Anomalous properties of high-T_c superconductors with twins

A. Vl. Gurevich and R. G. Mints
Institute of High Temperatures, Academy of Sciences of the USSR

(Submitted 17 June 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **48**, No. 4, 196–198 (25 August 1988)

Twins are shown to initiate in the superconductors the formation of metastable domains whose order-parameter phases differ by π. This situation gives rise to an incomplete Meissner effect, a reduction of the critical current and a nonexponential temperature dependence of the electronic specific heat.

The superconductivity of the twinning planes which occurs at a critical temperature T_c higher than the bulk temperature T_{c0},[1,2] may play an important role in the understanding of the properties of high-T_c superconductors[3–5] with a developed twinning structure.[6] We will discuss here the appearance in superconductors with twins of superconducting metastable domains in which the phases of the order parameter ψ differ by π.

The Ginzburg–Landau equation for a superconductor with N parallel twins separated a distance L from each other along the x axis can be written in the form[2]

$$\frac{1}{4m}\frac{\partial^2\psi}{\partial x^2}-a\tau\psi-b\psi|\psi|^2+U\psi\sum_{n=1}^{N}\delta(x-nL)=0. \qquad (1)$$

Here the parameter U determines the difference[2] T_c-T_{c0}, and other notation is standard. In the absence of currents we can assume $\mathrm{Im}\psi=0$. Equation (1) will then have 2^N solutions with various sign ψ_n distributions on the twins $[\psi_n=\psi(nL)]$. Antiphase domain walls, in which there is a plane, with $\psi=0$ (Fig. 1), in this case are formed between the twins with opposite signs of ψ_n. In a typical case for high-T_c superconductors we have $L\gg\xi_c\equiv\xi(T_c)$, where $\xi(T)$ is the coherence length. This condition allows us to solve Eq. (1) (see, e.g., Refs. 5 and 7) and to write the free energy F for an arbitrary configuration of sign ψ_n in the temperature interval $T_{c0}<T<T_c$ in the form

$$F=NF_0(1-\sqrt{\eta})^2(1+2\sqrt{\eta})-J\sum_{n=1}^{N}\mathrm{sign}(\psi_n\psi_{n+1}). \qquad (2)$$

The last term in (1) describes the contribution from the antiphase domain walls with the energy of formation $2J(T)$, where

$$J=16F_0\eta^{3/2}\frac{1-\sqrt{\eta}}{1+\sqrt{\eta}}\exp\left(-\frac{L\sqrt{\eta}}{\xi_c}\right). \qquad (3)$$

Here $F_0=\xi_cS(T_c-T_{c0})^2\Delta C/T_{c0}$, S is the area of the twin, $\Delta C=\alpha^2T_{c0}/b$ is an abrupt change in the heat capacity of a homogeneous sample at $T=T_{c0}$, and $\eta=(T-T_{c0})/(T_c-T_{c0})$.

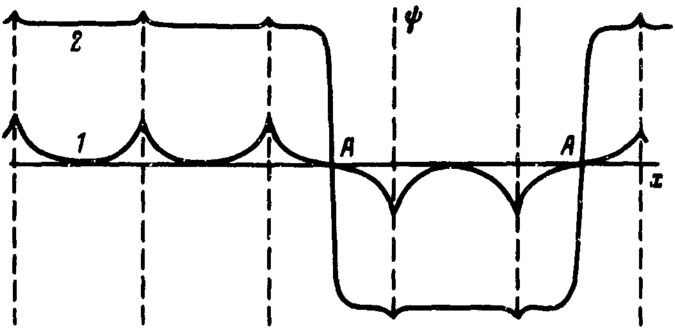

FIG. 1. A fragment of the distribution $\psi(x)$ in the superconductor with oppositely phased domain walls (A) for (1) $T_{c0} < T < T_c$ and (2) $T < T_{c0}$.

Equation (2) is similar to the Hamiltonian of a one-dimensional Ising model, in which there is no long-range order for any J. Consequently, the superconductor can be divided into domains with $\psi > 0$ and $\psi < 0$ and with an equilibrium number of antiphase domain walls, N_A, where

$$N_A = (1 - \tanh \frac{J}{T})N. \tag{4}$$

If $J \lesssim T$, we have $N_A \approx N$ and the average distance between the antiphase domain walls is $d = LN/N_A \approx L$. This situation is characteristic of high-T_c superconductors, in which the energy $J(T)$ is exponentially small because $L \gg \xi_c$. For $\eta = 0.9$, $\xi_c = 100$ A, $\Delta C/T_{c0} \approx 10^3$ erg/cm^3 C^2 (Ref. 8), $S \approx 10^{-6}$ cm^2 (Ref. 6), $T_c - T_{c0} = 4$ K (Ref. 4), for example, we find that $F_0 \cong 10^{-6}$ erg and $J \approx 0.3\ T_{c0}$ if $L/\xi_c = 15$ and $J \approx 10^{-7} \cdot T_{c0}$ if $L/\xi_c = 30$.

Accordingly, at $T = T_c$ the energy $J(T) \ll T$ and the superconductor forms an inhomogeneous state in which the number of antiphase domain walls is $N_A \sim N$. In the Ginzburg–Landau free-energy functional $F(\psi)$ these antiphase domain walls are stable against small perturbations of the modulus and the phase ψ. Calculations showed that $\delta^2 F/\delta|\psi|^2 > 0$ and $\delta^2 F/\delta \mathbf{H}^2 > 0$, where $\delta \mathbf{H}(\mathbf{r})$ is the variation of the magnetic field. The fact that antiphase domain walls are stable against small electric-field perturbations can be concluded, for example, from the nonsteady-state equations of the BCS theory.[9]

Having been formed at $T = T_c$, the structure with $N_A \approx N$ remains in the "frozen-in" state right up to T_{c0}. Because of the pinning of antiphase domain walls by the twins or by the irregularities of the crystallite boundaries, N_A will vary with decreasing temperature only as a result of fluctuational nucleation of antiphase nucleation centers. Let us consider, for example, a domain with $\psi < 0$ and a width d, in which a nucleus with $\psi > 0$, which links two domains with $\psi > 0$, is formed (Fig. 2). If the characteristic diameter R of the nucleus is larger than the critical diameter $R_c \approx d$, a further increase of R will cause the surface energy of antiphase domain walls to de-

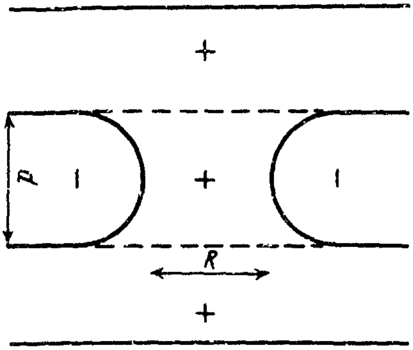

FIG. 2. Oppositely phased nucleus with $\psi > 0$ in the domain with $\psi < 0$. The $\pm$ signs correspond to the signs of ψ.

crease and eventually to vanish. If $\xi(T) \ll d$ and $T < T_{c0}$, the energy of the critical nucleus will be $W \sim \sigma d^2$, where $\sigma = \sqrt{2}\, \xi H_c^2 / 3\pi$ is the surface tension of an antiphase domain wall. Using the H_c and ξ-vs-T plots, we find that $W < T$ if

$$|T - T_{c0}| \lesssim 10^2 T_{c0} \left(\frac{\lambda(0)}{d}\right)^{4/3} \left(\frac{T\xi(0)}{\phi_0^2}\right)^{2/3}, \tag{5}$$

where ϕ_0 is the flux quantum, and $\lambda(T)$ is the London depth.

For $d \approx 2\lambda$ and $\xi \approx 20$ Å, $W < T$ in a narrow interval $|T - T_{c0}| \lesssim 6 \times 10^{-4}\, T_{c0}$, which lies in the critical region, for $YBa_2Cu_3O_7$ (Ref. 8). If the temperature is lowered in this narrow interval at a finite rate, not all antiphase domain walls will have time to vanish and at $T < T_{c0}$ the sample will have some frozen-in domain walls. The anomalous properties of the states with antiphase domain walls are determined by the presence of a plane in each of these domain walls, where the superconducting gap $\Delta = 0$.

In a magnetic field $H < H_{c1}$ a magnetic flux $\Phi_A = 2\lambda l \mathrm{H} \cos\theta$, where θ is the angle between **H** and the plane of an antiphase domain wall, enters the neighborhood of a solitary domain wall of length l. The penetration of magnetic flux into the neighborhood of metastable antiphase domain walls thus leads to an anisotropic partial Meissner effect, where the magnetic flux $\Phi = N_A \Phi_A$ enters the sample if $\lambda < d$. In the case of polycrystals and single crystals in which twinning occurs in different directions, the incomplete Meissner effect becomes isotropic. Because of the penetration of

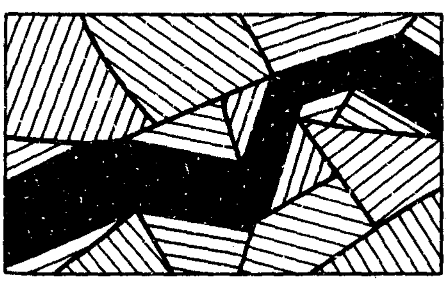

FIG. 3. The path taken by the current in the polycrystalline film (the black path). The heavy and the fine lines show the grain boundaries and the oppositely phased domain walls, respectively.

magnetic flux into the antiphase domain walls, their formation in an external magnetic field is desirable from the thermodynamics standpoint if $H > H_k$, where H_k is determined by the free-energy balance: $J = \lambda S H_k^2/8\pi$. For $\lambda = 200$ A and the parameter values given above we find that $H_k = 5\times 10^{-2}$ Oe when $L/\xi_c = 15$ and $H_k = 4\times 10^{-5}$ Oe when $L/\xi_c = 30$. Both of these values are much smaller than the Earth's magnetic field.

The superconducting current can flow only in the direction parallel to the domain walls, since an electric field is produced when the current crosses the plane where $\psi = 0$.[9] Twinning in different directions decreases the critical current because of the formation of three crystallites at the walls, which trap the current.[10] A typical example of a polycrystalline film in which the current "path" occupies only a small part of the sample is shown in Fig. 3.

The presence of a region in the antiphase domain walls where $\Delta(x) \ll T_c$ gives rise to the appearance of localized states of electrons with energies $\epsilon \ll T_c$. As a result, at $T \ll T_c$ the electron specific heat receives a nonexponential contribution which is similar to the contribution from vortex cores.

We wish to thank A. A. Abrikosov, A. I. Buzdin, L. N. Bulaevskiĭ, and D. I. Khomskiĭ for useful discussions.

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Translated by S. J. Amoretty