Differences in the effects of turns and constrictions on the resistive response in current-biased superconducting wire after single photon absorption

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Abstract
We study how turns and constrictions affect the resistive response of superconducting wire after instantaneous, localized heating, by modeling the absorption of a single photon by the wire. We find that the presence of constrictions favors the detection of photons with a range of energies whereas the presence of turns increases the ability to detect only relatively ‘low’ energy photons. The main reason is that in the case of a constriction the current density is increased over the whole length and width of the constriction while in the case of a turn the current density is enhanced only near the inner corner of the turn. This results in inhomogeneous Joule heating near the turn and worsens the conditions for the appearance of the normal domain at relatively small currents, where the ‘high’ energy photons could already create a normal domain in the straight part of the wire. We also find that the amplitude of the voltage pulse depends on the location at which the photon is absorbed, being smallest when the photon is absorbed near the turn and largest when the photon is absorbed near the constriction. This effect is due to the difference in the resistance of constrictions and turns in the normal state from the resistance of the rest of the wire.

(Some figures may appear in colour only in the online journal)

1. Introduction

Superconducting nanowire single photon detectors (SNSPD) have a wide range of applications due to their high sensitivity, reliability and good time resolution [1]. The basic element of such a detector is a narrow long thin superconducting wire, in the shape of a meander, biased by a current close to the critical current. Recently, the problem of the influence of turns in a superconducting meander on the detection efficiency has attracted much attention [2–6]. Indeed, due to the current concentration near the turn the local current density is maximal there. Consequently, the current density reaches the depairing value near the turn at a lower bias current than in the straight wire, leading to a decrease in the critical current $I_c$ of the meander as compared with a straight wire. As a result, the detection efficiency for relatively ‘low’ energy photons decreases, because it depends essentially on the proximity of the critical current to the depairing current $I_c$.\footnote{Our definition is that a photon has ‘low’ energy if, after absorption, it creates a hot spot (region where the order parameter is suppressed) with a radius much smaller than the width of the wire. If the photon creates a hot spot with a radius which is comparable to the width of the wire we call it a ‘high’ energy photon. The radius of the hot spot can be estimated, in the framework of the used theoretical model, from equation (16) of [7]. To detect a ‘low’ energy photon one has to closely approach the depairing (not the critical $I_c$) current, because only in this case does the current density near the hot spot reach the depairing current density such that the voltage pulse will appear. For example, in NbN superconducting meanders the critical current is about 50% of the depairing current [8] and the detection efficiency of ‘low’ energy (in our sense) photons is determined by the number of locations (turns, constrictions) at which the current density locally approaches the depairing value as $I \to I_c$.}
The suppression of the critical current $I_c$ in the presence of turns was calculated in [2] in the framework of the London model, while experimentally this effect was investigated in [3–5]. A comparison of theory with experiment has demonstrated qualitative agreement (the decrease of $I_c$ with decreasing angle of the turn and/or increasing curvature of the turn), however quantitatively theory predicts stronger suppression of $I_c$ than was observed in the experiment [3–5] (note that calculations based on Ginzburg–Landau theory [3] give smaller suppression of $I_c$ than the London model does).

In a recent theoretical work [6] the resistive response of wires with turns after photon absorption was studied and the authors found only a weak effect of a turn on the ability of photon detection. In our work we demonstrate that the result of [6] is correct only for 'high' energy photons, whereas the effect is opposite for 'low' energy photons.

In our work we also study how a constriction (a narrowing of the cross-section of the wire) affects the resistive response of the superconductive nanowire after photon absorption. Our interest in this problem was attracted by experiments showing that voltage pulses after photon absorption have different amplitudes [9, 10], and that with a decreasing energy of the incident photon the average amplitude of the voltage pulse increases [9, 10]. In [10] it was suggested that the latter effect could be caused by local inhomogeneities (for example, constrictions) of the superconducting wire. Our numerical results confirm this suggestion and, as a side effect, we also find that constrictions, in contrast to turns, favor the detection of both 'low' and 'high' energy photons.

2. Model

For numerical simulations of the dynamic response after single photon absorption we use the model which was described in detail in our recent paper [7]. In short, we use the approach of the effective electron temperature [11], which is correct when the inelastic relaxation time due to electron–electron interactions $\tau_{e-e}$ is smaller than the inelastic relaxation time due to electron–phonon interactions $\tau_{e-ph}$. To model the effect of photons we assume that at $t = 0$ in the superconductor there is instantaneous heating of the electrons in a spot with radius $R_{\text{init}}$ with a temperature change $\Delta T$ which is related to the energy of the absorbed photon by

$$\eta 2\pi hc/\lambda = \Delta T \pi R_{\text{init}}^2 dC_v.$$  

Here $\eta$ is the quantum efficiency (which determines the fraction of the photon energy that goes to the hot electrons), $\lambda$ is the wavelength of the incident electromagnetic radiation, $h$ is the Planck constant, $c$ is the speed of light, $d$ is the thickness of the wire, and $C_v$ is the specific heat capacity (for simplicity we use the normal state heat capacity at $T = T_c$).

In our previous work [7] we checked that the results depend only slightly on our choice of $R_{\text{init}}$ if $R_{\text{init}}$ is small enough and $R_{\text{init}}^2\Delta T = \text{const} \sim 1/\lambda$.

The further evolution of the hot spot and superconducting order parameter in the superconducting wire is based on the numerical solution of a system of equations, including the nonstationary Ginsburg–Landau equation, the heat conductance equation for electron temperature, and the Poisson equation for the electric potential (note that in a recent work [12] this model is compared with other models of photon detection [13, 14] and is demonstrated to show relatively good agreement with experiment). This system is supplemented by an equation that takes into account that the superconducting wire has a finite kinetic inductance $L_k$ and a parallel connected shunt resistance $R_{\text{shunt}}$. Because of presence of a finite kinetic inductance $L_k$, in the case when $l_c$ changes in time there is an additional voltage drop $\sim L_k (dl/dt)$ and the voltage drop via the superconductor $V_s$ is not equal to the voltage drop via the shunt $V_{\text{shunt}}$ (see equation (5) in [7] and figure 1).

We study a wire having two $90^\circ$ turns (modeling part of the meander—see figure 2(a)) and a straight superconducting wire with a constriction—see figure 2(b) (we model variations of width of the wire—note that variations in the thickness of the wire produce the same effect as variations in its width). For the parameters of the superconductor we use those corresponding roughly to NbN [15, 16] ($\tau_{e-e} = 7$ ps, $\tau_{e-ph} = 17$ ps, $L_k = 0.05 \text{ cm} \text{s}^{-1}$, $R_{\text{shunt}} = 50 \Omega$, critical temperature $T_c = 10$ K, $C_v = 2.4 \text{ mJ cm}^{-3} \text{ K}^{-1}$, diffusion constant $D = 0.5 \text{ cm}^2 \text{s}^{-1}$, Ginzburg–Landau coherence length at zero temperature $\xi_{\text{GL}}(0) = 5$ nm, $d = 5$ nm, length of the wire $l = 250 \mu\text{m}$, normal state resistivity $\rho = 2.5 \mu \Omega \text{ m}^{-1}$ and $R_{\text{init}} = 7.5$ nm). In the numerical calculations time is measured in units of $t_0 = \pi h/8k_B T_c u \approx 0.052$ ps, voltage in units of $\phi_0 = h/2e t_0 \approx 6.3 \text{ mV}$ and the temperature of the environment was fixed at $T_0 = T_c/2$.

3. Results

3.1. Wire with turns

We start by presenting our results for the wire with two turns (see figure 2(a)). In the calculations we chose $w = 15 \xi_{\text{GL}}(0) = 75$ nm and the wire separation is equal to $w$ (the critical current with these parameters is $I_c \approx 0.91 I_{\text{dep}}$ at $T_0 = T_c/2$, where $I_{\text{dep}}$ is a temperature-dependent depairing Ginzburg–Landau current).
Figure 2. Model geometry: (a) superconducting wire with two \(90^\circ\) turns (1—photon is absorbed near the turn, 2—photon is absorbed far from the turn); (b) superconducting wire with a constriction (1—photon is absorbed in the constriction, 2—photon is absorbed far from the constriction).

In figure 3 we present the time dependence of the voltages across the superconductor \(V_s\) and the shunt \(V_{\text{shunt}}\) at different currents with a photon absorbed \((\lambda/\eta = 1.7 \, \mu m, \Delta T = 5.5 \, T_c)\) both near and far from the turn.

After photon absorption near the corner a single vortex is nucleated at the edge of the film and passes through the film (after photon absorption in the center of the film a vortex and an antivortex are nucleated simultaneously and move in opposite directions—in numerical calculations we could visualize them by mapping the magnitude and phase of the calculated order parameter—see also figures 3 and 4 in [7]).

From figure 3 one can see that at a relatively low current \((I = 0.6 I_{\text{dep}})\) vortices appear in series—they are seen as small peaks (noise-like) in \(V_s(t)\) at \(t < 200 \tau_0\) after photon absorption both near the turn and far from it, however the normal domain and relatively large voltage pulse on the shunt appears only for a photon absorbed in the straight part of the wire. Only for \(I > 0.66 I_{\text{dep}}\) (which was found from numerical calculations in which we varied the current and the voltage pulse appeared at \(I > 0.66 I_{\text{dep}},\) in figure 2(b) the threshold is not shown) is a pulse observed after photon absorption near the turn (see figure 3(b)).

One can also note that the amplitude of the voltage pulse is slightly smaller when the photon is absorbed near the turn (see figure 3(b)). The effect becomes stronger when the length of the normal domain becomes comparable to the length of the turn (in our model it could be reached by decreasing \(R_{\text{shunt}}\) and \(L_k\) or by increasing heat removal to phonons by decreasing \(\tau_{c-ph}\)). The explanation of this effect is simple—in the normal state the resistance of the wire near the turn is smaller (because it is wider—see figure 2(a)) than the resistance of the straight part of the wire, resulting in a difference in the amplitudes of the voltage pulses.

In figure 4 we present results for the resistive response of the superconductor after absorption of photons of lower \((\lambda/\eta \approx 9.4 \, \mu m, \Delta T = T_c)\) and higher energies \((\lambda/\eta \approx 0.8 \, \mu m, \Delta T = 11.5 \, T_c)\). The results for the ‘high’ energy photons (see figure 4(b)) are similar to the results presented in figure 3(a). But the resistive response for ‘low’ energy photons is qualitatively different. The normal domain, and therefore the large voltage pulse, appears at a smaller current when the photon is absorbed near the turn (see figure 4(a)), and one needs to increase the current to observe a large voltage pulse after photon absorption far from the turn.

We explain the results as follows. The absorbed photon creates an area with a locally increased temperature of quasiparticles (or, alternatively, an increased number of quasiparticles [15]). As a result the superconducting order parameter in the hot spot area is suppressed, leading to current density redistribution in the superconductor (it decreases in the hot spot area and increases around it). The nonzero \(V_s\) at
Figure 4. Time dependence of the voltage across the superconductor at different currents with incident photons of different energy (λ/η = 9.4 µm (ΔT = Tc) (a) and λ/η = 0.8 µm (ΔT = 11.5Tc) (b)) both near and far from the turn of the nanowire.

τ < 20τ0 is associated with this process (see insets in figures 3(a) and 4(a)). The larger the energy of the photon, the larger the size of the area with a partially suppressed order parameter (which can be roughly estimated in the same way as in [7, 15]). In [7], for straight superconducting wire, we show that the creation of a region with a suppressed order parameter leads to the nucleation of the vortex–antivortex pair inside this region at a current larger than some threshold value (which in [7] is called the detection current ID). The motion of these vortices may heat the superconductor substantially if the applied current is large enough (larger than the so-called heating or retrapping current IR, which can be estimated roughly from the balance of heat dissipation and heat removal from the system—see equation (6) in [7]), leading to the appearance of the normal domain and the large voltage pulse via the shunt. For photons of relatively large energy (which create a large region with suppressed order parameter) ID < IR [7] and at I ≈ IR the absorption of such a photon does not lead to a large voltage pulse despite the nucleation and motion of the vortices.

Due to the intrinsically inhomogeneous current distribution (current is concentrated near the inner corner of the turn), the order parameter is suppressed more near the turn than far from it. The additional suppression of the order parameter due to photon absorption favors vortex nucleation near the turn at a smaller current than photon absorption far from the turn. This is confirmed by our numerical results for photons of both ‘low’ and ‘high’ energies (see insets in figures 3(a) and 4(a)) and coincides with the result found in [6].

But conditions for the appearance of the normal domain are worse near the turn than far from it. Indeed, due to inhomogeneous heating (as a consequence of the inhomogeneous current distribution even in the normal state) and the more intense heat diffusion to the surrounding wider superconductor, the normal domain appears near the turn at a larger current than in the straight part of the wire. One should also take into account that after photon absorption near the turn the single vortex is nucleated at the edge of the wire and passes through the wire, while after photon absorption in the central part of the straight wire the vortex and antivortex are nucleated simultaneously and move in opposite directions. In the latter case, heat dissipation is at least two times greater per unit of time, which also improves the condition for normal domain nucleation.

The retrapping or heating current IR depends also on the efficiency of heat removal from the electron subsystem to the phonons, which is governed in our model by the inelastic electron–phonon relaxation time τe–ph [7]. For our parameters we find that for photons with λ/η > 3.1 µm (ΔT < 3Tc) the normal domain appears at a smaller current when the photon is absorbed near the turn. By changing τe–ph or using a different model for heat removal and heat dissipation one may move this boundary. In recent work [6] the resistive response of wires with turns after the absorption of photons with a certain energy (ΔT = 11.5Tc in our units) was considered. The authors found that a large voltage pulse appears at a smaller current with photons incident in the straight part of the wire, and only at larger currents does the voltage pulse appear after photon absorption near the turn. This result coincides qualitatively with our findings for a ‘high’ energy photon, but it is not a universal one and depends on the energy of the incoming photon. For relatively ‘low’ energy photons the effect is opposite and the large voltage pulse appears at smaller currents for a photon incident near the turn. There is also a quantitative difference between our findings and [6] as to the value of the voltage pulse. This discrepancy could be explained by the fact that, in [6], the value of the heat removal coefficient (which is inversely proportional to τe–ph in our model) was two orders of magnitude smaller than the one used in our calculations, thus leading to a small heating effect in [6].

### 3.2. Wire with a constriction

In this section we present our results for the effects of a constriction (see figure 2(b)) on the response of a wire after single photon absorption. We consider a straight wire with width w = 13ξ(0) = 65 nm, length of constriction l1 = w = 13ξ(0) and various widths w1/w = 0.62–1.

In wires with widths of the order of tens of nanometers, width variations of about 10% are unlikely, but variations of
the wire with a constriction (or a turn) decreases the detection ability of both ‘low’ and ‘high’ energy photons. But the presence of detection ‘ability’ of the turn, because it ‘helps’ in detecting the detection ‘ability’ of the constriction is better than the ability of the wire at only at $T_c$. We consider variations of the width because they are easier to model than variations of the thickness of the wire. Because both types of constriction lead to the same concentration of various widths.

Figure 5 demonstrates that the amplitude of the voltage pulse via the shunt increases with decreasing $w_1$ when a ‘high’ energy photon is absorbed ($\lambda/\eta = 0.9 \mu m$, $\Delta T = 10.8 T_c$) in constrictions with various widths. The detection of a ‘low’ energy photon by a constriction is similar to the case of a ‘high’ energy photon (see figure 6(a)). At $I = 0.59 I_{dep}$ only the narrowest constriction can detect a ‘low’ energy photon with $\lambda/\eta \approx 9.4 \mu m$ ($\Delta T = T_c$), while the straight part of the wire can detect such photons only at $I \approx 0.9 I_{dep}$, which is larger than the critical current of the wire with a constriction ($I_c \approx w_1/w I_{dep}$). In this respect the detection ‘ability’ of the constriction is better than the detection ‘ability’ of the turn, because it ‘helps’ in detecting both ‘low’ and ‘high’ energy photons. But the presence of a constriction (or a turn) decreases the detection ability of the whole wire because the constriction/turn decreases the critical current and hence the detection ability of the rest of the wire [17].

4. Conclusion

The effects of turns and constrictions in a current-biased superconducting wire on the resistive response after instantaneous, localized heating of a superconductor is studied theoretically. In our work we assume that local heating of the superconductor originates from single photon absorption by the wire. We find that weak heating (due to the absorption of a ‘low’ energy photon) near the turn leads to a highly resistive state (large voltage pulse) at a smaller current than if the same heating occurs in the straight part of the wire, while the situation is the opposite for large heating (originating from the absorption of a ‘high’ energy photon).

We find that, in contrast to a turn, the presence of a constriction favors the detection of both ‘high’ and ‘low’ energy photons. The main difference between a constrictions and a turn is that in the first case the current density is increased over the whole width of the constriction, while in the case of a turn the current density is enhanced only near the inner corner of the turn and is suppressed in other parts of the turn, thus worsening the conditions for the appearance of the normal domain.

Here we have to stress that our definition of ‘low’ energy photon (see footnote 1) assumes that in absolute values it
could be a photon with $\lambda = 500$ nm or $5 \mu m$, depending on the width of the meander. Apparently, in modern SNSPD with $I_c \leq 0.5 I_{dep}$ [8] such 'low' energy photons can be detected only by parts of the meander where the current density approaches the depairing current density locally (turns, local defects) when $I \rightarrow I_c$, which leads to a low intrinsic detection efficiency (DE) of such photons. For example, in a recent paper [21], the detection of $5 \mu m$ photons with DE $\sim 1\%$ in SNSPD with linewidth 30 nm and 2 $\mu m$ photons with DE $\sim 2\%$ in SNSPD with linewidth 85 nm were experimentally observed.

In our work we also find that the amplitude of the voltage pulse is smaller when the photon is absorbed near the turn, while it is larger when the photon is absorbed near the constriction (in comparison with photon absorption in the straight part of the wire without a constriction). We explain this effect by differences in the resistance of the constriction, parts of the wire with turns and the rest of the wire. The effect becomes stronger when the size of the normal domain becomes less than or comparable to the length of constriction and the length of the turn.

Due to local fluctuations (for example, a local increase of the temperature) in the superconducting wire a finite region with a partially suppressed order parameter will appear. In this respect the effect of a fluctuation is similar to the effect of a 'low' energy photon, which also creates a relatively local enhancement of the current density near the turn (which just means that $\lambda \leq w/10$ there is a local enhancement of the current density near the turn). But the probability for vortex entrance is proportional to $\exp(-U/k_BT)$, where $U/k_BT \sim 100$ if one uses the London model for the energy barrier for a straight film—see for example equation (2) in [18] and typical parameters of NbN film with $d = 5$ nm and London penetration length $\lambda_L = 470$ nm. But in the straight part $I_c$ is larger than near the bend. If $(1 - I/I_c^{\text{straight}}) = 0.15$ and $(1 - I/I_c^{\text{bend}}) = 0.05$ (which just means that $I_c^{\text{bend}} \simeq 0.89 I_c^{\text{straight}}$ and the transport current $I = 0.95 I_c^{\text{bend}}$) the ratio of the exponents is $\exp(10) \simeq 2 \times 10^4$. This demonstrates the power of the exponential factor and answers the question as to why the single vortex becomes a much larger than near the relatively narrow constriction (where the current density is maximal) while parts of the meander without a constriction cannot detect such a photon. In this case the average amplitude of the voltage pulse will be larger (and the dispersion of the amplitudes of pulses will be smaller) in comparison with 'high' energy photons (compare figures 6(a) and (b)) because only narrow constrictions can detect 'low' energy photons.

In our simplified model we neglect heating of phonons and energy removal to the substrate, which definitely affects the amplitude of the voltage pulse via the size of the normal domain [19, 20]. One may use the approach of a single temperature for electrons and phonons (as was done in [19]) when the thermoelastic processes are relatively slow and develop on a time scale much larger than both $\tau_{e-\phi}$ and $\tau_{e-ph}$, and the time of escape of hot phonons to the substrate $\tau_{esc}$ is much larger than max [$\tau_{e-\phi}$, $\tau_{e-ph}$]. But this condition is definitely not valid in the initial period of nucleation of the normal domain, when the system is deciding whether a normal domain will appear or not. We expect that phonon heating does not influence the condition for normal domain nucleation (in the model with effective electron and phonon temperatures) because the suppression of the order parameter and the nucleation of the first vortices takes less than $200 \tau_0 \sim 10\%$ (for the parameters of NbN in our model—see insets in figures 3(a) and 4(a)), which is shorter than $\tau_{e-ph}$ in NbN; during this time one can neglect energy transfer from electrons to phonons in the two-temperature model.

At $t > 10$ ps one already should take into account heating of phonons, because the time growth of the voltage pulse is larger than $\tau_{e-ph}$ (see figures 3 and 4) and one can use the approach of [19]. But this will change our results only quantitatively—if for given material parameters and external conditions the length of the normal domain is shorter than the length of the constriction/turn then one should observe a noticeable variation in the amplitudes of the voltage pulses, and vice versa in the opposite limit. Also note that even our simple version of the heat conductance equation gives reasonable values for the maximal value of resistance of the normal domain ($\sim 1 k\Omega$ for NbN wire with $w = 13 \xi(0) = 65$ nm and $d = 5$ nm) and for the rise time of $V_{\text{shunt}}$ ($\tau_{\text{rise}} \sim 2000 \tau_0 \sim 100$ ps), which are close to values reported in the literature [1, 9], and in [19] if one takes into account the difference in the widths of the wires.

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