Transfer-Printed Single-Photon Detectors on Arbitrary Photonic Substrates

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Abstract: We demonstrate the integration of superconducting single-photon detectors onto arbitrary photonic substrates via transfer printing. Using this method, we show single-photon detection in a lithium niobate on insulator photonic circuit.

1. Introduction

Quantum photonic integrated circuits (PICs) are a promising candidate for large-scale quantum information processing, and require single-photon detection for quantum state preparation, gates, and readout [1]. Superconducting nanowire single-photon detectors (SNSPDs) are among the best single-photon detectors today due to their high efficiency, broadband operation, low dark counts, fast recovery times, and low timing uncertainty [2].

A major challenge is the integration of SNSPDs onto photonic substrates and PICs. This is due to 1) material incompatibility, 2) limited yields for SNSPD fabrication, and 3) limited control over the substrate fabrication process, such as in commercial foundries. Previous work on hybrid integration of SNSPDs [3] required PIC substrates with stringent geometries such as on-waveguide shallow metal lines, incompatible with most commercial foundries and PIC fabrication processes. A particularly challenging substrate is lithium niobate on insulator (LNOI). LNOI brings strong optical nonlinearities to PICs, and is thus finding classical and quantum applications in frequency conversion, high speed modulation, and photon generation [4]. However, integration of SNSPDs in LNOI PICs has proven challenging due to the aggressive fabrication processes required for lithium niobate, and, only recently, SNSPDs were integrated on LNOI with limited success using highly specialized fabrication flows [4].

Here, we demonstrate the integration of single-photon detectors onto arbitrary substrates using transfer printing, and use this method to integrate SNSPDs on a SiO_2 substrate and on LNOI PIC waveguides.

2. Description and fabrication

Our method, shown in Figure 1a, relies on transfer printing of SNSPD chiplets onto existing photonic substrates. The only requirements for the PIC substrates are access to waveguides and to nearby contact pads, requirements fulfilled by all PIC commercial foundries and most in-house PIC fabrication processes. Our method relies on SNSPD chiplets that combine a NbTiN layer containing SNSPDs and contact pads with an under-etched silicon nitride (SiN) frame. The SNSPDs consist of a hairpin detector coupled to a series inductor into contact pads. For our LNOI devices, our design efficiencies were >90%.

The device fabrication consists of the fabrication of 1) SNSPD chiplets, 2) substrate, and 3) SNSPD on substrate integration. The SNSPD chiplet fabrication followed [5] resulting in NbTiN SNSPDs on SiN chiplets. The LNOI chip was fabricated following [6], and includes low-loss LN waveguides with gold electrodes. We then performed hybrid integration of the combined SiN-SNSPD chiplets onto blank chips or on-chip waveguides using a home-built polymer stamp transfer printing setup. To electrically connect the SNSPDs, we locally deposit metal between the transfer-printed NbTiN pads and the on-chip metal pads using a focused ion beam.

We demonstrate integration on two kind of substrates: a SiO_2 chip, and a LNOI PIC chip. The SiO_2 chip was fabricated via lift-off of Ti-Au contact pads onto a SiO_2 on Si substrate. Our LNOI devices (Fig 1b) consist of an edge coupler for optical input, coupled into a directional coupler that splits the incoming light into 1) a loopback going back to a second edge coupler used for input power calibration, and 2) a socket for SNSPD hybrid integration. The SNSPD socket consists of a reduced-width waveguide, designed to enhance the interaction of the light with the SNSPD chiplet; and nearby metal pads for electrical contacting.

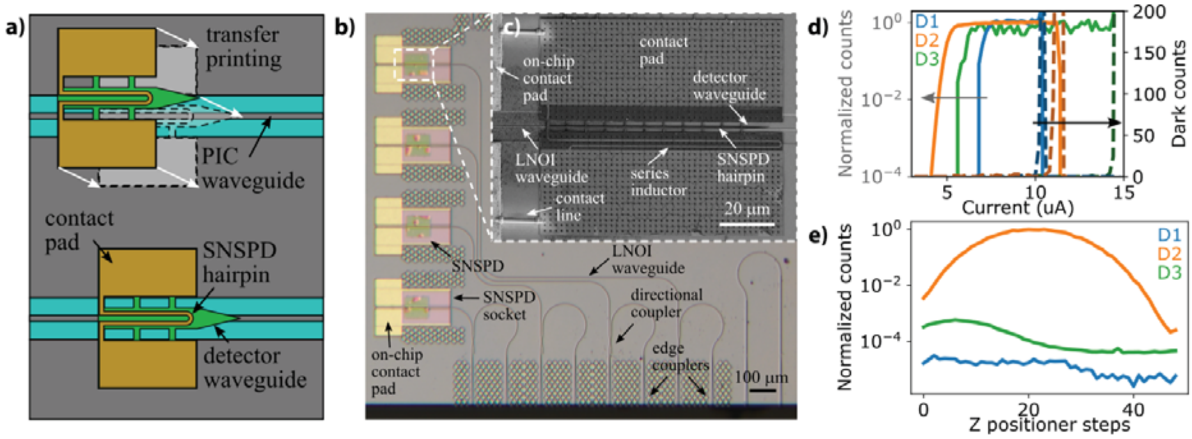

Fig. 1. a) Schematic of our hybrid integration process. b) Optical micrograph of the LNOI PIC with integrated SNSPDs. c) Scanning electron micrograph of a transfer-printed SNSPD. d) Photon and dark (dashed) count rates for our three detectors. e) Scanning our fiber array out of the chip plane (Z axis) yields 40 dB extinction between waveguide-coupled (D2) and uncoupled (D1, D3) SNSPDs.

3. Results and discussion

We perform our measurements inside a 1.3 K cryostat containing an optical probe station with active fiber-chip alignment. Light was coupled via cryogenic fiber feedthroughs into a fiber array aligned to the chip facet via micropositioners. Transfer-printed SNSPDs were electrically connected to a room temperature biasing and amplification stage via a printed circuit board and cryogenic RF lines. Our SNSPDs were biased using current sources connected to bias Ts, and the output pulses undergo room temperature amplification before reaching our counter.

Figure 1d shows our photon counting results. We transfered one SNSPD on our SiO_2 sample and observed saturating photon counts at visible wavelengths with a critical current of 12 μA. Out of 4 LNOI transferred devices, we observe 3 working devices. The non-working device clearly showed a fabrication defect and an order of magnitude lower room-temperature resistivity. For our working devices, we observed clearly saturating photon counts at 650 nm wavelength with critical currents between 10 and 15 μA, and low dark counts (Fig. 1d). We confirmed waveguide-coupled photon detection by displacing our fiber-array near the optimum coupling condition for one of our waveguides while measuring SNSPD counts with our three detectors, and show 40 dB extinction between coupled and uncoupled SNSPDs (Fig. 1e). Using our integrated loopback calibration, we measured SNSPD efficiencies of 0.3, 4.2, and 8.6% for detectors D1, D2, and D3 respectively. For detector D2, we measured a 250 ps jitter. Our limited efficiencies are due to transfer printing misalignment, visible under a scanning electron microscope, and will be improved via an optimized process.

4. Conclusion

We introduced a method for integration of single-photon detectors onto arbitrary photonic substrates, and demonstrated waveguide-coupled SNSPDs integrated onto LNOI PICs. Our work enables the integration of high-quality single-photon detectors into quantum PICs, critical for large-scale quantum information processing.

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