Resistance domain in type II superconductors

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We show that traveling domains with a finite resistance can exist in type II superconductors in the presence of a transport current. An experiment in which this effect generates an alternating electric field and current is proposed.

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The structure and mobility of the boundary between the normal phase and the superconducting phase in type II superconductors with a transport current have been investigated extensively in the literature (see, for example, Ref. 1). However, the existence and stability of normal regions with finite dimensions have been investigated very little under the same conditions. In this paper we show that the superconducting phase can sustain traveling resistive domains—solitons that have a finite resistance.

We shall examine a sample in which the current I flows along the x axis. The distribution of the superconducting phase ($T < T_1$) and the resistive phase ($T > T_1$) in the sample is determined by the temperature $T(x, y, z)$ and current density j (T_1 is determined from the equation $j = j_c(T_1)$, where j_c is the critical current density due to pinning). Let us assume that the heat transfer coefficient of the coolant $h(T)$, the thermal conductivity κ, the area A, and the perimeter P of the transverse cross section are such that $hA/P\kappa \ll 1$. Under these conditions the temperature in the yz plane is almost constant and the problem of the distribution of phases is reduced to a one-dimensional problem.

The equation for thermal conductivity for the self-similar solutions of interest to us $[T = T(x - vt)]$ has the form

$$\frac{d}{dx}\kappa\frac{d}{dx}T + (\nu v \mp q)\frac{dT}{dx} + Q - W = 0, \tag{1}$$

where ν is the specific heat, Q is the specific heat release, W is the heat transfer $[W = h(T)(T - T_0)P/A]$, T_0 is the coolant temperature, and the term qdT/dx depends on the thermoelectic effect (Thompson effect[2]). The expressions for Q and q can be written as follows:

$$Q = \frac{j^2}{\sigma}\eta, \qquad q = j\eta^2\Pi \tag{2}$$

$$\eta(T) = \begin{cases} 0, & T < T_1 \\ 1 - j_c/|j|, & T > T_1 \end{cases}, \tag{3}$$

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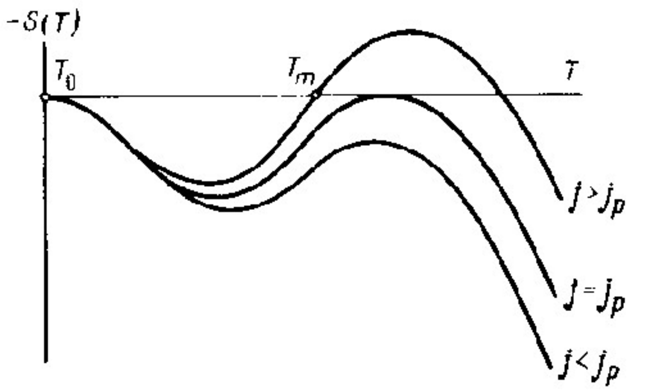

FIG. 1.

where σ is the conductivity in the magnetic-flux mode, and Π is the thermoelectric Thompson constant.[2] The η function determines whether the sample is in the superconducting, resistive, or normal state. Henceforth, we shall assume that $Q \gg q dT/dx$. This condition is always satisfied for the real ratio of the parameters.

Equation (1) has the form of the equation of motion of a "particle" in a potential field—$S(T) = \int_{T_0}^{T} (Q - W)\kappa\, dT$ in the presence of a fictional force $(\nu v - q) dT/dx$. Figure 1 shows the shape of $S(T)$ for different values of j. If $j > j_p$, then soliton solutions exist in the system. Assuming that the Thompson heat is a minor perturbation, we can easily obtain the corresponding temperature distribution and the velocity v:

$$|x| = \frac{1}{\sqrt{2}} \int_{T}^{T_m} \frac{\kappa\, dT}{S^{1/2}}, \qquad v = \frac{\int_{T_1}^{T_m} \frac{q S^{1/2}}{\kappa}\, dT}{\int_{T_0}^{T_m} \frac{\nu S^{1/2}}{\kappa}\, dT}. \tag{4}$$

Equation (4) shows that such resistive domain ($T_m > T_1$) at $q = 0$ is static and at $q \neq 0$ it is a traveling domain. We note that it can readily be shown that the Thompson effect produces an asymmetry in the velocity of the boundary between the normal phase and the superconducting phase in the direction of the current (v_+) and against (v_-) it; moreover, $v_+ - v_- = 2v$. This effect was observed experimentally in Ref. 3.

We shall now examine the volt-ampere characteristic $U = U(j)$ of the sample with a resistive domain. Using Eq. (4) we obtain

$$U = \sqrt{2} \int_{T_1}^{T_m} \frac{\kappa}{\sigma} (j - j_c) \frac{dT}{S^{1/2}}. \tag{5}$$

The qualitative behavior of $U(j)$ is shown in Fig. 2 as a solid line. The decreasing $U(j)$ means that such a domain is unstable in the fixed-current mode. The stability can be achieved at the given voltage or by connecting a shunt with a resistance r in parallel with the sample. In the latter case, the current across the superconductor is determined by solving the equation $r(I_0 - I) = U(I)$ for which $r < |dU/dI|$ (point 1 in Fig. 2), where $I_0 = A j_0$ is the current in the outer loop.

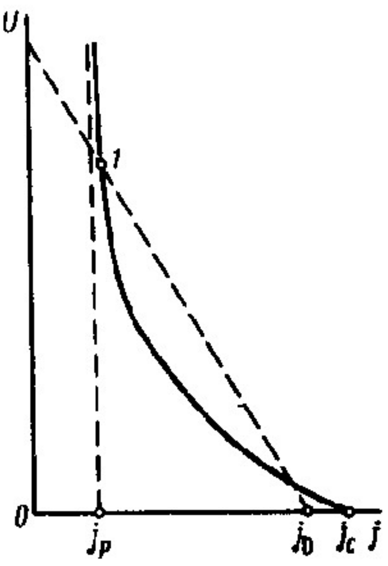

FIG. 2.

The traveling resistance domains allow the use of this effect for the generation of voltage and current oscillations at the frequency $\omega = 2\pi v/L$, where L is the sample length. Essentially, a "seeding" fluctuation $\delta T \sim T_1 - T_0$ is needed to produce a domain. Figure 3 shows a typical experimental arrangement.

The sample is divided into two regions: region 1, where $j > j_p$ and region 2, where $j < j_p$ (this can be accomplished, for example, by having different heat transfer h_1 and h_2 in the regions 1 and 2, respectively). As seen in Fig. 1, a domain can exist only in region 1; in the "colder" region 2 it dissipates. To form a domain in the active section a (see Fig. 3), we must locally reduce the critical current $\tilde{j}_c \tilde{A} < j_c A$ (for example, by reducing the cross section $\tilde{A} < A$). We now select I_0 and $\tilde{j}_c(T_0)$ in such a way that we can satisfy the inequalities $I_0 > \tilde{A}\tilde{j}_c(T_0)$ and $I < \tilde{A}\tilde{j}_c(T_0)$, where I is a solution of the equation $r(I_0 - I) = U(I)$. Thus, in the absence of a domain in the sample the section a is heated as a result of the first inequality, which produces the needed seeding to produce the domain. After the domain has formed, the current I evidently is such that the active section is "quenched" as a result of the second inequality. During the transit time $t_0 = L/v$ the domain reaches region 2 where it disappears; this increases the current I to I_0, and the entire process is repeated.

This type of self-oscillation mode can be achieved if the domain does not acquire inhomogeneities associated with the active section a and with the boundary between the region 1 and region 2. According to Ref. 4, it can be shown that when $A = \text{const}$,

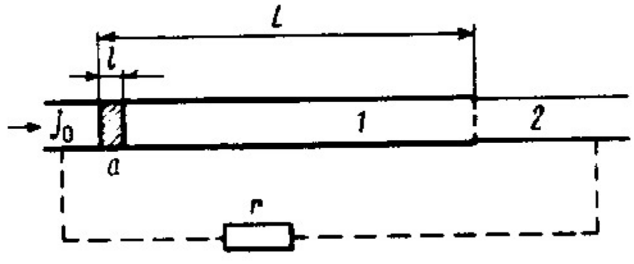

FIG. 3.

$\tilde{j}_c < j_c$, and h_1 is different from h_2 ($h_1 < h_2$), the domain cannot be localized, if

$$\frac{j_c(T_0) - j_0}{j_c(T_0) - \tilde{j}_c(T_0)} \lesssim \frac{j_c^2(T_0) l}{(T_c - T_0)\sigma} \sqrt{\frac{A}{h_1 \kappa P}}, \quad r > r_c \simeq \frac{1}{\sigma} \sqrt{\frac{\kappa}{APh_1}}, \tag{6}$$

where l is the length of the active section and T_c is the critical temperature.

To preclude discontinuities of the magnetic flux in the experiment[5] and, therefore, to increase the transport current, it is usually easier to use a superconductor coated with a layer (of the order of A/P) of normal metal. Thus, for the characteristic parameters $\sigma = \sigma_n$, $\kappa = \kappa_n$, and $\nu = x_n \nu_n + x_s \nu_s$, x_s and x_n are the relative concentrations of the superconducting material (s) and of the normal metal (n) ($x_s + x_n = 1$), and $q \approx q_n = jTd(\alpha_n \eta)/dT$, where α_n is related to Π_n by the relation $\Pi_n = Td\alpha_n/dT$.[2]

We shall now estimate the velocity of the resistive domains, and r_c and j_0. Assuming that $\nu \sim 10^4$ erg/cm^3. K, $j \sim j_c \sim 5 \times 10^4$ A/cm^2, $\Pi_n \sim 10^{-7}$ V/K, and $T \sim T_c \sim 10$ K, we obtain $v \sim 10$ cm/sec. This estimate is in good agreement with the asymmetry of the propagation rate of the normal phase observed in Ref. 3. At $\sigma_n \sim 10^{20}$ sec^{-1}, $\kappa_n \sim 10^8$ erg/cm·sec·K, $h \sim 10^7$ erg/sec·cm^2·K, $l \lesssim A/P \sim 0.1$ cm, $r_c \sim 10^{-6}$ Ω, the characteristic length of the domain $l_0 = \sqrt{A\kappa/hP}$ is ~ 1 cm, and $j_c(T_0) - j_0 \lesssim 0.1 j_c(T_0)$.

We also note that the resistive solitons, similar to those examined by us, can exist in thin superconducting films, where j_c is determined by the critical velocity.[6]

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