Reconfigurable Hybrid Quantum Photonic Circuits

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ABSTRACT

In this paper, we realize hybrid quantum photonic circuits, combining III-V quantum sources, silicon nitride photonics, piezo-electric crystals, and superconducting materials. We developed a pick and place technique to deterministically integrate on-demand single photon sources with silicon nitride waveguides. We also show that we are able to configure the photonic circuit and control the emission properties of the quantum sources using strain-tuning. Finally, we build a full quantum transceiver consisting of a nanowire quantum dot source, a single stage ring resonator filter, and a waveguide-coupled superconducting single photon detector, all on a single chip.

Keywords: Quantum dots, waveguides, piezoelectric, SNSPD, ring resonators, silicon nitride

1. INTRODUCTION

Photons are ideal carriers for quantum information, they travel at the speed of light with possibility of several degrees of freedom for encoding such as polarization [1], time-domain [2,3], frequency-domain [4], and even combinations of more than one coding schemes [5,6]. In order to take advantage of the potential computation and communication applications photons offer, large scale integrated systems with on-demand single photon sources need to be realized. There are generally two schemes to generate single photons on-chip, either through non-linear interactions [7-9], or using bright optical transitions in atoms-like structures [10-13]. Each approach has its own advantages and disadvantages in terms of the photonic circuit quality, on-demand emission of photons, and control of the quantum source properties. Here we combine III-V quantum sources with silicon nitride photonics[14-16], piezoelectric crystals[17], and superconducting nanowire single photon detectors[18] to realize different hybrid systems that surpass the limitations imposed by each material platform enabling new functionalities and applications.

2. Strain-reconfigurable hybrid photonic circuits

Strain is a particularly attractive tuning mechanism for quantum emitters and circuits, as it provides negligible thermal budget which is compatible with integration of superconducting single photon detectors. Our goal is to build hybrid quantum photonic circuits directly on a piezoelectric substrate[17]. We start with a commercially available PMNPT crystal and perform a polishing routine to smooth the surface for photonic circuit integration (RMS roughness 22.5nm). We metallize top and bottom surfaces forming contacts to apply electric field across the substrate [17]. We form the photonic layer by depositing bottom cladding of silicon oxide and a waveguide core layer of silicon nitride. Next, we employ electron beam lithography and reactive ion etching to form different photonic elements like waveguides and resonators in the silicon nitride layer. In order to combine the circuits with III-V quantum sources, we developed a pick and place technique to transfer single InP/InAsP nanowire quantum dots and deterministically couple them to the waveguides on the piezoelectric substrate. To increase the strain transfer between the piezoelectric substrate and the quantum emitter, we deposite a thin layer of silicon nitride and silicon oxide to anchor the nanowire to the substrate[17]. Figure 1a shows an artistic representation of the device, while Figures 1b and 1c show SEM images of the nanowire quantum dot and the ring resonator filter[17].
Applying electric field across the piezoelectric crystal exerts biaxial strain which is transferred to the top photonic layer hosting the quantum emitters. In Figure 2a, we show second order correlation function of the nanowire quantum dot with multiphoton emission probability $g^{(2)}(0)=0.1\pm 0.04$, well below the classical limit. Figures 2b and 2c show tuning of the quantum emitter and a ring resonator filter, respectively, for different voltages applied to the piezoelectric crystal\cite{17}.

![Figure 1](image1.png)

**Figure 1.** (a) Artistic representation of a silicon nitride photonic waveguide coupled to nanowire quantum dot, all fabricated on piezoelectric substrate. (b) SEM image of nanowire QD coupled to SiN waveguide. (c) Ring resonator filter fabricated on piezoelectric substrate.

### 3. On-chip quantum transceiver

Our ultimate goal is to generate, manipulate, and detect quantum states of light on-chip. Superconducting nanowire detectors are very attractive for detecting quantum states of light on-chip, they can be evanescently coupled to photonic waveguides, and they offer low dark counts with high time resolution. High performance single-photon detectors require sputtering high-quality superconducting films and precise control over the nanowire dimensions during lithography and etching steps. Any imperfections in the nanowire width will affect the performance of the detector by limiting the device switching current well below its theoretical critical current. Here, we developed a deterministic approach to couple only the best detectors to our photonic circuits and quantum sources. In this proof of concept, we realized the circuits on a silicon substrate. We start by sputtering NbTiN films on an oxide bottom cladding grown on a silicon wafer. Next, we perform electron beam lithography and dry etching to realize an array of detectors. After testing all of the detectors and identifying the best performing ones, we deposit silicon nitride as photonic guiding layer. Next, we pattern the photonic circuit to couple waveguides only to the best performing detectors. Finally, we transfer nanowire quantum dot to the photonic circuit chip. The process is deterministic, we test all the detectors and quantum sources independently, then build any arbitrary circuit configuration with the desired emission and detection characteristics\cite{18}.

Figure 3a shows SEM image of the selected superconducting detector, it shows detection saturation at 80\% of its critical current with flood illumination, high critical current of 11.6 $\mu$A, and timing-jitter of ~23 picoseconds as shown in Figure 3b. We excite the nanowire QD using 515 nm pulsed laser. The wavelength is chosen within the absorption window of silicon nitride, so that the waveguide core acts as a natural filter to suppress the pump and pass only the single photons emitted from the QD at ~880 nm. We filter the emission of the QD using a ring resonator filter, terminated with superconducting detector at the drop port to detect the QD emission. Using a time-resolved start-stop correlation measurement with the laser signal, we measure the QD signal decay time of 0.62 ± 0.02 ns.

![Figure 2](image2.png)

**Figure 2.** (a) Second order correlation function waveguide integrated nanowire quantum dot, $g^{(2)}(0)=0.1\pm 0.04$. (b) Tuning of waveguide-coupled nanowire QD emission as a function of the voltage applied to the piezoelectric crystal. (c) Tuning drop port transmission of a ring resonator filter with voltage applied to the piezo.
4. CONCLUSIONS

We presented our approach for realizing reconfigurable quantum photonic circuits. We showed that strain can be used to tune waveguide-integrated quantum sources and reconfigure integrated optical elements on-chip. Additionally, we realized a full quantum transceiver on-chip from generation to detection, with high control over the detector characteristics, and the quantum source properties in terms of emission wavelength and brightness. We measured the emission lifetime of a nanowire quantum dot with waveguide-coupled detector with 23 picoseconds timing-resolution. We believe that the presented results are very important for the advancement of quantum integrated photonics, with applications for quantum communication, computing, and sensing.

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