Indistinguishable photons from deterministically integrated single quantum dots in heterogeneous GaAs/Si_3N_4 quantum photonic circuits

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Abstract: With *in situ* electron beam lithography we deterministically integrate single InAs quantum dots into heterogeneous GaAs/Si_3N_4 waveguide circuits. Through micro-photoluminescence spectroscopy, we show on-chip quantum dot emission of single, post-selected indistinguishable photons into Si_3N_4 waveguides.

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Integrated silicon photonic circuits offer low-loss, reconfigurable, complex and scalable waveguide (WG) circuits, and as such, they hold great potential for advanced quantum optics like boson-sampling requiring high-rates of identical photons in many well-defined spatial modes. Incorporating single quantum emitters as single photon sources and optical non-linearities in such circuits yields an efficient light-matter interface enabling the fabrication of highly functional quantum photonic chips [1].

To date, Stranski-Krastanov (SK) InAs quantum dots (QDs) have shown superior degrees of two-photon interference (TPI), thus exhibting the highest potential for advanced quantum optics. Such QDs have succesfully been integrated into Si_3N_4 WG-coupled single-phothon sources in a heterogeneous GaAs/Si_3N_4 platform, with no deterministic control of spatial location [2]. Moving towards multiple emitters and scalable fabrication methods, deterministic fabrication of hybrid nanophotonic structures with precisely positioned, pre-selected QDs is necessary. Here, we use cryogenic cathodoluminescence (CL) spectroscopy and determinisitc *in situ* electron beam lithography (EBL) [3] to produce hybrid GaAs/Si_3N_4 WG devices containing precisely aligned, single SK InAs QDs. These QDs act as on-chip, Si_3N_4 WG-coupled sources of on-demand single photons. Our precise emitter positioning in the center of the nanostructure allows us to observe for the first time post-selected indistinguishable photons from a single InAs QD in a hybrid quantum photonic device.

Fabrication started from a heterogeneous bonded sample wafer shown in Fig. 1 a) comprising 3 μm SiO_2, 250 nm Si_3N_4, 100 nm SiO_2 and 190 nm of GaAs containing SK InAs QDs at its center [2]. As visualized in Fig. 1 b), we used CL scans on the EBL resist coated sample at 7 K temperature to locate single InAs quantum dots with an accuracy of about 55 nm. Immediately afterwards we patterned tapered nanowaveguide structures ($\geq$400 nm width, 100 nm tip width) at the QD positions using proximity-corrected grey-scale *in situ* EBL [3]. Alignment markers were patterned at a well-defined distance to the QDs. Even though Si_3N_4 and SiO_2 are insulators, we were able to find EBL parameters (20 kV acceleration voltage, 0.5 nA beam current) that allow QD localization and EBL patterning without excessive sample charging.

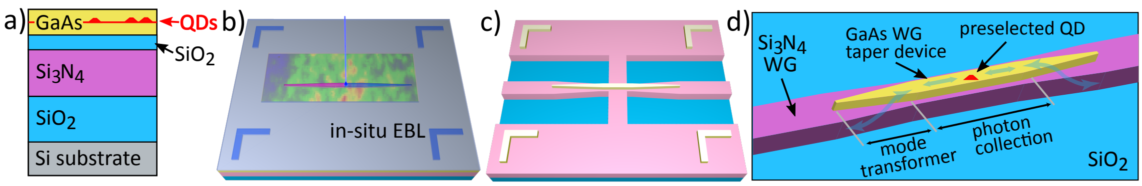

Fig. 1. a) Schematic sample stack b) Visualization of the *in situ* EBL process c) Schematic drawing of the final device d) Visualization of the device functionality

After etching, we continued with 100 kV EBL to define the Si_3N_4 WGs, obtaining the hybrid device shown schematically in Fig. 1 c). As seen in Fig. 1 d), emission from the preselected QD is captured by the 5 μm long

GaAs WG and lauched into the Si_3N_4 WG through a 20 µm mode transformer section. We confirmed successful deterministic integration through CL maps during and after fabrication as well as micro-photoluminescence (µPL) spectroscopy on the fully fabricated device, finding emission patterns that spatially and spectrally match the preselected dots. Our fabrication approach is based on entirely top-down and scalable methods.

We performed µPL spectroscopy at 7 K exciting the QDs from the top with tunable lasers and detecting the QD emission from the cleaved Si_3N_4 WG endface using optical fibers inside the cryostat. Pumping the QD p-shell at ≈904 nm gave rise to a sharp emission line at 916.3 nm, see Fig. 2 a). Using pulsed excitation, a grating filter and superconducting nanowire single photon detectors (SNSPDs) we measured the radiative lifetime to $\tau_r = (1.39 \pm 0.04)$ ns (standard error), see Fig. 2 a) inset, and the photon autocorrelation function to $g^{(2)}(0) = 0.11 \pm 0.04$ (Fig. 2 b), clearly demonstrating on-chip, triggered single-photon emission into the Si_3N_4 WG. Since etched surfaces close to the QD are detrimental to QD coherence, the emitter linewidth and the observation of TPI can act as baseline criterion for the quality of our fabrication process. Through Fabry-Perot interferometer (FPI) measurements and a Voigt line fit, we found a linewidth of the p-shell-pumped 916.3 nm line of $\Delta\Gamma_V = (2.20 \pm 0.19)$ GHz full-width at half-maximum (FWHM), see Fig. 2 c). In continuous wave excitation, we coupled one linear polarization component of the QD emission into a Hong-Ou-Mandel (HOM) interferometer and measured the TPI autocorrelation curves for parallel and orthogonal polarization configuration shown in Fig. 2 d). Through fits we determined the coherence time to $\tau_{c,HOM} = (0.33 \pm 0.12)$ ns, in which post-selected indistinguishable photons with a TPI visibility of $V \approx 0.89$ are available. (Uncertainties are 95 % fit confidence intervals.) Even though our sample is a hybrid chip, the QD linewidth and coherence times shown here are comparable with those from purely GaAs-based devices with which high degrees of two-photon interference were demonstrated, indicating the high potential our fabrication technique.

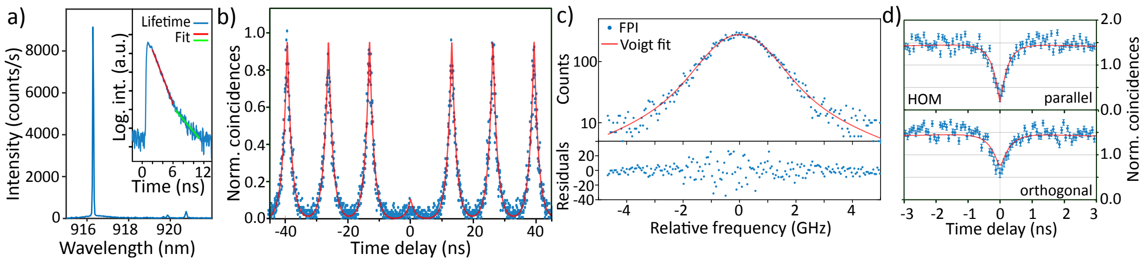

Fig. 2. µPL results on the 916.3 nm line in p-shell excitation: a) Emission spectrum. Inset: Radiative lifetime trace. b) Photon autocorrelation curve showing single-photon emission c) FPI trace giving the linewidth d) TPI autocorrelation curves showing emission of indistinguishable photons. Error bars are the Poissonian $1/\sqrt{N}$ uncertainty.

1. Conclusion

Emplyoing *in situ* EBL to a heterogeneous bonded wafer, we precisely integrated preselected InAs QDs into $GaAs/Si_3N_4$ WG devices. For the first time we demonstrate triggered single-photon emission and post-selected indistinguishable photons from a single QD in a hybrid photonic circuit. Our results show a clear path towards scalable, chip-based quantum photonics.

References

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