Resistive current states in narrow superconducting films

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Abstract. The I–V characteristics of superconducting channels are studied experimentally in the region of low ($j \sim j_c$) and high ($j \gg j_c$) transport currents. The analytical expressions obtained for the I–V characteristics by Ivlev and Kopnin provide a good description of the experiment. The theoretical results suggest the existence of two temperature regions where the relaxation of the charge disbalance proceeds in different ways.

Keywords. Superconductivity; resistive state; critical current; excess current.

1. Introduction

The resistive current states and the effects of non-stationary and non-equilibrium superconductivity present one of the most important problems in the physics of superconductors. The development of the resistive state theory (Bezugly *et al* 1977) yielded analytical expressions for I–V characteristics (IVC) of channels in the vicinity of the critical temperature T_c (Ivlev *et al* 1980; Ivlev and Kopnin 1984). It is therefore possible to compare experimental and theoretical IVCs of such objects, which is the subject of this paper.

2. Experimental procedure

The experiment was conducted on superconducting tin films $w \leq \xi(T)$, $\lambda(T)$ wide and $d \ll \xi(T)$ thick. The parameters of two typical samples are given in table 1.

A quantitative comparison of experimental and calculated IVCs (Ivlev *et al* 1980) requires the knowledge of electron-phonon relaxation time τ_e for the sample in question, since this magnitude enters, as a parameter, into the expression describing IVCs and is responsible for the temperature range within which the appropriate formulae are valid. The measurement of the differential resistance R_g from the linear part of IVC corresponding to the first phase-slip centre (PSC) can give the penetration depth of the longitudinal electric field $l_E(T)$ permitting subsequent calculation of τ_e (Skocpol *et al* 1974). The obtained value $\tau_e = 1.5 \times 10^{-10}$ s is used below.

3. Experimental study of IVC

The typical IVCs taken on the whole sample Sn 1 (curve 3) and its two parts (curves 1, 2) are given in figure 1. The broken straight lines show IVC of the sample at normal state at 4.2 K. The current and voltage scale fails to display the jump-like structure of IVCs in the low current region. According to Ivlev *et al* (1980), the sample Sn 1 is a long channel since $L \gg l_E(T)$. Hence, the IVC should look like a smooth curve, which can be

Table 1. The parameters of the samples.

Nos.	Sample length, L 10^{-6} m	Width, w 10^{-6} m	Thickness, d , 10^{-6} m	Resistance at temperature		
				$T = 300$ K R_{300} , Ohm	$T = 4.2$ K $R_{4.2}$, Ohm	T_c , (K)
Sn 1	101	1.5	0.1	88	7	3.847
Sn 2	40	2.0	0.35	7.55	0.126	3.733

Figure 1. Experimental IVCs for Sn 1 (curve 3) and its two parts (curves 1,2). Two broken curves from I'_c and I''_c are the IVC calculated by equation (1).

described by the following expressions (Ivlev *et al* 1980):

$$J = J_c \exp(-0.91 J_c R_{4.2}/V) \quad (1)$$

in the temperature interval

$$(\tau_e k T_c / \hbar)^{-2} \ll 1 - t \ll (\tau_e k T_c / \hbar)^{-1} \quad (2)$$

and

$$J = J_c + J_c \exp \left\{ -1, 1 \frac{J_c R_{4.2}}{V} \ln^{\frac{1}{2}} [\tau_e k (T_c - T) / \hbar] \right\} \quad (3)$$

in the temperature interval

$$(\tau_e k T_c / \hbar)^{-1} \ll 1 - t \ll (\tau_e k T_c / \hbar)^{-\frac{1}{2}} / \ln [\tau_e k (T_c - T) / \hbar]. \quad (4)$$

The temperature intervals (2) and (4) are responsible for the effect of the superconducting current upon the relaxation rate of the phase-slip-induced disbalance between the

Figure 2. Temperature dependence of critical current density J_c for two parts of the sample (curves 1,2) and non-Josephson generation current density J_g (curves 1', 2', 3') for Sn 1.

chemical potentials of the pairs and quasi-particles (Ivlev *et al* 1980). At the temperatures corresponding to (2) this effect on the above disbalance is negligible, while at the temperatures (4) it becomes significant. For sample Sn 1 the temperature intervals (2) and (4) correspond to $0.986 \ll t \ll 0.9998$ and $0.93 \ll t \ll 0.986$, respectively. Because of high overheatings at low temperatures and fluctuations near T_c , the experimental range is 0.98–0.995.

In addition to the experimental IVC of the whole sample (curve 3), figure 1 also shows the one calculated by equation (1) (a broken curve). No agreement is seen between the theoretical and experimental curves. This may result from the fact that the uniformity condition of the order parameter Δ (or T_c) is not obeyed along the sample length. If $R(T)$ is taken separately on two parts of Sn 1, we have two values of T_c differing by $\approx 15 \times 10^{-3}$ K. This T_c variation for two parts of the sample is obtained when T_c is calculated from the temperature dependence of the critical current (figure 2, straight lines 1, 2). Moreover, finding T_c from the temperature dependence of the non-Josephson generation current density j_g (Churilov *et al* 1986) gives the third value of T_c (figure 2, straight lines 1', 2', 3'). The T_c variation along the sample would lead to the situation when the critical currents of individual parts, which are at the same absolute but varying reduced temperatures can be several times different since $j_c \sim (1 - t)^{3/2}$. In our case j_c of one part of the sample differs nearly by a factor of two from j_c of the other part. The geometric nonuniformities at the edge or along the thickness, which do not exceed 10%, produce much smaller effect on local j_c values.

It is easier to meet the requirement of T_c uniformity in shorter samples, which is seen in figure 1, where experimental curve 2 is closer to the calculated (broken) curve running from the point I_c'' than curve 3 from the point I_c' .

The IVCs of the sample Sn 2, whose total length is $L \approx 4l_E(T)$, are given in figure 3. The dispersion of T_c data along the sample length is not more than 1×10^{-3} K;

Figure 3. IVCs for Sn 2 taken on part a , part b , on the whole sample c at various reduced temperatures t . Arrows show IVC portions with excess current. The broken curve for t_2 (c) is the initial portion of IVC calculated by equation (1).

accordingly, the critical currents of the two parts are practically the same. The dependence calculated by equation (1) for the initial part of IVC (figure 3c, the broken curve for t_2) describes well the experimental one.

4. Excess current in narrow superconducting films

At $j - j_c \gg j_c$ the experimental IVC taken on a superconducting film reaches the linear part with $R_g = R_{4.2}$. This part of the IVC corresponds to the sample state with an excess current j_{exc} and is described as follows:

$$j = V/R_{4.2} + j_{exc}. \quad (5)$$

According to Ivlev *et al* (1980) in the temperature interval (2)

$$j_{exc} = aj_c, \quad (6)$$

where $a \simeq 0.68$, while in the temperature interval (4)

$$J_{exc} = J_c b / \ln^{\frac{1}{2}} [\tau_e k (T_c - T) / \hbar], \quad (7)$$

where $b \simeq 1.22$.

The relatively uniform sample Sn 2 is schematically shown in figure 3 (insert). Seen are three groups of IVCs. Here a and b are the IVCs of the two corresponding parts of the sample, c is the IVC of the whole sample.

As seen in figure 3, after the PSC formation, each part containing one centre, a linear part appears in the IVC, which is parallel to the straight line referring to the normal state. The resistive region is however shorter for part b than for part a . Thus, the transition to the pure normal state in part b occurs earlier than in part a . This may be associated, for example, with different conditions of the

Figure 4. Dependence of excess current normalized to the critical current upon t for Sn 2. Experimental results were taken on part a ($\square$), part b ($\triangle$), the whole sample ($\diamond$) (see figure 3c), on the whole sample in portions marked with arrows in figure 3c ($\times$). Solid straight line 1 is theoretical dependence (6), curve 2 is theoretical dependence (7) with numerical factor 0.2.

thermal balance along the sample length because of varying degree of adhesion between the film and the substrate. The arrows on the total IVC show two parts of the IVC, which can be considered as the states with excess current. The part outlined with solid arrows indeed refers to the state with excess current of the whole sample. The region outlined with broken curves refers to the resistive state with excess current of part a , while part b is already normal.

Figure 4 shows the temperature dependence j_{exc}/j_c for separate parts of the film ($\square$, $\triangle$) and for the whole sample ($\diamond$) in conformity with figure 3. The series of experimental points ($\times$) in figure 4 reflect, as we have found out, the situation, when one part of the film is normal and the other is still resistive. It is this situation that leads to about a two-fold decrease in j_{exc}/j_c , since both a and b parts have close $R_{4.2}$ values. Solid straight line 1 in figure 4 shows the theoretical dependence (6) and curve 2 the dependence (7) multiplied by 0.2. As seen in the figure, the experimental values of j_{exc}/j_c agree fairly well with the theoretical ones within the temperature interval (2), where the current effect on the disbalance relaxation rate is negligible. At lower temperature there is a transient region, in which the behaviour of the j_{exc}/j_c magnitude has not been determined analytically. At still lower temperature the experimental points fall on to the theoretical dependence (7), the fitting factor 0.2 being taken into account.

In non-uniform samples of the Sn 1 type j_{exc} is usually $(0.1-0.2)j_c$.

5. Conclusion

Thus, it is shown for the first time that the analytical expressions derived in Ivlev *et al* (1980) for IVCs in the regions of low ($j \sim j_c$) and high ($j \gg j_c$) currents describe well the experimental IVC for superconducting channels. Experimental support is provided for

the theoretical results suggesting the existence of two temperature regions in which the relaxation of the charge disbalance proceeds in different ways: in one region, near T_c , the relaxation rate is independent of current and the ratio j_{exc}/j_c is independent of temperature, in the other, with lower temperature, the relaxation rate is affected by the transport current, and the ratio j_{exc}/j_c is a function of temperature.

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