1. Introduction

Superconducting nanowires [1] have attracted considerable attention recently due to their promising application in single photo detection [2–4], qubit and nanoscale superconducting quantum interference devices (SQUID) [5–7], etc. The typical lateral size of nanowires is about 10 nm, smaller than the coherence length, and the nanowire behaves as a one-dimensional superconductor. In this paper we will focus on the use of short nanowires as a weak link in the Josephson junctions and symmetric SQUID and derive their $I$–$V$ characteristics. To describe these weak links we will use the phase slip approach.

For a long nanowire, the dynamics of superconductivity under current bias using the phase slip approach has been studied for several decades [8–14]. With a small bias current, the nanowire is in a zero-voltage state. The nanowire develops instability when the current is ramped up to a threshold value $J_c$ which is well below the depairing current. At currents above $J_c$ the nanowire is in resistive (voltage) state. When the current is reduced, the voltage state is stable until a critical current $J_r$, where the nanowire jumps back into the zero-voltage state. Therefore, there is hysteresis in the $I$–$V$ curve, which is qualitatively similar to that in underdamped Josephson junctions. Experimentally, one can measure the voltage of the nanowire by applying a bias current to infer the dynamics.

In the resistive state, the electric field cannot be uniform in the nanowire, since the superconducting electrons will be accelerated to a critical velocity that breaks superconductivity. The voltage change is generated by a process known as the phase slip. At some area of nanowire, where the amplitude of the superconducting order parameter vanishes, the superconducting phase jumps by $2\pi$. The length, $\ell_{ps}$, of the area with vanishing order parameter amplitude around the phase slip center, depends on the electron inelastic scattering time because there the energy of superconducting electrons should be dissipated into phonon systems. The voltage generated at the phase slip center obeys the Josephson relation $V_{PSC} = \frac{\hbar \omega}{2e}$, where $\omega$ is the angular frequency of the phase slip. As the current increases, so does the number of phase slip centers, which manifest as stairs in the $I$–$V$ curves observed experimentally [12]. The general theoretical description of the nonequilibrium dynamics of superconductivity in nanowire is extremely difficult. For convenience, one usually employs the simplest time-dependent Ginzburg–Landau (TDGL) equations. Strictly speaking, the TDGL equations are only valid in the temperature region close to $T_c$. Nevertheless, even with the phenomenological TDGL, the dynamics are rich and capture the main features of the experiments. Moreover, the phenomenological TDGL produces qualitatively similar results to those obtained using microscopic methods.

Abstract

We derived the $I$–$V$ characteristics of short nanowire in a circuit with and without resistive and inductive shunt. For this we used numerical calculations in the framework of time-dependent Ginzburg–Landau equations with different relaxation times for the amplitude and phase dynamics. We also derived the dependence of the $I$–$V$ characteristics on flux in a superconducting quantum interference device made of two such weak links.

Keywords: superconducting nanowire, phase slip, time-dependent Ginzburg–Landau equation, $I$–$V$ curves

(Some figures may appear in colour only in the online journal)
The phase slips in the nanowire can also be excited by quantum and/or thermal fluctuations, which results in stochastic switching from the zero-voltage state to the voltage state [15–19]. In particular, thermal effects may play an important role in certain configurations of the nanowires. For a free-standing nanowire, the Joule heating produced by the phase slip is removed only at the electrodes. In this case, the self-heating effect alone can change the transport properties of the nanowire and leads to a hysteretic $I$–$V$ curve [20]. For a short shunted nanowire, the heating effect is minimized. Once the phase slip in the nanowire occurs, the bias current redistributes into the shunt branches, and this allows the nanowire to cool down [21, 22].

The transport properties in long nanowires with voltage bias were studied both experimentally and theoretically, and S-shaped $I$–$V$ curves were observed [13, 14]. Recently, a nanoscale SQUID made of superconducting short nanowire was fabricated [5–7]. The aluminum nanowire with a radius down to 100 nm and a length of about 10 nm was embedded in a circuit with shunt. The nanoscale SQUID shows high magnetic flux sensitivity with a spatial resolution of the order of 100 nm. These experiments call for theoretical understanding of the dynamics of the superconductivity in short nanowires with a length comparable to or smaller than the phase slip center length $l_{ps}$ under different bias and shunt conditions.

Before discussion of the properties of these weak links in the framework of the phase slip approach, let us sketch the alternative treatment associated with ballistic point contact [23, 24] in its quantum version [25–27]. At this approach point, contact is assumed to be of atomic size and one or several channels corresponding to quantized transverse modes are taken into account. The propagation of electrons and holes in such constriction is described by one-dimensional Bogoliubov-de Gennes equations, and scattering between modes with different transverse momenta is neglected. For that, the thickness of the constriction $d$ should be less than the superconducting correlation length $\xi_{GL}$ as well as the electron elastic and inelastic scattering lengths $\ell_{el}$ and $\ell_{in}$. For constrictions with a length much shorter than $\xi_{GL}$, the Fermi energy inside the constriction is much larger than the superconducting energy gap and thus the constriction may be described as a normal metal. Hence, the concept of Andreev multiple reflections was used. In terms of constriction conductance, this approach describes the subharmonic energy gap structure and $I$–$V$ characteristics well [25, 27]. The phase slip approach allows us to consider constrictions which do not obey restrictions $d \ll l_{ps}$. Such an approach is physically very transparent, and one is able to consider the effect of shunts in a simple way. However, rigorously speaking, such an approach is restricted to the temperature region close to $T_c$.

In this work, we study the dynamics of superconductivity in a short nanowire embedded in a shunted circuit. The remaining part of the paper is organized as follows. In section 2, we introduce the TDGL and boundary conditions for the nanowire. In section 3, we present the results for the nanowire with different shunt circuits. In section 4, we derive the $I$–$V$ curve of a symmetric SQUID made of nanowires. The paper is concluded in section 5.

2. Model

In our description of phase slip dynamics we neglect the thermal fluctuations in the present work for the following reasons. For a short nanowire, the Joule heating can be removed quickly through the electrodes attached to the nanowire. Furthermore, the presence of the shunt allows the nanowire to cool down by current redistribution. The dynamics of superconductivity in the nanowire can be described by the Ginzburg–Landau functional $\mathcal{F}$ for the superconducting order parameter $\Psi = \Delta \exp(i\phi)$,

$$\mathcal{F} = \int d^2 r \left( \frac{T - T_c}{T} |\Psi|^2 + \frac{\zeta(3)}{16\pi^2 T^2} |\Psi|^4 + \frac{-D}{8\pi} \left( \nabla - \frac{2i\epsilon}{c} A \right) |\Psi|^2 + \frac{\nabla \times A^2}{8\pi} \right),$$  \hspace{1cm} (1)$$

and by the dissipation function $\mathcal{W}$. Here, $\nu$ (0) is the electron density of states, $D$ is the diffusion coefficient and $\zeta(3)$ is the zeta function. The dissipation function for the time-dependent Ginzburg–Landau equation was found by Gor’kov and Kopnin in [11].

$$\mathcal{W} / \hbar \omega_{GL} = \frac{1}{2} \int d^2 r \left[ \Gamma_\Delta (\partial_\phi \Delta)^2 + \Gamma_\phi \Delta^2 (\partial_\phi \phi)^2 + (\partial_\phi \phi)^2 \right]$$  \hspace{1cm} (2)$$

where $\phi$ is the electric potential and $\Gamma_\phi = u (\Delta^2 / I^2 + 1)^{1/2}$ is the relaxation rate of the order parameter amplitude, while $\Gamma_\Delta = u$.
\((\Delta^2/I^2 + 1)^{-1/2}\) is the relaxation rate of the gauge-invariant phase. Here, \(I = (2\Delta_{GL}\tau_{ph}/\hbar)^{-1}\) characterizes the pair-breaking effect, where \(\tau_{ph}\) is the inelastic electron-phonon scattering time, \(\Delta_{GL} = k_B n^2 T (T_c - T) / [T(\beta)]\) and \(n = 5.79\) for superconductors with ordinary impurities in the dirty limit. We have also used dimensionless units: time in units of \(\omega_{GL}\); current density is in units of \(\pi k_B T\); length is in units of superconducting coherence length \(\xi_{GL} = \sqrt{\pi k_B T (T_c - T)}\). Here, \(\omega_{GL} = \pi k_B T\). Note that we have accounted for the different relaxation rates of the amplitude and the phase of the order parameter in equation (2).

The dynamics for the amplitude \(\Delta\) and phase \(\phi\) of the superconducting order parameter follow from the Euler–Lagrangian equation

\[
\frac{\partial}{\partial t} \Delta - \frac{\partial F}{\partial \Delta} + \frac{\partial^2 \Phi}{\partial \Delta^2} = 0,
\]

and similarly for \(\phi\). For a one-dimensional nanowire with non-circular geometry, we can neglect the effect of the magnetic field and put \(\Lambda = 0\). We then arrive at equations for the amplitude of the order parameters \(\Delta(x, t)\), gauge-invariant electric potential \(\Phi = \phi(x, t) + \partial_x \phi\) and superconducting momentum \(Q(x, t) = -\partial_x \phi\) inside one-dimensional nanowires at \(-L/2 < x < L/2\).

\[
-I_\text{ext} \partial_x \Delta - \frac{\partial_f^2 \Delta}{\xi_{GL}^2} - (1 - \Delta^2) = 0 \quad \text{(4)}
\]

\[
I_\text{ext} \partial_x^2 \Phi + \partial_x (\Delta^2 Q) = 0 \quad \text{(5)}
\]

The electric field is \(E = -\partial_x Q - \partial_t \Phi\) and the total current in the nanowire is given by

\[
j = -\Delta^2 Q - \partial_t \Phi \quad \text{(6)}
\]

Equations (4) and (5) hold in the temperature interval where the electric and space derivatives are small, i.e. \(\omega, D \nabla \phi \ll \tau_{ph}\), while the length of wire \(L\) should satisfy the condition \(D/L^2 \ll \tau_{ph}^{-1}\). These conditions are fulfilled in the temperature interval close to \(T_c\).

\[
(T_c - T)/T_c \ll (k_B T_c/\tau_{ph} / \hbar)^{-1} \quad \text{(7)}
\]

and for

\[
L \gg \xi_{GL} \frac{8k_B(T_c-T)\tau_{ph}}{\pi \hbar} \quad \text{(8)}
\]

For Pb, In, Sn and Al the values \(k_B T_c \tau_{ph}/\hbar\) are 20, 40, 100 and 1,000, respectively [10].

To solve these equations for short wires we need to formulate the boundary condition. We assume that both ends of the nanowire are connected to superconducting electrodes. At \(x = \pm L/2\), we have \(\psi(x = \pm L/2) = 0\) and for the electric field \(E = -\nabla \Phi\) we have \(\psi(x = \pm L/2) = 0\). We can choose the potential \(\Phi\) such that \(\psi(x = -L/2) = 0\). The voltage across the nanowire can be obtained by integrating equation (6),

\[
V = -\Phi(x = L/2) = jL - \frac{1}{2\pi} \int_{-L/2}^{L/2} dx (\Psi^* \partial_x \Psi - \Psi \partial_x \Psi^*) \quad \text{(9)}
\]

The superconducting phase at \(x = L/2\) is obtained by the Josephson relation \(\partial_x \Phi(x = L/2) = V\).

Equations (4) and (5) are nonlinear and are difficult to solve analytically. We solve them numerically. To avoid numerical instability when \(\Delta = 0\), we rewrite the order parameter in real and imaginary parts \(\Psi = \Psi_R + i\Psi_I\). We consider four typical circuits as shown in figure 1. Thus, we will be able to compare the \(I-V\) curves for current- and voltage-biased circuits as well as circuits with and without resistor and inductor shunts. For the simple current or voltage bias figures 1(a) and (b), the \(I-V\) curve can be obtained by numerical integration of equations (4), (5) and (9). For the shunted nanowire as shown in figures 1(c) and (d), we have additional relations:

\[
I_\text{ext} = jS + V / R_s \quad \text{(10)}
\]

for (c) and

\[
R_s(I_\text{ext} - jS) = L_\text{ind} \partial_j S + V \quad \text{(11)}
\]

for (d). Here, \(S\) is the cross-section of the wire, \(I_\text{ext}\) is the bias current, \(L_\text{ind}\) is the shunt inductance and \(R_s\) is the shunt resistance. The voltage \(V\) is in units of \(\pi \Delta_{GL}^2 / (4e k_B T)\), the current \(I_\text{ext}\) is in units of \(\pi \Delta_{GL}^2 S / (4e k_B T \xi_{GL})\), the resistance \(R_s\) is in units of \(\xi_{GL}/(\sigma S)\), and the inductance \(L_\text{ind}\) is in units of \(\xi_{GL}^2/(\sigma S \xi_{GL})\).

### 3. \(I-V\) curves for a nanowire

To understand the numerical results, we note that the length of the phase slip center \(\ell_p^{ph} \approx \xi_{GL} \sqrt{T_c} \alpha \tau_{ph}^{1/2}\) in long wires [10]. Thus, one can anticipate that qualitatively the same relation holds for short wires. The \(I-V\) curve for the current bias...
nanowire (figure 1(a)) is depicted in figure 2. The switching current, where the nanowire develops non-zero voltage, increases approximately as $1/L$ as $L$ decreases. This dependence follows from the fact that it is more difficult energetically to create a phase slip center with high gradients of the superconducting order parameter inside a shorter wire. For a fixed $L/\xi_{GL}$, hysteresis develops for a small $\Gamma = 0.01$, as shown in figure 2(b), while for a fixed $\Gamma = 0.1$ hysteresis develops only for $L > 1$. This behavior corresponds to the notion that hysteresis in relatively short wires develops when the ratio $L/\ell_{ps} \geq 10$.

Figure 3. $I$–$V$ curves for a nanowire under a voltage bias with different $L(a)$ and $(b)$, and different $\Gamma(c)$. In $(c)$ the $I$–$V$ curves are almost identical for a large $\Gamma \geq 1$.

Figure 4. $I$–$V$ curve of nanowires with a shunt resistor with different $R_s(a)$, different $L(c)$ and different $\Gamma(e)$. The corresponding current in the wire $j$ is shown in $(b)$, $(d)$ and $(f)$.

For the voltage-biased nanowire, there is no hysteresis in the $I$–$V$ curve, as depicted in figure 3. For a short wire, $L/\ell_{ps} < 10$, the $I$–$V$ curve is monotonic when the bias voltage is increased. However, for a longer wire, the $I$–$V$ curve is non-monotonic as the number of phase slip centers increases with voltage. This non-monotonic behavior was observed experimentally in long wires and explained in [13, 14]. For a large $\Gamma$, the $I$–$V$ curve depends weakly on $\Gamma$ because in this case $L < \ell_{ps}$ and the frequency of oscillations $\omega = 2eV/\hbar$ is well below the dissipation rate $\hbar/\tau_{ph} = 2\Delta_{GL}/\Gamma$ at not very low voltages $eV > \Delta_{GL}/\Gamma$. 
We calculate the dependence of the total current and current in the wire on voltage (external current-biased) in the presence of shunt resistance. One peculiar feature is the non-monotonic dependence of the current in the wire on the voltage when the shunt resistance $R_s$ is small, as depicted in figure 4. For a large $R_s$, the dependence is monotonic. The dependence of $I-V$ curves on $\Gamma$ is present in figure 4(e). For large $\Gamma > 1$, the $I-V$ curve is virtually the same. Thus, the non-monotonic dependence of the current in wire on voltage also occurs in the time-dependent Ginzburg–Landau limit with $\Gamma \to \infty$. This non-monotonic dependence is a unique feature when shunt resistance is present. Such a behavior $j(V)$ is a consequence of the sublinear dependence of $I_{ext}(V)$ at a small $V$, as shown in figure 2 and in the upper panels of figures 4(a), (e) and (c). Then $S = I_{ext} - V/R_s$, and at a low $V$ the second term results in a negative derivative with respect to $V$. On the other hand, the sublinear dependence of $I_{ext}(V)$ is inherent to any superconducting system because the superconducting state suppresses the development of phase slips.

We then add an inductance in serial with the nanowire and check the effect of the inductance on the $I-V$ curve. As drawn in figure 5, the non-monotonic behavior is less pronounced for a larger inductance $L_{ind}$. We also study the $R_s$ dependence when inductance is present. For a small $R_s$, the system is close to the voltage bias case, and we see non-monotonic dependence of voltage on the current in the wire. For a large $R_s$, the system is close to the current bias case, and we observe a hysteresis when the current is swept. Note that these results with both inductive and resistive shunt cannot be obtained from the $I-V$ curve without shunt because the dynamics of phase slips are affected by inductive shunt; see equation (11).

Figure 5. $I-V$ curve of the nanowire with a shunt resistor and an inductor for different $L_{ind}(a)$ and different $R_s(c)$. The corresponding current in the wire $j$ is shown in (b) and (d). The arrows denote the current sweep direction.

4. $I-V$ curves for a SQUID

We proceed to investigate the $I-V$ curve of a SQUID shunted by a resistance, as schematically shown in figure 6. For simplicity, we assume that the nanowires in the two branches are identical. The dynamics of the superconductivity in the nanowire are still governed by equations (4), (5) and (9). For a SQUID with circular geometry we need to account for the vector potential in the expression for $Q$:

$$Q = A - \frac{\Phi_0}{2\pi} \nabla \Phi,$$

(12)

where $\Phi_0 = hc/(2e)$ is the quantum flux. Integrating this relation over the SQUID contour we see that the flux enclosed by the SQUID is quantized, which yields

$$\int_1^2 \text{d}x Q_1 + \int_2^1 \text{d}x Q_2 + \Phi_0 + L_{ind}(j_1 - j_2) S = 2\pi n$$

(13)

with an integer $n$. Here, $j_i$ is the current density in the different nanowires, $\Phi_0$ is the applied flux and $L_{ind}$ is the geometry inductance of the SQUID. For a small SQUID, $L_{ind}$ is small and we neglect this contribution in the following calculations. In equation (13), $\Phi_0$ is in units of $\Phi_0/2\pi$. Without loss of generality, we restrict to $0 \leq \Phi_0/\Phi_0 < 1$. The total current in the circuit is $I_{ext} = (j_1 + j_2)S + V/R_s$.

The $I-V$ curve is shown in figure 7. The $I-V$ curve is identical for $\Phi_0/\Phi_0 = 1 - \Phi_0/\Phi_0$. As $\Phi_0$ increases from 0 to 0.5, the quasiparticle current and voltage increase because of the destructive interference of the supercurrent in the different nanowires. At $\Phi_0/\Phi_0 = 0.5$, the supercurrents in the SQUID are completely
Figure 6. Schematic view of a SQUID shunted by a resistor and biased by a current source.

Figure 7. (a) I–V of a SQUID and (b) current in one branch of the SQUID with a shunt resistor in the presence of a flux $\Phi_a$. Here, $R_s=1.0$, $I=0.1$ and $L_1=L_2=0.2$.

canceled out, and the $I$–$V$ curve becomes linear. The conductance of the circuit is given by $\sigma=\frac{dI}{dV}=R_s^{-1}+L_1^{-1}+L_2^{-1}$ in this case. For a symmetric SQUID, the current in one branch is half of the total current passing through the SQUID. For a small voltage $V \ll 1$, the frequency of the phase slip is small; thus it needs an extremely long simulation time to obtain a smooth curve. The oscillation of $I$–$V$ curves in figure 7(b) at low voltages is therefore a numerical artifact.

It has been firmly established both theoretically and experimentally that the time-dependent Ginzburg–Landau approach becomes questionable. The $I$–$V$ curve for a nanoscale SQUID, the applicability of the Ginzburg–Landau equations to the coherence length, as realized in the recently fabricated nanoscale SQUID, the applicability of the Ginzburg–Landau approach becomes questionable. The $I$–$V$ curve for a nanoscale SQUID has been measured experimentally in [7]. The SQUID remains superconducting below a switching current, then the current drops as voltage increases for a low voltage. This behavior is qualitatively similar to the calculated $I$–$V$ curve shown in figure 7, which suggests that one might still be able to describe the dynamics of superconducting nanowires based on time-dependent Ginzburg–Landau equations. However, in [7] data for high voltage are not presented and there we expect an increase of current when the voltage is increased according to figure 7. This predication can be used to check the validity of the Ginzburg–Landau approach to this system.

5. Conclusion

To summarize, we have studied the $I$–$V$ characteristics and the dynamics of superconductivity of a short nanowire with different bias and shunt, by numerically solving the time-dependent Ginzburg–Landau equations. For current bias without shunt, we show that the $I$–$V$ curves are hysteretic for a small $I$ and short wire. For voltage bias without shunt, the $I$–$V$ curves are non-monotonic for a long wire while they are monotonic for a short wire. The $I$–$V$ curves do not depend on $I$ for a large $I$. Interestingly, for current bias with a shunt resistance, the current through the nanowire depends non-monotonically on the voltage. The current first drops and then increases with voltage. In the presence of an inductance in serial to the resistance in the shunt circuit, the non-monotonic dependence of the nanowire current on voltage becomes less pronounced. Meanwhile, by tuning the shunt resistance, one can interpolate between the current bias and voltage bias. The time-dependent Ginzburg–Landau equations might be promising to describe the dynamics of superconductivity in nanowires, which has been demonstrated through the comparison between our results and the experimentally measured $I$–$V$ curves in a nanoscale SQUID. Moreover, it is easy to describe the circuits with resistive and inductive shunts in the framework of this model.

Acknowledgments

We thank E Zeldov for helpful discussions. This project is supported by the US Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences and Engineering. Computer resources for numerical calculations were supported by the Institutional Computing Program in LANL.

References

[1] Bezryadin A 2008 J. Phys.: Condens. Matter 20 043202
[2] Il'in K S, Lindgren M, Currie M, Semenov A D, Goltzman G N, Sobolewski R, Cherfedrichenko S I and Gershenzon E M 2000 Appl. Phys. Lett. 76 2752
[3] Goltzman G N, Okunev O, Chulkova G, Lipatov A, Semenov A, Smirnov K, Voronov B, Dzardanov A, Williams C and Sobolewski R 2001 Appl. Phys. Lett. 79 705
[4] Natarajan C M, Tanner M G and Hadfield R H 2012 Supercond. Sci. Technol. 25 063001
[5] Finkler A, Segev Y, Myasoedov Y, Rappaport M L, Neeman L, Vasyukov D, Zeldov E, Huber M E, Martin J and Yacoby A 2010 Nano Lett. 10 1046
[6] Finkler A, Vasyukov D, Segev Y, Ne’eman L, Lachman E O, Rappaport M L, Myasoedov Y, Zeldov E and Huber M E 2012 Rev. Sci. Instrum. 83 073702
[7] Vasyukov D et al 2013 Nature Nanotechnol. 8 639
[8] Kramer L and Watts R J 1978 Phys. Rev. Lett. 40 1041
[9] Gorkov L P and Eliashberg G M 1968 Zh. Eksp. Teor. Fiz. 56 1297
[10] Ivlev B I and Kopnin N B 1984 Adv. Phys. 33 47
[11] Gorkov L P and Kopnin N B 1982 Sov. Phys.—Usp. 19 496
[12] Tinkham M 1996 Introduction to Superconductivity
   (New York: McGraw-Hill)
[13] Vodolazov D Y, Peeters P M, Piraux L, Matefi S and
   Michotte S 2003 Phys. Rev. Lett. 91 157001
[14] Michotte S, Matefi S, Piraux I, Vodolazov D Y and
   Peeters F M 2004 Phys. Rev. B 69 094512
[15] Shah N, Pekker D and Goldbart P M 2008 Phys. Rev.
   Lett. 101 207001
[16] Pekker D, Shah N, Sahu M, Bezryadin A and Goldbart P M
   2009 Phys. Rev. B 80 214525
[17] Sahu M, Bae M-H, Rogachev A, Pekker D, Wei T-C,
   Shah N, Goldbart P M and Bezryadin A 2009 Nature Phys.
   5 503
[18] Brenner M W, Roy D, Shah N and Bezryadin A 2012 Phys.
   Rev. B 85 234507
[19] Lin S-Z and Roy D 2013 J. Phys.: Condens. Matter 25 325701
[20] Tinkham M, Free J U, Lau C N and Markovic N 2003 Phys.
   Rev. B 68 134515
[21] Kerman A J, Dauler E A, Keicher W E, Yang J K W,
   Berggren K K, Gol G and Voronov B 2006 Appl. Phys.
   Lett. 88 111116
[22] Yang J K, Kerman A J, Dauler E A, Anant V, Rossfjord K M
   and Berggren K K 2007 IEEE Trans. Appl. Supercond.
   17 581
[23] Kulik I O, Omel A N 1977 Fiz. Nizk. Temp. 3 945
   Kulik I O and Omel A N 1978 Sov. J. Low Temp. 4 296
[24] Likharev K K 2000 Applications of Superconductivity
   Weinstock H (Dordrecht: Kluwer) p 247
[25] Klapwijk T M, Blonder G E and Tinkham M 1982 Physica B
   109&110 1657
[26] Beenakker C W J and van Houten H 1991 Phys. Rev. Lett.
   23 3056
[27] Averin D V, Bardas A and Imam H T 1998 Phys. Rev. B
   58 11165