Spatially-dependent sensitivity of superconducting meanders as single-photon detectors

G. R. Berdiyorov, M. V. Milošević, and F. M. Peeters
Departement Fysica, Universiteit Antwerpen, Groenenborgerlaan 171, B-2020 Antwerpen, Belgium
(Dated: May 5, 2014)

The photo-response of a thin current-carrying superconducting stripe with a 90-degree turn is studied within the time-dependent Ginzburg-Landau theory. We show that the photon acting near the inner corner (where the current density is maximal due to the current crowding [J. R. Clem and K. K. Berggren, Phys. Rev. B 84, 174510 (2011)]) triggers the nucleation of superconducting vortices at currents much smaller than the expected critical one, but does not bring the system to a higher resistive state and thus remains undetected. The transition to the resistive state occurs only when the photon hits the stripe away from the corner due to there uniform current distribution across the sample, and dissipation is due to the nucleation of a kinematic vortex-antivortex pair near the photon incidence. We propose strategies to account for this problem in the measurements.

PACS numbers: 74.78.Na, 73.23.-b, 74.25.Fy

Superconducting current-carrying thin-film stripes have recently received a revival of interest due to their promising application for single-photon detection [1] with a high maximum count rate, broadband sensitivity, fast response time and low dark counts [2,3]. The single-photon absorption event leads to the formation of a nonequilibrium “hotspot” with suppressed superconductivity, the area of which grows in time, forming a normal belt across the strip [5]. The latter leads to redistribution of the current between the now resistive superconductor and a parallel shunt resistor, where a voltage pulse is detected, before a hotspot region cools down (on a timescale of few hundred picoseconds [6]) and the system returns to its initial superconducting state. Although the hotspot mechanism nicely explains the photon detection in the visible and near UV range, the detection mechanism in the near-infrared range is still debated (see e.g. Ref. [7] and references therein). Superconducting fluctuations, e.g., excitation of superconducting vortices [8,12], have been put forward as an explanation. Dissipative crossing of such vortices, which hop over the edge barrier, or are created due to the unbinding of thermally activated vortex-antivortex pairs, provides a good description of the experiment [10]. This vortex-based mechanism was also shown to be the dominating origin for dark counts [11,12,14], which leads to decoherence in the photon detection process.

To increase the efficiency of the photon counting, detectors are usually fabricated as a meandering superconducting wire [4]. However, these structures are vulnerable to edge imperfections [8], which significantly reduce the photon counting rate. Moreover, the critical current in these systems is mostly determined by sharp inner corners where the supercurrent density is maximal due to current crowding [15,10]. While the appearance of edge imperfections can be reduced by present day technology [3], the effect of current crowding in such meandering geometries still demands further investigations.

In this work we therefore study the effect of the turns of a meandering superconducting stripe on the response to a single-photon absorption event. Counterintuitive to many, we reveal that the current crowding at meandering turns does not facilitate dissipative vortex crossings upon the photon impact. Actually, the turning corner is virtually insensitive to photon absorption, which must be accounted for in practice.

We consider a superconducting strip (with thickness $d \ll \xi,\lambda$ and width $w \ll \Lambda = 2\lambda^2/d$, where $\xi,\lambda$ are the coherence length and magnetic penetration depth) with a 90-degree turn in the presence of a transport current (see Fig. 1). For this system we solve the following generalized time-dependent Ginzburg-Landau equation [17]

$$\frac{u}{\sqrt{1 + \gamma^2 |\psi|^2}} \left( \frac{\partial}{\partial t} + i \phi + \frac{\gamma^2 \partial^2 |\psi|^2}{2 \partial t} \right) \psi = (\nabla - i\mathbf{A})^2 \psi + (1 - T - |\psi|^2) \psi,$$

which is coupled with the equation for the electrostatic potential $\Delta \phi = \nabla \cdot \{\text{Im}[\psi^* (\nabla - i\mathbf{A}) \psi]\}$. Here distance is scaled to $\xi(0)$, the vector potential $\mathbf{A}$ is in units of $\Phi_0/2\pi\xi(0)$, temperature $T$ is in units of $T_c$, time is in units of $t_0 = 4\pi\lambda(0)^2/\rho_n c^2$ ($\rho_n$ is the normal state resistivity), and voltage is scaled to $\varphi_0 = \hbar/2et_0$. Using

![FIG. 1: (Color online) The model system: a superconducting stripe (width $w$, length $L$ and thickness $d \ll \lambda, \xi$) with a 90° turn. The current is applied via normal-metal contacts and the voltage is measured at a small distance away from these leads. Impact of a photon is modeled by a hotspot with radius $R$. Arrows indicate the supercurrent distribution.](arXiv:1206.4298v1 [cond-mat.supr-con] 19 Jun 2012)
\(\rho_n = 18.7 \ \mu\Omega \text{cm}, \ \xi(0) = 4.2 \ \text{nm} \) and \(\lambda(0) = 390 \ \text{nm}\), which are typical for NbN thin films \[8\], one obtains \(\tau_0 \approx 1.25 \ \mu\text{s}\) and \(\varphi_0 \approx 0.26 \ \text{mV}\) at \(T = 0.9T_c\), which will be the working temperature in our simulations. The coefficients \(\nu\) and \(\gamma\) are chosen as \(\nu = 5.79\) and \(\gamma = 10\) \[17\]. To model the thermal coupling of our sample to the substrate and the change of the local temperature we use the heat diffusion equation \[18\]:

\[
\nu \frac{\partial T}{\partial t} = \zeta \Delta T + j_n^2 - \eta(T - T_0),
\]

where \(T_0\) is the bath temperature, \(\nu\) is the effective heat capacity, \(\zeta\) is the effective heat conductivity coefficient, \(j_n\) is the normal current density, and \(\eta\) is the heat transfer coefficient which governs the heat removal from the sample. Following the approach of Ref. \[19\] we used \(\nu = 0.05, \ \zeta = 0.05\) and \(\eta = 2 \cdot 10^{-3}\). This allows us to treat the formation and expansion of photon-induced hotspots in our approach. We solve the above equations self-consistently on a 2D Cartesian grid using the Euler and multi-grid iterative procedures. We use superconducting-vacuum boundary conditions \((\nabla - iA)\psi|_{n} = 0, \nabla\varphi|_{n} = 0\) and \(\nabla T|_{n} = 0\) at all sample boundaries, except at the current contacts where we use \(\psi = 0, \ T = T_0\) and \(\nabla\varphi|_{n} = -j\), with \(j\) being the applied current density in units of \(j_0 = c\varphi_0/8\pi^2\xi(0)\lambda(0)^2\).

As a representative example, we consider a superconducting stripe as shown in Fig. 1 of length \(L = 400 \ \text{nm}\) and width \(w = 110 \ \text{nm}\), where we use the parameters for NbN thin films (i.e., \(\xi(0) = 4.2 \ \text{nm}\) and \(\lambda(0) = 390 \ \text{nm}\)). Time averaged voltage vs. applied current characteristics of the sample is shown in Fig. 2 for two values of the sample width \(w\). With increasing the external current, zero resistance of the sample is maintained up to a threshold current density \(j_c = 0.382j_0\) (see solid black curve), above which the system goes into the resistive state. This resistive state is characterized by the periodic nucleation of vortices near the inner corner (see panels 2 and 2′), where the current density is maximal due to the current crowding \[13\] \[16\] (see panels 1 and 1′). However, the distribution of the supercurrent is strongly inhomogeneous, and decays fast away from the inner corner towards the outer one. The Lorentz force drives the nucleated vortex towards the outer corner of the sample where it leaves the sample (panel 2), but this motion is slow and weakly dissipative. The nucleation rate of vortices in the inner corner increases with further increasing the applied current, and at sufficiently large current (labeled \(j_{cd}\)) the system transits to a higher dissipative state with a larger voltage jump, characterized by fast-moving (kinematic) vortices (see panel 3) \[13\] \[20\]. We point out that the critical current \(j_c\) decreases considerably with increasing width of the sample, while \(j_{cd}\) only moderately decreases (see dashed curve in Fig. 2 for \(w = 160 \ \text{nm}\)). The weakly-dissipative state is still characterized by vortex nucleation near the corner (see panel 4), but starts at low current (low \(j_c\)) and occurs in a broader range of the applied current (\(j_c < j < j_{cd}\)).

In what follows, we study the response of our system to a single-photon absorption event. Following the effective temperature approach \[21\], we assume that the single photon creates a hotspot of radius \(R\), where the local temperature becomes \(T = 2T_c\) (see Ref. \[12\] for the effect of such instant increase of the temperature). First, we consider the case when the photon acts in the middle of the sample away from the corner. Fig. 3(a) shows the \(V(t)\) characteristics of the sample with \(L = 400 \ \text{nm}\) and \(w = 110 \ \text{nm}\) for different values of the applied current density \(j\). For each value of \(j\), we started from the state obtained during the current increasing regime (i.e. states from Fig. 2). The photon acts on the sample over the time interval of \(\Delta t = 25 \ \mu\text{s}\) (the shaded area in Fig. 3(a)), creating a hotspot of radius \(R = 15 \ \text{nm}\) (c.f. panels 1 and 1′ in Fig. 3). At low bias currents (\(j < 0.315j_0\)) the superconducting state is stable against the photon action (not shown here). With increasing applied current, the system reacts to the photon absorption event by nucleating a vortex-antivortex pair (see panel 2), which is subsequently unbound and split towards the edges of the sample by the current, resulting in a voltage pulse (see solid curve in Fig. 3(a)). The system relaxes back into its initial state after the vortex and the antivortex have left the sample and no voltage signal is observed at later times. The amplitude and duration of the voltage signal, as well as the delay in the response of the system to the photon, all depend on the applied current value. At larger current (still below \(j_c\)) several vortex-antivortex pairs can be formed one after another leading to several voltage pulses per single photon absorption (see dashed curve in Fig. 3(a)). With further increasing \(j\), the fast moving
FIG. 3: (Color online) Voltage vs. time characteristics of the sample (of size $L=400$ nm and $w=110$ nm) at $T=0.9T_c$ for different applied currents. A single-photon (with pulse duration $\Delta t = 25$ ps (shaded area in (a)) and spot radius $R = 15$ nm) acts: (a) in the middle of the stripe, c.f. panel 1, or (b) near the inner corner, c.f. panel 4. Panels 1-7 show snapshots of $|\psi|^2$ (zoomed at the part of interest) at times indicated on the $V(t)$ curves. Arrows in panel 2 show the direction of motion of the unbinding vortex-antivortex pair.

vortices create a normal belt across the sample (panel 3) bringing the sample into the resistive state. A finite average voltage develops across this resistive region which now can be detected electronically (see dotted curve in Fig. 3(a)). In this sense, for applied currents just below $j_c$, we confirm the recently predicted vortex-assisted single-photon counting mechanism [11, 12], where each photon is detected thanks to the generated periodic motion of kinematic vortex-antivortex pairs [13].

FIG. 4: (Color online) Phase diagram: voltage response of the sample of Fig. 3 as a function of the location of the photon absorption for two values of the applied current: (a) $j = 0.373j_0$ and (b) $j = 0.383j_0$.

Our findings are summarized in Fig. 4 where we plot a phase diagram, showing the voltage response of the sample as a function of the location of the photon absorption. The voltage is averaged over the time interval $t = 0.4 - 2$ ns to exclude the oscillating features of transient voltages during the photon action (such as those shown in Fig. 3). It is clear from this figure that the photoresponse of the meandering detector is spatially dependent with maximal sensitivity away from the turning point. Only at currents above $j_c$ (Fig. 4(b)) the regions near the turning corner of the sample become responsive to the incident photon. Here we assume that the small and short-lived resistance due to the slow moving vortices nucleated near the inner corner of the sample (see solid curve in Figs. 2 and 3(b)) is not sufficient to induce current at the shunting load, so that it is beyond the sensitivity of the photodetecting measurement.

In conclusion, we confirmed that vortex-assisted energy dissipation is the dominant origin for single photon counting in superconducting single-photon detectors. However, sensitivity of the commonly used meandering detectors is spatially dependent with maximal response to single-photon absorption away from the sharp corners, and with small response at the turns. Our suggestion is therefore to perform measurements at currents just under $j_c$, the critical current which by itself induces a moving vortex at the inner corners of the meander, and calcu-
late the photon density as the number of detected counts over the area of only the straight parts of the detector. Alternatively, one can perform measurements at currents just under $j_{cd}$, which corresponds to the jump to large dissipation. In this weakly dissipative regime every impact of a photon would lead to a count, but one must cope with enduring heating issues and non-zero dynamic resistance of the detector in the electronic circuit. However, the latter strategy may be the only one suitable for wider meandering detectors, which provide larger surface to capture photons, but suffer from particularly low $j_c$.

This work was supported by the Flemish Science Foundation (FWO-Vl). G.R.B. acknowledges individual support from FWO-Vl.

* Electronic address: francois.peeters@ua.ac.be

[1] V. Anant, A. J. Kerman, E. A. Dauler, J. K. W. Yang, K. M. Rosfjord, and K. K. Berggren, Opt. Express 16, 10750 (2008).
[2] G. N. Goltsman, O. Okunev, G. Chulkova, A. Lipatov, A. Semenov, K. Smirnov, B. Voronov, A. Dzardanov, C. Williams, and R. Sobolewski, Appl. Phys. Lett. 79, 705 (2001).
[3] A. J. Kerman, E. A. Dauler, B. S. Robinson, R. Barron, D. O. Caplan, M. L. Stevens, J. J. Carney, S. A. Hamilton, W. E. Keicher, J. K. W. Yang, K. Rosfjord, V. Anant, and K. K. Berggren, Lincoln Laboratory Journal 16, 217 (2006).
[4] F. Marsili, F. Najafi, E. Dauler, F. Bellei, X. Hu, M. Csete, R. J. Molnar, and K. K. Berggren, Nano Lett. 11, 2048 (2011).
[5] A. M. Kadin and M. W. Johnson, Appl. Phys. Lett. 69, 3938 (1996).
[6] A. Semenov, P. Haas, H.-W. Hübners, K. Il'in, M. Siegel, A. Kirste, D. Drung, T. Schurig, and A. Engel, J. Mod. Opt. 56, 345 (2009).
[7] M. Hofherr, D. Rall, K. Il'in, M. Siegel, A. Semenov, H.-W. Hübbers, and N. A. Gippius, J. Appl. Phys. 108, 014507 (2010).
[8] A. Semenov, P. Haas, B. Günther, H.-W. Hübbers, K. Il'in, M. Siegel, A. Kirste, J. Beyer, D. Drung, T. Schurig and A. Smirnov, Supercond. Sci. Technol. 20, 919 (2007); Physica C 468, 627 (2008).
[9] A. Engel, A. D. Semenov, H.-W. Hübbers, K. Il'in, and M. Siegel, Physica C 444, 12 (2006).
[10] H. Bartolf, A. Engel, A. Schilling, K. Il'in, M. Siegel, H.-W. Hübbers, and A. Semenov, Phys. Rev. B 81, 024502 (2010).
[11] L. N. Bulacskii, M. J. Graf, and C. D. Batista, Phys. Rev. B 83, 144526 (2011); Phys. Rev. B 85, 014505 (2012).
[12] A. N. Zotova and D. Y. Vodolazov, Phys. Rev. B 85, 024509 (2012).
[13] G. R. Berdiyorov, M. V. Milošević, and F. M. Peeters, Phys. Rev. B 79, 184506 (2009).
[14] T. Yamashita, S. Miki, M. Sasaki, and Z. Wang, Appl. Phys. Lett. 99, 161105 (2011).
[15] J. R. Clem and K. K. Berggren, Phys. Rev. B 84, 174510 (2011).
[16] J. R. Clem, Y. Mawatari, G. R. Berdiyorov, F. M. Peeters, Phys. Rev. B 85, 144511 (2012).
[17] L. Kramer, R. J. Watts-Tobin, J. Mod. Phys. 40, 1041 (1978); R. J. Watts-Tobin, W. Krähenbühl, and L. Krame, J. Low Temp. Phys. 42, 459 (1981).
[18] A. V. Gurevich and R. G. Mints, Rev. Mod. Phys. 59, 941 (1987).
[19] D. Y. Vodolazov, F. M. Peeters, M. Morellé, and V. V. Moshchalkov, Phys. Rev. B 71, 184502 (2005).
[20] A. Andronov, I. Gordion, V. Kurin, I. Nefedov, I. Shereshevsky, Physica C 213, 193 (1993).
[21] F. Giazotto, T. T. Heikkilä, A. Luukanen, A. M. Savin, and J. P. Pekola, Rev. Mod. Phys. 78, 217 (2006).
[22] D. Y. Vodolazov and F. M. Peeters, Phys. Rev. B 66, 054537 (2002).
[23] J. Zhang, W. Slysz, A. Pearlman, A. Verevkin, and R. Sobolewski, Phys. Rev. B 67, 132508 (2003).
[24] H. L. Hortensius, E. F. C. Driessen, T. M. Klapwijk, K. K. Berggren, and J. R. Clem, Appl. Phys. Lett. 100, 182602 (2012).