1573

Progress Towards On-chip Single Photon Sources Based on Colloidal Quantum Dots in Silicon Nitride Devices

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Abstract: New results on integration of colloidal quantum dots (QDs) into SiN microstructures are reported, including QD positioning with nanometric accuracy and the efficient coupling of their emission to waveguides and cavities. The results are relevant to on-chip quantum optics and information processing.

OCIS codes: (270.0270) Quantum Optics; (220.4000) Microstructure fabrication.

1. Introduction

In the beginning of the years 2000, "optical quantum computing" [1] has emerged as a new and very promising paradigm to demonstrate that quantum computers have the potential to radically outperform classical digital computers. Optical quantum computation is appealing because it requires only single-photon sources, linear optical elements and single-photon detectors. In addition it has been shown that fault tolerant computing is possible if the product of the single-photon emission efficiency η_S and the single-photon detection efficiency η_D satisfies $\eta_S\times\eta_D>2/3$, and all other optical components operate perfectly [2].

At visible wavelengths, Si avalanche photodiodes (APDs) reach detection efficiencies as high as $\eta_D=80\%$. The linear optical networks (made of beam-splitters, phase-shifters, etc.) needed for optical quantum computing can be with table-top optical components or fiber optics. These approaches offer high flexibility but suffer from thermal and mechanical instabilities that hinder their scalability. Complex optical networks are best realized using integrated photonics devices on a microchip. Many recent experiments successfully validated this approach by performing quantum optics experiments with photons at 800 nm (a wavelength at which Si APDs are still very efficient) propagating in integrated photonic circuits [3,4]. Nowadays, the major technological obstacle to optical quantum computing is the lack of efficient (high η_S) sources of indistinguishable photons at wavelengths compatible with Si APDs. Single photons are always generated by parametric down-conversion, which is an inefficient, probabilistic (the photons are heralded) and therefore unscalable method.

In this work, we study the possibility to integrated triggered solid-state single photon emitters directly on a photonic chip. We specifically investigate photonic chips made of silicon nitride (Si_3N_4) because this material has a larger refractive index than silica ($n=2$), while is highly transparent in the visible and near-infrared range. Si_3N_4 devices and circuits can be realized using standard CMOS compatible processing technology on a SOI chip. Most importantly, the technology offers the possibility to embed alien solid-state single-photon emitters (such as colloidal quantum dot or diamond nanoparticles) inside the Si_3N_4 host.

The major challenges consist in (i) deterministically positioning quantum emitters at predefined sites, (ii) simultaneously exciting a selected number of emitters and (iii) efficiently coupling the emitted single photons to a waveguide. Here, we discuss the problems (i) and (iii), since an elegant solution to the problem (ii) has been already proposed elsewhere [5]. Our solution to the problem (i) is restricted to the integration of colloidal quantum dots (QDs), while our solutions to the problem (iii) apply to any single photon emitting nanoparticle.

2. Coupling single-photons to photonic circuits

We analyze the coupling of single-photons emitted by single QDs to Si_3N_4 waveguides using FDTD simulations. For rectangular strip waveguides, we find no significant Purcell enhancement of the emission (Purcell factors ranging between 0.7 and 1.3 for all dipole polarizations and little wavelength dependence). The coupling of the light to the waveguide is nevertheless high. For instance, for a 270×300 nm strip waveguide, we find a 58% coupling efficiency for a central emission wavelength of 650 nm and a randomly oriented dipole moment.

The polarization of the emitted photons can be better controlled by embedding the QD into a thin SiO_2 layer in the center of the Si_3N_4 waveguide (see inset of Fig. 1a). FDTD simulations show a significant Purcell enhancement of spontaneous emission in the polarization orthogonal to the SiO_2 layer. Fig. 1a shows the calculated Purcell factor

F_i in a (150 nm × h) Si_3N_4 waveguide with a 10-nm SiO_2 layer as a function of h and dipole orientation $\boldsymbol{n}_i$. For an otherwise isotropic emitter, the probability to emit a i-polarized photon is equal to $p_i = F_i/(\sum_i F_i)$. For h= 310 nm, we find that 65% of the emitted photons have a polarization orthogonal to the SiO_2 layer, 23% in the direction orthogonal to the waveguide, and 13% in the remaining direction. The emitted photons have an overall probability as high as 63% to be coupled into a guided mode. The photons emitted with a polarization orthogonal to the waveguide are not guided at all. Among the guided photons, 87.5% have a polarization orthogonal to the SiO_2 layer and only 12.5% have the complementary polarization. This shows that strongly polarized photons can be coupled to waveguides with high efficiency, even at room temperature. Although, a photon emitted in a waveguide is in a superposition of two opposite propagation direction, a directional emission can be easily obtained using reflectors of one end of the waveguide or by placing the emitting QD in a Sagnac loop as shown in the Fig. 1b.

We also simulated QDs in free-standing Si_3N_4 microdisk cavities. Such cavities can be manufactured with a high degree of reproducibility, can be vertically coupled to buried waveguides [6], and support high-Q modes. At cryogenic operation, QDs can have a spectrum as narrow as 5 GHz (20 μeV, 6.5 pm). In a 5-μm disk, we calculated that a Q-factor of 2000 would be enough to get a Purcell factor of 9 and an extraction efficiency of 90% into the coupled waveguide. We report on the fabrication of such cavities (see Fig. 1c) and are currently characterizing them. For room temperature operation, smaller cavities are required if single-mode emission is desirable. We simulated that a free spectral range of about 40 nm can be achieved in 2 μm-sized Si_3N_4 microdisk cavities and that the probability that the QD emit into the desired mode in such a cavity is 15% at room temperature.

3. Positioning QDs with nanometric accuracy

To efficiently couple single QD to waveguides or cavities, deterministic methods for positioning QDs at desired sites are needed. Here, we report on a novel and promising technique to achieve that goal. The technique combines substrate e-beam pattering, Langmuir-Blodgett deposition of a QD monolayer and site-selective lift-off. Fig. 1d shows that QD-patches of 62 nm are achievable. By mixing different types of QDs, it is possible to achieve a single optically active QD per patch.

4. Conclusion

In this work, we report on recent progress towards the efficient generation of single photons on a photonic chip. The techniques that we develop and combine are suitable for operating at room temperature as well as at cryogenic temperatures depending on the degree of coherence required for the photons. Simulations support the idea that single-photon sources with an efficiency $\eta_S > 2/3$ can be realized using colloidal QD in Si_3N_4 microstructures.

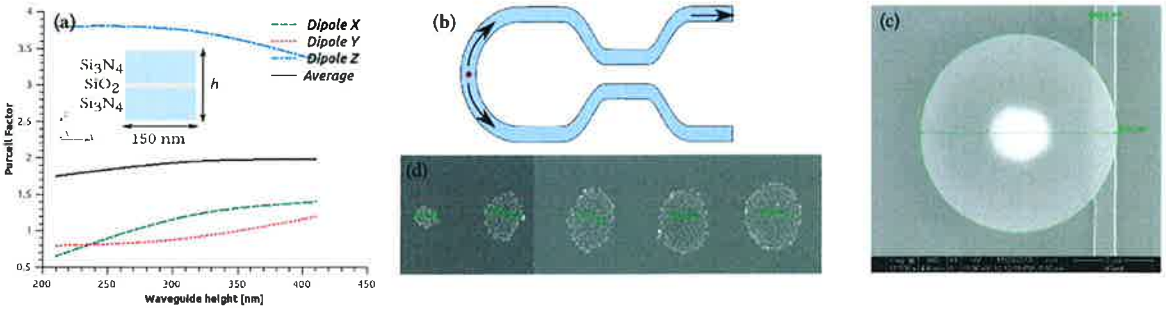

Figure 1: (a) Spontaneous emission enhancement factor for a single photon emitter embedded in Si_3N_4 waveguide with a thin SiO_2 layer. (b) Single photon self-interference makes it possible to collect all the emission in one output arm. (c) Fabricated 5μm-microdisks coupled to a buried waveguide. (d) Positioning QDs with nanometric accuracy.

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