Heterogeneous III-V / Si_3N_4 integration for scalable quantum photonic circuits

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Abstract: We develop a scalable heterogeneous integration platform for quantum photonic circuits based on Si_3N_4 waveguides and on-chip, self-assembled InAs quantum dot-based single-photon sources. Hybrid waveguides, photonic crystals, and microring resonators are demonstrated.
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Photonic integration is as an enabling technology for photonic quantum science, providing great experimental scalability, stability, and functionality. Although the increasing complexity of quantum photonic circuits has allowed proof-of-principle demonstrations of quantum computation, simulation, and metrology [1], further development is severely limited by the on-chip photon flux that can be made available from external quantum light sources [2]. Overcoming such limitations would not only allow significant scaling of quantum photonic experiments, but would also enable quantum-level investigation of many physical processes observable on chip through nanophotonic and nanoplasmonic structures - e.g., Kerr, optomechanical and single-photon nonlinearities. Towards these goals, we have developed a scalable, heterogeneous III-V/silicon integration platform to produce photonic circuits based on passive Si_3N_4 waveguides which directly incorporate GaAs-based nanophotonic devices containing self-assembled InAs/GaAs quantum dots (QDs) [3]. As suggested in Fig. 1(a), within our platform, QD-containing guided-wave GaAs geometries, with cross section shown in Fig. 1(b), are designed to efficiently capture QD-emitted single-photons and launch them into passive Si_3N_4 waveguides, with cross section and guided mode profile as in Fig.1(d). The two constituent materials offer complementary, highly desirable features for high-performance quantum photonic circuits: InAs/GaAs quantum dots constitute the most promising solid-state triggered single-photon sources to date [4], providing bright, pure and indistinguishable emission that can be electrically and optically controlled; Si_3N_4 waveguides offer low-loss propagation, tailorable dispersion and high Kerr nonlinearities which can be used for linear and nonlinear optical signal processing down to the quantum level.

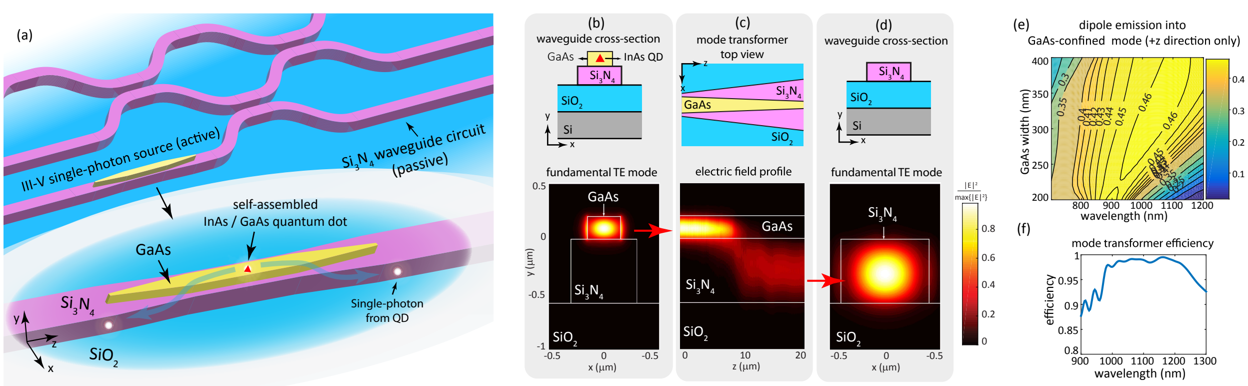

Fig. 1. (a) Conceptual heterogeneously integrated quantum photonic circuit with passive waveguide (WG) network and integrated III-V single-photon source. The source is composed of a single InAs QD embedded in a GaAs WG-based nanophotonic structure designed to efficiently capture QD emission and launch it directly into the Si_3N_4 WG. (b) and (d) top panels: cross-section of GaAs/Si_3N_4 (active) and Si_3N_4 (passive) WGs. Bottom: corresponding fundamental transverse-electric (TE) modes. (c) Top: top view of adiabatic mode transformer between active and passive WGs. Bottom: simulated electric field across mode transformer, when the mode in (b) is launched at the input. (e) QD emission coupling efficiency into the +z-traveling GaAs-confined mode of (b). (f) Conversion efficiency of the adiabatic mode transformer in (c).

Finite-difference time-domain simulations indicate, in Fig. 1(e), that capture of QD emission into the GaAs-confined guided mode of Fig. 1(b) can exceed 45 % in the $+z$ propagation direction (90 % in both $+z$ and $-z$), for optimized GaAs waveguides. The adiabatic mode transformer of Fig. 1(c), in turn, converts single-photons carried in the GaAs-confined mode into the Si_3N_4-confined mode of Fig. 1(d) with > 95 % efficiency (see Fig. 1(f)).

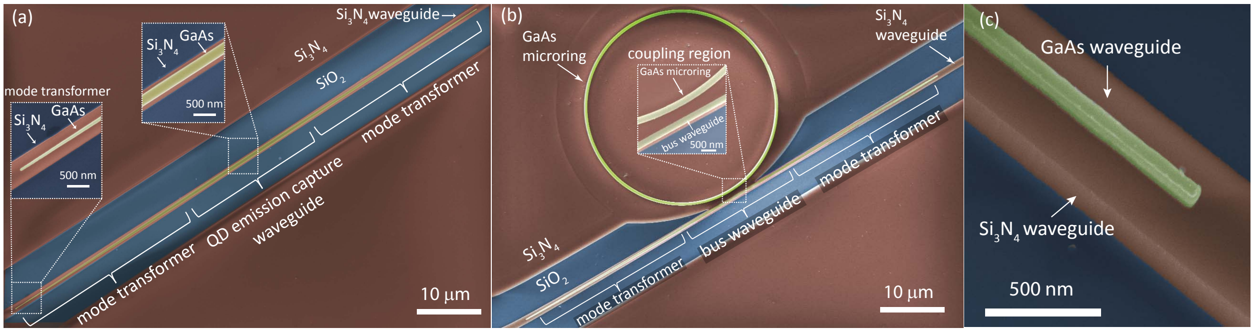

Fig. 2. False-color scanning electron micrographs of fabricated devices. (a) GaAs waveguide (yellow) over Si_3N_4 (red) waveguide. Insets: mode transformer end tip and QD photon capture waveguide. (b) GaAs microring evanescently coupled to bus waveguide over Si_3N_4 waveguide. Inset: microring-bus waveguide coupling region. (c) Tip of mode-transformer geometry, common to devices in (a) and (b).

Combining these elements, QD single-photons can be produced and launched into the Si_3N_4 network with > 90 % efficiency. Figures 2(a) and 2(b) show two types of devices created with our platform - respectively a straight GaAs waveguide and a waveguide-coupled GaAs microring resonator, both containing a high density (> 100 μm^{-2}) of InAs QDs. Both devices incorporate adiabatic mode transformers with > 90 % *measured* conversion efficiency into straight, ≈ 1 mm long Si_3N_4 waveguides. The fabricated devices were tested at 7 K inside a liquid He cryostat. As shown in Fig. 3(a), devices were pumped with a ≈ 1060 nm free-space laser beam, and the photoluminescence (PL) emitted by QDs, launched into Si_3N_4 waveguides by the adiabatic mode transformers, was collected from the Si_3N_4 waveguide facets at the cleaved chip edge with a lensed optical fiber mounted on a nanopositioning stage. Figure 3(b) shows the PL spectrum of a QD located inside a GaAs microring resonator, coupled to one of the ring's whispering-gallery modes (WGMs). The sharp line near 1125 nm corresponds to single-photon emission from an individual QD exciton, as indicated by the second-order correlation in the inset. For a second microring device, we demonstrate, in Fig. 3(c), strong control of spontaneous emission rate for a single QD exciton at ≈ 1111 nm (labeled X) coupled to a WGM that is spectrally tuned using a N_2 gas deposition technique [3].

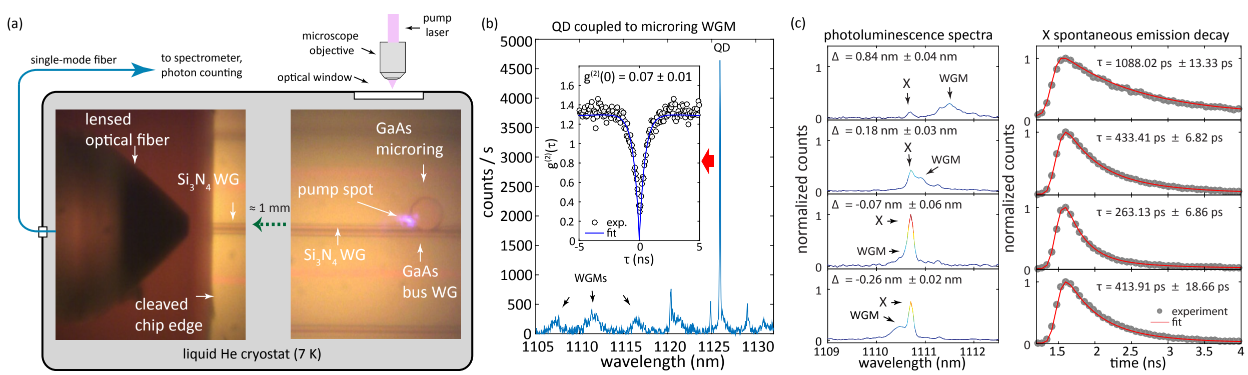

Fig. 3. (a) Cryogenic micro-photoluminescence setup. Optical micrographs: GaAs microring pumped by laser beam (right); PL collection fiber aligned to ≈ 1 mm long Si_3N_4 waveguide facet at chip edge (left). (b) PL spectrum of single QD exciton coupled to a GaAs microring whispering-gallery mode (WGM). Inset: second-order correlation for the QD emission. (c) Left panel: PL spectra for single QD exciton (X) coupled to a GaAs microring resonator, as the detuning Δ between X and the WGM is varied. Right panel: corresponding PL decay traces, with lifetime τ.

Together with our recently developed photoluminescence imaging-based technique, which allows the streamlined creation of GaAs devices with deterministically positioned InAs QDs [5], our integration platform will enable a new class of highly efficient and versatile integrated quantum photonic chip-scale devices [3].

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