Design of Superconducting-Nanostripe Single-Photon Detectors for Silicon Quantum Photonic Integrated Circuits

Loïc H. Djamen Tchapda
Center for High Technology Materials
University of New Mexico
Albuquerque, NM, USA
dtloicherve@unm.edu

Sami A. Nazib
Center for High Technology Materials
University of New Mexico
Albuquerque, NM, USA
snazib@unm.edu

Troy A. Hutchins-Delgado
Center for High Technology Materials
University of New Mexico
Albuquerque, NM, USA
troyhutchins@unm.edu

Erika M. Sommer
Center for High Technology Materials
University of New Mexico
Albuquerque, NM, USA
emsommer514@unm.edu

Tzu-Ming Lu
Center for Integrated Nanotechnologies
Sandia National Laboratories
Albuquerque, NM, USA
emsommer514@unm.edu

Ivan Komissarov
Department of Electrical and Computer Engineering)
University of Rochester
Rochester, NY, USA
komissarov@yahoo.com

Roman Sobolewski
Department of Electrical and Computer Engineering)
University of Rochester
Rochester, NY, USA
roman.sobolewski@rochester.edu

Marek Osiński
Center for High Technology Materials
University of New Mexico
Albuquerque, NM, USA
osinski@chtm.unm.edu

2022 IEEE Photonics Society Summer Topicals Meeting Series (SUM) | 978-1-6654-3489-8/22/$31.00 ©2022 IEEE | DOI: 10.1109/SUM53465.2022.9858324

***Abstract*—We report on design of traveling-wave superconducting-nanostripe single-photon detectors for integration with silicon quantum photonic integrated circuits, with varying segment lengths and meander numbers.**

Keywords—superconducting nanostripe single-photon detectors

I. Introduction

Single-photon detectors (SPDs) are essential for many quantum information applications, including quantum key distribution, quantum communications, quantum computing, quantum sensing, etc. Over the last two decades, superconducting-nanostripe single-photon detectors (SNSPDs) have emerged as the best SPD, surpassing other types of detectors. Compared to conventional SPDs – photomultiplier tubes (PMTs) and single-photon avalanche diodes (SPADs), SNSPDs offer much faster speeds, much wider spectral range from visible to mid-infrared, lower noise, and superior quantum efficiencies (>98%).

The original design of SNSPDs involved large-area square meanders (typically 10×10 µm2) normal to the direction of incoming photons, with very small propagation distance of ~10-nm, which severely limited the detection efficiency to only 0.2% at the wavelength of 1.55 µm [1]. To improve their detection efficiency, the meander SNSPDs have been combined with optical resonators, which resulted in the detection efficiency of 57% at 1.55 µm [2]. This approach, however, is not suitable for integration with photonic integrated circuits, since the SNSPD sensing element must be in-plane, with the incoming photon flux guided by a waveguide. Instead, waveguide-integrated traveling-wave (TW) SNSPDs have been proposed and implemented [3,4].

High speed is a distinctive advantage of SNSPDs. The noise is SNSPDs is primarily associated with dark counts. The intrinsic dark counts were shown to originate from vortices crossing the nanostripe cross section, triggered by thermal fluctuations or current-assisted unbinding of vortex-antivortex pairs [5]. The lowest dark count rate demonstrated thus far is 10^{-4} counts/s [6].

In this paper, we focus on design of TW-SNSPDs coupled to passive Si_3N4/SiO_2 optical waveguides, integrated on a single Si chip for future integration with silicon quantum photonic integrated circuits (SiQuPICs).

II. Design Considerations

The main parameters dictating the choice of a superconducting material are the critical temperature T_c, critical current density, and probability of photon absorption. Among various materials used so far in SNSPDs, the highest T_c of 7 K was demonstrated using TiNbN [7]. The critical temperature of TiNbN depends on film thickness and composition, with T_c increasing almost linearly when Ti content is changed from 0% to 50%. Probability of photon absorption depends on the length of the nanostripe segments, their number, and their proximity to the waveguide core. A symmetric transverse mode profile will result in higher probability of absorption compared to asymmetric profiles in air-topped semiconductor-based waveguides that shift the mode maximum towards the substrate, as in [3], for example.

III. TW SNSPD Design

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

NSF grant ECCS-1842712; CINT User Project #2019BU0169.

Authorized licensed use limited to: UNIVERSITY OF NEW MEXICO. Downloaded on April 04,2023 at 00:41:27 UTC from IEEE Xplore. Restrictions apply.

interaction distance is long enough, photon detection efficiency will be close to unity.

In our design, illustrated in Figs. 1 and 2, the waveguide has a 1-µm-wide Si_3N4 core, with core thickness varying from 100 to 300 nm. The TiNbN film thickness is varied from 5 to 18 nm. In the version shown in Fig. 2, 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.

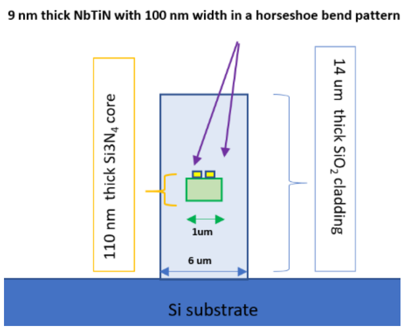

Fig. 1. Design of a Si_3N_4/SiO_2 waveguide with TW SNSPD deposited directly on a waveguide core.

To assist with the design, we developed a SPICE model of TW-SNSPDs based on the equivalent circuit proposed by Berggren *et al.* [8]. In this compact model, the entire device behavior is contained in its four 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.

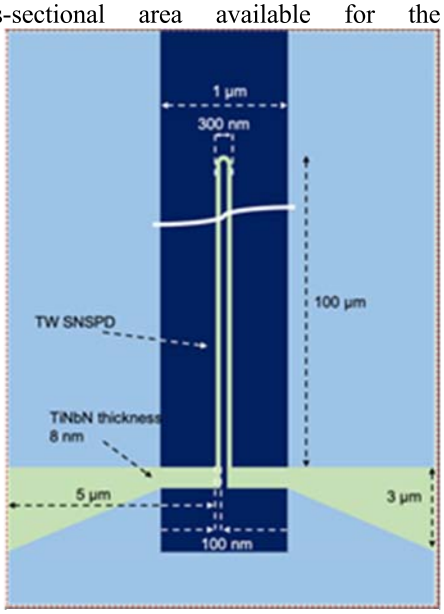

Fig. 2. Design of a TW SNSPD deposited directly on a waveguide core.

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. 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.

IV. Conclusions

We report on design of TW SNSPDs for integration with SiQuPICs, with varying segment lengths and meander numbers. Simulations show that the maximum counting rate decreases with the overall nanostripe length *L*, while the output signal power increases with *L*.

Acknowledgments

The authors acknowledge financial support from the National Science Foundation under the grant ECCS-1842712 “RAISE-EQuIP: Integrated Silicon Photonics Platforms for Scalable Quantum Systems”. This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science by Los Alamos National Laboratory (Contract DE-AC52-06NA25396) and Sandia National Laboratories (Contract DE-NA-0003525), under the User Project #2019BU0169.

References

[1] A. Verevkin, J. Zhang, R. Sobolewski, A. Lipatov, O. Okunev, G. Chulkova, A. Korneev, K. Smirnov, G. Gol’tsman, and A. Semenov, “Detection efficiency of large-active-area nbn single-photon superconducting detectors in the ultraviolet to near-infrared range”, Appl. Phys. Lett. 80 (#25), pp. 4687-4689, 24 June 2002.

[2] K. M. Rosfjord, J. K. Yang, E. A. Dauler, A. J. Kerman, V. Anant, B. M. Voronov, G. N. Gol’tsman, and K. K. Berggren, “Nanowire single-photon detector with an integrated optical cavity and anti-reflection coating”, Opt. Express 14 (#2), pp. 527-534, 23 Jan. 2006.

[3] J. P. Sprengers, A. Gaggero, D. Sahin, S. Jahanmirinejad, G. Frucci, F. Mattioli, R. Leoni, J. Beetz, M. Lermer, M. Kamp, S. Höfling, R. Sanjines, and A. Fiore, “Waveguide superconducting single-photon detectors for integrated quantum photonic circuits”, Appl. Phys. Lett. 99 (#18), Art. 181110 (3 pp.), 2011.

[4] W. H. P. Pernice, C. Schuck, O. Minaeva, M. Li, G. N. Goltsman, A. V. Sergienko, and H. X. Tang, “High-speed and high-efficiency travelling wave single-photon detectors embedded in nanophotonic circuits”, Nat. Commun. 3, Art. 1325, 2012.

[5] T. Yamashita, S. Miki, K. Makise, W. Qiu, H. Terai, M. Fujiwara, M. Sasaki, and Z. Wang, “Origin of intrinsic dark count in superconducting nanowire single-photon detectors”, Appl. Phys. Lett. 99 (#16), Art. 161105 (3 pp.), 2011.

[6] H. Shibata, K. Shimizu, H. Takesue, and Y. Tokura, “Ultimate low system dark-count rate for superconducting nanowire single-photon detector”, Opt. Lett. 40, pp. 3428-3431, 15 July 2015.

[7] R. Gourgues, J. W. N. Los, J. Zichi, J. Chang, N. Kalhor, G. Bulgarini, S. N. Dorenbos, V. Zwiller, and I. Esmaeil Zadeh, “Superconducting nanowire single photon detectors operating at temperature from 4 to 7 K”, Opt. Express 27 (#17), pp. 24601-24609, 19 Aug. 2019.

[8] K. K. Berggren, Q.-Y. Zhao, N. Abebe, M. J. Chen, P. Ravindran, A. McCaughan, and J. C. Bardin, “A superconducting nanowire can be modeled by using SPICE”, Superconductor Science and Technology 31 (#5), Art. 055010 (13 pp.), Apr. 2018.

Authorized licensed use limited to: UNIVERSITY OF NEW MEXICO. Downloaded on April 04,2023 at 00:41:27 UTC from IEEE Xplore. Restrictions apply.