Time delay of resistive-state formation in superconducting stripes excited by single optical photons

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(Received 5 August 2002; published 28 April 2003)

We have observed a 65(±5)-ps time delay in the onset of a resistive-state formation in 10-nm-thick, 130-nm-wide NbN superconducting stripes exposed to single photons. The delay in the photoresponse decreased to zero when the stripe was irradiated by multi-photon (classical) optical pulses. Our NbN structures were kept at 4.2 K, well below the material’s critical temperature, and were illuminated by 100-fs-wide optical pulses. The time-delay phenomenon has been explained within the framework of a model based on photon-induced generation of a hotspot in the superconducting stripe and subsequent, supercurrent-assisted, resistive-state formation across the entire stripe cross section. The measured time delays in both the single-photon and two-photon detection regimes agree well with theoretical predictions of the resistive-state dynamics in one-dimensional superconducting stripes.

DOI: 10.1103/PhysRevB.67.132508 PACS number(s): 74.78.–w

Recently proposed superconducting single-photon detectors (SSPDs), based on ultrathin, submicrometer-width NbN superconducting stripes, are characterized by picosecond response times, high quantum efficiency, broadband single-photon sensitivity, and extremely low dark counts. The devices immediately found a variety of applications ranging from noninvasive testing of very-large-scale integrated circuits to quantum cryptography. Their single-photon-counting ability has been interpreted within a phenomenological hot-electron photoresponse model proposed in Ref. 1, and elaborated upon in Ref. 6. The model describes the formation of a hotspot, right after the single-photon absorption event, followed by the in-plane growth of a resistive hotspot area due to the highly efficient multiplication process of excited quasiparticles in the NbN film. During this stage, however, the resistive state does not appear across the superconducting stripe because the size of a single hotspot, created by an optical photon, is significantly smaller than our stripe width. The resistive state appears due to a supplementary action of the device bias current density $j_c$, which needs to be close to the stripe critical current density $j_c$. After the supercurrent is expelled from the resistive hotspot region, the bias current density in the stripe “sidewalks” $j_{sw}$ exceeds $j_c$, resulting in a penetration of the electric field in the sidewalk areas of the stripe. As a result, we observe a voltage pulse, which reflects the initial act of photon capture.

The mechanism of the hotspot formation in superconducting films was earlier implemented in high-energy particle detectors. However, these detectors had large areas and were sensitive only to highly energetic excitations. The resulting response was slow (at least hundreds of ns), since the particle absorption led to the strong perturbation of the stripe’s vortex structure and the significant phonon-system heating. In our nanometer-width detectors, vortices cannot appear; at the same time, our films are thinner than the phonon mean free path, so the phonon escape time is minimized. The resistive-state formation process presented above should lead to an observable time delay $t_d$ in the superconducting stripe resistive photoresponse. This delay, in turn, if measured, would give us a direct confirmation of a supercurrent-enhanced, hotspot-induced photoresponse mechanism of our SSPD. The latter is the main experimental goal of this work.

The dynamics of the resistive-state formation in a photon-illuminated, ultrathin (two-dimensional) superconducting stripe depends on the radiation flux density incident on the device and the bias current density, as schematically illustrated in Fig. 1. At relatively high (macroscopic) incident photon fluxes, a large number of hotspots are simultaneously formed in our stripe [Fig. 1(a)]. In this case, the hotspots overlap with each other across the stripe cross section. Since the stripe thickness $d$ is comparable with the coherence length $\xi$, we can assume that for overlapping hotspots, a resistive barrier is instantaneously formed across the NbN stripe and, as a result, a voltage signal is generated within the electron thermalization time of 6.5 ps. When the photon flux is decreased, the hotspots become isolated [Fig. 1(b)]. Finally, for an incident flux containing one or less than one absorbed photon per pulse, we can expect that, at best, only one resistive hotspot will be formed in our stripe [Fig. 1(c)].

As we mentioned above, in the single-photon regime we postulate that the formation of a macroscopic resistive barrier can be realized only when $j_{sw}$ surpasses $j_c$, which is associated with a macroscopic current redistribution and should lead to a measurable $t_d$ in the resistive state formation, corresponding to the time period between the initial hotspot appearance and the eventual development of a resistive barrier across the entire cross section of the superconducting stripe.

Even if the two-photon detection mechanism does not correspond exactly to the situation presented in Fig. 1(b), since the hotspots may partially overlap, or coincide, we should still observe—as in the single-photon regime—a non-
Tinkham model 12 as $j_c$ with the constant described in Refs. 2 and 13; here we only wanted to stress that of their fabrication and implementation as SSPDs are de-

than

$$I_c$$

in the sidewalks and, for

photoresponse.2 The atomic force microscope images

ments of the stripe contribute the most to the SSPD

enhanced, resistive-state formation model, the narrowest seg-

narrowest segment, and, according to our supercurrent-

$E_f$ is the inelastic electron-phonon collision time at the

Fermi level at $T_c$ and

$\Delta$ is the gap relaxation time

$\omega$ is the 0–4-GHz bandwidth of the oscilloscope

had a bandwidth of 0.01–12 GHz. The laser radiation

power was attenuated down to a picowatt range using banks

of neutral density filters. Voltage pulses generated by our

SSPDs were amplified by a room-temperature amplifier and

fed either to a synchronously triggered Tektronix 7404

single-shot digital oscilloscope, or to a fast photon counter.
The ~100-ps, real-time resolution of our system was limited

by the 0–4-GHz bandwidth of the oscilloscope (the amplifier

had a bandwidth of 0.01–12 GHz). On the other hand, the

relative-time resolution, e.g., the delay between the photore-
sponse pulses generated under different photon excitations,

was below ~10 ps, due to the low jitter of our laser and the
digital accumulation procedure of acquired pulses (with no

averaging) implemented in our oscilloscope.

A fast photon counter was used in our experimental setup
to perform the statistical data analysis and to determine the
single-photon, two-photon, or multiphoton regimes of oper-
amination of our devices, as described in detail in Refs. 1 and 2.

Figure 2 presents the two dependences of the SSPD counting
probability vs the averaged number of photons incident on
the device area for two different biasing conditions. The ac-

ual values for the $x$ axis were obtained knowing the amount
of attenuation in our optical path, the beam size (typically
~100 $\mu m^2$), the incident energy per pulse of 810-nm pho-

tons, and, of course, the actual attenuation level of neutral

density filters. As we discussed before,1–3 the Poisson prob-

ability $P(n)$ of absorbing $n$ photons from a given pulse with
a mean number of $m$ photons, for $m \ll 1$ simplifies to $P(n) 

\sim m^n/n!$. Consequently, the data in Fig. 2 show that, for low
For supercurrent redistribution around a single, photon-in-the-10^3–10^2 incident photon flux range, which, for a QE \( \approx \) reached at about 10^4 incident photons/pulse, both values are respectively. We observe that for large incident photon fluxes SSPD single-photon and two-photon regimes of operations, which, as we have already shown in Fig. 2, correspond to the j level, is about 0.1% for single photons. The experimental quantum efficiency shifted into much higher photon fluxes, since the probability (\( n = 1 \)) at the normalized bias \( j/j_c = 0.85 \), as the detection probability is proportional to \( m \), while at \( j/j_c = 0.6 \) the detector operates in the quadratic, two-photon detection regime (\( n = 2 \)). It can be noticed that the two-photon dependence is shifted into much higher photon fluxes, since the probability of two-photon detection is significantly lower than that for single photons. The experimental quantum efficiency (QE), defined as the counting probability at the 1 photon/pulse level, is about 0.1% for \( j/j_c = 0.85 \) and the counting rate saturation level of 82 MHz (repetition rate of laser pulses) is reached at about 10^4 incident photons/pulse, both values are typical for our 4 \( \times \) 4-\( \mu \)m^2 SSPDs.

![Fig. 3](image-url)  
**FIG. 3.** Experimental time delay \( t_d \) of the resistive-state formation in a NbN superconducting stripe as a function of the number of incident photons per laser pulse per device area. Open circles correspond to \( t_d \) measured when the stripe was biased with \( j/j_c = 0.85 \) (single-photon regime), while closed circles represent \( j/j_c = 0.6 \) and the two-photon regime. Solid lines are guides to the eye. The measurement error is \( \pm 5 \) ps.

For the \( j/j_c = 0.6 \) bias, according to Fig. 2, the probability of detecting a single, 810-nm photon by our 4 \( \times \) 4-\( \mu \)m^2 device is negligibly small; thus, we need at least two photons in order to generate the resistive response. As we see in Fig. 3, the observed behavior (closed circles) is very similar to that measured for \( j/j_c = 0.85 \), we can clearly identify the time-delay effect and find \( \Delta t_d = 70 \pm 5 \) ps. The main difference is that the observed photoresponse delay is shifted into significantly higher levels of the incident photon flux. The value of \( t_d \) starts to be nonzero for \( \sim 10^6 \) incident photons/pulse, and it flattens below \( 10^4 \) photons/pulse. The latter value is very consistent with the two-photon (\( n = 2 \)) detection probability dependence observed in Fig. 2.

FIG. 4. Time delay \( t_d \) as a function of the normalized current \( j_{sw}/j_c \) in the sidewalks of the superconducting stripe. The two measured values of \( \Delta t_d \) (solid circles) correspond to the single-hotspot and two-hotspot formation at \( j_{sw}/j_c = 1.36 \) and \( j_{sw}/j_c = 1.28 \), respectively. The solid line represents the Tinkham theoretical prediction, calculated using Eq. (1). The horizontal error bars are calculated for the hotspot-diameter variations of 30\pm 1 \) nm.

The data presented in Figs. 2 and 3 show that, in full accordance with the proposed earlier current-enhanced, hotspot-induced photoresponse model\(^1\)–\(^3\) the voltage signal generated across our superconducting stripe becomes time delayed as we lower the incident photon flux and the device is transferred from the classical, intensity detection mode to the quantum one- or two-photon regime.

Finally, we compare our experimental results with \( t_d \) calculated for our experimental conditions, using Eq. (1) and \( \tau_E = 10 \) ps.\(^1\) The current density in the sidewalks in the narrowest (most active) segments of the meander can be calculated as: \( j_{sw} = \frac{j_E}{(w_c/d_{h0})} \), where \( d_{h0} = 30 \) nm is the diameter of the hotspot generated by a single 810-nm photon.\(^2\) Thus, for the experimental \( j/j_c = 0.6 \) condition, \( j_{sw}/j_c = 0.96 \), and is subcritical in the single-hotspot regime. However, doubling the hotspot size\(^1\) gives \( j_{sw}/j_c = 1.28 \), which is sufficient to generate a resistive barrier across our stripe. In a similar manner, when \( j/j_c = 0.85 \), \( j_{sw}/j_c \) is supercritical and reaches 1.36, when the single hotspot is formed. Figure 4 shows the \( t_d \) dependence on \( j_{sw}/j_c \). The solid line represents the Tinkham model,\(^1\) while the two closed circles refer to our measured \( \Delta t_d \) values, corresponding to the single-
hotspot ($j_{sw}/j_c = 1.36$) and double-hotspot ($j_{sw}/j_c = 1.28$) conditions, respectively. We note that our experimental values are reasonably close to the theoretical prediction, remembering that the Tinkham theory is applicable for one-dimensional clean superconductors, while our 10-nm-thick NbN films are in the dirty limit and the “sidewalks” are only quasi-one-dimensional. In addition, the discrepancy can be related to the accuracy of our $w_e$ estimation. Within the framework of the Tinkham model, $t_d$ should not depend directly on the number of incident photons, in agreement with the experiment.

In conclusion, we observed the time-delay effect in the resistive-state response in ultrathin, submicrometer-width superconducting stripes, excited by single optical photons. The observed phenomenon directly shows that the resistive state across two-dimensional superconducting stripes upon absorption of an optical photon is due to photon-induced hotspot formation and to the subsequent redistribution of the supercurrent into the sidewalks of the stripe. Our measurements agree well with a theoretical prediction based on the Tinkham model of the resistive-state formation in superconducting stripes under the supercurrent perturbation.$^{12}$

The authors thank Ken Wilsher for many very valuable discussions. This work was funded by the NPTest, San Jose, CA. Additional support was provided by the US Air Force Office for Scientific Research Grant No. F49620-01-1-0463 (Rochester) and by the RFBR Grant No. 02-02-16774 (Moscow).

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$^{14}$In the case when two hotspots are present in the film, we have taken the average effective size of the double hotspot across the cross section of the NbN stripe to be $\sqrt{2d_{hs}}$, in order to take into account a possible overlap between the hotspots.