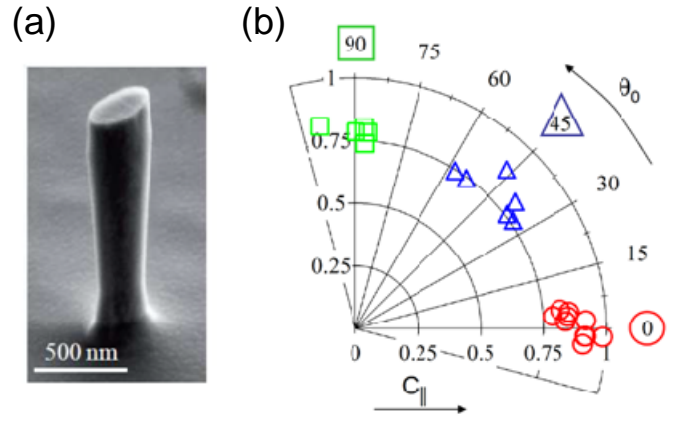

Figure 5. Scanning electron micrograph of the elliptical nanowire (a). Degree of linear polarization (b) as function of polarization angle for various ellipse orientations θ_0 = 0°, 45° and 90°. From [10].

define the degree of linear polarization as $C_\parallel = I_\parallel / (I_\parallel + I_\perp)$. Polarized emission was collected for a number of devices, and $C_\parallel$ and the polarization angle θ_0 are shown in Fig. 5(b). We observe that a high degree of linear polarization $C_\parallel \geq 75$ % is reproducibly obtained demonstrating that the orientation of polarized light is indeed imposed by the orientation of the ellipse. [10]

REFERENCES

[1] A. Shields, "Semiconductor quantum light sources," Nat. Photonics, vol. 1, pp. 215-223, April 2007.

[2] E. Moreau, I. Robert, L. Manin, V. Thierry-Mieg, J. M. Gérard and I. Abram, "A single-mode solid-state source of single photons based on isolated quantum dots in a micropillar," Physica E, vol. 13, pp. 418-422, 2002.

[3] Y.-R. Nowicki-Bringuier, R. Hahner, J. Claudon, G. Lecamp, P. Lalanne and J. M. Gérard, "A novel high-efficiency single-mode single photon source," Ann. Phys. Fr., vol. 32, pp. 151-154, 2007.

[4] N. Gregersen, T. R. Nielsen, J. Claudon, J. M. Gérard and J. Mørk, "Controlling the emission profile of a nanowire with a conical taper," Opt. Lett., vol. 33, pp. 1693-1695, August 2008.

[5] I. Friedler, P. Lalanne, J. P. Hugonin, J. Claudon, J. M. Gérard, A. Beveratos and I. Robert-Philip, "Efficient photonic mirrors for semiconductor nanowires," Opt. Lett. **33**, 2635-2637, November 2008.

[6] I. Friedler, C. Sauvan, J. P. Hugonin, P. Lalanne, J. Claudon and J. M. Gérard, "Solid-state single photon sources: the nanowire antenna," Opt. Express, vol. 17, pp. 2095-2110, February 2009.

[7] N. Gregersen, T. R. Nielsen, J. Mørk, J. Claudon and J. M. Gérard, "Designs for high-efficiency electrically pumped photonic nanowire single-photon sources," Opt. Express, vol. 18, pp. 21204-21218, September 2010.

[8] J. Claudon et al, "A highly efficient single-photon source based on a quantum dot in a photonic nanowire," Nat. Photonics, vol. 4, pp. 174-177, March 2010.

[9] J. Bleuse, J. Claudon, M. Creasey, N. S. Malik and J. M. Gérard, "Inhibition, Enhancement and Control of Spontaneous Emission in Photonic Nanowires," Phys Rev. Lett., vol. 106, pp. 103601, March 2011.

[10] M. Munsch et al, "Single Mode Spontaneous Emission in an Elliptical Photonic Nanowire," accepted for publication in Phys. Rev. Lett.