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SUPERCONDUCTING GLASSY STATE INDUCED BY TWINS

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1. INTRODUCTION

A number of recent publications treated the states of the superconducting glass produced as a result of the Josephson interaction between some superconducting granules (see, e.g.,[1]). Boundaries between these granules are usually identified with grain boundaries or with twinning planes on which the critical temperature T_c is assumed to decrease locally in comparison with the bulk value T_{c0}. In this paper, we consider the properties of superconducting glass in the reverse case, $T_c > T_{c0}$, which can also be realized, at least in traditional superconductors[2]. In this case, metastable superconducting domains may arise even in zero magnetic field H_0; these domains will have the phases of order parameter Ψ that differ by π and are not related to the Josephson interaction between granules[3]. The domain boundaries are domain walls (DW) of width on the order of the bulk coherence length ξ ; DW are randomly distributed between twins. Within each DW, there is a plane of $\Psi=0$. If, however, high-T_c superconductors have different twinning directions, certain orientational disorder arises in addition to positional disorder at DW locations.

If $T_{c0}<T<T_c$, this antiphase glass is in thermodynamic equilibrium because owing to the relation $L>>\xi$ typical of high-T_c superconductors, the DW formation energy $J=J_0\exp(-L/\xi)<T$. Here L is the spacing between twins, $J_0 \sim \xi H_c^2 S/8\pi$, S is twins area, and H_c is the critical magnetic field. As T is reduced, the equilibrium number of DW rapidly decreases; however, as a sample is cooled at a finite rate, not all nonequilibrium DW manage to annihilate among themselves in the range $T \approx T_{c0}$ (owing to the energy barriers due to pinning of DW[3]). As a result, metastable DW survive in the sample if $T<T_{c0}$, at a characteristic value of domain thickness $d \sim L \sim 10^{-5}$ cm. This state can be interpreted as a "frozen" cellular structure composed of normal layers of thickness $\sim\xi$. This results in a finite electron state density at the Fermi level and in a number of anomalies in properties of high-T_c superconductors.

2. MAGNETIC PROPERTIES

A sample with frozen DW, cooled in zero magnetic field, evinces after switching on the field at $T<T_{c0}$ incomplete Meissner effect at any arbitrarily low H_0. This is connected with magnetic field penetration into the DW neighborhood.

In the Ginzburg-Landau theory in case $\lambda>>\xi$ and $T_{c0}-T>>T_c-T_{c0}$, it is possible to obtain explicit dependences H(x) and Ψ(x) for a lone DW in parallel magnetic field H_0:

$$\Psi(x)=\Psi_0(1-h^2)^{1/4}\mathrm{th}[x(1-h^2)^{1/4}/\xi 2^{1/2}],\quad \mathrm{abs}(x)<<\lambda \qquad (1)$$

$$H(x)=2H_c\sinh[(x+x_0)/\lambda]\cosh^{-2}[(x+x_0)/\lambda],\quad x>0 \qquad (2)$$

where $h=H_0/H_c$, $2\sinh(x_0/\lambda)\cosh^{-2}(x_0/\lambda)=h$, and Ψ_0 is the equilibrium value of Ψ for H_0. As follows from Eqs.(1), (2), DW exists only if $H<H_c$; if $H>H_c$, a DW transforms into a string of Abrikosov vortices. An analysis of the situation at $T \approx T_{c0}$ shows that here DW can exist at $H_0<H_m \approx \Phi_0/4\pi L^2$, where Φ_0 is a flux quantum. For $L \approx (3\text{-}13)\ 10^{-6}$cm, the magnetic field $H_m \approx 100\text{-}2000$ G.

Therefore, the possibility of existence of DW at $T<T_{c0}$ in a superconductor cooled in a magnetic field H_0 depends on the ratio of H_0 and H_m. If $H_0>H_m$, then all DW vanish at $T \approx T_{c0}$ and the superconductor transforms to the vortex state. If, however, $H_0<H_m$, then the coexistence of vortices and

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DW is possible down to $T=0$.

3. CRITICAL CURRENTS

If the singular plane $\Psi=0$ within DW is intersected by lines of current, the instability of the corresponding solutions of Ginzburg-Landau equations implies that electric field must appear. Hence, the critical transverse current of the planar DW structure is zero, and the dissipative current can flow only along DW. Note that this condition can be satisfied only for certain current paths in polycrystals with different twinning directions, in which DW form a disordered "network". In this situation, the current distribution becomes essentially nonuniform, with the current "channel" occupying only a small fraction of sample cross section; this leads, in its turn, to a considerable reduction in critical current.

The critical current j_c that can flow along a DW is determined by DW pinning. For example, if $d>>\lambda$, then DW exists only if $H<H_c$; if $H=H_c$, the metastable structure of DW vanishes and the critical current of antiphase glass drops to zero for any pinning mechanism. As a result, the dependence of $j_c(H)$ for the DW structure is stronger than for the vortex state, because in the former case the value of $j_c(H)$ varies over a scale $H\sim H_c<<H_{c2}$.

4. ELECTRON HEAT CAPACITY C(T)

The presence of the plane $\Psi=0$ produces low-energy levels corresponding to electrons with energies $E_n<<\Delta$. Here Δ is the equilibrium superconducting gap, and E_n is measured off the Fermi energy E_F. As shown[4], there are the lowest level $E_0\sim\Delta^2/E_F$ and a serie of levels $E_n\sim\Delta\ (\Delta/E_F)^{1/3}$, $n=1, 2, \dots$. These levels result in a characteristic nonexponential dependence C(T) in the range $T<<T_c$. In addition, C(T) is proportional to $\exp(-T_0/T)$ if $T\leq T_0$, where $T_0\sim T_c\ \Delta/E_F$; if $T\approx T_0$, the C(T) curve has a peak $C(T_0)\sim k/da^2$, where k is the Boltzmann constant and a is the interatomic spacing. In the interval $T_0<<T<<T_k$ where $T_k\sim T_c(\Delta/E_F)^{1/3}$, the mechanism suggested above[4] gives that C(T) is proportional to $T^{-2}\ln(T/T_0)$. Note that a similar dependence was observed in many high-T_c superconductors; at present it is attributed to the Schottky anomaly.

If we compare contributions to C(T) due to DW and to magnetic ions, we notice that their dependences on H_0 are different. Thus, as DW width increases with increasing H_0 (see Eq.(1)), energies $E_n(H_0)$ are reduced, and the peak on C(T) is shifted to lower T. However, in the case of the Schottky anomaly, the behavior is reversed: as H_0 increases, the peak on C(T) shifts to higher T.

5. NMR ABSORPTION

Consider the NMR absorption lineshape in the superconductor with frozen DW (for simplicity, we neglect nuclear relaxation and assume that no vortices are formed in the sample and $d>>\lambda$). We then have the following expression for the absorption rate P at a frequency ω:

$$P(\omega)=0.25\pi d^{-1}VH_1^2\mathrm{abs}(\omega)M(x_0)/(dH(x_0)/dx_0) \qquad (3)$$

where H_1 is the amplitude of the time-dependent signal, M(x) is the equilibrium magnetization of nuclei in a magnetic field H(x) that penetrates the neighborhood of DW, the point $x=x_0$ is defined by the condition $\omega=\gamma H(x_0)$, and γ is gyromagnetic ratio. Using Eq.(2), we finally obtain

$$P(f)=P_0\mathrm{abs}(f)[1+(1-f^2)^{1/2}]^{1/2}/(1-f^2)^{1/2} \qquad (4)$$

where $f=\omega/\omega_c$, $\omega_c=\gamma H_c$, $P_0=0.56VH_1^2\chi\omega_c\lambda/d$ and χ is the magnetic susceptibility of a nucleus. Formula (4) holds for $f<f_0=H_0/H_c$; if $f>f_0$, we find $P(f)=0$. If $T\approx T_{c0}$, P_0 and ω_c depend on T as $(T_{c0}-T)^{1/2}$ and $(T_{c0}-T)$, respectively.

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