Picosecond superconducting single-photon optical detector

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We experimentally demonstrate a supercurrent-assisted, hotspot-formation mechanism for ultrafast detection and counting of visible and infrared photons. A photon-induced hotspot leads to a temporary formation of a resistive barrier across the superconducting sensor strip and results in an easily measurable voltage pulse. Subsequent hotspot healing in ~30 ps time frame, restores the superconductivity (zero-voltage state), and the detector is ready to register another photon. Our device consists of an ultrathin, very narrow NbN strip, maintained at 4.2 K and current-biased close to the critical current. It exhibits an experimentally measured quantum efficiency of ~20% for 0.81 μm wavelength photons and negligible dark counts. © 2001 American Institute of Physics.

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Superconducting devices are the natural choice for fast and ultrasensitive optical detection, because of their quantum nature and low-noise, cryogenic operation environment. The superconducting energy gap 2Δ is two to three orders of magnitude lower than in a semiconductor, thus, photon absorption in a superconducting detector creates an avalanche electron charge two to three orders of magnitude higher for the same photon energy. This results in an enhanced resolution in energy-resolving devices, such as superconducting tunnel junctions,1 and extends the range of detectable energies well into the infrared for photodetectors.2 In addition, as we have recently demonstrated, energy relaxation time constants of excited electrons in superconductors are in the picosecond range for both the low-temperature3 and high-temperature4 superconductors, assuring the gigahertz repetition rate for superconducting photon counters.

The dynamics of the hotspot formation in a superconductor at temperature T below its critical temperature T_C, at the position where the photon is absorbed has been described before5 and the supercurrent-assisted mechanism experimentally demonstrated in this work was theoretically studied in Ref. 6. Therefore, we only mention that the absorption of a photon with energy ħω>>2Δ creates, through electron–electron and electron–Debye–phonon interactions, a local nonequilibrium perturbation with a large number of excited hot electrons (above 300 in the case of NbN, excited with 790 nm wavelength light),2 and an increase of the average electron temperature above T_C. This initial thermalization phase for ultrathin NbN films is characterized by the thermalization time τ_T=6.5 ps (Ref. 3) and results in the formation of a hotspot—a local nonsuperconducting region of the thermalization length 2λ_T [Fig. 1(a)]. After the initial thermalization, the resistive hotspot size grows [Fig. 1(b)] as hot electrons diffuse out of its center. At the same time, the supercurrent is expelled from the hotspot volume and is concentrated in the “sidewalks” between the hotspot and the edges of the film [Fig. 1(c)]. If the bias current I_bias is sufficient to exceed the critical current in the sidewalks, the phase slip centers are sprung7 and a nonsuperconducting barrier is formed across the entire width w of the device [Fig. 1(d)], giving rise to a voltage signal, due to a collaborative effect of the bias current and the radiation quantum. For a given experiment, the response magnitude is proportional to the barrier resistance, however, in general, the current-assisted hotspot process creates a nonlinear, multidimensional space of operating parameters, such as w, I_bias, ħω, and T.

The hotspot formation process competes, of course, with the cooling process, as electrons diffusing out of the hotspot lose their energy through electron–phonon scattering. Thus, after the time depending on both the diffusion rate and the quasiparticle relaxation dynamics,6 the hotspot heals itself, leading to the restoration of the superconducting path along the microbridge. As a result of the hotspot creation and relaxation processes, the NbN device switches temporarily be-

![FIG. 1. Schematics of the supercurrent-assisted hotspot formation mechanism in an ultrathin and narrow superconducting strip, kept at temperature far below T_C are shown. The arrows indicate direction of the supercurrent flow.](http://ojps.aip.org/aplo/aplcr.jsp)
tween the superconducting and resistive states on a time scale of $\sim 30$ ps.

We have developed simple to manufacture, easy to operate, superconducting single photon detectors (SPDs) using nominally $0.2 \, \mu m$ wide and $1 \, \mu m$ long microbridges patterned from ultrathin ($5 \, nm$ thick) NbN films deposited on sapphire substrate. The microbridge was connected to the external circuit, via much thicker and larger, Au-coated contact pads. Figure 2 presents a current–voltage ($I–V$) characteristics of a NbN microbridge, operated at $4.2$ K and biased using a voltage source. The characteristics are typical for a long superconducting constrictions and show that the bridge can be operated in either of the two distinct states: the superconducting (flux–flow) state or the resistive (hotspot) state. The hotspot plateau under dc conditions corresponds to the growing normal-state region, as the voltage across the device is increased, eventually reaching the bridge normal-state resistance, which in our case is approximately $500$ $\Omega$. The thick, dashed line represents a $50$ $\Omega$ load line, when the device is connected to the output microwave transmission line. From Fig. 2, we see that the device $I_C$ is approximately $78 \, \mu A$.

For our experiments, a NbN SPD was mounted on a cold plate ($T = 4.2$ K) inside an optical liquid-helium cryostat. We used two cold glass filters (inner glass window was at $\sim 4.2$ K) to block thermal radiation longer than $2.5 \, \mu m$ from the sample. The sample was dc biased through a bias tee and mounted on a rigid, $50$ $\Omega$ coplanar transmission line with the ac output connected through a stainless-steel, semirigid coaxial cable to a cryogenic low-noise amplifier (placed inside the dewar), characterized by $30$ dB gain and $1$ to $2$ GHz bandwidth. The noise temperature of our cryogenic amplifier was below $15$ K, which yielded voltage fluctuations below $7 \, \mu V$—several orders of magnitude below our signal level. Outside the dewar, the signal passed through an isolator and a second broadband power amplifier ($9$ GHz; $20$ dB gain) before going to a $6$ GHz bandwidth single-shot oscilloscope for display, or to a $200$ MHz voltage-level threshold counter for real-time event counting and statistical analysis. We worked with $100$ fs wide, $\sim 50 \, \mu m$ diameter optical pulses with a $1$ kHz repetition rate at $0.4$, $0.81$, $1.55$, and $2.1 \, \mu m$ wavelengths, with the bulk of the measurements performed using $0.81 \, \mu m$ photons. During our experiments, the fluence per pulse reaching the device plane inside the dewar was approximately $J_{\text{in}} = 1 \,\mu \text{W} / \mu \text{m}^2$, and could be further attenuated using banks of neutral density filters, giving the total attenuation of $10^{-7}$.

The actual fluence per pulse absorbed by our SPD, $J_{\text{abs}}$, can be estimated according to the relation $J_{\text{abs}} = J_{\text{in}} S_d \eta$, where $S_d$ is the active area of the device and $\eta$ is the radiation absorption coefficient of a metallic film, given by

$$\eta = 4(R_s/Z_0)[(R_s/Z_0)(n_{\text{sub}} + 1) + 1]^2,$$

where $n_{\text{sub}}$ is the index of refraction of the SPD substrate, $R_s$ is the surface resistance of the NbN film measured just above $T_C$, and $Z_0 = 377 \, \Omega$ is the free-space impedance. For our sapphire substrate ($n_{\text{sub}} = 1.72$), $\eta_{\text{max}} = 37\%$. $\eta$ is frequency independent as long as $n_{\text{sub}}$ remains frequency independent and the film is much smaller than the radiation skin depth, and can be regarded as the intrinsic quantum efficiency (QE) of our device.

For a device biased near, but below $I_C$ (point A in Fig. 2), photon absorption instigated the supercurrent-assisted hotspot formation leading to a temporary switch from the superconducting state to the hotspot resistive state (point B in Fig. 2) along the $50$ $\Omega$ load line. As a result, an output voltage was generated with a magnitude corresponding to the voltage level at point B, and that was independent of the actual photon energy, as long as the photon energy was sufficient to form a hotspot large enough to trigger the supercurrent redistribution effect. The response time of the voltage pulses followed the formation and subsequent healing of the resistive state induced by the photon absorption.

The measured response of our SPDs (not shown) was indeed "quantum" or "granular," in a sense that the voltage pulse amplitude was roughly the same ($\sim 400$ mV after amplification), with a signal-to-noise ratio above $100:1$ for all tested laser wavelengths. The response pulse width was $\sim 100$ ps, limited by the bandwidth of our chain of output amplifiers, and with negligible shot-to-shot jitter.

True single-photon counting requires that the photon detection probability has a linear dependence on the number of photons incident on the device. For a mean number of $m$ photons per pulse, the probability $P(n)$ of absorbing $n$ photons from a given pulse is $P(n) \sim (e^{-m}m^n)/(n!)$. When $m \ll 1$ (achieved by drastically attenuating the flux of photons incident on the SPD), the probability $P(n)$ simplifies to

$$P(n) \sim \frac{m^n}{n!}.$$  

Consequently, the probability of absorbing one photon is proportional to $m$, the probability of detecting two photons is proportional to $m^2$, and so on.

Figure 3 shows the probability of the detector producing an output voltage pulse as a function of the average number $[J_{\text{bias}} S_d / h \omega]$ of $0.81 \, \mu m$ wavelength photons in a $100$ fs pulse, incident on the device area, for two different values of $I_{\text{bias}}$. Since all photons arrive within the $100$-fs-laser-pulse window, only spatial correlations (number of photons per device area) are important in the experiment. The left vertical
axis in Fig. 3 shows the experimental data i.e., the number of
detector counts per second (equivalently, per 1000 laser
pulses), based on the average number of counts detected by
the SPD over a 10 s counting period for the highest photon
doses, and up to 1000 s for the lowest. The counter threshold
was adjusted to minimize spurious counts. The right vertical
axis corresponds to the probability $P$ of detecting an optical
pulse. Open squares correspond to the SPD performance
when it was biased at 0.92 $I_{c}$. For high incident photon
fluxes, the detector managed to count all 1000 laser pulses in
each second ($P = 1$), without actually resolving the number
of photons. For smaller fluxes, however, our experimental
data show that for over four orders of magnitude, the detec-
tion probability decreases linearly with the decrease of the
average number of photons per pulse incident upon the device, for two
stray photon background since the joint probability of
two stray photons hitting the device area within the required
space and time is negligibly small. Further reduction of $I_{bias}$
(not shown in Fig. 3) resulted, unsurprisingly, in a cubic
(three-photon detection) dependence of detection probability
to the number of photons per pulse.

In conclusion, we have demonstrated that a supercurrent-
assisted, hot-spot mechanism can be implemented
using an ultrathin NbN strip for ultrafast single-photon de-
tection and counting of visible and infrared photons with an
experimentally measured 20% QE for 0.81 $\mu$m photons and
negligible dark counts. The bandwidth-limited measured re-
response time was $\sim 100$ ps, corresponding to a 10 GHz pho-
ton counting rate. Already identified applications for our su-
perconducting SPDs range from sensing ultraweak
electroluminescence from submicron complementary metal–
oxide–semiconductor very large scale integrated circuits,11
to quantum communication systems.

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