Modeling of Traveling-Wave Superconducting-Nanowire Single-Photon Detectors

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Abstract: We report on SPICE circuit modeling of traveling-wave superconducting-nanowire single-photon detectors integrated with Si_3N_4/SiO_2 optical waveguides.

1. Introduction

Photonic devices create a particular excitement in the context of quantum information processing (QUIP), since they combine low decoherence rate and high propagation speed, combined with a large number of degrees of freedom of light, such as polarization, spatial or temporal modes, wavelength, and angular momentum. QUIP photonic devices include single- or entangled-pair photon sources, passive optics to coherently mix photonic modes, active optics and delay lines to reconfigure those modes, high extinction ratio filters, and single-photon detectors. Individually, these devices form the basis for implementation of future silicon quantum photonic integrated circuits (SiQuPICs). In this paper, we focus on traveling-wave superconducting-nanowire single-photon detectors (TW-SNSPDs) coupled to passive Si_3N_4/SiO_2 optical waveguides, integrated on a single Si chip. SNSPDs are currently the best detectors for counting and sensing photons over a wide range of wavelengths, from visible to mid-infrared. They can reach close to 100% detection efficiency, which is absolutely critical for the successful demonstration of high-performance quantum systems.

2. Device Design

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 nanowire, must be in-plane, with the incoming photon flux guided by a 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 our implementation, the superconducting nanowire is deposited directly on top of a Si_3N_4 core, and covered with SiO_2 cladding, thus maximizing the probability that the evanescent field outside the core could be absorbed by the detector. If the interaction distance is long enough, photon detection efficiency will be close to unity.

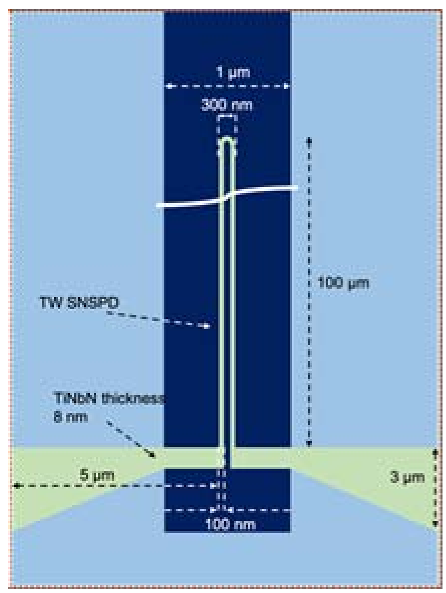

Fig. 1. Design of a TW SNSPD deposited directly on a waveguide core.

In our design, illustrated in Fig. 1, the waveguide had a 1-μm-wide Si_3N_4 core, with core thickness varying from 100 to 300 nm. In the version shown in Fig. 1, the 8-nm-thick TiNbN TW-SNSPD had the nanowire width of 100 nm and the length of each segment was 100 μm. 8 different devices have been designed. The number of meanders was varied from 1 to 2, while the segment lengths were varied between 50 μm, 100 μm, 150 μm, and 200 μm.

3. Device Modeling

The SPICE model of TW-SNSPDs was based on the equivalent circuit proposed in [4]. In this compact model, the entire device behavior is contained in its 4 terminal characteristics (the gate, the gate return, the drain, and the source). The circuit model also requires a mechanism by which a photon-detection event can be introduced. A photon absorption results in a brief hotspot that reduces the cross-sectional area available for the superconducting current to flow. To replicate this effect, we injected a 100-ps current spike into the portion of the nanowire used by the model to sense the device state. The gate and the gate-return terminals are used to simulate a photon arrival and absorption, while the drain and the source are the terminals that will be connected to an external circuit in order to simulate the current flow.

Modeling the detector allows us to select optimal device parameters, while optimizing for the overall performance and accounting for the external characterizing circuit specifications. The overall performance parameters include: the detection efficiency, the output response power, the output response recovery time, the maximum counting rate, and timing jitter. The detection efficiency increases with the overall nanowire length *L*. Timing jitter is created by the statistical absorption of the photon along the nanowire length and the propagation delay of the signal along the nanowire. The external characterizing circuit specifications include: the trigger source type (voltage source), the readout line impedance, and the readout circuit frequency response. The readout line impedance affects the detector output recovery time and can cause latching. In the superconducting state, the nanostripe behaves electrically as an inductor, where the source of the inductance is almost entirely kinetic, rather than geometric.

4. Results

Fig. 2 shows the simulated output voltage response to a single-photon absorption event, taking place at t = 20 ns. The time to recovery depends on the kinetic inductance of the detector, and increases with the overall length *L*. For the shortest detectors (*L* -= 50 µm), the calculated fall time is 1.42 ns, while for the longest ones (*L* = 200 Ω) it increases to 10.04 ns. The readout line resistance causing latching is also ncreasing with *L*. For the shortest detectors, the maximum readout line resistance is 76 Ω, while for the longest ones it increases to 205 Ω.

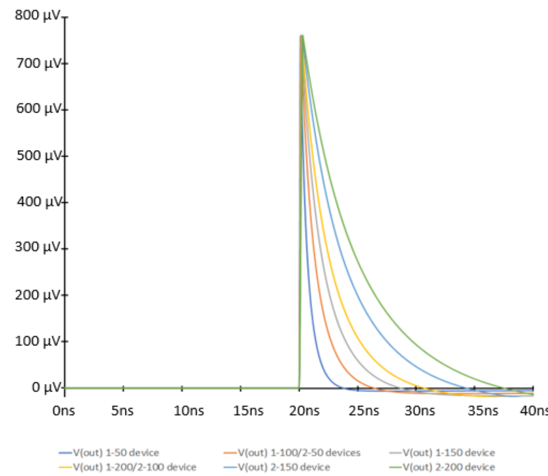

Fig. 2. Output voltage response over 20 ns for a 100-ps absorption pulse recorded at *t* = 20 ns (40 ns simulation range).

5. Conclusions

A model for TW SNSPDs has been created to facilitate the design of devices, with varying segment lengths and meander numbers. The 8 devices modeled were the single-meander TW SNSPDs with single-segment length of 50 µm, 100 µm, 150 µm, and 200 µm, and the double-meander TW SNSPDs with single-segment lengths of 50 µm, 100 µm, 150 µm, and 200 µm. Simulations show that the maximum counting rate decreases with the overall nanowire length *L*, while the output signal power increases with *L*.

6. Acknowledgments

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6. References

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