Surface superconductivity in ferromagnets

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A surface superconductivity can occur in ferromagnets because of the branching domains near the surface. This effect accounts for the experimental evidence of superconductivity in the normal ferromagnetic phase of recoverable superconductors.

1. Superconductivity in recoverable superconductors occurs at a temperature T_{c1}: A further reduction of the temperature leads to a destruction of superconductivity below the point $T_{c2} < T_{c1}$ and to a transition to the normal ferromagnetic phase (see the review by Buzdin *et al.*,[1] for example). It follows from the experimental data of Refs. 2 and 3 that below T_{c2} the resistance of polycrystalline samples of recoverable superconductors $ErRh_4B_4$ and $HoMo_6S_8$ (these compounds have been studied in great detail) is approximately 10–40% lower than it is at $T > T_{c1}$. The application of a small external magnetic field restores the resistance to its original value. Recent studies[3] of a $HoMo_6S_8$ sample consisting of several crystallites have revealed the presence of a zero-resistance state in the normal ferromagnetic phase. These data show that the normal ferromagnetic phase has superconducting domains.

It has been suggested that the superconductivity of the magnetic domain wall in the normal ferromagnetic phase is responsible for this phenomenon.[4] Analysis[5] has shown, however, that if the exchange field h is taken into account, the conditions for the existence of a superconductivity of this sort are very stringent: $h < h_c \approx T_{c1}$. At low temperatures ($T < \Theta$ is the Curie point) the exchange field h_0 in magnetic superconductors is considerably higher than h_c. In $HoMo_6S_8$, for example, $T_{c1} \approx 2$ K ($T_{c2} \approx 0.6$ K) and $h_0 \approx 20$ K (Ref. 1), has a situation which rules out superconductivity on the domain wall.

In the present letter we offer an alternative explanation.

2. A progressive branching of the domains near the surface is a desirable situation.[6] Privorotskiĭ[7] has studied this question in detail. We assume that the ferromagnet is characterized by an easy-axis (z) anisotropy—this situation applies[3] to $HoMo_6S_8$. We then find that "wedge-shaped" domains of length $L \gg d$ (their thickness[7] will appear on the surface) (Fig. 1). Analyzing the conditions under which the surface superconductivity appears, we can assume that the domain walls are parallel to each other, since $L \gg \xi$—much greater than the superconducting correlation length (more on this below). We are thus concerned with Cooper pairing in a periodic exchange field[1)] $h_z(x) = \pm h_0$ (Fig. 1b).

Since $h_0 \gg T_{c1}$, there is no bulk superconductivity in thick domains ($d > \xi$), and there can be only a surface conductivity in thin domains ($d \ll \xi$). Since we are dealing with $HoMo_6S_8$, we consider a dirty superconductor $l \gg \xi_0$ [in $HoMo_6S_8$ $l \sim 50$ Å is the

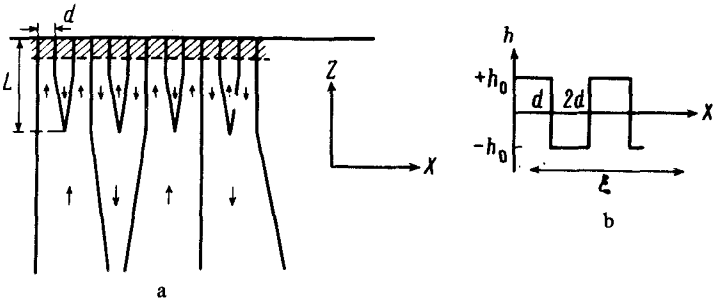

FIG. 1. (a) Schematic representation of a branched domain structure at the surface. The hatching shows the region in which superconductivity can occur because of rapid oscillations (on the ξ scale) of the exchange field. (b) Dependence of the exchange field on the x coordinate.

mean free path of electrons, $\xi_0 = 0.18\ v_F/T_{c1} \sim 1500$ Å, and $\xi = (\xi_0 l)^{1/2}$ (Ref. 1)]. We write Usadel's[8] equations for Green's functions g and f, which are integrated over the energy and velocity directions (in this case, they depend only on x):

$$[\omega + ih(x)]f + \frac{1}{2}D(fg'' - gf'') = \Delta g\ , \tag{1}$$

$$g^2 + |f|^2 = 1,\ \ \omega = \pi T(2n+1),\ \ D = v_F l/3\ . \tag{2}$$

The superconducting parameter $\Delta(x)$ satisfies the equation

$$\Delta(x) = \lambda \pi T \sum_\omega f(x), \tag{3}$$

where λ is the Cooper pairing constant. Because of rapid oscillations of $h(x)$, the f and g functions are nearly independent of x; i.e., $f = f_0 + f_1(x)$ and $g = g_0 + g_1(x)$, where $f_1 \ll f_0$ and $g_1 \ll g_0$ (in terms of the parameter $h_0 d^2/v_F l \ll 1$), and we can assume that $\Delta = \text{const}$. Expanding these functions in a Fourier series, we find the following expressions for the corresponding components of f and g:

$$g_k = -f_k f_0/g_0 \ \text{and}\ f_k = -2ih_k g_0 f_0 / Dk^2\ . \tag{4}$$

Substituting (4) into (1), we find the equation f_0 and g_0

$$\omega f_0 + \tau_s^{-1} f_0 g_0 = \Delta g_0,\quad \tau_s^{-1} = 2\sum_k \frac{|h_k|^2}{Dk^2} \approx 0.5\ \frac{h_0^2 d^2}{v_F l}\ . \tag{5}$$

The solution of (5) is $g_0 = \omega'(\omega'^2 + \Delta'^2)^{-1/2}$, $f_0 = g_0 \Delta'/\omega'$, where Δ' and ω' are determined by the equations used for a superconductor with magnetic impurities with a magnetic scattering time[9] τ_s. An expression for τ_s^{-1} for a domain structure was derived by Bulaevskiĭ *et al.*[10] by another method.

Using a formal analogy with a superconductor with magnetic impurities, we conclude that a surface superconductivity can occur at $\tau_s^{-1} < 0.88\ T_{c1}$. if $\tau_s^{-1} > 1.76\ T_{c1}\ \exp(-\pi/4)$, we will have a gap-free surface superconductivity.[9] Consequently, the domains must be thinner than their critical thickness, $d < d_c$:

$$d_c^2 = 0.18\, v_F l T_{c1} / h_0^2 \approx (T_{c1} / h_0)^2\, \xi_0 l. \tag{6}$$

For $HoMo_6S_8$ we have $d_c \sim 100$ Å. The width of the domain wall, δ, in this case is on the order of the interatomic distance (since the anisotropy energy is of the same order of magnitude as the magnetic energy,[3] the division of domains continues to scale dimensions smaller than d_c). The length of the "critical" domain of the surface conductivity,[7] $L_c \sim d_c (d_c/\delta)^{1/2}$, is greater than ξ.

3. In the normal ferromagnetic phase of $HoMo_6S_8$ the surface superconductivity is accordingly seen in a layer of thickness (L_c), of several hundred angstrom, rather than near a domain wall in the bulk of the sample. Experimentally, these alternatives can be distinguished by measuring the anisotropy of the resistance of the single crystal. In the case of surface superconductivity, the resistance vanishes at the outer surface which is perpendicular to the easy axis and, in the case of superconducting domain walls, the resistance vanishes along the plane parallel to the easy axis. $HoMo_6S_8$ single crystals now can be produced[3] and such measurements are possible. In polycrystals the surface of the normal ferromagnetic phase should consist of alternating superconducting and normal crystallite faces (depending on the orientation of the surface with respect to the easy axis of the crystallite). This physical picture of the surface hopefully will be borne out by the magneto-optical methods.

Experimentally,[2] the onset of superconductivity in the normal ferromagnetic phase of $HoMo_6S_8$ is characterized by strong hysteresis effects in a field. This behavior can be explained in a natural way in terms of the physical picture given above. The surface superconductivity clearly has its intrinsic superconducting characteristics which are distinct from those of the bulk superconductivity above T_{c2}.

Finally, the search for surface superconductivity in nonsuperconducting ferromagnets is of considerable interest. A branching of the domain structure may give rise to the appearance of surface superconductivity while suppressing the bulk superconductivity. Accordingly, an easy-axis ferromagnetic $HoRh_4B_4$, with $\Theta \approx 6.7$ K, whose nonmagnetic analog $LuRh_4B_4$ has[1] a $T_c \approx 11$ K, is highly promising.

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[1)]The orbital effect of magnetization can be ignored.[1]

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