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RESEARCH ARTICLE

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Experimental demonstration of vortex pancake in high temperature superconductor

Abstract In order to demonstrate the existence of the vortex pancake in high temperature superconductor experimentally, a configuration in which the current and voltage electrodes lies separately on the top and bottom surface is used. The *E-j* relation obtained with this electrodes spatial configuration is different from the expected *E-j* behavior of the stiff vortex line model. Thus, the current results support the existence of the vortex pancake in high temperature superconductor.

Keywords high temperature superconductor, vortex pancake, vortex line, electrodes spatial configuration

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1 Introduction

The theory of flux creep founded by Anderson [1] gives the linear relationship of $\delta H' \propto \ln t$. This theory has dominated the superconductive physics for more than twenty years.

But soon after the discovery of high-T_c superconductivity, at least four experiments have been found unable to be explained by the Anderson model: *M*-ln *t* relationship deviates from linearity in experiment; *V-I* (or *E-j*) curves at different temperatures exhibit positive/negative curvature; the argument whether the limit of $\rho(j \to 0)$ goes to zero or a finite value; the peak of $S = \frac{\mathrm{d}M}{\mathrm{d}(\ln t/t)}$ - T relation.

Griessen *et al*. [2] and van de Beek *et al*. [3] have given the relationship between pinning potential *U* and current density *j*, electric field *E* and *j*, *M-t* by using the Anderson-Kim model.

In Equation $v = v_0 \mathrm{e}^{-(U - j\Phi_B d^2)/k_B T}$ when the magnetic field is applied at a certain time *t*, $v = v_0$, and $U_0 - j_c \Phi_B d^4 = 0$. Here j_c is the maximum current without magnetic flux in the potential, $\Phi_B d^4 = U_0/j_c$. Then

$$U = U_0\left(1 - \frac{j}{j_c}\right)$$

$$E \propto \exp\left[-U_0\left(1 - \frac{j}{j_c}\right)\Big/ k_B T\right]$$

$$M \propto \begin{cases} 1 - \frac{k_B T}{U_0}\ln\left(1 + \frac{t}{t_0}\right) t_0 < t < t^* \\ \exp\left(1 - \frac{t}{t_0}\right) t > t^* \\ t < t_0 \end{cases}$$

where $t_0 = 1/v_0$ is the time when the magnetic field H_a is applied on the superconductor, $t^* = t_0\,[\exp(U_0/k_B T) - 1]$, j_c is defined by Kim-Anderson as $j_c = \alpha_c / |B(r)| + B_0$, α_c is the maximum pinning force. Nevertheless, the theory still gives a linear relationship of $M \propto \ln t$ and cannot explain the positive/negative curvature phenomenon of ln $E(j)$-ln j in high-T_c superconductors.

In order to study flux dynamics of high temperature superconductors, researchers have presented all kinds of models.

Fisher's votex-glass model [4, 5] and Feigel'man *et al* introduced the theory of collective pinning presented by Larkin [6—8] into high-T_c superconductors and gave:

$$U = U_0\left[\left(\frac{j_c}{j}\right)^{\mu} - 1\right]$$

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$$E \propto \exp(-A / j^{\mu})$$

$$M \propto \left[1+\frac{k_{\mathrm{B}}T}{U_0}\mathrm{In}\left(\frac{t}{t_0}\right)\right]^{-\frac{1}{\mu}}$$

In the votex-glass model, $\mu \leq 1$; in the collective pinning model, $\mu = \frac{1}{7}, \frac{3}{2}, \frac{7}{9}, \frac{1}{2}$.

Zeldov *et al.* [9] gave the logarithm relationship of U (j) and j from ρ-T experiment results with different j:

$$U = U_0 \ln\left(\frac{j_{\mathrm{c}}}{j}\right)$$

and obtained:

$$E \propto \left(\frac{j_{\mathrm{c}}}{j}\right) - \frac{U_0}{k_{\mathrm{B}}T}$$

$$M \propto \left(1+\frac{t}{t_0}\right)^{-\frac{k_{\mathrm{B}}T}{U_0}}$$

Hagen and Griessen [10] modified the Anderson-Kim's thermally activated model. They added a distribution function $m(U^*)$ of activation energies in the thermally activated model, introduced flux flow in Anderson's theory, and gave:

$$U(T,B) = U^* b(T)[1 - B / B_{\mathrm{c2}}(T)]$$

$$E = \left\{S \exp\left(\frac{U}{k_{\mathrm{B}}T}\right)\left[\sinh\left(\frac{Aj}{k_{\mathrm{B}}T}\right) - 1 + \frac{B_{\mathrm{c2}}}{Bj\rho_n}\right]\right\}^{-1}$$

$$M(t,T,B) = M_0 \frac{b(T,B)}{a(T,B)} \int_{U_0^*}^{\infty} m(U^*) \left[1 - \frac{k_{\mathrm{B}}T}{U^* b(T,B)} \ln\left(1+\frac{t}{t_0}\right)\right] \mathrm{d}U^*$$

Yin *et al.* [11] suggested that there is dissipation in the thermally activated flux flow (TAFF). They rewrote the Anderson's equation as:

$$E(j) = 2V_0 B \exp[U_0 / k_{\mathrm{B}}T] \exp[-W_{\mathrm{VS}} / k_{\mathrm{B}}T] \sinh[W_{\mathrm{L}} / k_{\mathrm{B}}T]$$

where W_{L} is the work by the Lorentz force, W_{VS} is the viscous dissipation in the TAFF.

All these models can give the fitting of *E-j, M-t* relationship, but neither none is perfect.

Busch *et al.* [12] attached two current and two voltage contacts on both sides of $Bi_2Sr_2CaCu_2O_{8+\sigma}$ single crystals and performed transport measurement with the current applied in the ab plane. In the Ohmic regime, the voltage signal on the side of the current contacts was more than a factor of 100 larger than at the opposite side. The results are interpreted within an anisotropic resistivity model to determine the true resistivities $\rho_{ab}(B,T)$ and $\rho_{\mathrm{c}}(B,T)$. They presented a model based on the movement of pancake vortices involving vortex shear, vortex cutting, and generation of Josephson vortices between the layers.

In order to testify the validity of Busch's model of pancake vortices movement, we designed a configuration with the current and voltage contacts on the same and different sides respectively and measured the *E-j* relationship. It is found that the *E-j* relationship with the current and voltage contacts on the same side is quite different from on the different side, no matter the applied magnetic field is parallel or perpendicular to the c axis of the sample. These results are consistent with the pancake vortices movement model.

2 Experiments

Measurement of the transport properties is a general way to study the flux dynamics in high-T_{c} superconductors. The "flux transformer" arrangement is a most effective method because the direct proofs of the flux movement on different surfaces of the crystal can be obtained with this arrangement. Based on those, we used the "flux transformer" arrangement to measure the transport properties of the $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal. Our purpose is studying in detail the flux dynamics in the $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystal at "flux flow" temperature regime through investigating the situations of pancake vortices and Josephson vortices under uniform and nonuniform Lorentz force.

To investigate the situation of pancake vortices under nonuniform Lorentz force, we used the traditional "flux transformer" arrangement, as shown in Fig. 1 (a). Two current and two voltage contacts are attached on the top *ab* plane of the sample. Another two current contacts are attached on the bottom *ab* plane, aligning with the current contacts on the top side. Here we attached two current instead of voltage contacts on the bottom surface in order to avoid the possible voltage deviation introduced by the variety of the voltage contact position. The measuring current is applied along the *a* axis on the *ab* plane. The current distribution is nonuniform along the *c* axis. As shown in Fig. 1 (b), when the magnetic field is parallel to the *c* axis, the pancake

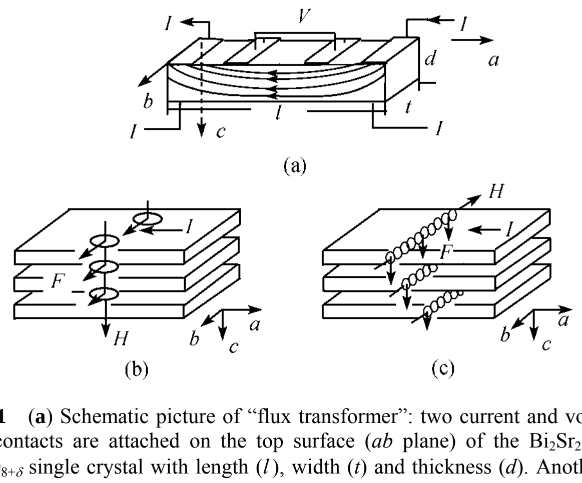

Fig. 1 (**a**) Schematic picture of "flux transformer": two current and voltage contacts are attached on the top surface (*ab* plane) of the $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal with length (l), width (t) and thickness (d). Another two current contacts are attached on the bottom surface, aligning with the top current contacts. The current density is nonuniform along the *c* axis. (**b**) the pancake vortices experiencing the nonuniform Lorentz force when $H \parallel c$. (**c**) the Josephson vortex line experiencing a uniform Lorentz force when $H \perp c$.

vortices formed by the field inside the crystal will experience a nonuniform Lorentz force. When the field is perpendicular to the c axis [Fig. 1 (c)], a Josephson vortex line will experience a uniform Lorentz force, but the force acting on the vortex line on the top surface is different from on the bottom surface.

3 Results and discussions

Figure 2 presents the *E-j* relationship with the field parallel to the c axis of the sample. Figures 2 (a), (b), (c), (d) corresponds to H = 0, 2, 4, 6 T, respectively. The solid squares represent the data with the current and voltage contacts on the same surface, while the hollow circles represent the data with contacts on the different sides. It can be seen that no matter how much the field is, the results with contacts on the same side and opposite side are completely different at various temperatures below the critical temperature.

Figure 3 presents the *E-j* relationship with the field perpendicular to the c axis of the sample. Figures 3 (a), (b), (c), (d) corresponds to H = 0, 2, 4, 6 T, respectively. The solid squares represent the data with the current and voltage contacts on the same surface, while the hollow circles represent the data with contacts on the different sides. Similar as the situation with $H \parallel c$, no matter how much the field is, the results with contacts on the same side and opposite side are completely different at various temperatures below the critical temperature.

The flux vortex lines are pinned in a superconductor. If there is an applied field, the vortex lines will experience a Lorentz force. When the force is large enough, the vortex lines will break away from the pinning and move. Hence a voltage signal appears in the superconductor. This signal and the current in the superconductor reflect the movement of the flux vortices.

If a flux vortex line is considered as a rigid line, different parts of the line will experience different pinning forces. Under the driving of applied field, the line should overcome the maximum pinning force before it can move without distortion in the superconductor, i.e., the distribution of the Lorentz forces acting on different parts of the rigid vortex line will not affect the movement of the vortex line. Whether the line moves or not only lies on the value rather than the position of the maximum pinning force acting on it. Only when the maximum force is overcome, can the whole vortex line begin to move. As the magnetic field is parallel to the c axis, the vortex lines penetrate normal and superconducting layers. Pancake vortices form in the superconducting layers. Each pancake vortex experiences the same pinning force. But due to the difference of the current density between the top and bottom surfaces [Fig. 1 (a)], the Lorentz force acting on each pancake vortex is different. According to the rigid model, only when the Lorentz force on the pancake of the bottom is larger than the pinning force, can the rigid line move. Therefore in Fig. 2, the *E-j* curves with the current

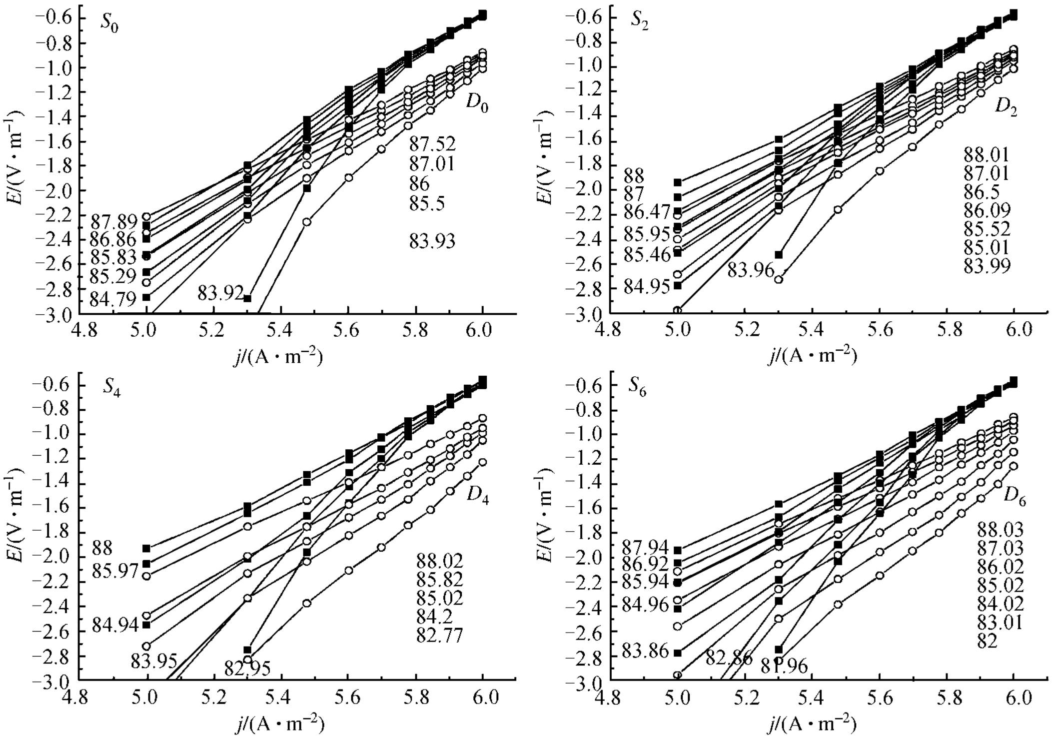

Fig. 2 The *E-j* relationship as the field parallel to the c axis of the sample. S_n represents for the top surface and D_n for the bottom surface. n = 0, 2, 4, 6 represents for H = 0, 2, 4, 6 T.

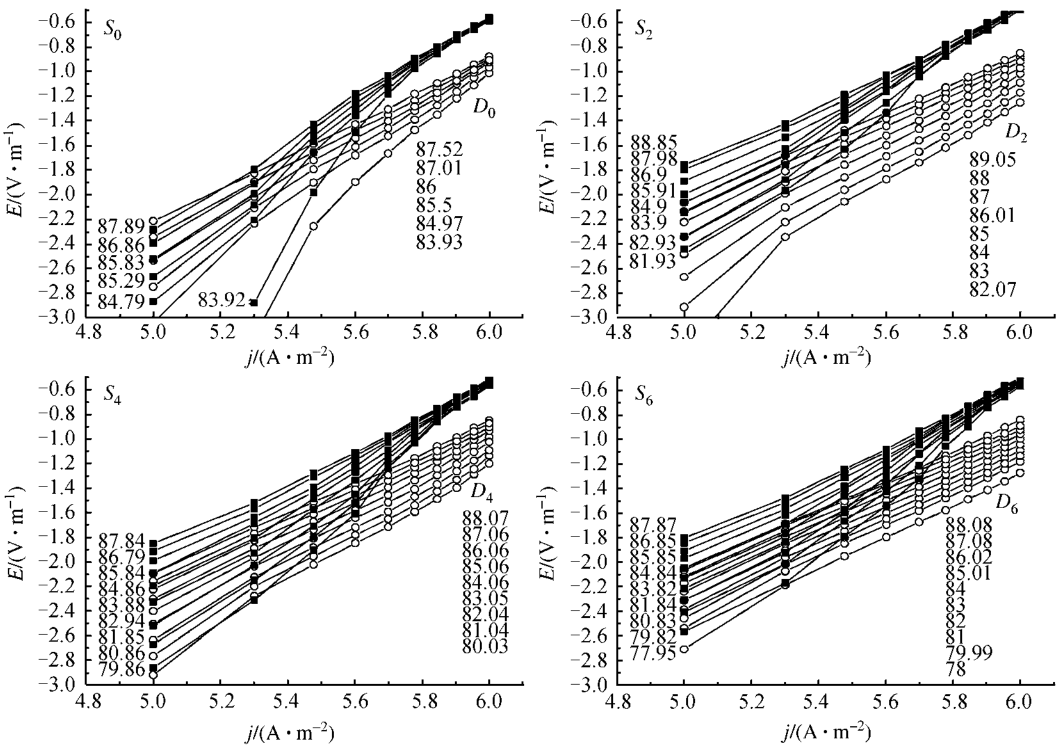

Fig. 3 The *E-j* relationship as the field perpendicular to the *c* axis. The meaning of S_n and D_n is the same as Fig. 2.

and voltage contacts on the same side should superpose those with contacts on different sides. However, the experiment results point out that the voltage with contacts on the same side is higher than on different sides, which indicates that it is the pancake vortices instead of vortex lines that move in the superconductors. According to Busch's pancake vortices model, the pancake vortices in the same vortex line can move individually. The movement is determined by the Lorentz force. For each pancake vortex, as long as the Lorentz force overcomes the pinning force, the pancake begins to move and consequently produces a voltage signal. It means that within the pancake vortices model, when the pancake vortices on the top surface experience a Lorentz force that is larger than the pinning force while those on the bottom surface experiences a Lorentz force smaller than the pinning force, the pancakes on the top begin to move individually and a voltage signal appears in the sample. It is opposite to the rigid model that only when the maximum pinning force is overcome, can the voltage signal appear. It should be noted that here the pancake vortices are connected by the Josephson coupling between the pancakes. So as long as the Lorentz force overcomes the Josephson coupling, the pancake vortices move individually.

As the field is perpendicular to the c axis, it is the vortex lines instead of pancake vortices that form in the ab plane of the superconducting layers. Still due to the nonuniform distribution of the current, each vortex line experiences different Lorentz forces. Obviously, the vortex lines on the top surface overcome the pinning from the normal layers and move firstly. Then with the increase of the current, the vortex lines in the layers below move in turn, leading to the difference of the *E-j* relationship with contacts on the same sides and on different sides in Fig. 3.

4 Conclusions

With the "flux transformer" configuration, different *E-j* relationships are obtained when the current and voltage contacts are attached on the same surface and on different surfaces respectively. This difference rules out the rigid flux vortex line movement model and supports the pancake vortices model.

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