Superconducting single photon detectors with minimized polarization dependence

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Superconducting single photon detectors are usually fabricated in such a way that a polarization dependence of the quantum efficiency is inevitable. Their meandering nanowire leads to a preferential polarization absorption, this is undesired in experiments where the polarization degree of freedom is used. We have designed two new geometries for which the polarization dependence is minimized: a detector with two meander-type parts oriented perpendicular with respect to each other and a spiraling detector. Focusing on individual parts of the detectors shows polarization dependent quantum efficiency. When the detectors are illuminated uniformly, the maximum polarization dependent quantum efficiency cannot be achieved, however, the polarization dependence of the quantum efficiency is minimized. © *2008 American Institute of Physics*.
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Superconducting single photon detectors (SSPDs) are strong competitors for semiconducting single photon detectors. SSPDs outperform their semiconducting counterparts with a number of properties such as recovery time,[1] low dark count rate and noise equivalent power,[2,3] quantum efficiency in the infrared,[4] and low timing jitter.[5] Because of these advantages, they were recently implemented in quantum information experiments.[6,7] In particular at telecommunication wavelengths, they show a high quantum efficiency [30% for 1.26 μm and 17% for 1.55 μm (Ref. 4)] compared to typical InGaAs avalanche photodiodes (10% at 1.55 μm). Moreover it has been demonstrated that their sensitivity expands to the mid-IR (up to 6 μm).[4] It has already been reported that the quantum efficiency of SSPDs is dependent on the polarization of the incident light.[7,8] This effect is usually unwanted as the polarization degree of freedom is often used in quantum information experiments. Here we present a solution to the problem by exploring two new geometries.

There are two reasons for the polarization sensitivity of SSPDs, both arising from the geometry of the detector, consisting of a long narrow wire (100 nm wide and approximately 500 μm long) typically arranged in a meander-type geometry to maximize the active area of the device [Fig. 1(a), lower part]. This geometry leads to an increased quantum efficiency for light polarized parallel to the wire with respect to light polarized perpendicular to the wire. The first reason for this effect is that light polarized parallel to the wire has a higher probability of being absorbed. This originates from the fact that a large number of parallel wires acts as a wire-grid polarizer.[9] Light polarized perpendicular to the wire grid causes surface charges, which screen the field and reduce the electric field intensity at the wire edges, leading to a decreased absorption. For light polarized parallel to the wire grid, the electric field intensity is uniform across the wire.[8] Anant *et al.*[8] suggested a second reason for polarization sensitivity of SSPDs as they found that the optical effect was not sufficient to describe the polarization dependence, also the intrinsic detection probability of polarization parallel to the wire is larger with respect to light polarized perpendicular to the detector.

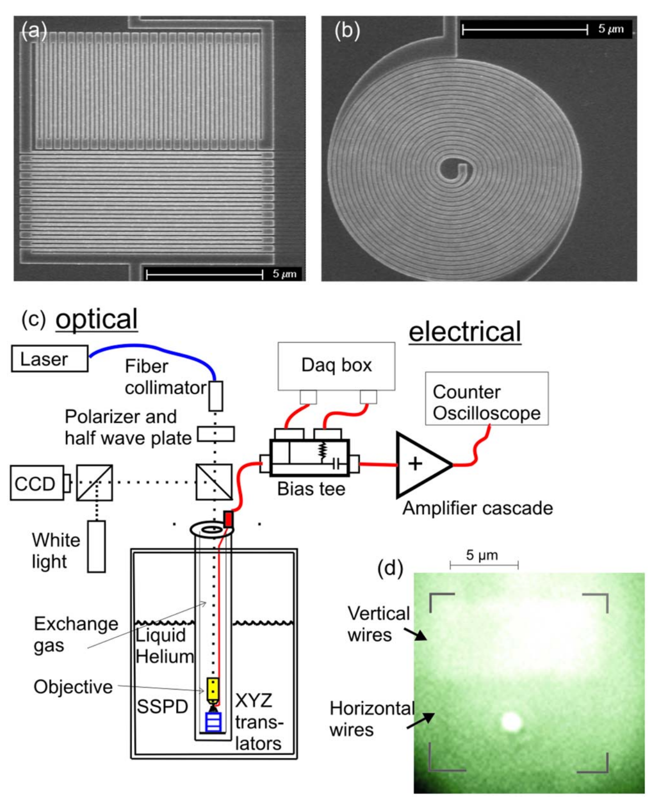

FIG. 1. (Color online) (a) SEM image of a perpendicular NbN detector. (b) SEM image of a spiraling NbTiN detector. (c) Readout system: the detector is placed on *XYZ* piezotranslators. Optical access is provided by a window. The electrical part consists of a bias tee, amplifiers (46 dB), and a pulse counter. (d) White light image of the perpendicular detector, the contours are indicated. The two directions give distinct reflections of the white light (horizontal: dark and vertical: bright). The bright spot is the laser.

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Building an SSPD consisting of two subparts of the original meander-type design, where the subparts are oriented perpendicular to each other, creates two preferential polarization absorption directions and detection probabilities are created, giving an equal quantum efficiency to all polarization directions. When we let the nanowire run in a circular geometry [Fig. 1(b)] no single preferential direction is left. This detector is minimally polarization dependent.

Detectors are made from two different materials: NbN, the material typically used for SSPDs, or NbTiN, a material recently shown to detect single photons with a very high signal-to-noise ratio.[2] A sapphire substrate with a thin NbN layer (approximately 4 nm) was commercially obtained.[10] The NbTiN detectors are made from a 6 nm layer of NbTiN sputtered on a silicon substrate at room temperature.[2] To fabricate the detectors, we follow the same procedure for both materials. At first, we make contacts of 20 nm Nb and 60 nm AuPd using electron beam lithography and liftoff technique. The thin film is patterned by reactive ion etching with a mask of hydrogen silsesquioxane, defined with e-beam lithograpy.[11] Dose modulation is used to correct for the proximity effect. Scanning electron microscope (SEM) images of the unpolarized detectors are shown in Figs. 1(a) and 1(b). The first detector type consists of two subparts, oriented perpendicular with respect to each other, each orientation filling half of the detector. The wires are 100 nm wide and 4–6 nm thick, with 50% fill fraction. The active area is $10 \times 10\ \mu m^2$. The second type consists of spiraling wires, first going toward the center of the detector, after which they spiral out. The width of the wires is again 100 nm, with 50% fill fraction, and the diameter of the detector is 10 μm.

The detection principle of SSPDs has already been described in detail.[12,13] Typically, the superconducting wire is current biased close to the critical current ($>90\%\ I_c$). When a single photon is absorbed, a part of the detector switches to a normal resistive state, giving rise to a voltage pulse. The measurement setup is shown in Fig. 1(c). The detector is placed in an exchange gas in a helium bath cryostat (tube length 1 m, with a coaxial feedthrough and optical window) on *XYZ* piezotranslators, allowing scanning and focusing. White and laser light are collimated outside the cryostat and focused in situ with a microscope objective (0.85 Numerical aperture). A white light image of a perpendicular [Fig. 1(a)] detector is shown in Fig. 1(d), revealing the exact position of the laser spot (diameter 1 μm) on the detector. The two different parts of the detector can be distinguished by the different reflection of the polarized white light (horizontal wires: dark and vertical wires: bright). The laser polarization is controlled with a polarizer and a half wave plate. The zero position of the half wave plate is set such that it gives a maximum (minimum) count rate, corresponding to the parallel (perpendicular) direction of the polarization to the horizontal (vertical) wires, i.e., the reference polarization angle is fixed with respect to the setup.

The measurements reported here were performed at 4.2 K. The device is biased from the outside via a bias tee through the coaxial connection with a constant current source and voltage pulses are led, via the bias tee again, to an amplifier cascade (total amplification: 46 dB) and measured with a pulse counter. The quantum efficiency for a wavelength of 650 nm (without polarizer) is determined to be 2.6% for the NbN perpendicular detector, 1.8% for the NbTiN perpendicular detector, and 0.6% for the NbTiN spiral detector.

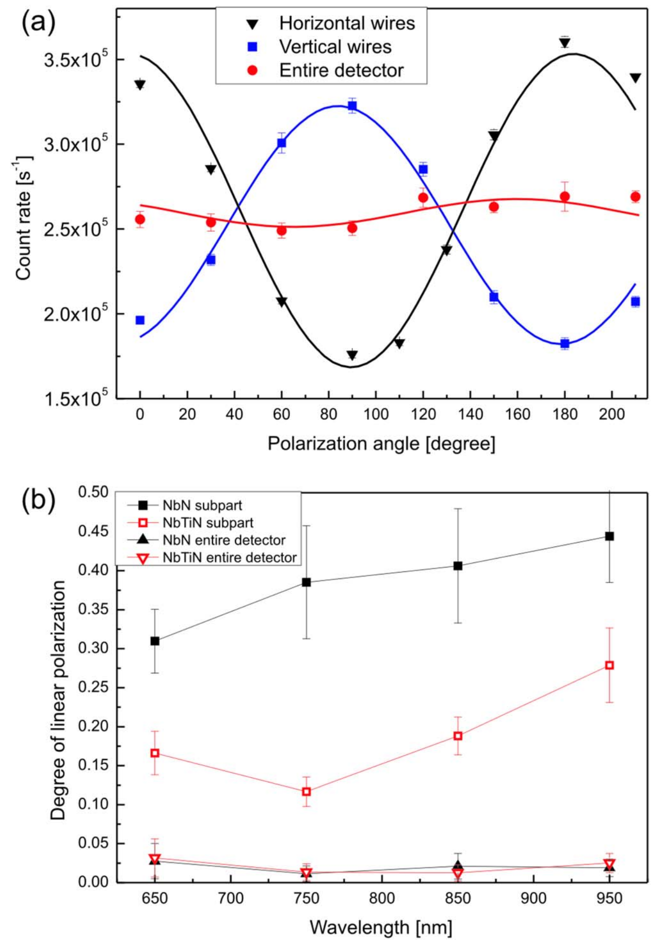

FIG. 2. (Color online) (a) Count rate versus polarization angle for the perpendicular detector made of NbN. The laser spot (wavelength 650 nm) is focused on respectively the horizontal wires (red triangles), the vertical wires (green squares) and the entire detector (orange circles). (b) Degree of polarization versus wavelength for the perpendicular detectors, made of NbN and NbTiN, with one sub-part (squares) or the entire detector (triangles) illuminated.

In Fig. 2(a), we show the polarization dependent count rate for the NbN perpendicular detector. Focusing on the two distinct (horizontal and vertical) parts of the detector give count rates shifted by 90° with respect to each other. When we illuminate the entire detector by defocusing the beam to a diameter of 8–10 μm the dependence on the polarization nearly vanishes. The count rate is then the mean of the maximum and minimum count rate when one subpart is illuminated, i.e., minimum polarization sensitivity cannot be achieved together with maximum detection efficiency. The dependence on the polarization of light can be quantified with the degree of linear polarization

$$C = \frac{N_{\parallel} - N_{\perp}}{N_{\parallel} + N_{\perp}}, \tag{1}$$

where $N_{\parallel}$ is the number of counts for light polarized parallel and $N_{\perp}$ the number of counts for light polarized perpendicular with respect to the wire. For clarity, we note that this corresponds to the maximum ($N_{\parallel}$) and the minimum ($N_{\perp}$) countrate. The degree of linear polarization versus wavelength of the perpendicular detectors made of NbN or NbTiN is shown in Fig. 2(b). It is measured by rotating the $\lambda/2$

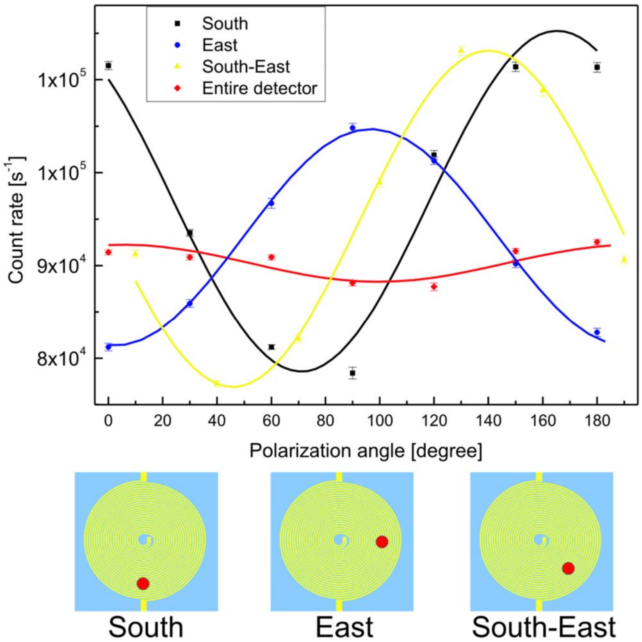

FIG. 3. (Color online) Polarization dependent count rate for a spiraling SSPD. The laser spot (wavelength 650 nm, diameter 1 μm) is focused on different regions (indicated in the lower part). When the entire active area is illuminated uniformly, the count rate exhibits almost no polarization dependence (red curve).

waveplate over 360° (corresponding to 720° of the polarization direction), and fitting a sine through the data points. When the laser is focused on one of the two subparts of the perpendicular detector, the degree of polarization ranges from 0.31 to 0.45 for a detector made of NbN and from 0.12 to 0.28 for a detector made of NbTiN. However, when we illuminate the whole detector uniformly, the degree of linear polarization is 0.03 ± 0.02.

The results for the spiraling detector are shown in Fig. 3. For this measurement, we focused the laser spot (1 μm diameter) on different regions of the detector (called south, east and south-east). Although the wires are not straight, subareas still show a polarization dependence, but the polarization angle at which a maximum count rate is measured differs for each region of the detector. The direction of the wires can be recognized, e.g., the maximum count rates for the south region is shifted by 90° with respect to the east region. The count rate versus polarization angle for three regions is shown in Fig. 3. The degree of linear polarization is 0.19 ± 0.03 for the south, 0.13 ± 0.01 for the east, and 0.19 ± 0.02 for the south-east region. When the entire detector is illuminated, the degree of polarization reduces to 0.02 ± 0.01 and also for this detector the count rate is then averaged. The fabrication yield and performance of the perpendicular and spiraling detector was almost equal. The spiraling detector has the advantage that it is more robust against misalignment because of its intrinsic symmetry.

In conclusion, we have fabricated two new SSPD geometries to overcome the problem of polarization dependence of the quantum efficiency. By using geometries with either two perpendicular preferential directions or no preferential direction, the polarization dependence can be significantly reduced.

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