Pinning in layered inhomogeneous superconductors

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The angular and magnetic-field dependence of a critical current parallel to the layers in layered superconductors is studied. The critical-current value is found under the assumption that strong pinning centers are present in the layers and between the layers of the superconductor.

I. INTRODUCTION

High-T_c superconductors have a layered structure. Due to the weakness of the coupling between the layers, such materials are strongly anisotropic. This property makes high-T_c superconductors especially interesting materials for the study of critical current density. The calculation of the critical current due to pinning of vortices on different kinds of inhomogeneities is very complicated. Usually we can find the temperature and magnetic field dependence of the critical current with some number of fitting parameters.[1,2] In layered superconductors we have an additional independent parameter—the angle θ between the *ab* plane and the direction of the magnetic field. The critical current now is the function of three parameters—temperature T, magnetic field B, and angle θ. For a given number of fitting parameters we can make a better comparison theoretical and experimental data.

A large concentration of weak pinning centers leads to collective pinning.[3] For strong enough pinning centers we get a single-particle pinning.[4] From experimental work[5] we see that the critical current density in epitaxial $YBa_2Cu_3O_x$ films is large (order of 5×10^7 A/cm^2) and weakly depends on a magnetic field in a wide region of magnetic field. For collective pinning we have typically a strong dependence of the critical current density on the magnetic field[3] and a small value of current density. For this reason, we shall study the magnetic field and angle dependence of the critical current in layered superconductors under the assumption that pinning centers in the *ab* planes are strong enough to lead to single-particle pinning.

There exist large differences between layered superconductors and anisotropic ones, connected with the existence of intrinsic pinning in layered superconductors. In these superconductors there are two different contributions to the critical current density due to the pinning: one is connected with the layered structure of the order parameter and the other is the same as in anisotropic superconductors. As we shall see below, for a suitable choice of fitting parameters it is possible to get good agreement between the theoretical data given here and the experimental ones reported in Ref. 5.

II. THE MODEL

In the absence of a complete theory of high-T_c superconductors we must first take into account the layered structure of the high-T_c materials. For this reason we shall consider a model of the superconductor consisting of layers separated by a distance d. The order parameter on each kth layer is Δ_k.[6] Near the transition temperature the free energy $\mathcal{F}$ of such a system can be given in the form

$$F=\nu d\int d^2x\sum_k\left[\frac{a}{d^2}\left|\Delta_k-\Delta_{k+1}\exp\left[-2ie\int_{kd}^{(k+d)d}A_z dz\right]\right|^2 +b\left|\left[\frac{\partial}{\partial x}-2ieA_x\right]\Delta_k\right|^2-\tau|\Delta_k|^2+\frac{C}{2}|\Delta_k|^4\right]+\frac{1}{8\pi}\int[(\mathrm{rot}\,\mathbf{A})^2-2H_0\mathrm{rot}\,\mathbf{A}]\ , \tag{1}$$

where $\mathbf{A}$ is a vector potential, H_0 is the external magnetic field $\tau=1-T/T_c$, ν is the density of states at the Fermi level. Coefficients a,b,C determine the correlation lengths $\xi_{ab,c}$:

$$\xi_{ab}=\left[\frac{b}{\tau}\right]^{1/2},\quad \xi_c=\left[\frac{a}{\tau}\right]^{1/2},\quad \lambda_{ab}^{-2}=32\pi\nu e^2|\Delta|^2 b,\quad \lambda_c^{-2}=32\pi\nu e^2|\Delta|^2 a,\quad |\Delta|^2=\frac{\tau}{C}\ . \tag{2}$$

The behavior of the system depends on the dimensionless parameter $a/\tau d^2$. Below we shall consider the limiting case when this parameter is smaller then unity.

For the magnetic field direction forming an angle θ with ab plane, in the superconductor exists an Abrikosov vortex state. To find the structure and properties of this state we shall use the London expression for free energy for an anisotropic superconductor[7,8]

$$\mathcal{F}=\frac{1}{8\pi}\int d\mathbf{r}[\mathbf{B}^2+(\mathrm{rot}\mathbf{B}\Lambda\mathrm{rot}\mathbf{B})] , \tag{3}$$

where the penetration depth matrix Λ is given by

$$\Lambda=\begin{bmatrix} \lambda_c^2\cos^2\theta+\lambda_{ab}^2\sin^2\theta & 0 & -(\lambda_c^2-\lambda_{ab}^2)\sin\theta\cos\theta) \\ 0 & \lambda_{ab}^2 & 0 \\ -(\lambda_c^2-\lambda_{ab}^2)\sin\theta\cos\theta & 0 & \lambda_c^2\sin^2\theta+\lambda_{ab}^2\cos^2\theta \end{bmatrix} . \tag{4}$$

In (4) we use the coordinate system with the z axis along the magnetic field and the y axis in the ab plane. The expression (3) for the free energy is valid for all temperatures, but the temperature dependence of coefficients $\lambda_{ab,c}$ is known only near the transition temperature T_c, where they are given by formula (2).

In the model described by free energy (1), the order parameter is defined only in the planes. Pinning in such a model is connected with defects located on the planes. The spots of normal region (kinks) in the planes are pinned by defects. This normal region is formed as a vortex crossing the superconducting plane.

To find the critical current value, it is necessary to determine the reaction of the vortex lattice on the shift of one such kink in two direction on the ab plane.

If we suppose that a kink can be trapped by a defect from a distance ρ_y along the y axis and can be kept until the shift is smaller then ρ_x then the area of the trapping S of one defect is

$$S=2\rho_x\rho_y . \tag{5}$$

We suppose here that the pinning is strong enough and the following condition is satisfied:

$$S\gg\xi_{ab}^2 . \tag{6}$$

In this case the middle distance R between trapped kinks belonged to the one vortex (in the direction perpendicular to the ab plane) is

$$R=d+d[1-\exp(-nS)]\sum_{k=1}^{\infty}\exp(-nSk) = \frac{d}{1-\exp(-nS)} , \tag{7}$$

where n is the concentration of the strong defects in the superconducting ab plane. The critical current density j_{cr}, flowing in the ab plane perpendicular to the magnetic field B, is

$$j_{\mathrm{cr}}^{(1)}\Phi_0 R=F_{\mathrm{pin}} , \tag{8}$$

where $\Phi_0=\pi/e$ is a flux quantum, F_{pin} is the maximum value of the pinning force acting on the kink.

From formulas (7) and (8) we get

$$j_{\mathrm{cr}}^{(1)}\frac{F_{\mathrm{pin}}}{\Phi_0 d}[1-\exp(-nS)] . \tag{9}$$

As it was mentioned above, here we find only the part of the critical current $j_{\mathrm{cr}}^{(1)}$, connected with the layered structure of superconductor.

To find the full value of the critical current density, we must calculate the value of the critical current $j_{\mathrm{cr}}^{(2)}$ in inhomogeneous anisotropic superconductor and add it to $j_{\mathrm{cr}}^{(1)}$, that is,

$$j_{\mathrm{cr}}=j_{\mathrm{cr}}^{(1)}+j_{\mathrm{cr}}^{(2)} . \tag{10}$$

Now two possibilities can be realized: $j_{\mathrm{cr}}^{(2)}$ can be connected with collective or single-particle pinning. We shall assume below that the single-particle pinning takes place. The value of $j_{\mathrm{cr}}^{(2)}$ in the chosen coordinate system is equal to

$$j_{\mathrm{cr}}^{(2)}=\frac{n^{(2)}F_{\mathrm{pin}}^x}{B} , \tag{11}$$

where $n^{(2)}$ is volume concentration of strong pinning centers, that trap vortices. F_{pin}^x is the maximum value of the x component of the pinning force on one defect. The concentration $n^{(2)}$ can be expressed through the full concentration of the strong pinning centers $n_0^{(2)}$:

$$n^{(2)}=n_0^{(2)}\frac{S^{(2)}B}{\Phi_0} . \tag{12}$$

Here $S^{(2)}$ is the "trapping" area of one pinning center, that we shall find below.

III. ELASTIC ENERGY OF THE DEFORMED VORTEX

If pinning centers are small and each of them can act only on one vortex, the space dispersion of elastic moduli is essential. The change of free energy $\delta\mathcal{F}$ in this case can be written as

$$\delta F=\int dz\left\{\frac{1}{2}\left[\epsilon_{xx}\left[\frac{\partial U_x}{\partial z}\right]^2+\epsilon_{yy}\left[\frac{\partial U_y}{\partial z}\right]^2+C_{xx}U_x^2 + C_{yy}U_y^2\right]-(\mathbf{F}_{\mathrm{pin}}\cdot\mathbf{U})\delta(z)\right\} , \tag{13}$$

where the elastic moduli $\epsilon_{xx}, \epsilon_{yy}, C_{yy}$ now are essential functions of the angle θ. To find these we shall use the London expression for free energy (3). First of all we find the change of free energy if one vortex is shifted by a distance $\mathbf{U}$. In this case from formula (3) we get

$$\mathcal{F}=\frac{\Phi_0}{8\pi}\int d\mathbf{r}\, \boldsymbol{l}\cdot\mathbf{B}(\mathbf{r})\left[\sum_{i,j}\delta(\mathbf{r}_\perp-\mathbf{r}_{ij})-\delta(\mathbf{r}_\perp)+\delta(\mathbf{r}_\perp-\mathbf{U})\right] . \quad (14)$$

Magnetic field is a solution of the equation system

$$\mathbf{B}+\mathrm{rot}(\Lambda \mathrm{rot}\mathbf{B}) =\Phi_0 \boldsymbol{l}\left[\sum_{i,j}\delta(\mathbf{r}_\perp-\mathbf{r}_{ij})-\delta(\mathbf{r}_\perp)+\delta(\mathbf{r}_\perp-\mathbf{U})\right] , \quad (15)$$

where $\boldsymbol{l}$ is the unique vector along the vortex core, $\mathbf{r}_\perp$ is a vector lying on the plane, orthogonal to the vector $\boldsymbol{l}$.

Equation (15) can be solved with the help of Fourier's transformation. After some direct calculation for the change of free energy $\delta\mathcal{F}$ we find

$$\delta\mathcal{F}=\int dz\frac{\Phi_0^2}{4\pi}\left[-\frac{B}{\Phi_0}\sum_{k=k_{ij}}+\frac{1}{(2\pi)^2}\int d^2k\right] \times\frac{[1-\cos(\mathbf{k}\mathbf{U})](1+\mathbf{k}^2\lambda_c^2\alpha^2)}{(1+\mathbf{k}^2\lambda_{ab}^2)(1+k_y^2\lambda_c^2+k_x^2\lambda_c^2\alpha^2)} , \quad (16)$$

where $\alpha^2=\sin^2\theta+(\lambda_{ab}/\lambda_c)^2\cos^2\theta$, k_{ij} is the inverse lattice vectors. Now the structure of the vortex lattice is essential. We suppose that the lattice is formed by isosceles triangles with the angle β at base equal to

$$\tan\beta=(3)^{1/2}\alpha . \quad (17)$$

From Eqs. (16) and (17) in this case we find

$$\delta\mathcal{F}=\frac{\Phi_0 B}{16\pi\lambda_{ab}^2}\int(U_x^2+\alpha^2U_y^2)dz ,$$
$$C_{xx}=\frac{\Phi_0 B}{8\pi\lambda_{ab}^2} , \quad (18)$$
$$C_{yy}=\frac{\Phi_0 B}{8\pi\lambda_{ab}^2}\alpha^2 .$$

More complicated is to find the elastic modula $\epsilon_{xx}, \epsilon_{yy}$. The free energy F of one distorted vortex is

$$\mathcal{F}=\frac{\Phi_0}{8\pi}\int dz\left[\frac{\partial U_x}{\partial z};\frac{\partial U_y}{\partial_z};1\right]\mathbf{B}(\mathbf{U}(z)) . \quad (19)$$

The magnetic field $\mathbf{B}$ is a solution of the equation system

$$\mathbf{B}+\mathrm{rot}(\Lambda\mathrm{rot}\mathbf{B})=\Phi_0\left[\frac{\partial U_x}{\partial z}\{\delta(x,y)-[\mathbf{U}\delta'(x,y)]\}\frac{\partial U_y}{\partial z}\{\delta(x,y)-[\mathbf{U}\delta'(x,y)]\} ;\delta(x,y)-[\mathbf{U}\delta'(x,y)]+\tfrac{1}{2}U_iU_k\delta''(x,y)\right] . \quad (20)$$

Solving the equation system (20) with the help of Fourier's transformation and inserting the solution in Eq. (19) we find with logarithmic accuracy the expressions for the elastic moduli $\epsilon_{xx};\epsilon_{yy}$:

$$\epsilon_{xx}=\frac{\Phi_0^2\tilde{\epsilon}_{xx}}{8\pi^2\lambda_{ab}^2}\ln\left[\frac{1}{d\cos\theta+\alpha\xi_{ab}}\left[\frac{\alpha\Phi_0}{B}\right]^{1/2}\right],\quad \epsilon_{yy}=\frac{\Phi_0^2\tilde{\epsilon}_{yy}}{8\pi^2\lambda_{ab}^2}\ln\left[\frac{1}{d\cos\theta+\alpha\xi_{ab}}\left[\frac{\alpha\Phi_0}{B}\right]^{1/2}\right] , \quad (21)$$

where

$$\tilde{\epsilon}_{xx}=\frac{\cos^2\theta+\gamma\sin^2\theta}{1+\alpha}+\frac{\alpha}{1+\alpha}-\frac{1}{2}-\frac{2\sin^2\theta\cos^2\theta(1-\gamma)^2}{\alpha(1+\alpha)^2} +\frac{\cos^2\theta(1-\gamma)}{2}\left[\frac{1}{(1+\alpha)^2}+\frac{\cos^2\theta+\gamma\sin^2\theta}{\alpha(1+\alpha)^2}-\frac{(1+3\alpha)(1-\gamma)^2\sin^2\theta\cos^2\theta}{\alpha^3(1+\alpha)^3}\right] ,$$

$$\tilde{\epsilon}_{yy}=\frac{\alpha^2}{1+\alpha}+\frac{\gamma}{\alpha(1+\alpha)}+\frac{2(1-\gamma)^2\sin^2\theta\cos^2\theta}{\alpha(1+\alpha)^2}-\frac{1}{2} +\frac{\cos^2\theta(1-\gamma)}{2}\left[-\frac{1}{(1+\alpha)^2}+\frac{(2+\alpha)(\cos^2\theta+\gamma\sin^2\theta)}{(1+\alpha)^2}-\frac{(3+\alpha)\sin^2\theta\cos^2\theta(1-\gamma)^2}{\alpha(1+\alpha)^3}\right] , \quad (22)$$

where

$$\gamma = \left[\frac{\lambda_{ab}}{\lambda_c} \right]^2 . \tag{23}$$

We emphasize here that the change of free energy, connected with the distortion of the vortex, depends on the direction of vector $\partial \mathbf{U}/\partial z$. At $\theta = \pi/2$ it has a simple form on paper.[9]

It is easy to prove that in homogeneous isotropic superconductors by a small shift of one vortex only and for a fixed position of all other vortices, the sum of the forces acting from the side of vortices placed at equal distances from the shifted vortex is zero. It means that the reaction arises from distances of the order of the penetration depth λ. The same property is conserved for anisotropic superconductor, if condition (17) is fulfilled. As a result, it appears that the number parameter $3^{1/2}/2\pi$ on the shifts of neighboring vortices, connected by the shift of one vortex, are small.

IV. THE VALUE OF THE TRAPPING AREA

Now, that we have studied the elasticity properties of the vortex lattice, it is possible to find the trapping areas $S; S^{(2)}$.

From expression (13) we get the equations for $U_x(z), U_y(z)$:

$$-\epsilon_{xx} \frac{\partial^2 U_x}{\partial^2 z} + C_{xx} U_x = F_{\text{pin}}^{(x)} \delta(z) ,$$
$$-\epsilon_{yy} \frac{\partial^2 U_y}{\partial^2 z} + C_{yy} U_y = F_{\text{pin}}^{(y)} \delta(z) . \tag{24}$$

Equations (24) give for the shift $\mathbf{U}$ at $z=0$ the value

$$U_x(0) = \frac{F_{\text{pin}}^{(x)}}{2(\epsilon_{xx} C_{xx})^{1/2}}, \quad U_y = \frac{F_{\text{pin}}^{(y)}}{2(\epsilon_{yy} C_{yy})^{1/2}} . \tag{25}$$

Below we shall make assumptions, that the trapping distance $\rho_\perp$ in the y direction is much larger than ξ_{ab} and the pinning centers are attractive. Then if the vortex is passing on the impact distance R from the pinning center we have

$$2(\epsilon_{yy} C_{yy})^{1/2} U_y = \frac{F_{\text{pin}}^y \xi_{ab}^3}{(R - U_y)^3} . \tag{26}$$

The trapping distance $\rho_\perp$ is defined from Eq. (26) under the condition

$$\frac{\partial U_y}{\partial R} \Big|_{R=\rho_\perp} = \infty . \tag{27}$$

From Eqs. (26) and (27) we get

$$\rho_\perp = 4 \left[\frac{F_{\text{pin}}^y \xi_{ab}^3}{54(\epsilon_{yy} C_{yy})^{1/2}} \right]^{1/4} . \tag{28}$$

For a pinning center of small size the force F_{pin}^y is independent from angle θ and F_{pin}^x is equal to

$$F_{\text{pin}}^x = \frac{F_{\text{pin}}^y}{\alpha} . \tag{29}$$

The formulas (25), (28), and (29) enable us to find the trapping areas $S, S^{(2)}$:

$$S^{(2)} = \frac{\tilde{F}_{\text{pin}}^y}{\alpha(\epsilon_{xx} C_{xx})^{1/2}} \left[\frac{128 \tilde{F}_{\text{pin}}^y \xi_{ab}^3}{27(\epsilon_{yy} C_{yy})^{1/2}} \right]^{1/4} ,$$
$$S = \frac{F_{\text{pin}}^y}{\sin\theta(\epsilon_{xx} C_{xx})^{1/2}} \left[\frac{128 F_{\text{pin}}^y \xi_{ab}^3}{27(\epsilon_{yy} C_{yy})^{1/2}} \right]^{1/4} . \tag{30}$$

Finally, using formulas (9), (10), (11), (12), and (30) we get the value of critical current density

$$j = \frac{n_0^{(2)} (\tilde{F}_{\text{pin}}^y)^2}{\Phi_0 \alpha^2 (\epsilon_{xx} C_{xx})^{1/2}} \left[\frac{128 \tilde{F}_{\text{pin}}^y \xi_{ab}^3}{27(\epsilon_{yy} C_{yy})^{1/2}} \right]^{1/4} + \frac{F_{\text{pin}}^y}{\Phi_0 d} \left\{ 1 - \exp\left[-\frac{n F_{\text{pin}}^y}{\sin\theta(\epsilon_{xx} C_{xx})^{1/2}} \left[\frac{128 F_{\text{pin}}^y \xi_{ab}^3}{27(\epsilon_{yy} C_{yy})^{1/2}} \right]^{1/4} \right] \right\} . \tag{31}$$

Here F_{pin}^y is the maximal value of pinning force of the defects, lying in the superconducting planes, $\tilde{F}_{\text{pin}}^y$ is the same for the pinning centers in volume of the superconductor n, $n_0^{(2)}$ is the concentration of pinning centers in the superconducting planes and in the volume of the superconductor.

V. COMPARISON WITH EXPERIMENTAL DATA

The formula (31) for critical current density can be rewritten in the form

$$j = \frac{A_1}{\alpha^2 (\tilde{\epsilon}_{xx} B)^{1/2} (\tilde{\epsilon}_{yy} B \alpha^2)^{1/8} \ln^{5/8} \left[(\Phi_0 \alpha)^{1/2} / B^{1/2} (d \cos\theta + \xi_{ab} \alpha) \right]}$$
$$+ A_2 \left[1 - \exp\left[-\frac{C}{\sin\theta (B \tilde{\epsilon}_{xx})^{1/2} (\tilde{\epsilon}_{yy} B \alpha^2)^{1/8} \ln^{5/8} ([(\Phi_0 \alpha)^{1/2} / B^{1/2} (d \cos\theta + \xi_{ab} \alpha)])} \right] \right] . \tag{32}$$

TABLE I. Critical current at $T=4.2$ K.

$B(T)$	$\theta(10^{-7}$ A/cm$^2)$	0	$\pi/18$	$\pi/9$	$\pi/6$	$2\pi/9$
0.5	j_{exp}	5.9	4.8	4.2	3.8	3.4
	j_{theor}	6.2	4.7	4.1	3.9	3.8
3	j_{exp}	5.05	3	2	1.5	1.3
	j_{theor}	4.9	2.1	1.8	1.7	1.7
7	j_{exp}	4.7	1.7	1	0.83	0.8
	j_{theor}	4.6	1.4	1.15	1.1	1.1

Here the coefficients A_1, A_2, C are independent on the magnetic field value B and angle θ and are functions of temperature T only. The temperature dependence of the coefficients A_1, A_2, C determined by the temperature dependence of the coefficients $\lambda_{ab}, \xi_{ab}, F_{pin}$. Below we shall consider the coefficients A_1, A_2, C as fitting parameters. From the experimental paper[5] we find at temperature $T=4.2$ K for the coefficients A_1, A_2, C the values

$$A_1=0.145\times 10^7 \text{ A/cm}^2 ,\quad A_2=4.15\times 10^7 \text{ A/cm}^2 ,\quad C=0.275 \tag{33}$$

if the magnetic field B is measured in tesla. The anisotropy factor is taken equal to $\lambda_c/\lambda_{ab}=5$ (the experimental estimated value of anisotropy in $YBa_2Cu_3O_x$ crystals). We find these values from the minimum condition of deviations of theoretical values of critical current density j from the experimental one at magnetic fields $B=0.5$ T, 3 T, 7 T in points $\theta=\pi K/18$, $K=0,1,\ldots,4$. The experimental and theoretical values of critical current density are given in Table I.

As it follows from Table I, the agreement between theoretical and experimental data can be considered as satisfactory.

To determine the value of the coefficients A_1, A_2, C at temperature $T=40$ K we use 8 points: at $B=3$ T, 7 T we use the value of j at angle θ equal to $\theta=0$, $\pi/18$, and at $B=0.5$ T the value of j at angle θ equal to $\theta=0$, $\pi/18$, $\pi/9$, $\pi/6$. As result we get that the best agreement is achieved at values of A_1, A_2, C equal to

$$A_1=0.11\times 10^7 \text{ A/cm}^2 ,\quad A_2=0.72\times 10^7 \text{ A/cm}^2 ,\quad C=0.08 \tag{34}$$

The values of current density j at temperature $T=40$ K are given in Table II.

At temperature $T=40$ K we have even better agreement with experimental data than at $T=4.2$ K.

The region of high temperature demands a separate consideration. It is possible, that the density of strong pinning centers quickly drops at high temperature [due to threshold criterion $U_x(0)>\alpha\xi_{ab}$]. In this case the collective pinning under the condition of strong anisotropy and spatial dispersion of elastic modula is essential.

VI. CONCLUSION

We studied the angle and magnetic field dependence of the critical current density j in layered high-temperature superconductors. One essential assumption was made: a strong or one-particle pinning takes place in such superconductors. Under this assumption we get a satisfactory agreement between theoretical and experimental data in a wide region of magnetic field $B \ll H_{C2}$.

We consider also all pinning centers as approximately of the same strength. But actually exists some distribution of pinning centers on strength, that can change the magnetic field dependence of the critical current. As it was mentioned above at high temperature the collective pinning may be essential.

We use here the London expression for free energy to determine the elastic property of layered superconductors. We think that the free energy (1) better describes the superconductors with layered structure than the London approximation. But so far we do not have the possibility of carrying out all the calculations with the free energy (1).

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TABLE II. Critical current at $T=40$ K.

$B(T)$	θ $(10^{-7}$ A/cm$^2)$	0	$\pi/18$	$\pi/9$	$\pi/6$
0.5	j_{exp}	2.2	1.65	1.2	1
	j_{theor}	2.25	1.5	1.18	1
3	j_{exp}	1.45	0.4	0.4	.4
	j_{theor}	1.27	0.54	0.42	0.36
7	j_{exp}	0.95	0.2	0.2	0.2
	j_{theor}	1	0.3	0.26	0.22

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