Superconducting nanowire single-photon detector in an optical cavity for front-side illumination

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We have integrated superconducting nanowire single-photon detectors (SNSPDs) with an optical cavity design for front-side illumination. Our optical cavity design increases the coupling efficiency of light to the nanowire detector and enables straightforward proximity fiber-coupling for a multichannel detector system. Using a confocal optical scanning technique, we measured a significantly enhanced optical absorptance of 73% in comparison with 20% in a typical bare nanowire device at 1550 nm and 3 K. Our method of fabrication of these devices on a silicon wafer and the local optical absorptance measurement are important steps toward developing next-generation SNSPD technology. © *2009 American Institute of Physics*.
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Superconducting nanowire single-photon detectors (SNSPDs)[1] have shown impressive performance in high-fidelity quantum optics measurements. Their broad spectral response from ultraviolet to infrared wavelengths, low dark count rate (<100 Hz), and high timing resolution (less than 100 ps full width at half maximum) is unmatched by other single-photon detector technologies.[2,3] By use of these properties, important progress has been made in recent experiments regarding long-distance quantum key distribution,[4] photon-pair source characterization,[5] quantum dot single-photon source characterization,[3] and quantum gate characterization.[6]

For future applications, the detection efficiency requires significant improvement. NIST and others have been applying SNSPD technology to various research areas,[3,7] but the efficiency in the system has been at most 4% (at 1550 nm and dark count rate 100 Hz). The low efficiency of SNSPDs stems from the low absorptance in the ultrathin ($\sim$4 nm) nanowire structure. Rosfjord *et al.*[8] have achieved a significant improvement in detection efficiency (greater than 50%) through fabrication processing and an optical cavity design formed by the nanowire and metallic mirror layers for back-side illumination. However, this architecture is not compatible with simple butt-coupling with an optical fiber. In contrast, the optical cavity structure developed for transition edge sensors (TESs) makes possible front-side illumination, and thus inexpensive fiber butt-coupling, and a 95% detection efficiency system was realized.[9] Our optical cavity design is based on a similar principle to that used with TES devices, although a dielectric mirror and a lattice-matching buffer layer were employed to overcome the challenge of growing an ultrathin, high-quality superconducting layer on a nonlattice-matched substrate (Si). Our use of a silicon wafer as substrate makes this technology very promising for future applications such as micromachining of chips for better fiber coupling[10] and photonic integrated circuit technology compatibility. In this paper, we describe our measurements of the spatial distribution of the optical absorptance and the detection efficiency of the fabricated device, leading to a detailed understanding of the device performance.

The full detector structure from top to bottom is SiO_2/hydrogen silsesquioxane (HSQ)/NbTiN/MgO/SiO_2/dielectric mirror. The substrate is a commercially available dielectric mirror deposited on a silicon wafer with $\sim$96% reflectance estimated at 1550 nm. MgO/SiO_2 deposited on top of the dielectric mirror substrate serves as a quarter-wavelength dielectric spacer and provides a lattice-matching buffer layer for an ultrathin NbTiN film.[11] Electron-beam resist HSQ and the top SiO_2 serve as both a passivation and a top-level optical coating.

Figure 1 shows the stack structure (inset) and the calculated absorptance characteristics. The refractive indices and the thicknesses of the layers we used in our calculation are room temperature values from literature including $n_{NbN} = 5.3+5.8i$ (Ref. 12) that we used for our n_{NbTiN}. The range of uncertainty including the temperature dependence limits the accuracy of our calculation, but it does not undermine the qualitative estimation, and in fact guides our design well. We estimate the effective refractive index of the nanowire layer by a wire grid polarizer theory with the electric fields parallel to the nanowire orientation at which the absorptance is maxi-

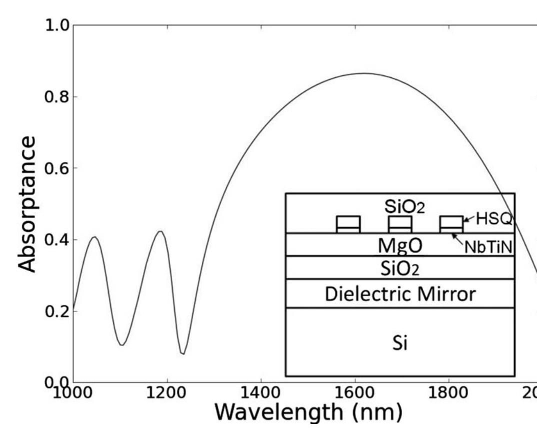

FIG. 1. Modeled spectral absorptance. Inset: optical cavity SNSPD layer structure. Nominal thicknesses are 45, 30, 4.5, 20, and 246 nm from top to bottom (SiO_2, HSQ, NbTiN, MgO, and SiO_2 in order).

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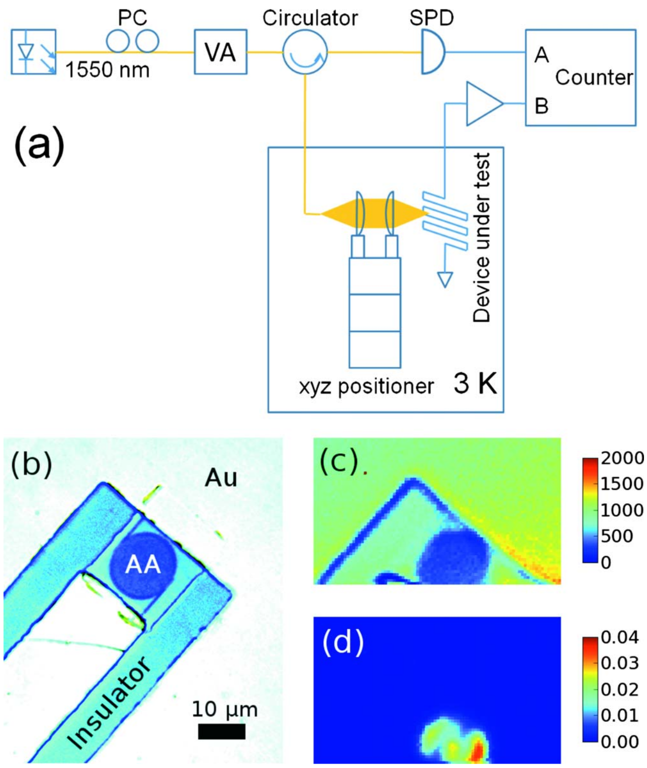

FIG. 2. (Color online) (a) Local reflectance/detection efficiency distribution measurement setup at 1550 nm and 3 K. PC: polarization controller. VA: variable attenuator. SPD: single-photon detector. (b) Optical micrograph of a fabricated round-shape device of 15 μm diameter. AA: active area. (c) Measured spatial distribution of local reflected photon count rate in hertz. (d) Measured local detection efficiency distribution. (b)–(d) are presented in the same spatial scale.

mized since, in many applications, the incident polarization is optimized for maximum efficiency. With a fill factor of 0.5, the effective refractive index is simply $n_{\mathrm{eff}}=(0.5\cdot n_{\mathrm{SiO}_2}^2+0.5\cdot n_{\mathrm{NbTiN}}^2)^{1/2}=3.7+4.0i$.[13] Using the thickness and refractive index information of the comprising layers, we calculated optical absorptances based on Fresnel equations at normal incidence. Figure 1 shows the calculated absorptance versus wavelength, in which the absorptance reaches 86% at 1620 nm with a 3 dB bandwidth of 600 nm. The absorptance at 1550 nm is 85%. In contrast, a calculation for a common bare nanowire detector on top of a sapphire substrate resulted in 20% absorptance at 1550 nm. Assuming no difference in the nanowire quality and negligible absorption in the dielectric layers or interfaces, approximately four times higher detection efficiency is predicted at 1550 nm.

Experimentally, to isolate and assess the performance of the optical cavity from the total detector efficiency, we used a confocal optical scanning technique [Fig. 2(a)]. An *xyz* stage based on piezoelectric control moves a compact two-lens optic relative to an SNSPD chip that is affixed to a brass mount equipped with coaxial connectors. Light is guided by a standard single-mode optical fiber and focused on the surface of the chip by the lenses. Focusing and *xy* scanning of the light spot is controlled by the *in situ xyz* positioner. We used a 1550 nm diode laser with variable attenuators as a light source. An inline fiber polarization controller was used to optimize the polarization state by maximizing the detector count rate or minimizing the reflectance. If the light is focused on the chip surface, the reflected light is efficiently collected back by the fiber. In this confocal setup, the alignment angle or the insertion loss in the optics components reduce the collection efficiency, but this scheme still allows us to measure a relative spatial distribution of reflectance, since those coupling losses remain constant over a small scanned area. We used a circulator at room temperature to collect and measure the intensity of the reflected light with another single-photon detector (fiber-coupled SNSPD). The SNSPD holder and the *xyz* stage were mounted together on the cold stage of a closed-cycle cryostat, enabling long and continuous measurements. The temperature was maintained at 3 K with negligible fluctuation. The lateral resolution of the local reflectance measurement is about 2.5 μm, and is the diffraction-limited light spot size determined by the numerical aperture of our optics. Mechanical vibrations due to the cryocooler caused negligible smearing ($\ll 1$ μm). We verified that our confocal scheme accurately measures relative reflectance by comparing it with a scheme in which a beamsplitter and a wide-area photodiode measures the reflected light at room temperature.

We measured the absorptances of our optical cavity devices and a bare nanowire device at 1550 nm for comparison. Figure 2(c) is the local intensity distribution of the reflected light on a circular optical-cavity device [Fig. 2(b)] at 1550 nm and 3 K. This image clearly reveals the less-reflective active area of the device in contrast to highly reflective (Au) areas. Due to the unknown coupling efficiency of the light reflected back to the fiber, these data serve as relative reflectance measurements. However, from the known reflectance of gold thin film (98%), we can estimate 27% ± 2% reflectance or 73% ± 2% absorptance in the optical cavity. We observed a good uniformity in the local absorptance distribution within a device and the device-to-device variation. In a measurement of a bare nanowire detector, we added a wide-area photodiode behind the device to measure the transmitted light intensity. Although this measurement was carried out at room temperature, we expect that the optical properties at room temperature and cryogenic temperature are close enough to each other to show the enhancement by our optical cavity design. In this measurement, we obtained ~20% absorptance, as our calculation predicted. These measurements unambiguously demonstrate that the use of an optical cavity can increase the optical absorptance by a factor of ~4.

At the same time as carrying out the scanned reflectance measurement, we can also measure the local efficiency of the detector at a diffraction-limited spatial resolution by monitoring its electrical pulse emission rate.[14] The bias current was set for a 100 Hz dark count rate. Figure 2(d) shows the resulting local detection efficiency distribution. In most of our tested detectors, we observed spatially distributed local efficiency with multiple local maxima as in this plot; such a nonuniform distribution could be caused by the nonuniformity in the superconducting thin film, patterning, or postprocess degradation. The peak efficiencies of the devices we measured varied in a wide range, implying that nanowire quality has a margin for improvement. Our measured best (local) efficiency is 10% in a detector of 10×10 μm^2 square shape. This 10% of total efficiency indicates $0.1/0.73=14\%$ internal quantum efficiency, i.e., the conditional efficiency after absorption. Because the internal efficiency of a good SNSPD is known to reach a much higher value,[12] we

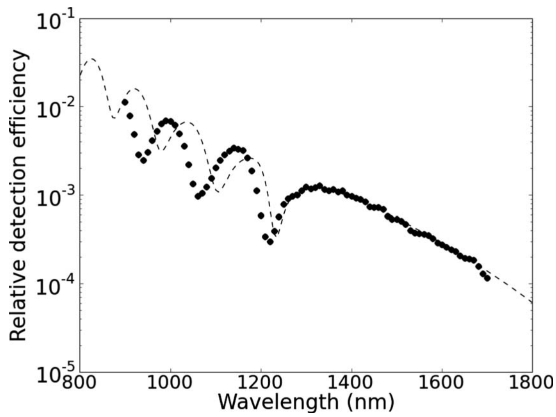

FIG. 3. Spectral response of the optical cavity SNSPD. Solid circles are measurements and dashed curve is a calculation with the exponential factor as a fitting parameter.

believe that the quality of the nanowire can be significantly improved by improving the fabrication.

We also took the same set of measurements with a polarization for a minimum efficiency (perpendicular polarization). We observed reduced absorptance (~64%) and peak detector efficiency (~8%). We also noticed that the decrease in the efficiency is lower than the value expected from the absorptance change. This implies an internal efficiency dependence on polarization similar to what has been pointed out by Avant *et al.*[12] from the measurement of bare nanowire detectors. This implies that more complex detector physics might underlie the photodetection process in an SNSPD.

Finally, we measured the spectral response at 900–1700 nm to verify the expected wavelength dependence of the absorptance because of the presence of the cavity (Fig. 3). We used an incandescent lamp as a light source, a grating monochromator, filters (long-pass and neutral density), and fiber coupling optics. An InGaAs diode optical power meter was used to estimate the optical power in the fiber. We used a large light spot on the SNSPD to avoid the effect of nonuniform spatial efficiency with wavelength change; thus, the *y* scale does not represent its efficiency with an optimal spot size. We observed a broad hump around 1550 nm and multiple dips at the short wavelength side, similar to our calculated stack absorptance. On the other hand, there is an exponential increase in the measured efficiency for a shorter wavelength. Such an exponential trend has been observed in a bare nanowire device by Verevkin *et al.*[2] Thus the total efficiency given by the optical absorptance and the internal efficiency has the trend shown in our measurement result that can be fitted by the multiplication of our absorptance calculation by an exponential factor. We attribute the discrepancy of the dips on the short-wavelength side to our limited knowledge of the actual material properties composing our multilayer stack.

In summary, we developed and characterized SNSPDs in an optical cavity. We measured a significantly enhanced optical absorptance of 73% at 1550 nm and 3 K. The front-side coupling and the use of silicon wafer promise the next generation of innovation in SNSPD technology. Our design makes vertical-proximity fiber-coupling possible, and the same procedure as the packaging technique demonstrated by NIST (Ref. 3) can be applied if we use a wavelength outside the high-reflectance band of the dielectric mirror to monitor the alignment from the backside of the chip. A more interesting approach could be to micromachine the silicon substrate and make a self-assembled package.[10] This will enable efficient and reliable production of high-efficiency, fiber-coupled SNSPD packages for a multichannel system.

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