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Cavity-Integrated Ultra-Narrow Superconducting Nanowire Single-Photon Detector Based on a Thick Niobium Nitride Film

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Abstract: We propose a design for cavity-integrated Superconducting Nanowire Single-Photon Detectors based on 20-nm-wide 10-nm-thick nanowires. Our simulations show that these detectors can potentially reach ~90% device detection efficiency.

OCIS codes: (270.5570) Quantum detectors; (040.5570) Quantum detectors; (040.3060) Infrared; (040.3780) Low light level

State-of-the-art Superconducting Nanowire Single-Photon Detectors (SNSPDs) [1], based on 100-nm-wide, ~4.5-nm-thick niobium nitride (NbN) nanowires, are unmatched in sensitivity (< 10^{-20} W/Hz^{0.5} NEP [2]), speed (< 2ns reset time) and timing jitter (< 35ps FWHM [3]) by any other detector technology at 1550nm wavelength. The detection efficiency ($\eta$) of SNSPDs is the product of the optical absorption of the nanowire meander ($A$, which increases with the thickness of the nanowires) and the probability of photon induced resistive state formation in the nanowire ($P_r$, which increases with decreasing cross-sectional area of the nanowires [4]). Due to the low optical absorption of 5-nm-thick NbN, state-of-the-art SNSPDs without additional optical structures have $\eta <$ 10% at 1550nm wavelength. Operational detectors based on thicker NbN (~10-nm-thick 200-nm-wide nanowires) were reported in Refs. [5, 6]. However, while thicker films have a higher optical absorption [7], they exhibit a lower $P_r$. As a result [8] these detectors showed low (< 1%) detection efficiency as well.

![Fig. 1. Ultra-narrow SNSPD. a. Measured detection efficiency ($\eta$, see Ref. [9] for further details) of SNSPD based on 30-nm-wide ~5-nm-thick nanowires as a function of bias current $I_b$ normalized by the critical current of the detector $I_c$. The detection efficiency saturated at high bias currents to ~19±2.5%. The dashed line represents the calculated optical absorption of the detector (~21%). b. Scanning electron micrograph (SEM) of an SNSPD based on 30-nm-wide ~5-nm-thick nanowires, as reported in Ref. [9].](image)

We recently reported (1) near-absorption-limited single-photon detection ($P_r = \eta/A \sim 0.9$) with SNSPDs based on 30-nm- and 20-nm-wide nanowires [9] (Fig. 1); and (2) high-fill-factor detectors [10]. These technological advances will allow us to fabricate high-detection-efficiency SNSPDs based on ultra-narrow (20-nm-wide), thick (10-nm-thick) nanowires arranged in a high-fill-factor (50%) meander. In this detector, we expect the decrease of $P_r$ due to the thicker nanowire to be compensated by reducing the width of the nanowire down to 20nm. The full potential of the detector we propose will be unleashed when integrating it with a quarter-wavelength optical cavity, which we have previously employed to increase the detection efficiency of standard SNSPDs to 57% [11]. The proposed geometry is shown in Fig. 2a. We simulated the optical absorption of the detector using a COMSOL model reported in Ref. [12]. The simulation results are shown in Fig. 2b. The simulated peak optical absorption is 96.5%. The nanowire cross-sectional area (200nm^2) of the proposed detector is comparable to the nanowire cross-sectional area of the detector in Fig. 1 (~ 150nm^2), motivating the assumption of a similar $P_r$ value. Based on the assumption of $P_r \sim 0.9$, the detector we propose is expected to have a detection efficiency of ~ 90%.
Other approaches to improving the detection efficiency of bare NbN nanowires are integration with plasmonic antennas [13] or optical waveguides [14], but these structures are challenging to fabricate as they require very precise alignment to the detector or low-temperature growth of NbN on top of photonic integrated circuit samples. The fabrication of the design we propose offers significant advantages compared to other approaches: First, the fabrication of cavities is less demanding than the fabrication of nanoantennas since no alignment to the detector is necessary. As a result we expect cavity-integrated SNSPDs to have a significantly higher yield than antenna-integrated SNSPDs. Furthermore, the proposed design poses little constraint on the accuracy of cavity thickness. As shown in Fig. 2b, a 15% variation in the cavity thickness results in a variation of < 1% in the absorption, further relaxing the fabrication constraints. Finally, the fill factor is only 50%, which reduces proximity effects during e-beam lithography.

Fig. 2. Cavity-integrated SNSPD. a. Cross-sectional view of an SNSPD based on 20-nm-wide and 10-nm-thick NbN nanowires with an integrated HSQ cavity. The pitch is 40nm (the nanowires fill 50% of the detector area). The detector is illuminated from the back of the substrate with light polarized in parallel to the nanowires. The thickness of the cavity was optimized for maximum absorption in the NbN nanowires. The optimum cavity thickness was found to be 270nm. b. Simulated optical absorption at 1550nm wavelength for the geometry shown in (a) as a function of cavity thickness.

Unlike 20-nm-wide nanowires fabricated on 4-nm-thick films, pulses from thick-film nanowires are expected to be detectable with room temperature electronics since thicker nanowires result in a larger output current diverted into the readout. However, due to the smaller relative contact area to the substrate, which serves as a low-temperature thermal bath, thicker-nanowire SNSPDs might suffer from latching [15, 16].

We are currently working on the experimental implementation of this cavity-integrated detector. The work at MIT Lincoln Laboratory was sponsored by the United States Air Force (contract #FA8721-05-C-0002). Opinions, interpretations, recommendations and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

[8] $P_f$ of the detectors demonstrated in Refs. [4,5] was small due to both the large thickness ($10\text{nm}$) and width ($200\text{nm}$) of the nanowires.