

Silicon Nitride Integrated Photonics with Intrinsic Quantum Emitters

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Abstract: We create intrinsic quantum emitters in silicon nitride, study their structure and temperature-dependent optical properties, and demonstrate monolithic integration with photonic waveguides to evaluate the potential of these single-photon sources for quantum information applications. © 2023 The Author(s)

Solid-state single-photon emitters are essential resources for several emerging applications in photon-based quantum computation and communication. Silicon nitride (SiN) is one of the leading material platforms for quantum photonic integrated circuits (QPICs). SiN QPICs offer wafer-scale waveguides with ultralow optical losses, a broad transparency window, the absence of two-photon absorption in the telecommunication bands, a high refractive index, strong optical Kerr nonlinearity, and CMOS compatible fabrication. Until recently, an intrinsic atomic-like source of single photons in SiN has been missing, which required hybrid heterogeneous integration with other materials that host quantum emitters. Despite the rapid development of hybrid approaches in the past years, they are often characterized by high insertion losses and challenging fabrication procedures. In our study, we discovered intrinsic quantum emitters in SiN and established methods of their creation [1]. SiN quantum emitters are formed in low-autofluorescence nitrogen-rich SiN grown on SiO₂ by post-growth thermal annealing at 1100°C in nitrogen ambient. We assign these emitters to SiN/SiO₂-interface-related defects, which can consist of N-Si-O bonding configurations resulting in defect states in the band gap.

At room temperature, quantum emitters in SiN exhibit high brightness, producing a photoemission rate of up to 10⁶Hz (Fig.1a), single-photon purity of $g^{(2)}(0) < 0.2$ without spectral filtering or background corrections (Fig.1b, inset), and stable emission [1]. These characteristics make them promising for applications in quantum communication protocols based on single-photon states such as quantum key distribution (QKD) with polarization-encoded qubits, which do not require photon indistinguishability and can operate at ambient conditions.

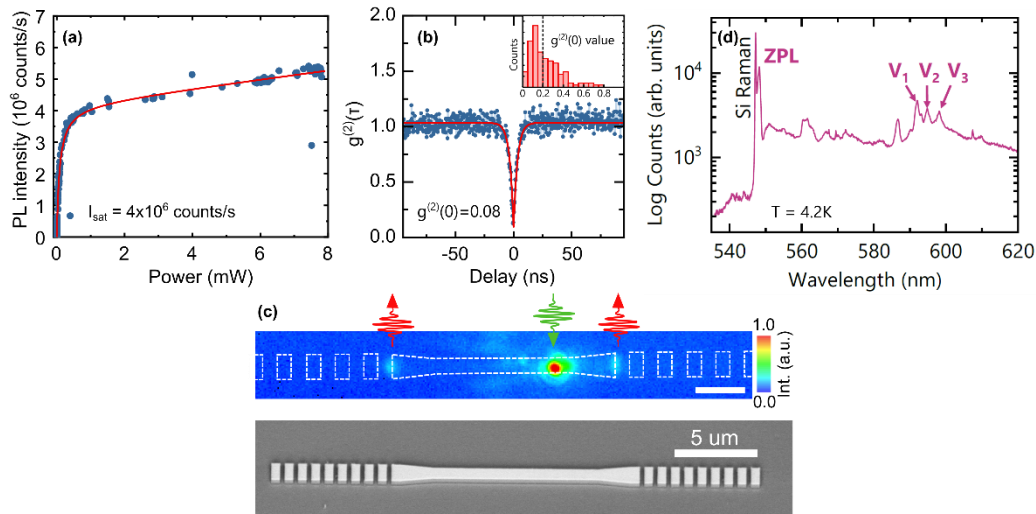


Figure 1. (a) Emission saturation curve. (b) Second-order autocorrelation histogram $g^{(2)}(\tau)$. Inset: histogram of $g^{(2)}(0)$ values distribution obtained from 130 emitters. (c) Top panel: coupling of emission from a single-photon source to a waveguide mode captured by CCD. Bottom panel: SEM images of a fabricated waveguide [2]. (d) 4.2K spectrum of a representative emitter showing the presence of a ZPL and vibronic peaks [3].

Pursuing on-chip integration, we also studied the monolithic coupling of single-photon sources with photonic components by fabricating planar waveguides from SiN layers containing a high density of intrinsic quantum emitters (Fig.1c) [2]. We found that emitters retain their photophysical properties after waveguide fabrication. We demonstrated coupling of single-photon emission into the waveguide mode by performing second-order autocorrelation measurements of the light outcoupled off the photonic chip. The outcoupled photon rate was measured to be $\sim 6 \times 10^3$ Hz, which can be further improved using topology-optimized couplers [4] and techniques for precise positioning of emitters within waveguides [5].

To investigate the possibility of using SiN defects for more advanced quantum photonic applications, we characterized intrinsic single-photon emitters in SiN at cryogenic temperatures to study the fine structure of the optical transitions and dephasing mechanisms, and evaluate their potential for the generation of indistinguishable photons [3]. Specifically, we perform temperature- and time-resolved photoluminescence studies of SiN quantum emitters to reveal optical transition wavelengths, linewidths, and photon antibunching from 4.2K to 300K. At cryo-temperatures, the zero-phonon line (ZPL) becomes more prominent, allowing us to address its wavelength distribution, and inhomogeneous and temperature-dependent homogeneous broadening. We found that the main broadening mechanism at 4.2K is spectral diffusion, which exhibits dependence on the excitation power and can be hence mitigated by low-power excitation at resonance frequencies. Importantly, time-resolved photoluminescence spectroscopy allowed us to resolve individual emission peaks with instrument-limited linewidth, which calls for further Hong-Ou-Mandel interferometry measurements to quantify photon indistinguishability beyond this limit. Moreover, we observe at cryo-temperatures a series of narrow emission lines red-shifted relative to the ZPL transition, which is tentatively assigned to vibronic sidebands. The rich structure of the vibronic modes further corroborates the assumption of the more complex defect structure, which could include N-Si-O bonding configurations forming at the SiN/SiO₂ interface (Fig.1d).

The ongoing work on intrinsic single-photon emitters in the SiN photonic platform is focused on improving their figures of merits required for applications in quantum information processing. For example, the brightness of SiN quantum emitters can be substantially improved by employing enhancement of spontaneous emission in plasmonic cavities. Moreover, plasmonic enhancement may allow emission rate speed-up to the level sufficient to overcome the rate of decoherence processes and generation of indistinguishable photons at non-cryogenic temperatures [6].

References

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