Silicon Quantum Photonic Integrated Circuits Comprising Superconducting Nanostripe Single-Photon Detectors

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Abstract: We report on design, fabrication, and characterization of silicon quantum photonic integrated circuits comprising superconducting nanostripe single-photon detectors integrated with dielectric optical waveguides. In order to enhance absorption of photons by the superconducting nanostripes, the detectors are located directly on the dielectric waveguide core.

1. Introduction. Traveling-wave superconducting nanostripe single-photon detectors (TW SNSPDs) integrated on Si substrates are expected to be the basic photon counting and sensing tools for future silicon quantum photonic integrated circuits (SiQuPICs). SNSPDs are currently the best detectors for counting and sensing photons over a wide range of wavelengths, from visible light to mid-infrared range. They can reach close to 100% detection efficiency, which is absolutely critical for the successful demonstration of high-performance quantum systems.

The most common SNSPD design consists of large-area (typically 10×10 μm^2) square meanders, with photons approaching the device at the direction normal to the detector plane [1]. Such approach is not suitable for SiQuPICs, since the SNSPD sensing element, a superconducting nanostripe, must be in-plane, with the incoming photon flux guided by waveguide. This requires a different, non-meander geometry. For an SNSPD efficiently coupled to a dielectric optical waveguide, the best device geometry is a traveling-wave structure, described for the first time in [2] and more recently reviewed in [3]. In this paper, we focus on integration of TW SNSPDs with passive optical waveguides on a single Si chip.

2. SiQuPIC Description. In our design, illustrated in Fig. 1, the waveguides have a 1-μm-wide Si_3N_4 core, with core thickness varying from 100 to 300 nm, deposited on top of a Si substrate with 8-μm-thick layer of SiO_2. The waveguide core is buried in SiO_2 cladding, extending laterally by4 μm on either side, and covered with additional 6 μm of SiO_2. Single photons are inserted through an optical fiber coupled to the top left waveguide. In order to maximize the coupling efficiency between a fiber carrying photons from an external source and the on-chip waveguide, a narrow funnel-like taper is fabricated at the edge of the chip, such that the guided mode profile in the fiber closely overlaps with the mode profile in the straight section of the funnel-taper [4]. A Y-junction splitter directs the photons either to an external detector located at the end of another single-mode fiber coupled to the output waveguide, or to a U-shaped TiNbN TW SNSPD in the lower section of the chip in Fig. 1. The superconducting nanostripe centered on the waveguide axis is deposited directly on top of the Si_3N_4 core, so that the evanescent field outside the core could be absorbed by the stripe. If the interaction distance is long enough, the probability of a photon being absorbed should be close to 100%. The dimensions of the TiNbN nanostripes are 100 nm in width and 100 μm in length, with the nanostripe thickness varied between 4 and 16 nm. The number of straight sections in meandering SNSPDs was varied from 1 to 4 between different devices, with 100-nm separation between parallel sections.

3. SiQuPIC Fabrication. The fabrication process started with deposition of the SiO_2 bottom cladding on a Si wafer using a Trion Orion III chemical vapor deposition (CVD) system, followed by the deposition of the Si_3N_4 core material using the same system. A blanket layer of TiNbN was then deposited using a Kurt J. Lesker PVD 75 physical vapor deposition system. The next step was to pattern the NbTiN nanostripes using a JEOL JBX-6300F electron beam lithography system with an acceleration voltage of 100 kV. After development of e-beam resist, an Oxford Instruments Plasmalab80Plus Reactive Ion Etching tool was used to etch/pattern the NbTiN nanostripes, with SF_6 as the etchant gas. A Heidelberg MA150 maskless photolithography aligner (MLA) was then used to write the pattern of the waveguide core. Subsequently, the waveguide core was defined using a Plasmatherm Apex SLR fluorine inductively coupled plasma (ICP) etching reactor. A CHF_3-based etch chemistry was used to perform the etching. The successive step was to deposit the top cladding of SiO_2, using again the Trion Orion III CVD system. The Heidelberg MA150 MLA was used again to write the pattern of the lateral waveguide claddings. A Temescal FC-

2000 e-beam evaporation tool was then used to deposit a 400-nm-thick Ni layer, followed by a lift-off process. This resulted in Ni emulating the shape of the waveguide structure. This Ni layer served as hard mask that was utilized to preserve the shape of the waveguide structure during the dry etching process. Therefore, our final step was to define the waveguide structure by using the same Plasmatherm Apex SLR fluorine Inductively Coupled Plasma (ICP) etching reactor. After the 14-µm-deep etching, the Ni layer was removed using a wet etching process.

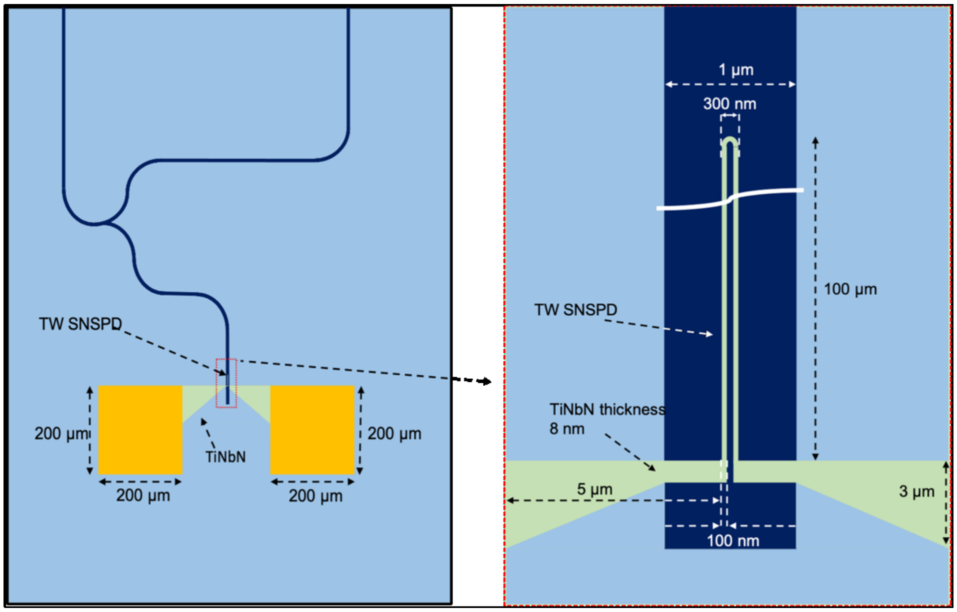

Fig. 1. Design of a TW SNSPD SiQuPIC suitable for a direct integration with a quantum information circuit on a single silicon platform. The left panel shows the entire element together with input and reference optical waveguides, while the right panel (inset) presents the TW SNSPD in detail, placed directly on top of a dielectric waveguide core.

4. Device Characterization

Cryogenic experiments were performed using a customized HYPRES ICE-T24B cryostat, with inserted Corning ClearCurve ZBL (zero-bend-loss) single-mode fibers for optical signal input and output. An attenuated light from an external 1.55-µm semiconductor laser was coupled to the fiber, butt-coupled to the chip. The light was then sent to a 50-50 splitter, with one arm redirecting the photons to an output fiber for monitoring and quantum tomography purposes, and the other arm connected to the SNSPD. Measured parameters, such as dark count rate, detector efficiency, recovery time, timing jitter, *etc*. will be reported at the conference.

5. Conclusion

Our results confirm that the waveguide-coupled TW SNSPD is, in general, a very promising detector scheme for SiQuPICs, ideally suited for cryogenic quantum information processing demonstrations.

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7. References

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