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Increase of the critical current by an external electric field in high-temperature superconductors

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An electric field directed perpendicular to the surface of a superconductor changes the superconducting properties near the surface and creates an additional barrier for flux penetration into the sample. This effect is characterized by the value l_D/ξ, where l_D is the Debye screening length and ξ is the coherence length, and can be neglected in conventional superconductors with $l_D \ll \xi$. However, in high-temperature superconductors, where $l_D/\xi \sim 1$, the effect is very pronounced and could be used for improvement of the transport critical current.

I. INTRODUCTION

The influence of the external electric field on superconductivity has been intensively investigated.[1-9] The electric field, directed perpendicular to the surface of the sample, increases the carrier density n in the thin layer of the width of the Debye screening length, $l_D=(4\pi\nu e^2/\varepsilon)^{-1/2}$, where ν is the density of states at the Fermi level and ε is the dielectric constant. As a result, the local surface density of states ν and, in turn, the superconducting coupling constant g grow too. This leads to the appearance of a surface layer of the width l_D where the superconducting characteristics are improved. Note that this effect is asymmetric and depends on the polarity of the electric field, i.e., there appears a layer with suppressed superconductivity at the surface if the electric field is inverted.

Though l_D is extremely small (of the order of 1–5 Å), the superconducting state is affected by the electric field at larger distances from the surface (of the order of the coherence length ξ) because of the proximity effect.[7,8] However, the shift of the critical temperature is determined by the ratio $l_D/\xi \ll 1$ and therefore can be neglected in conventional superconductors with $\xi \sim 100-1000$ Å. But as has already been predicted,[9] the effect should be more pronounced in the superconductors with $l_D/\xi \sim 1$. Thus, the high-temperature superconductors (HTSC) are the best candidates to observe this effect. Indeed, these system are characterized by both small ξ and by large l_D, owing to small density of states and large dielectric constant $\varepsilon \sim 20-30$.[10,11]

So far the main efforts have been focused on the increase of the local critical temperature and formation of a localized state at the surface due to the external electric field.[7,8] However, the recent measurements[9] of the critical current J_c have attracted great interest. The transport current J, being parallel to the surface, creates the magnetic field H. The critical current J_c is determined by the condition $H(J_c)=H_{c1}$ (see, for example, Ref. 12), where the Abrikosov vortices are nucleated at the surface and carried by the current into the sample, thus leading to energy dissipation. It was shown experimentally[4,9] that the 10% growth of the carrier density due to the electric field (for $YBa_2Cu_3O_7$ film at the electric field $E \approx 10^7$ V/cm) leads to the 50% growth in J_c. This cannot be explained in the framework of the usual pinning theory since the electric field does not penetrate deeper than the thin Debye layer (for high-temperature superconductors $l_D \sim 5$ Å). On the other hand, the Debye layer can be crucial for the Abrikosov vortex penetration into the sample from the surface. Therefore we deal here with the surface effect.

In this paper we consider the increase of the vortex energy that results from the interaction between the Abrikosov vortex and the layer at the surface with increased carrier density due to the electric field. Because of such an interaction, the vortex energy increases and, in turn, the lower critical magnetic field H_{c1} grows as well. This mechanism has already been investigated for very small ratio l_D/ξ.[13] Now we consider the general case and show that at $l_D/\xi \sim 1$, the local H_{c1} at the surface exceeds the bulk H_{c1}^0. Since the magnetic field in the system is only due to the transport current, the increase in H_{c1} means the same increase in J_c. It is worth mentioning here that there could exist another obstacle for flux penetration into the bulk, namely, the Bean-Livingston surface barrier.[14] Such a barrier has proved to be very important in high-temperature superconductors for the same reason: small ξ.[15,16] Because of the Bean-Livingston barrier, the vortex penetration starts, even in the absence of the electric field, at $H_p > H_{c1}$. In the case of perfect surface $H_p = H_c$, where H_c is the thermodynamic critical field, but generally $H_{c1} < H_p < H_c$.[17] In this case the electric field creates an additional barrier at the background of the Bean-Livingston one. Thus, our further analysis of the effect of the electric field applies regardless of the efficiency of the Bean-Livingston barrier.

II. ENERGY BARRIER DUE TO ELECTRIC FIELD

The Ginzburg-Landau free energy G, in the inhomogeneous medium, can be expressed as follows:[18,19]

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$$G=\int\left[\frac{(B-H)^2}{8\pi}+\nu\left\{\left|\xi_j\left[\nabla-\frac{2ie}{c}A\right]_j\Delta\right|^2-\alpha|\Delta|^2+\frac{\beta}{2}|\Delta|^4\right\}\right]d^3r\ , \quad (1)$$

where Δ is the superconducting energy gap (which has the meaning of the order parameter), B and H are the magnetic induction and external magnetic field, respectively, and $j=x,y,z$. The electric field E, being perpendicular to the surface y-z of the sample (Fig. 1), can be accounted for[18] by an expansion of α in Eq. (1) over $\delta n/n_0$, where n_0 is the carrier density far from the surface and δn is the deviation of the charge density at the surface due to E:

$$\alpha=\tau+\frac{1}{g}\frac{\delta n}{n_0}\ , \quad (2)$$

where $\tau=(T_c-T)/T_c$, T_c is the critical temperature at $E=0$, and g is the superconducting coupling constant. The form of the expansion (2) is justified by the small amplitude of order parameter $\Delta(r)$ (see, for example, Refs. 18, 20, and 21).

In the framework of the Thomas-Fermi approximation we get

$$\delta n/n_0=(E/E^*)\exp(-x/l_D)\ , \quad (3)$$

where $E^*=4\pi e l_D n_0/\varepsilon$. In order to calculate the correction to the vortex energy caused by its interaction with the surface layer, it is convenient to write $\Delta=\Delta_0+\delta\Delta$, where Δ_0 is the order parameter in the absence of the electric field. Near the vortex core, Δ_0 is space dependent, vanishing at the center of the vortex. If a vortex is located at $(x_0,0)$, we can use the approximation

$$|\Delta_0(x,y)|^2=\frac{[(x-x_0)/\xi_\perp]^2+(y/\xi_\parallel)^2}{1+[(x-x_0)/\xi_\perp]^2+(y/\xi_\parallel)^2}\frac{\tau}{2\beta}\ , \quad (4)$$

where we account for the anisotropy by introducing the perpendicular ($\xi_\perp$) and parallel ($\xi_\parallel$) to the surface coherence lengths. Taking the variation of the Eq. (1), we get (see Ref. 13) the correction to the Ginzburg-Landau free energy due to the electric field E:

$$\Delta G=-\frac{\nu}{g}\frac{E}{E^*}\int_0^\infty dx\int_{-\infty}^{\infty}dy\,\exp(-x/l_D)\times(|\Delta_0(x,y)|^2-|\Delta_0(\infty)|^2)\ , \quad (5)$$

where $\Delta_0^2(\infty)=\tau/2\beta$ is the order parameter far from the vortex. Performing integration in (4), we get

$$\Delta G=\frac{\nu\tau\pi}{2\beta g}\frac{E}{E^*}\xi_\parallel I(\xi_\perp/l_D)\ , \quad (6)$$

where

$$I(a)=\int_0^\infty\frac{\exp(-xa/\xi_\perp)dx}{\sqrt{1+[(x-x_0)/\xi_\perp]^2}}\ . \quad (7)$$

The energy correction ΔG as a function of $x_0/\xi_\perp$ forms the energy profile (see Fig. 2), which a vortex has to surmount while entering the sample. Its maximum is located at x_0^m, which can be found from the condition $\partial\Delta G/\partial x_0=0$ and Eqs. (6) and (7). Correspondingly, $\Delta G(x_0^m)$ is the energy barrier for a vortex due to the electric field. The dependence of $\Delta G(x_0^m)$ on temperature is shown in Fig. 3 for different values of $\xi_\perp/l_D$. One notes that at large $\xi_\perp/l_D\sim100$, which is relevant for conventional superconductors, the barrier $\Delta G(x_0^m)$ is negligible. At smaller $\xi_\perp/l_D\sim1$, relevant for HTSC, $\Delta G(x_0^m)$ becomes significant. Below we estimate the renormalization of the lower critical field in HTSC due to such a barrier.

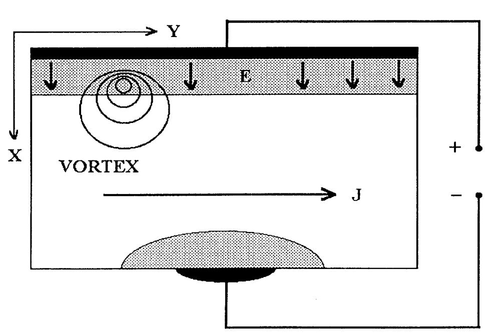

FIG. 1. Geometry of the problem. The electric field is directed perpendicular to the surface and creates the layer with improved superconducting characteristics. Current is parallel to the surface.

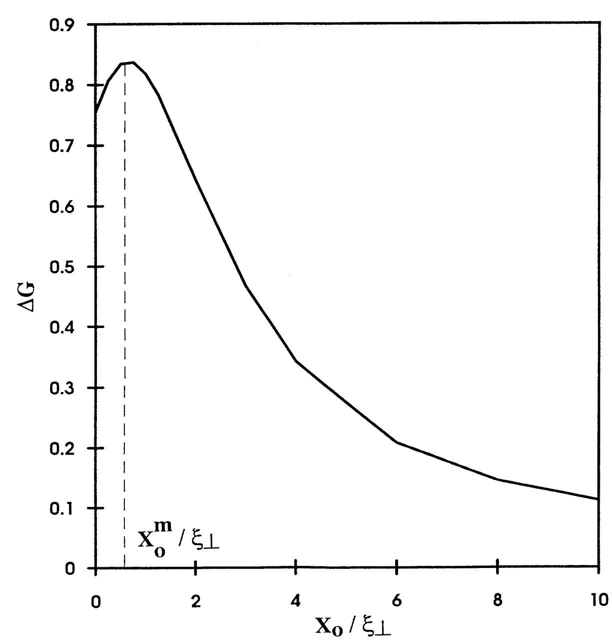

FIG. 2. The electric field contribution to the vortex energy, ΔG [in terms of $(\nu\tau\pi/2\beta g)(E/E^*)\xi_\parallel$] vs its distance from the surface, $x_0/\xi_\perp$.

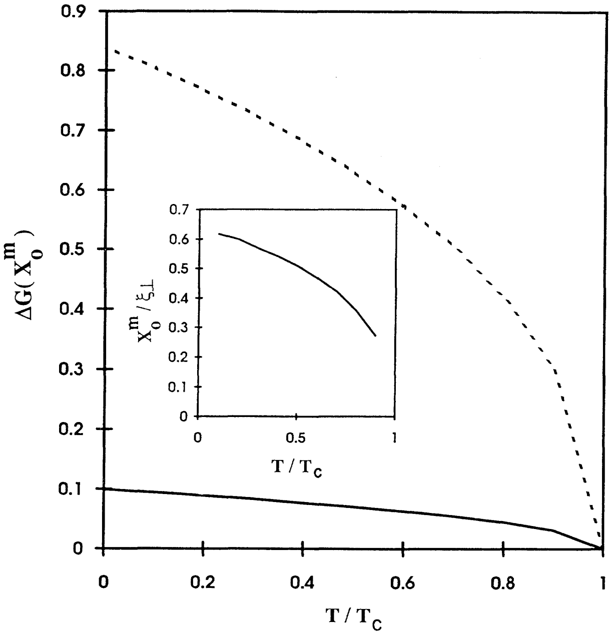

FIG. 3. Energy barrier, $\Delta G(x_0^m)$, in terms of $(\nu\tau\pi/2\beta g)(E/E^*)\xi_\parallel$, vs temperature (T/T_c), at $\xi_\perp/l_D \sim 1$ (dashed line) and at $\xi_\perp/l_D \sim 100$ (solid line). The inset presents the position of the barrier, x_0^m, vs temperature.

The maximum force of the vortex interaction with the surface layer, $F = \partial\Delta G/\partial x_0$, can be expressed easily from Eqs. (6) and (7). In the limit $\xi/l_D \gg 1$, we return to the result, $F \sim \tau$ obtained by Geshkenbein,[13] who considered a similar problem of a vortex interaction with a twin boundary. For arbitrary ξ/l_D, the dependence $F \sim \tau$ no longer holds (see Fig. 4).

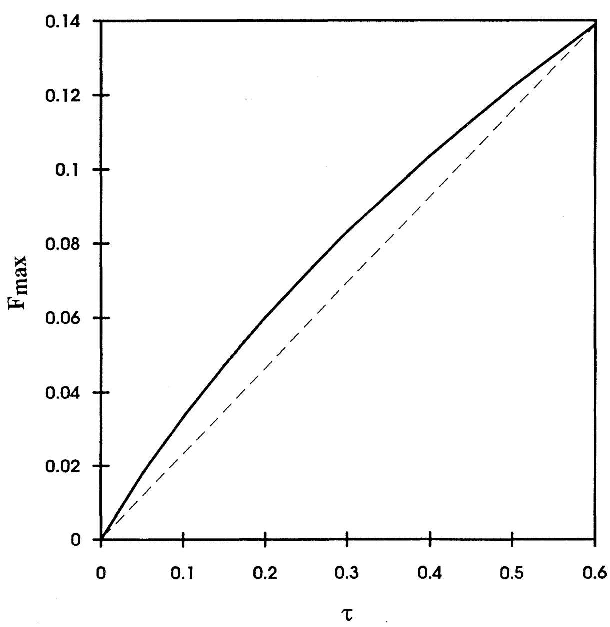

FIG. 4. Maximum pinning force $F_{\max}$, in terms of $(\nu\tau\pi/2\beta g)(E/E^*)(\xi_\parallel/\xi_\perp)$ vs $\tau = 1 - T/T_c$.

III. THE LOWER CRITICAL FIELD

The lower critical field H_{cl} can be obtained from the condition

$$G = \varepsilon_0 + \Delta G - \frac{\phi_0 H_{c1}}{4\pi} = 0 , \tag{8}$$

where $\varepsilon_0 = (\phi_0/4\pi)^2[\ln(\kappa)/\lambda_\perp\lambda_\parallel]$, ϕ_0 is the flux quantum, and $\lambda_\perp$, $\lambda_\parallel$ are the London penetration depths perpendicular and parallel to the surface. As a result we get

$$H_{c1} = H_{c1}^0 + \frac{4\pi}{\phi_0} \frac{\nu\tau}{2\beta} \frac{\xi_\parallel}{g} \frac{E}{E^*} I(\xi_\perp/l_D) , \tag{9}$$

where $H_{c1}^0 = 4\pi\varepsilon_0/\phi_0$ is the lower critical magnetic field at $E = 0$ and I is determined by Eq. (7). Using Eqs. (8) and (9), we can easily get for the relative increase of H_{c1}

$$\Delta h \equiv \frac{H_{c1} - H_{c1}^0}{H_{c1}^0} = \frac{\nu\tau}{2\beta} \frac{E}{E^*} \frac{\xi_\parallel}{\varepsilon_0 g} I(\xi_\perp/l_D) . \tag{10}$$

As follows from Eq. (10), Δh vanishes at $\tau = 0$, since $\xi(\tau \to 0)$ diverges and, therefore, the vortex core does not feel the potential at the surface caused by the electric field E. But at lower temperatures Δh becomes significant, and its estimation for $YBa_2Cu_3O_7$ at the limit $\tau = 1$ gives $\Delta h \approx 30\%$. We used parameters[9] $l_D \approx 6$ Å, $\xi_\perp \approx 6$ Å, $\xi_\parallel \approx 20$ Å, $g \approx 1/3$, $\lambda_\parallel \approx 2000$ Å, and $E \approx 10^7$ V/cm, and we estimated $\beta = 7\zeta(3)/8\pi^2 T_c^2$ in the framework of the BCS theory.

In the geometry we have chosen (see Fig. 1), the magnetic field is due to the transport current, and the vortex penetration at $H = H_{c1}$ means the onset of the energy dissipation. Therefore, if H_{c1} is increased due to the electric field E, the same relative enhancement should be observed in J_c. An enhancement of J_c, comparable with our prediction, was observed experimentally in Ref. 9.

IV. APPLICABILITY OF THE PROBLEM

In the previous sections we considered formation of the energy barrier at the surface and enhancement of H_{c1} due to the electric field. We mentioned that the same enhancement should be observed in the transport critical current J_c. Let us discuss this in detail. In our problem there is no external magnetic field except due to the transport current J. As above, J flows in the y-z plane of a slab sample of the thickness (along x) d and produces a certain magnetic field H outside the slab. If we consider J as a mean current density across the slab section, then, from the condition $H = H_{c1}$ at $J = J_0$, we have

$$J_0 = \frac{H_{c1} c}{2\pi d} \approx 1.6 \frac{H_{c1}}{d} , \tag{11}$$

where H is measured in Oe, d in cm, and J in A/cm^2. Certainly at $d \gg \lambda$, the current flows only along the surfaces of the slab and decreases $\propto \exp(-x/\lambda)$ with the depth, and at $d \ll \lambda$ the current density is almost constant over the section of the slab. Nevertheless, by using the mean current density J, which is usually measured in experiments, we have the same result [see Eq. (11)] at all

d. The enhancement of H_{c1} by Δh (see Sec. III) means that at the same time we get $\Delta J_0 = J_0 \Delta h$.

Let us emphasize once more that we are discussing here the critical current J_0 that is sufficient to produce the field $H = H_{c1}$ at the surface and which has no relation to the bulk critical current determined by pinning, J_{pin}. For thick samples, J_0 is small, as follows from Eq. (11). For instance, at $H_{c1} \approx 100$ Oe (which corresponds to H_{c1} for $YBa_2Cu_3O_7$ in the ab plane at $T=0$) and $d=0.1$ mm we have $J_0 \approx 10^4$ A/cm^2, that is much less then $J_{\text{pin}} \approx 10^{6-7}$ A/cm^2 in samples with a strong bulk pinning. Therefore, for thick slabs the effective J_c should be determined by J_{pin} and the electric field cannot be expected to affect significantly the transport currents, since J_0, which enhancement we discuss, is much less than J_{pin} and vortices, even being created at the surface, will be immediately trapped due to strong pinning. Contrary to that, for thin films of the order of 1 μm and less, J_0 likely exceeds J_{pin}; thus J_0 determines the onset of vortex motion and $J_c = J_0$. In this case the electric field can be a direct and convenient tool for J_c enhancement.

In the experiment[4,9] we mentioned above, the samples are polycrystals with low T_c and probably with very low H_{c1}. Therefore, though they are thin, the critical current J_0 in that case should be much lower than is shown in our estimation, as we observed experimentally. It is worth mentioning also, a possible mechanism of the electric field effect onto bulk pinning in thin granular films, which were used in the experimental study.[4,9] The intergranular space in such films has poor metallic properties, therefore the enrichment of the surface by charge carriers due to the electric field could be accompanied by the depletion of the grain boundaries. This gives rise to additional attraction of vortices to the grain boundaries. Since at the same time the grain boundaries are natural pinning cites, the electric can enlarge the bulk pinning properties at the grain boundaries in such samples.

V. DISCUSSION

We considered the effect of the external electric field E on flux penetration into a superconductor. For the case where the magnetic field is caused by the transport current, the flux penetration determines the onset of energy dissipation and critical current J_c. It was shown that if the polarity of the electric field is chosen such that vortices enter through a surface layer with enhanced superconductivity, there appears an energy barrier at the surface which shifts up the penetration field and, in turn, the critical transport current by about 30% at moderate electric fields E of order 10^7 V/cm (for $YBa_2Cu_3O_7$). This effect is proportional to E and could be very pronounced at high electric fields. Thus J_c appears to be dependent on the electric field, which can be used, therefore, as a suitable tool for improvement of the transport characteristics in HTSC. This effect should be especially significant in thin films, where the critical current J_c is determined by the condition of flux penetration from the surface, $H(J) = H_{cl}$, rather than by the bulk pinning.

The barrier due to the electric field is additional with respect to other barriers for flux penetration that could exist at the surface in the absence of electric field, as, for instance, the Bean-Livingston barrier, that has been proved to play an important role in HTSC. In this case the sign of the effect should depend on the polarity of E. If, instead of enhancement of superconductivity at the surface, we choose the polarity in order to deplete it, then the barrier and, in turn, J_c decrease.

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