Single-Photon Emitters in SiN Integrated Quantum Photonics

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Abstract: We report on the generation of single-photon emitters in silicon nitride. We demonstrate monolithic integration of these quantum emitters with silicon nitride waveguides showing a room-temperature off-chip count-rate of ~10^4 counts/s and clear antibunching behavior.

1. Room-temperature single-photon emitters in silicon nitride

On-chip integration of atom-like quantum emitters with resonant cavities and waveguides is essential for the realization of an emitter-photon interface and efficient generation, manipulation, and detection of quantum states of light. Development of material platforms which host quantum emitters and are suitable for fabrication of photonic components may enable monolithic integration of these intrinsic emitters with high coupling efficiencies and simplified fabrication processes. Among various material platforms for integrated quantum photonics, silicon nitride stands out as a technologically mature, low propagation loss, CMOS compatible material platform which is well established for linear and nonlinear integrated optics [1,2] and has recently emerged as a potential platform for integrated quantum photonics [3]. Our group recently discovered bright, stable, linearly polarized, and high-purity sources of single-photon emission in SiN operating at room temperature [4]. Quantum emitters in SiN were produced by careful selection of the growth conditions of high-density plasma chemical vapor deposition and subsequent thermal annealing. Rapid thermal annealing of SiN films at 1100°C for 120s in a nitrogen atmosphere resulted in the formation of single-photon emitters, which was revealed by confocal scanning photoluminescence imaging and second-order autocorrelation $g^{(2)}(\tau)$ measurements [4]. Moreover, we found that quantum emitters in SiN can be also created and/or activated using a conventional thermal annealing furnace. This observation suggests that the emitter formation mechanism is connected to a threshold temperature rather than the dynamics of the temperature change. For both annealing approaches, having SiN grown on silicon dioxide (SiO_2) is a critical prerequisite for quantum emitter formation, which places the emitter origin at the SiN/SiO_2 interface.

2. Monolithic integration of silicon nitride quantum emitters with photonic platform

We studied the monolithic integration of SiN quantum emitters with waveguides made of the same low-autofluorescing SiN. For this study, we grew 250-nm-thick nitrogen-rich SiN on commercially available SiO_2-coated silicon substrates, which were suitable for waveguide fabrication following the recipe described in [4].

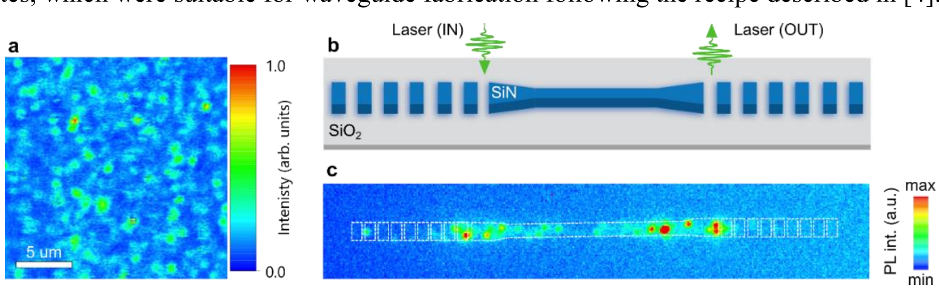

Figure 1. Integration of SiN quantum emitters with waveguides. (a) Confocal PL intensity map of the continuous SiN film before waveguides fabrication. Bright spots are single-photon emitters. (b) Schematic of the laser coupling to a waveguide through grating couplers. The laser light propagates along the structure and excites quantum emitters. (d) CCD camera image of the whole waveguide showing PL signal from integrated quantum emitters, which is partially scattered into the far field. The laser light at 532 nm is filtered out with the long-pass filter.

Ellipsometry characterization of the samples revealed the refractive index n of the resultant SiN films was ~1.7. The photophysical properties of quantum emitters in the samples were characterized before waveguide fabrication and were in line with previously reported emitters [4] (Fig. 1a). The waveguides were designed and simulated with a commercial Maxwell solver using the 3D finite-difference time-domain method. Simulation results for a centrally placed emitter shows 33% bi-directional coupling of the emission from the dipole source to the fundamental waveguide mode (β) and 22% outcoupling efficiency for the grating coupler at 600 nm. Waveguide arrays were patterned via electron beam lithography, hard masked with chrome, and etched using reactive ion etching. The high density of quantum emitters in the SiN layer prior to patterning (Fig. 1a) ensured the integration of a few emitters in each waveguide without special alignment of the waveguide arrays. Fig. 1b shows the schematic of the laser light coupling to a waveguide through grating couplers to excite emitters integrated to it. Quantum emitters integrated to the waveguide were imaged using a charge coupled device (CCD) camera showing the emission outcoupled to the far field (Fig. 1c).

The individual quantum emitters were measured using a decoupled excitation and detection scheme providing direct excitation of quantum emitters and remote collection of photons outcoupled by one of the grating couplers as shown in Fig. 2a. Fig. 2b shows distinct photoluminescence spots corresponding to the emission outcoupled to the far field from the waveguide at the excitation spot and from grating couplers upon excitation of an emitter with a 532 nm focused laser beam. Several SiN waveguides were measured to find those containing a quantum emitter which was properly oriented and positioned to efficiently couple to the waveguide mode. The emission outcoupled from one of the grating couplers was then collected to perform the second-order correlation measurement of the emission. The resulted $g^{(2)}(\tau)$ histogram is shown in Fig. 2c. The data was fit with a three-level model yielding a $g^{(2)}(0)$ value of 0.26 without spectral filtering and background correction (Fig. 2d). We also assed the emitter emission count rate and found it to be on the order of 10^4 counts/s.

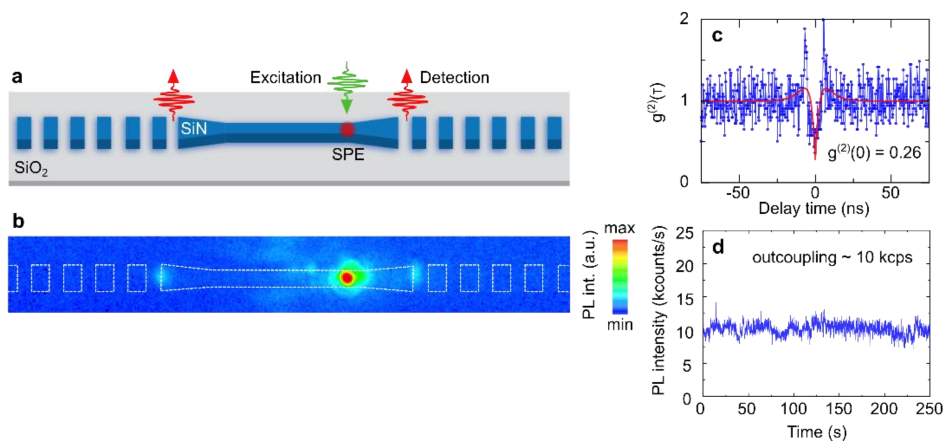

Figure 2. Characterization of a quantum emitter coupled to a waveguide. (a) Schematic illustration of a measurement scheme for direct excitation and remote detection of single-photon emission outcoupled from the grating couplers. (d) Photoluminescence image obtained with a CCD camera showing emission intensity from a quantum emitter partially scatter into the far field at the excitation spot and outcoupled by grating couplers. (c) Second-order autocorrelation measurement of the emission at the grating coupler yielding the $g^{(2)}(0)$ value of 0.26 without spectral filtering and background correction. (d) Photoluminescence stability measured from the coupler position showing some blinking behavior of the quantum emitter.

Monolithically integrated quantum emitters in SiN have a potential to enable a low-loss and scalable quantum photonic platform that is mature in terms of fabrication, quality control, and integration. Our findings spark further studies of SiN quantum emitters aimed at gaining a deeper understanding of their nature, devising deterministic formation schemes, and their scalable integration with on-chip quantum photonic circuitry.

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3. References

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