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Role of nanometer PrBCO layers in $(YBa_2Cu_3O_{7-\delta})_{24}/(PrBa_2Cu_3O_{7-\delta})_2$ multilayer film

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Abstract

The field and angular dependencies of the resistive transition for an epitaxial $(YBa_2Cu_3O_{7-\delta})_{24}/(PrBa_2Cu_3O_{7-\delta})_2$ nanometer multilayer film have been measured at magnetic fields up to 7.5 T parallel and perpendicular to the *c*-axis and at constant fields of 0.12 T and 4 T for various angles, respectively. The coupling and decoupling between the YBCO layers have been investigated. A special field dependence of activation energy for $H \parallel ab$, namely, a field independent behaviour in fields smaller than 0.12 T, a logarithmic dependence in medium fields and an exponential behaviour in fields higher than 1 T is observed. The angular dependence of the activation energy reveals that when the parallel field component is less than 0.12 T, the dissipation is only related to the perpendicular field component, which is consistent with Kes's two-dimensional (2D) pancake model. Above this field the activation energy depends on the decoupling and coupling between the superconducting YBCO layers.

1. Introduction

It is well known that oxide multilayers can be used to probe superconductivity in high-T_c materials at the unit cell level, as well as to understand how systematic changes of certain material parameters influence characteristic physical properties [1]. It is also well known that the *c*-axis coherence length ξ_c is about 0.3 nm in $YBa_2Cu_3O_{7-\delta}$ (YBCO) [2], while YBCO films thicker than 40 nm show a three-dimensional (3D) behaviour [3]. Therefore, if we insert an insulating layer, such as a one unit cell $PrBa_2Cu_3O_{7-\delta}$ (PrBCO) layer between the superconducting YBCO layers to form a multilayer thin film, the coupling between the superconducting YBCO layers should be destroyed. Each of the YBCO layers in the multilayer

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behaves as an isolated 2D layer [3]. The multilayer may be ideal for studying the unusual vortex dynamics of high-temperature superconductors.

Multilayer thin films of $(YBCO)_m/(PrBCO)_n$ and $(YBCO)_m/(YPrBCO)_n$ have been prepared successfully by many groups, but these studies mostly focused on the effect of the thickness of the superconducting and/or insulating layers and on the thermal activation energy [3], the magnetoresistance [4] and the critical current density [5], etc. A natural question will be if and how coupling between the YBCO layers can be mediated across the PrBCO layers. Although Brunner *et al* [3] have reported that the activation energy U is proportional to the YBCO thickness up to 26.4 nm, there is little knowledge of the vortex dynamics of the multilayer thin films. In order to investigate the role of these PrBCO layers, we have to choose a $(YBCO)_{24}/(PrBCO)_2$ multilayer where the thickness of two unit cell PrBCO layers is enough to completely isolate the individual YBCO layers and the thickness of the latter is 28 nm (smaller than 30 nm), so that 2D behaviour is exhibited. If the multilayer film were actually 2D, one would expect that the properties of such a film would essentially be the same as a unit cell layer. On the other hand, if the coupling between the layers in the film is of importance, then the properties of the multilayer thin film might be very different from those of the thin films, showing 2D behaviour.

The main idea of this paper is to measure the resistive transition at different magnetic fields, and then to reveal the vortex dynamics in the multilayer film. The experimental result shows that a special field dependence of the activation energy results from the insertion of the insulating PrBCO layers.

2. Sample and experiment

The $(YBCO)_{24}/(PrBCO)_2$ multilayer thin film used in this study was prepared by continuous sequential high pressure dc sputtering onto heated $SrTiO_3$ (100) substrate in pure oxygen atmosphere ($P_{O_2} \approx 3$ mbar) from planar stoichiometrical YBCO and PrBCO targets ($\phi = 50$ mm), as reported in [6]. The thickness of the YBCO and PrBCO layers were about 28 and 2.4 nm, respectively. The multilayer film with 10 periods was patterned into a narrow bridge 0.2 mm wide and 2 mm in length. The current and voltage leads were soldered with indium on silver terminals deposited onto the surface of the film. Then the film was held on a rotatable sample holder, where the angle between the field H and the film surface could be adjusted conveniently and the resolution of the angle was 0.1°. The measurements were performed by using a data collecting system consisting of a Keithley-182 nanovoltmeter, a Keithley-220 programmable current source and an IBM computer. Every data point was the average of measured data for positive and negative orientation transport current. The applied dc current was 100 μA (about 170 A cm^{-2}). The high magnetic field source was a superconducting solenoid magnet system, and a copper coil solenoid magnet supplied the low magnetic field. The temperature was measured by a calibrated Rh–Fe resistance thermometer and corrected for the effect of magnetic field. The zero resistance temperature of the $(YBCO)_{24}/(PrBCO)_2$ multilayer thin film was 87.93 K at self-field.

3. Results and discussions

It is well known that the effective activation energy serves as an important parameter in determining the flux dynamics feature in the mixed state. In general, the effective activation energy can be extracted from the resistive transition curve for $\rho < 0.01\rho_n$, where ρ_n is the normal resistivity [7]. To investigate the real vortex dynamic behaviour in the nanometer

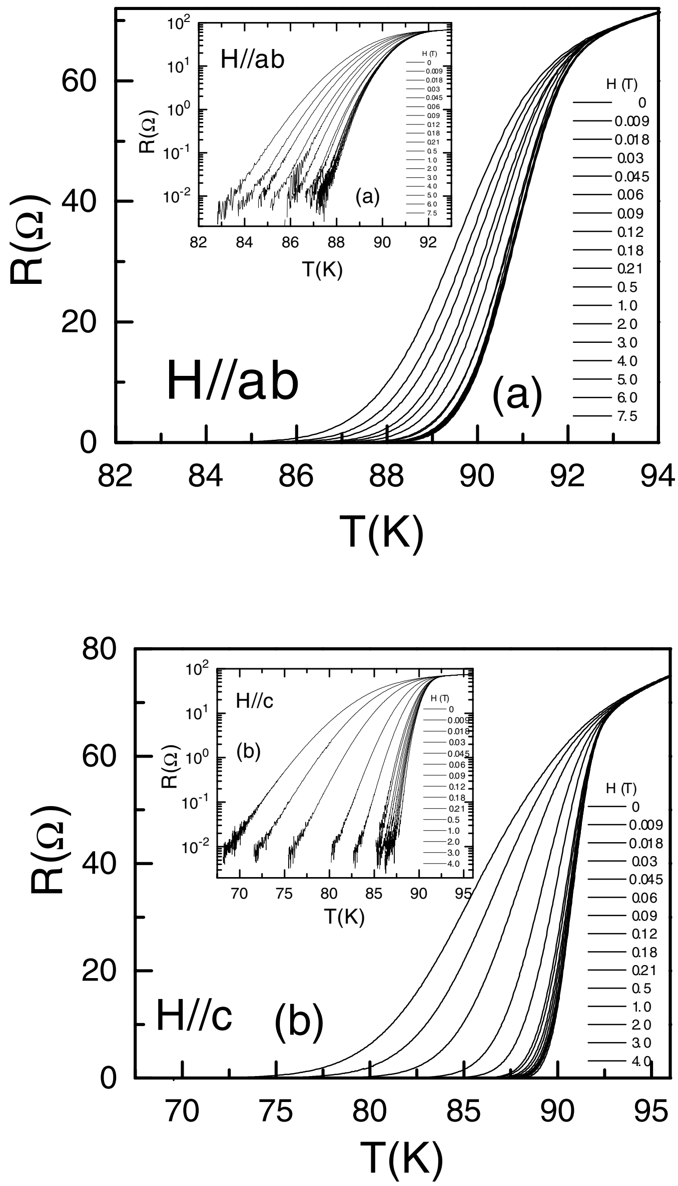

Figure 1. Resistive transition curves of an epitaxial $(YBa_2Cu_3O_{7-\delta})_{24}/(PrBa_2Cu_3O_{7-\delta})_2$ nanometer multilayer film at magnetic fields up to 7.5 T for (a) $H \parallel ab$ and (b) $H \parallel c$ with $H \perp J$, respectively inset: semi-logarithmic plot of the resistive transition curves.

YBCO layers and the role of nanometer spacing PrBCO layers, we carried out a detailed measurement of the resistive transition curve for $H \parallel ab$ and $H \parallel c$, respectively, with $H \perp J$ at magnetic fields up to 7.5 T, as shown in figure 1. From figure 1(b), we can clearly observe a field-induced large broadening effect of the transition for $H \parallel c$, such as a lower magnetic field of 0.009 T. However, from figure 1(a), we see that the resistive transition is independent of the field for magnetic fields between 0.02 T and 0.12 T. Above this range, broadening of

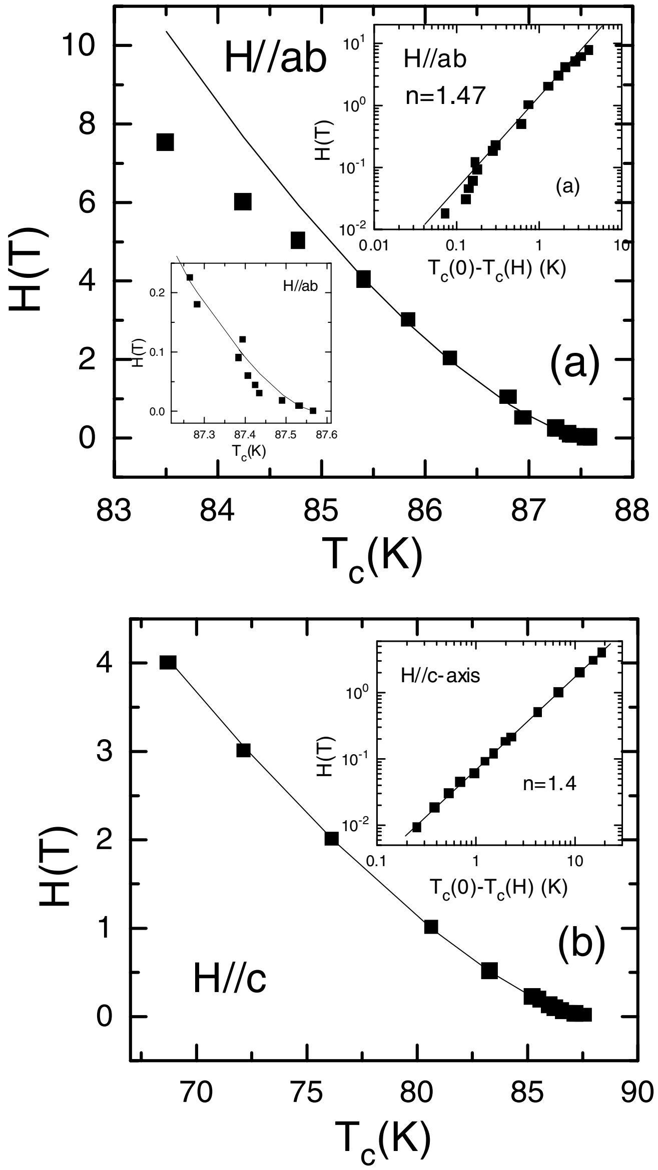

Figure 2. Field dependence of critical temperature defined by the criterium of 1 μV or 10^{-2} Ω for (a) $H \parallel ab$ and (b) $H \parallel c$. Inset: log–log plot of H versus. ($T_c(0)$-$T_c(H)$).

the transition appears. In order to observe this behaviour clearly, the curves are replotted in a semi-logarithmic diagram, as shown in the inset of figure 1. The tail of the resistive transition shows a thermally activated behaviour. Fischer *et al* [8] first reported this non-dependence behaviour in a 2.4 nm YBCO/ 9.6 nm PrBCO multilayer film in fields up to 19.5 T for $H \parallel ab$. For a better understanding of the independence in our sample, we will discuss it from the point of view of the field dependence of the critical temperature and the activation energy for $H \parallel ab$ and for $H \parallel c$ respectively.

Figure 2 gives the field dependence of the critical temperature T_c for $H \parallel ab$ and $H \parallel c$

respectively, where the critical temperature T_c is defined by the criterium 1 μV or 10^{-2} Ω. The log–log plot of H versus $(T_c(0)$-$T_c(H))$, as shown in the inset of figure 2, provides further insight. For $H \parallel c$, a good agreement with a single power law, $H \propto (1 - T/T_c)^n$, is found in the whole experimental range and the best-fit exponential factor n is 1.4. However, in the case of $H \parallel ab$, the power law with $n = 1.47$ holds only between 0.12 T and 4 T. The solid lines shown in figure 2 are fitted lines calculated by the power law. The breakdown of the power law in the low-field ($H < 0.12$ T) and high-field ($H > 4$ T) regions is clearly observed as a departure of the experimental data from a straight line, as shown in the upper inset of figure 2(a). To clearly show the power law in the low field region, the field dependence of critical temperature is enlarged, as shown in the lower inset of figure 2(a). The experimental data for magnetic fields between 0.02 T and 0.1 T lies below the power law line, showing the decrease of the critical temperature. However, Civale *et al* [9] and Li *et al* [10] observed an enhancement of the irreversibility temperature in YBCO thin films and YBCO/PrBCO multilayers. We contest that the two deviations result from different origins. The deviation in the low field region may be explained by the flux lines trapped in the PrBCO layers, namely the magnetic field in the PrBCO layers is higher than the applied magnetic field. However for the higher field region the deviation can be easily understood by the fact that the flux lines in the PrBCO layers destroy the coupling of the superconducting YBCO layers, namely the irreversibility temperature is strongly depressed by the applied magnetic field. Civale *et al* [9] have reported that for films (25 nm) thinner than the London penetration depth, when the field is applied parallel to the film surface, the lower critical field H_{c1} can be greatly enhanced. An estimate of the lower critical field H_{c1} yields [1]

$$H_{c1} = \frac{2\lambda_{ab}\phi_0}{\pi\lambda_c d^2}\ln\left(\frac{d}{\sqrt{\xi_{ab}\xi_c}}\right) = \frac{2\phi_0}{\pi\gamma d^2}\ln\left(\frac{d}{\xi_c\sqrt{\gamma}}\right) \qquad (1)$$

with λ_{ab}, λ_c, ξ_{ab} and ξ_c being the ab plane and c-axis penetration depths and the coherence lengths, respectively, d is the thickness of a YBCO layer, while γ is the anisotropic parameter. From this formula, one sees that for a 28.8 nm YBCO layer with anisotropic factor $\gamma = 10$ [11], H_{c1} is about 0.65 T, using standard parameters for YBCO ($\xi_{ab} = 1.5$ nm). If we consider the fact that the magnetic field is essentially expelled from the YBCO layers into the PrBCO layers, the magnetic field in PrBCO layers should be seven times that of the applied magnetic field, according to the ratio of the PrBCO and YBCO layer thicknesses. This means that H_{c1} is reached when the applied magnetic field is about 0.1 T. The value of H_{c1} is consistent with the lower deviation field H observed in figure 2(a). This result indicates that no vortices are present in the YBCO layers below H_{c1} and the vortices enter the superconducting YBCO layers only above H_{c1}.

Figure 3 shows the field dependence of the activation energy for $H \parallel ab$ and $H \parallel c$, respectively. The activation energies quoted here are the average slopes of the Arrhenius plots for $\rho < 0.01\rho_n$. For $H \parallel c$, the activation energy depends logarithmically on the applied magnetic field, instead of the usually observed power-law dependence, $U \propto H^{-\alpha}$, in bulk YBCO samples. However, for $H \parallel ab$, we find a special field dependence of the activation energy, namely, a field independent behaviour below a characteristic field H_c ($H_c < 0.12$ T), a logarithmic field behaviour in the medium field $0.12 < H < 1$ T and an exponential behaviour above another characteristic field H^{**} ($H^{**} > 1$ T), as shown in the inset of figure 3(a). The logarithmic field dependence of the activation energy, which is a 2D behaviour, has been observed by Brunner *et al* [3] in YBCO/PrBCO multilayer films for $H \parallel c$. Similar results have also been reported by Baier *et al* [12] in YBCO/$Nd_{1.83}Ce_{0.17}CuO_x$ superlattices, White *et al* [13] in Mo/MoGe superlattices and Suzuki *et al* [14] in a-axis superlattices. This result suggests that the dissipation might be mainly caused by the motion of 2D pancake vortices in

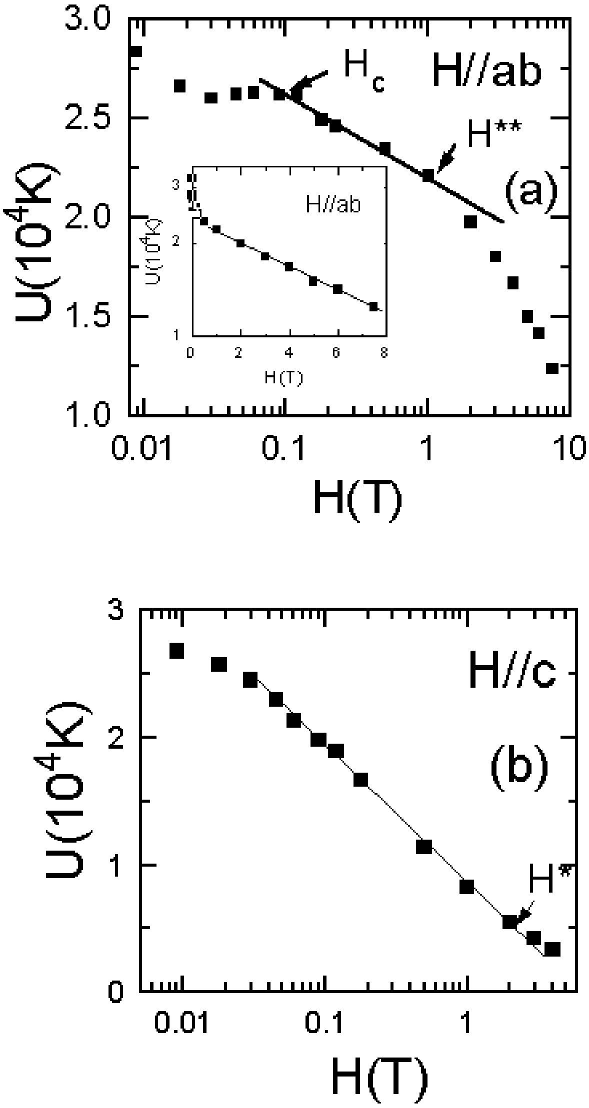

Figure 3. Field dependence of the activation energy extracted from the average slope of the Arrhenius plots for $\rho < 0.01\rho_n$ for (a) $H \parallel ab$ and (b) $H \parallel c$. The enset is the semi-logarithmic plot.

the multilayer thin film.

As has been pointed out by Brunner *et al* [3], the activation energy can be written as

$$U = p(\mu_0 H_c^2/2)V_c \tag{2}$$

where p is the fraction of the condensation energy density and $V_c = R_c^2 L_c$, the correlation volume, is the volume of flux involved in the activation process. The correlation lengths R_c and L_c give the size of the correlated region perpendicular and parallel to the magnetic field, respectively. In the 2D collective pinning theory, Fiegel'man *et al* [15] proposed that the interaction between two dislocations is logarithmic up to distances of the order of $R_0 + R_c$

($R_0 \approx a_0^2/\xi$), with a_0 the vortex–vortex separation and R_c the vortex translational correlation length. For larger distances, it decreases exponentially, so that the energy required to activate a dislocation pair becomes finite and equal to:

$$U = \frac{\phi_0^2 d}{16\pi^2\mu_0\lambda^2} \ln\left(\frac{R_c}{a_0} + \frac{a_0}{\xi}\right) \tag{3}$$

where d is the film thickness, ϕ_0 the flux quantum, ξ the coherence length and λ the penetration depth. It was noted by Brunner *et al* [3] that for a short translational correlation length R_c, the free energy to create a dislocation pair is reduced to $U \propto \ln(a_0/\xi)$. Since $a_0 \approx \sqrt{\phi_0/H}$, we see that the activation energy U is proportional to $-\alpha \log H + \beta$, which is consistent with our experimental result shown in figure 3. Since the activation energy for thermally activated flux flow is proportional to L_c, one expects U to be proportional to the film thickness d for d smaller than L_c^* (L_c^* is cut off by the finite thickness) as reported by Brunner *et al* [3] and Baier *et al* [12]. The maximum correlation length L_c, which is about 45 nm for bulk YBCO, has been estimated [3, 8]. If 2.4 nm thick insulating PrBCO layers separate completely the 28.8 nm superconducting YBCO layers, the vortices should be considered to behave dynamically as 2D pancake vortices in the multilayer film since the YBCO single layer thickness is smaller than L_c^* (45 nm). In the absence of coupling in multilayer films, L_c should be equal to the thickness of the individual layers for $H \parallel c$. But in the case of $H \parallel ab$, L_c should be equal to 45 nm, larger than that for $H \parallel c$. The activation energy will depend on the anisotropy and thus on the Josephson coupling between the individual CuO_2 layers since the energy involves the tilt modulus C_{44} of the vortex lattice.

Comparing the field dependence of activation energy for $H \parallel c$ with that for $H \parallel ab$, we find a deviation with an upward curvature for $H \parallel c$, and a downward curvature for $H \parallel ab$ for higher fields. For $H \parallel ab$, the deviation with a downward curvature means the actual activation energy is lower than that predicted by the 2D behaviour. From the above discussion, the correlation length L_c should be equal to L_c^* along the ab plane since the width of the sample is larger than L_c^*. Therefore, the decrease of activation energy is only related to the anisotropy and the Josephson coupling between the individual CuO_2 layers. In the inset of figure 3(a), we replot the field dependence of activation energy in the semi-logarithmic diagram. The field dependence of activation energy shows an exponential behaviour for $H \parallel ab$ at magnetic fields above 1 T. The exponential field behaviour of activation energy above 1 T for $H \parallel ab$ may seem to result from the decoupling between the individual CuO_2 layers. However, in the case of $H \parallel c$, the deviation with an upward curvature implies that the actual activation energy is larger than that predicted by the 2D behaviour. The increase of activation energy indicates that the correlation length L_c is larger than the thickness of the individual layers. This result should be evidence for the coupling between the superconducting YBCO layers, which gives rise to a proximity effect.

In the decoupled 2D superconducting materials, Kes *et al* [16] have proposed that the dissipation is only related to the perpendicular field component. From figure 3(a), the field dependence of the activation energy indicates that a field independent activation energy occurs at magnetic fields below 0.12 T for $H \parallel ab$. To further confirm this behaviour in multilayer thin films we carried out a systematic measurement of the temperature dependence of the resistance for various angles θ, where θ is the angle between the applied magnetic field and the surface of the film (ab-plane) with $H \perp J$, as shown in the inset of figure 4 for a measuring current density of 170 A cm^{-2}. Figure 4 and the inset give the angular dependence of the resistive transition curve at constant magnetic fields of 0.12 T and 4 T for various angles θ, respectively. In the figure, we can see that the broadening of the resistive transition increases with increasing angle θ from 0° to 90°. From these curves, we obtain the angular dependence of the activation

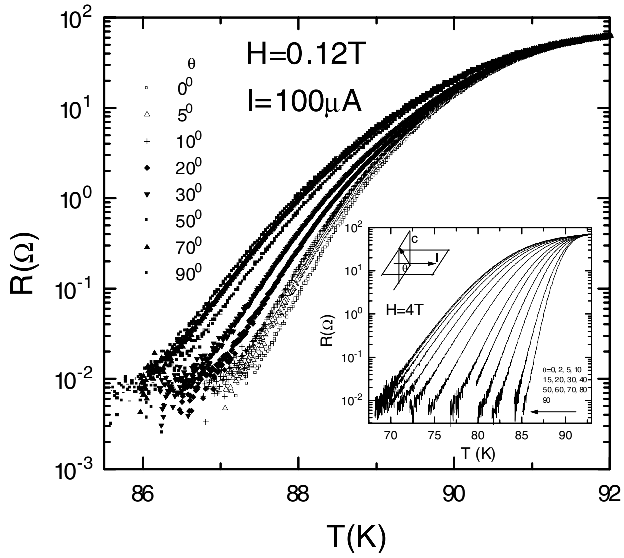

Figure 4. Angular dependence of the resistive transition curve at a constant magnetic field of 0.12 T for various angles θ. Inset: angular dependence of the resistive transition curve at a constant magnetic field of 4 T.

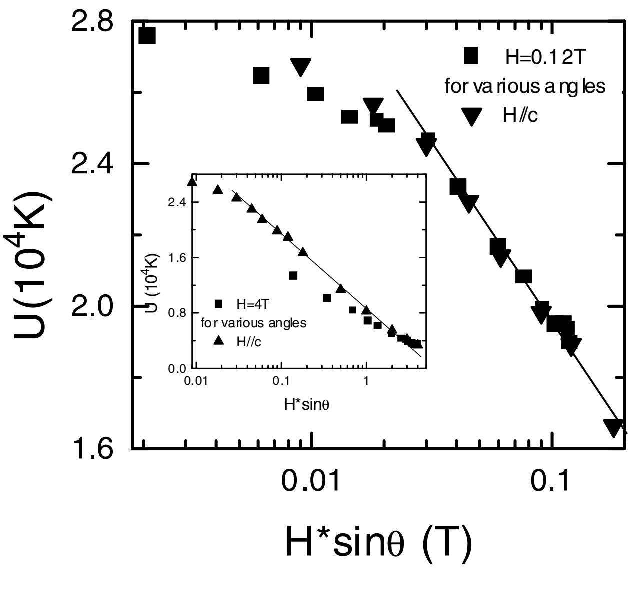

Figure 5. Angular dependence of activation energy at 0.12 T and field dependence of activation energy for $H \parallel c$. Inset: angular dependence of activation energy at 4 T and field dependence of activation energy for $H \parallel c$ up to 4 T.

energy. Figure 5 shows the angular dependence of activation energy at 0.12 T. The angular dependence of activation energy at 4 T is also shown in the inset of figure 5. To compare the angular dependence of activation energy at 0.12 T and 4 T with the field dependence of activation energy for $H \parallel c$, we plot the effective field ($H \sin\theta$) dependence of activation energy for $H \parallel c$ in figure 5 and the inset. We can see that the effective field dependence of activation energy is consistent with the field dependence of that for $H \parallel c$, indicating that the dissipation is only related to the perpendicular field component. The magnetic field below 0.12 T for $H \parallel ab$ has no effect on the activation energy. However, when $H = 4$ T, the effective field ($H \sin\theta$) dependence of activation energy deviates from the field dependence of that for $H \parallel c$, implying that the dissipation is not only related to the perpendicular field component, but is also related to the parallel applied field component.

4. Conclusion

Measurement of the transport characteristics in an epitaxial $(YBCO)_{24}/(PrBCO)_2$ nanometer multilayer film shows that there is a different vortex dynamic behaviour resulting from the insertion of 2.4 nm PrBCO layers for $H \parallel ab$ and $H \parallel c$. For $H \parallel ab$, when the magnetic field H is lower than 0.12 T, the flux lines are trapped in the PrBCO layers, causing the 28.8 nm YBCO layers to show 2D behaviour; when H is higher than 1 T, the superconductivity in the intralayer of YBCO layers is destroyed. In the case of $H \parallel c$, the PrBCO layers have no effect on the flux pinning. The angular dependence of activation energy at a magnetic field of 0.12 T shows that the dissipation is only related to the perpendicular field component. Above 0.12 T along the c-axis, the activation energy is not only related to the perpendicular field component but is also related to the parallel field component.

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