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Integrating optical waveguides with superconducting single-photon detectors

Alessandro Gaggero, Döndü Sahin, Francesco Mattioli, Roberto Leoni, Giulia Frucci, Saeedeh Jahanmirinejad, Arjan Sprengers, Johannes Beetz, Matthias Lermer, Sven Höfling, Martin Kamp, and Andrea Fiore

A new step toward full on-chip integration of active elements (single-photon detectors) and passive elements (quantum photonic circuits) enables important functionalities in quantum information processing.

Quantum information processing (QIP) enables new protocols and functionalities in communication and computing. Single photons are one of the most promising implementations of quantum bits because they exhibit very low noise. Quantum computers will enhance the computational speed for a number of important applications. For example, quantum simulators could help solve molecular dynamics problems that cannot be solved using a classical approach. The integration of key functionalities, such as single-photon generation and detection and linear processing, on the same chip is a crucial step toward optical quantum processing.

Passive quantum circuits have already been demonstrated.[1] We are trying to develop an approach that will enable full integration of active and passive devices, such as sources and detectors of single photons. Gallium arsenide (GaAs) technology is promising for the integration of quantum-dot single-photon sources and passive photonic circuitry with single-photon detectors. We chose to use superconducting single-photon detectors (SSPDs),[2] which are typically made of a thin superconducting film, usually niobium nitride (NbN) a few nanometers thick. The film is patterned as a narrow, uniform nanowire with a typical width of 30 to 100nm. The nanowire is folded as a meander for better coupling with the incident radiation and is kept at a working temperature between 2 and 4K.

In these detectors, the absorption of a single photon in the thin superconducting layer generates local suppression of the superconductivity (the so-called hotspot). Because the hotspot is usually smaller than the nanowire width, the nanowire must be biased as close as possible to its superconducting critical current to detect the arrival of the photon. If the bias current is large enough, the creation of the hotspot can trigger the transition to the normal state across the entire cross section of the nanowire. In the range of wavelengths between the near- and mid-IR, SSPDs are an interesting alternative to other single-photon detectors (indium gallium arsenide single-photon avalanche photodiodes or transition-edge sensors)[3] because, in this range, they have simultaneously exhibited high detection efficiencies, low dark count rates, and high timing resolution. In the past, we

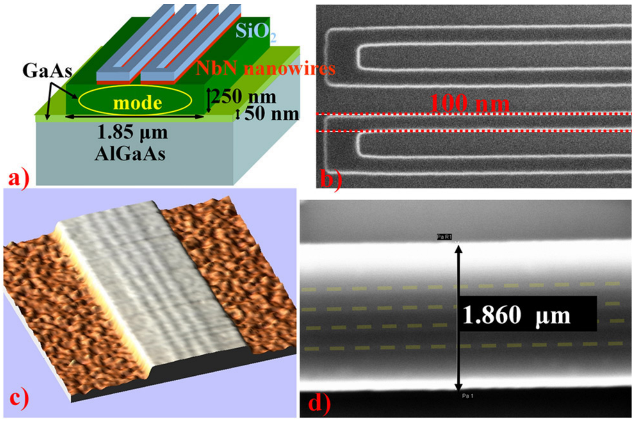

Figure 1. *(a) Schematic view of our waveguide single-photon detector (WSPD). (b) Scanning electron microscopy (SEM) image of the niobium nitride (NbN) nanowires still covered with hydrogen silsesquioxane (HSQ). Distance between red dotted lines is 100nm. (c) Atomic force microscopy enlarged view of the waveguide HSQ etching mask. (d) SEM top view of the etched GaAs waveguide covered with HSQ. Dashed lines indicate positions of the barely visible nanowires. AlGaAs: Aluminum gallium arsenide. SiO$_2$: Silicon dioxide.*

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developed an SSPD on a GaAs/aluminum arsenide distributed Bragg reflector mirror,[4] showing that full integration of active and passive elements is possible using GaAs technology.

We have demonstrated the first waveguide single-photon detectors (WSPDs), which are based on superconducting nanowires patterned on top of a GaAs/aluminum gallium arsenide (AlGaAs) ridge waveguide: see Figure 1(a).[5] A GaAs/$Al_{0.75}Ga_{0.25}As$ heterostructure is grown by molecular beam epitaxy on top of an undoped GaAs (001) substrate. On the GaAs epilayer, a 4.0nm-thick NbN superconducting film is grown by a DC magnetron reactive sputtering technique at 350°C. The detectors are fabricated using four iterations of direct-writing electron beam lithography at an accelerating voltage of 100kV. Figure 1(b) shows a scanning electron micrograph of the 100nm-wide nanowires, and Figure 1(c) shows an atomic force microscopy image of the 1.85μm-wide hydrogen silsesquioxane (HSQ) mask used to etch the GaAs ridge waveguide. Figure 1(d) shows a top view of a portion of the nanowires realigned with the etched ridge.

The WSPDs can sense the evanescent field of photons propagating in the waveguide with a maximum detector quantum efficiency of about 20%, corresponding to a system quantum efficiency (from fiber input) of 3.4%, with a timing resolution of 60ps and dead times of a few nanoseconds. Moreover, if the ridge waveguide is designed appropriately, it is possible to make the WSPD independent of the polarization of the light. Indeed, Figure 2 shows that the detector is polarization-independent because the absorption of the 50μm-long nanowires is very high for both polarizations. We also demonstrate ultracompact single-photon autocorrelators consisting of two electrically separated nanowires on top of the same ridge waveguide (see Figure 3). The particular spatial configuration of the autocorrelators allows direct measurement of the second-order autocorrelation function $g^{(2)}(\tau)$, which is usually measured in free space or by means of optical fibers with a Hanbury-Brown and Twiss interferometer[6] using a beam splitter and two distinct detectors on the two output arms. In our approach, the two nanowires sense directly the evanescent field of the same waveguide mode, making the use of a beam splitter unnecessary, similar to free-space illumination of multi-element SSPDs as shown in the literature.[7]

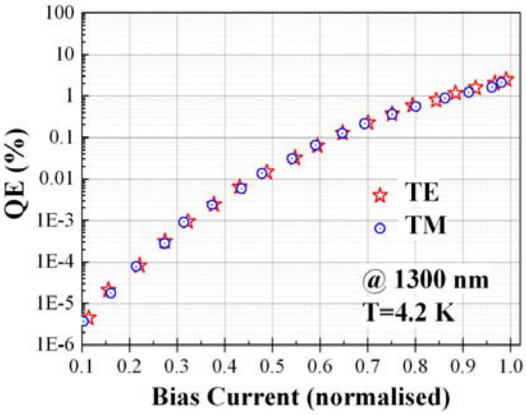

Figure 2. *Detector quantum efficiency (QE) as a function of the normalized bias current (measured for one detector in the autocorrelator in Figure 3), at 1.3μm and 4.2K with both transverse electric (TE) and transverse magnetic (TM) polarization.*

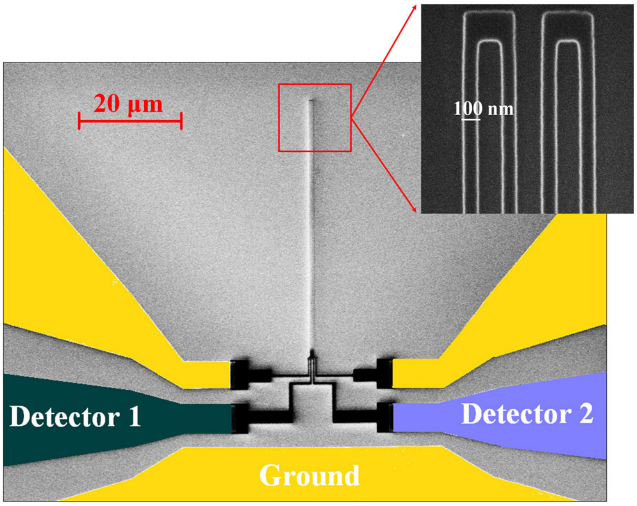

Figure 3. *Scanning electron micrograph of an integrated autocorrelator based on two nanowires on top of the same waveguide (false color). Inset: Zoomed SEM image of the 100nm NbN nanowires still covered with HSQ.*

In conclusion, our WSPDs demonstrate the first integration of an SSPD with a GaAs/AlGaAs ridge waveguide. We also show ultracompact intensity autocorrelators with a polarization-independent response. These devices enable on-chip measurement of the second-order correlation function $g^{(2)}(\tau)$ and represent the first step toward integrated photon-number-resolving detectors.[8,9] As the next step in our work, we plan to integrate, on the same chip, detectors and single-photon sources to measure $g^{(2)}(\tau)$ for single photons emitted by a single quantum dot.

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Author Information

Alessandro Gaggero, Francesco Mattioli, and Roberto Leoni
Institute for Photonics and Nanotechnologies, CNR
Rome, Italy

Döndü Sahin, Giulia Frucci, Saeedeh Jahanmirinejad, Arjan Sprengers, and Andrea Fiore
Eindhoven University of Technology
Eindhoven, Netherlands

Johannes Beetz, Matthias Lermer, Sven Höfling, and Martin Kamp
Technische Physik
University of Würzburg
Würzburg, Germany

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