# Thermally Activated Flux Motion in Artificially Grown $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ Superlattices

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(Received 9 October 1990)

We have studied the thermally activated flux-flow resistance in $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ (YBCO/PrBCO) artificial superlattices in magnetic fields perpendicular to the *a-b* plane. We find for multilayers with thick enough ($>24$ Å) insulating PrBCO layers and for YBCO thicknesses smaller than 300 Å that the activation energy has a logarithmic magnetic-field dependence and that it is proportional to the YBCO thickness in the multilayer.

PACS numbers: 74.60.Ge, 74.70.Jm, 74.70.Vy, 74.75.+t

Among the many remarkable features of the high-temperature superconductors, the unusual properties of the mixed state have attracted much interest. The difference from conventional superconductors comes to a large extent from the importance of thermal fluctuations, leading for instance to the existence of an "irreversibility line" in the $H$-$T$ phase diagram which represents the boundary between reversible and hysteretic behavior of the magnetization [1,2]. Perhaps the most direct manifestation of the unusual property of the flux-line lattice is the observed broadening of the resistive transition when a magnetic field is applied. In particular it has been found that the resistivity $\rho$ shows a tail which for $\rho < 0.01\rho_n$ ($\rho_n$ is the normal-state resistance) has a thermally activated behavior [3]: $\rho(T,H)=\rho_0\exp(-U/k_BT)$.

This behavior is generally understood as a thermally activated flux flow (TAFF) [4] resulting from the activation of individual flux units. $U$ is the activation energy which is normally both field and temperature dependent. Such thermally activated flux motion was first proposed by Anderson [5] and by Kim, Hempstead, and Strnad [6] and has been observed also in the conventional superconductors [7]. What makes this effect especially important in the high-temperature superconductors is that the ratio $U/T$ is small in a wide range below $T_c$. One of the central problems here is to understand the actual process which is being activated and why this one becomes so important in the high-temperature superconductors. For a qualitative discussion we first write the activation energy as $U=p(\mu_0H_c^2/2)V_c$, where $p$ is the fraction of the condensation energy density and $V_c$, the correlation volume, is the volume of flux involved in the activation process.

Writing $V_c=R_c^2L_c$, the correlation lengths $R_c$ and $L_c$ give the size of the correlated region perpendicular and parallel to the magnetic field. As has been pointed out by Kes and van den Berg [8], $L_c$ depends on the tilt modulus $C_{44}$ of the flux-line lattice and, assuming the field to be parallel to the $c$ axis, will decrease as the anisotropy of the substance increases. Palstra *et al.* [9] studied the activation energies of $YBa_2Cu_3O_7$ (YBCO) and $Bi_2Sr_2CaCu_2O_8$ (BiSCCO) and suggested that the lower activation energies in BiSCCO can be directly related to the lower value of $L_c$ resulting from the higher anisotropy of this material.

In this Letter we report a study of the activation energies of a series of multilayers $YBa_2Cu_3O_7/PrBa_2Cu_3O_7$ (YBCO/PrBCO) for magnetic fields perpendicular to the *a-b* plane. Because of the nonmetallic nature of PrBCO it is possible in this system to systematically change the anisotropy and thereby explore the role of the anisotropy for the properties of the flux-line lattice and the flux motion. The details of the preparation of our superlattices and of their superconducting properties can be found in Refs. [10–12]. Briefly, we use a dc magnetron sputtering technique with $R$BCO ($R$ denotes rare earth) stoichiometric targets. The substrate temperature is between 700 and 800 °C and highly oriented $c$-axis multilayers have been prepared on both (100) MgO and (100) $SrTiO_3$ substrates. They have been built with at least seven YBCO/PrBCO layers and a minimum total thickness of about 1500 Å. A TEM study of some of our films [13] reveals very sharp interfaces between the YBCO and PrBCO layers without detectable traces of interdiffusion. The Hall coefficient and resistivity per YBCO layer (12 Å) is found to be almost identical in all our multilayers, demonstrating that the current flows uniformly through all YBCO layers [14].

The standard technique to extract $U$ from the resistivity data is to plot $\ln[\rho(T)]$ vs $1/T$ for different magnetic fields. Figure 1 shows these Arrhenius plots for three samples: (a) a YBCO thin film, (b) a 96-Å/96-Å YBCO/PrBCO multilayer, and (c) a 24-Å/96-Å multilayer. The striking result is that the activation energy is strongly reduced as we reduce the thickness of the individual YBCO layers [12]. This result can be easily understood if we assume that 96 Å of PrBCO is enough to decouple the YBCO layers and that $L_c$ of YBCO is several hundred Å. In this case we expect that $L_c$ will be reduced to the thickness of the YBCO layer. If this is correct, then reducing $d_{YBCO}$ from 96 to 24 Å should induce a reduction of $U$ by a factor of 4 and this is actually the case as can be seen directly from Fig. 1. To further check this result we have studied a series of multilayers where we kept $d_{YBCO}$ ($=24$ Å) constant and varied the thickness of the PrBCO layers, $d_{PrBCO}=24$, 48, and 96 Å. For the two latter multilayers the activation energies are identical showing that $U$ is independent of the PrBCO thickness and that the YBCO layers are decoupled. For

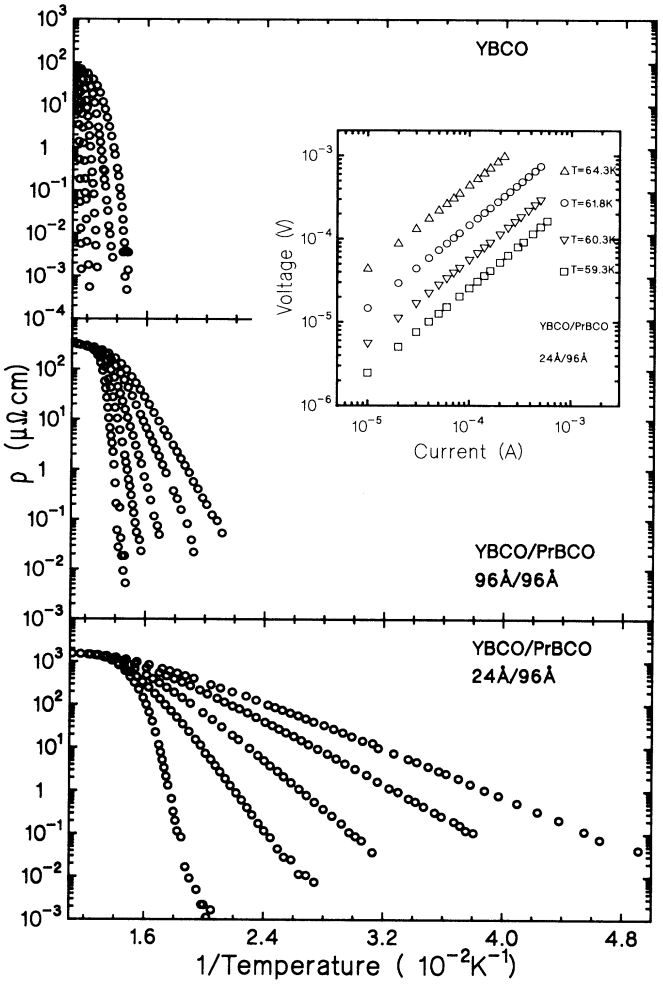


FIG. 1. Resistivity $\rho(T,H)$ vs $1/T$ for a YBCO thin film (top), a 96-Å/96-Å superlattice (middle), and a 24-Å/96-Å superlattice (bottom). The various curves are, counting from left, for magnetic fields of 0, 1, 3, 6, and 9 T, respectively. Inset: Typical linear $I$-$V$ curves for 24-Å/96-Å sample, as described in the text.

$d_{\mathrm{PrBCO}}=24$ Å we find that the activation energies are larger, demonstrating a certain degree of coupling across the PrBCO layer. This is in agreement with our investigations on the resistive transition in a parallel magnetic field where a complete decoupling of the layers was observed when $d_{\mathrm{PrBCO}}>24$ Å [15]. Note that we have verified that $U$ is current independent by changing the measuring current from 10 to 500 $\mu$A. In addition, we found the $I$-$V$ characteristics to be linear in the temperature, field, and current ranges investigated here, as shown in the inset of Fig. 1 for the 24-Å/96-Å sample.

We have determined the activation energies from the Arrhenius plots taking the average slope in the interval $10^{-4}\rho_n<\rho<10^{-2}\rho_n$. Since these values are determined at different reduced temperatures for the different fields and samples, one should, in principle, correct the obtained values for the temperature dependence of $U$. In the following we use the uncorrected values which we denote $\bar{U}$. The analysis given below gives strong evidence that we actually measure the zero-temperature activation energy or a value close to it.

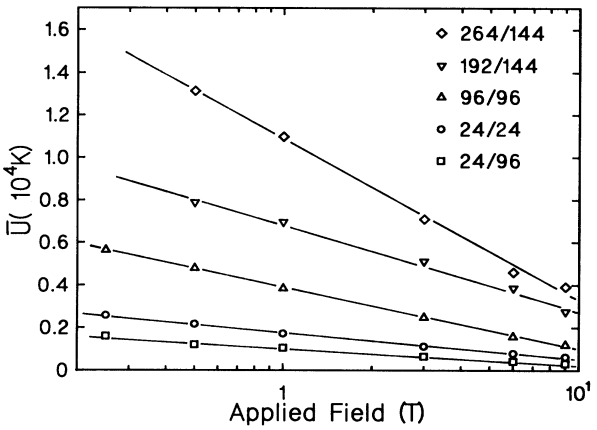


FIG. 2. Activation energy as a function of magnetic field for different superlattices: from high to low activation energies, a 264-Å/144-Å, 192-Å/144-Å, 96-Å/96-Å, 24-Å/24-Å, and 24-Å/96-Å multilayer.

In Fig. 2 we plot $\bar{U}$ as a function of $\ln(B)$ for a series of multilayers. We find that for all samples the field dependence is essentially logarithmic in the field interval investigated. Furthermore, it is not possible to fit our data with a field dependence of the type $U\approx H^{-\alpha}$. A double-logarithmic plot does not give straight lines but an exponent $\alpha$ smoothly varying in the range $\frac{1}{4}$ to $\frac{1}{2}$. In Fig. 3 we show the activation energies at three different fields and as a function of $d_{\mathrm{YBCO}}$ for a series of samples. All these samples have thick PrBCO layers ($d_{\mathrm{PrBCO}}=96$ or 144 Å) so that we may safely assume that the YBCO

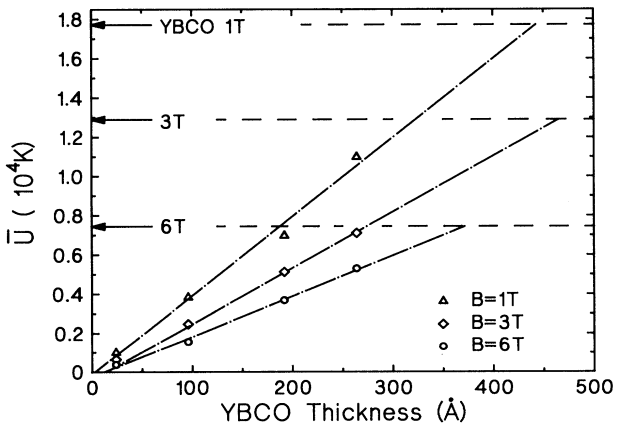


FIG. 3. Activation energy at 1, 3, and 6 T as a function of the YBCO thickness in multilayers with thick PrBCO separation thicknesses. The arrows show the values for a 1500-Å YBCO thin film.

layers are uncoupled. Figure 3 illustrates two simple but essential results of our investigation. First, we find that $\bar{U}$ varies linearly with $d_{YBCO}$ in the range studied, from $d_{YBCO}=24$ Å to $d_{YBCO}=264$ Å, demonstrating that $L_c=d_{YBCO}$. Second, extrapolation of these results to the activation energy of a 1500-Å-thick YBCO film ($\bar{U}_{YBCO}$) suggests that $L_c$ in this film is about 450 Å, corresponding to a lower limit for bulk YBCO, for which even higher activation energies have been reported. A consequence of these results is that for all multilayers investigated here we can write our data as $\bar{U}/d_{YBCO}=-\alpha\ln(B)+\beta$. From the data shown in Figs. 2 and 3 we obtain ($B$ in tesla) $\alpha=13\pm3$ K/Å and $\beta=45\pm5$ K/Å, where the errors reflect the scatter between different samples.

We now turn to discuss the temperature dependence of $U$. The expected temperature and field dependence is $U(t,B)=U_0(B)(1-t)^q$ with $q$ in the range from 1 to 2. Let us first consider the case $q=1$ for which the TAFF resistivity can be written as $\rho(t,B)=\bar{\rho}_0\exp[-U_0(B)/T]$, where $\bar{\rho}_0=\rho_0\exp[U_0(B)/T_c]$. In this case $\bar{U}=U_0$ and one obtains directly the zero-temperature activation energy from the Arrhenius plots. To further check whether our experimental curves correspond to this temperature dependence, we note that the experimentally obtained $\bar{\rho}_0$ contains a large exponential factor and should depend in a unique way on the measured activation energy $\bar{U}$ and the critical temperature $T_c$ for various fields and samples: $\ln(\bar{\rho}_0)=U_0/T_c+\ln(\rho_0)$. In Fig. 4 we plot $\ln(\bar{\rho}_0)$ vs $\bar{U}/T_c$ for various samples and fields. We obtain a remarkably straight line with a slope of 0.98, very close to the expected value. Furthermore, the value for $\rho_0$ is close to the measured normal-state resistivity of YBCO in our multilayers ($=200\ \mu\Omega$ cm). This is illustrated in Fig. 4 where we show a plot of the above equation for $\bar{\rho}_0$ vs $U=U_0$ with $\rho_0=200\ \mu\Omega$ cm.

We consider next the case $q>1$. As pointed out by Palstra *et al.* [9] the $\bar{U}$ determined from the Arrhenius plots is not $U(t)$ but $\bar{U}(t)=U(t)[1+qt/(1-t)]$. When $q>1$ this gives a result intermediate between $U(t)$ and $U_0$. For the case $q=\frac{3}{2}$ the corrections to $U_0$ vary between 0.88 and 0.46 in the temperature range $t=0.9$–$0.5$. Note that in this range the Arrhenius plots should be strongly nonlinear when $q=\frac{3}{2}$. Since the activation energies for thin YBCO layers are small, we actually cover this temperature range and the very weak curvature seen for the two multilayers in Fig. 1 is smaller than a $(1-t)^{3/2}$ dependence would predict. Furthermore, if the temperature dependence were very different from $1-t$, the plot shown in Fig. 4 should deviate from a straight line. We thus conclude that our results are consistent with a temperature dependence of $U$ close to $(1-t)^q$, $q\approx1$–$1.25$, and that the experimentally determined $\bar{U}$ are very close to $U_0$. Direct fits with the above $t$ dependence for the two multilayers shown in Fig. 1 also gave $q$ values in the 1–1.25 interval. The corresponding $U_0$ values are systematically 10%–15% higher than $\bar{U}$ but showed the same basic $B$ and $d$ dependences.

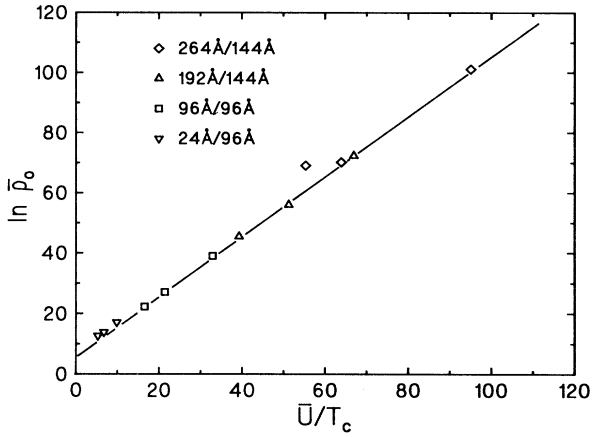


FIG. 4. $\ln(\bar{\rho}_0)$ plotted as a function of $\bar{U}/T_c(B)$. $\bar{\rho}_0$ is in $\mu\Omega$ cm and $\bar{U}$ in K. Plotted are values at 3, 6, and 9 T for the superlattices.

The observation of an activation energy which is proportional to the thickness of the YBCO layers demonstrates that in these superlattices the vortices in different layers are uncoupled and therefore behave as 2D "pancake" vortices [16]. It also has some implications for the mechanism responsible for the activated behavior. If one assumes that the activation energy is determined by the pinning of individual vortices, then our results can only be understood if the pins are densely distributed along the flux line on a scale small compared to 24 Å, i.e., there has to be a pinning center in each unit cell along the flux line. In the case where the pinning is due to defects, this would imply a large number of defects, unless $R_c$ is very large. Another possibility is that the pinning is due to the twin boundaries which are parallel to the $c$ axis. This would give an activation energy proportional to the YBCO thickness. In any case, if pinning is directly determining the activation energy, our results imply that the density of pinning sites is about the same in all our samples. This is certainly possible, but by no means proven. Another possibility is that the activation process is of a more intrinsic nature. There is presently considerable interest in the occurrence of thermally activated vortex-antivortex pairs [17] and the process observed here in finite magnetic fields could correspond to the creation of dislocation pairs in the flux-line lattice. Following Feigel'man, Geshkenbein, and Larkin [18], we note that in the collective pinning model the weak pinning leads to a finite range (of the order $a_0^2/\xi$) of the interaction between the dislocations in the pair. This leads to a finite energy to activate one dislocation pair. The resistance will then be proportional to the number of thermally activated dislocation pairs and for a 2D system the activation energy becomes approximately (MKSA units)

$$U=(\Phi_0^2 d/16\pi^2\mu_0\lambda^2)\ln(a_0/\xi)\,. \qquad (1)$$

Here $d$ is the thickness of the layer ($=d_{YBCO}$ in our case), $\lambda$ the penetration depth, and $a_0$ the flux-line lattice spacing. Note that this expression predicts a logarithmic field dependence, a proportionality to the thickness, and approximately a $1-t$ dependence. Assuming $\lambda=1400$ Å and $\xi=20$ Å for our multilayers we find that this expression predicts $U_0/d=-3.73\ln B+23.7$ ($U_0$ in K, $d$ in Å, and $B$ in T). Taking into account the complexity of the vortex motion the correspondence of the theoretical prediction and the experimental results is striking. Let us finally note that $T_c$ of the four samples shown in Fig. 3 are 63, 77, 78, and 78 K for $d_{YBCO}=24$, 96, 192, and 264 Å, respectively. We thus do not find a strong correlation between $T_c$ and $U$. This is in fact expected from Eq. (1), which implies $U\approx\Phi_0^2 d/\lambda^2\approx H_c^2\xi^2 d$. Thus the reduction in condensation energy density with $T_c$ is compensated by the increase in $\xi$. The result is that $U_0$ does not depend strongly on $T_c$, but rather on the carrier density which does not vary significantly from sample to sample [14].

In conclusion, we have measured the activation energies for a series of superconducting/insulating YBCO/PrBCO multilayers and for fields perpendicular to the $a$-$b$ plane. We find for decoupled thin YBCO layers that the activation energy scales with the thickness of YBCO, thus demonstrating that $U$ is proportional to a flux bundle volume limited in the field direction by the thickness of the individual YBCO layers. We are thus actually working in the 2D limit and this may give us simpler, therefore easier to identify, field, temperature, and thickness dependences than in the 3D case not studied here. However, from our results we estimate the correlation length $L_c$ for bulk YBCO to be about 450 Å or more. We find furthermore for our thin YBCO layers that the magnetic-field dependence of $U$ is approximately logarithmic and the linearity of the Arrhenius plots suggests that its temperature dependence is close to $(1-T/T_c)^q$, $q\approx 1$-1.25. We have presented evidence for an explanation of the thermally activated flux flow in terms of thermally activated dislocation pairs in the flux-line lattice.

We acknowledge discussions with M. Decroux, A. D. Kent, M. G. Karkut, and R. Griessen. We are grateful for technical assistance from T. Boichat and A. Stettler.

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