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Dynamics of the superconducting mixed state in $YBa_2Cu_3O_{7-\delta}$/$PrBa_2Cu_3O_{7-\delta}$ superlattices in radio frequency regime

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Abstract. Epitaxial multilayers of $YBa_2Cu_3O_{7-\delta}$ and $PrBa_2Cu_3O_{7-\delta}$ have been deposited on (100) cut $SrTiO_3$ substrates using the technique of pulsed laser deposition. Standard θ–2θ X-ray diffraction measurements on the films showed excellent superlattice reflections. The mixed state of these superlattices has been probed through measurements of radio frequency penetration depth (λ) as a function of temperature (T), magnetic field (H) and it's orientation (θ) with respect to the planes of the superlattices. These data reflect the two-dimensional nature of the mixed state in these systems.

Keywords. Superconducting mixed state; YBCO/PBCO superlattices; radio frequency penetration depth.

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1. Introduction

Understanding the dynamics of vortices in superconductors of different dimensionality is an active field of research. For three-dimensional superconductors with a weak pinning disorder, theory predicts a gradual freezing of the vortex matter to a glassy state where the barriers for vortex motion diverge with the decreasing current [1]. In a two-dimensional system, however, the glass correlation length remains finite down to absolute zero. Artificial superconducting superlattices with non-superconducting spacer layers of different conductivity, provide ideal systems to study the effects of dimensionality on vortex dynamics. While a considerable amount of work has been done on superlattices based on niobium, the low transition temperature (T_c) and upper critical field (H_{c2}) of Nb provide a narrow phase space in which dimensional effects are difficult to observe. Superlattices based on high T_c cuprates, on the other hand, provide a wide phase space where interesting effects of competing energy scales can be seen easily. Work on high T_c superlattices has been confined to dc transport and magnetization measurements. A complete understanding of vortex dynamics and dimensional crossover, however, requires experimental probes of varying time scales and strength. The rf-penetration depth measurement is one such probe. In this paper we report measurements of rf-penetration depth in $YBa_2Cu_3O_{7-\delta}$/$PrBa_2Cu_3O_{7-\delta}$ (YBCO/PBCO) superlattices.

2. Experimental

The sequential deposition of epitaxial YBCO and PBCO layers was carried out on (100) cut $SrTiO_3$ (STO) and $LaAlO_3$ (LAO) substrates in a multi-target pulsed laser deposition system. Thickness of the insulating space layer (PBCO) was varied for different depositions in order to change the Josephson coupling between the YBCO layers. The number of YBCO/PBCO bilayer in each superlattice however, was kept constant at 15.

3. Results and discussion

Figure 1 shows the X-ray diffraction pattern of three superlattices each with 15 periods in the 2θ range of 6 to 9°. The strong (001) reflection at $2\theta \approx 7.65°$ of these c-axis oriented films is evident in the figure. The reflection at $2\theta \approx 6.9°$ in all diffractograms is due to the K_β line of the X-ray source. In curves 'a' and 'b' satellite reflections of the (001) peak are also seen. These reflections are symmetrical about the (001) peak. In curve 'c', the low-angle superlattice reflection is buried under the K_β peak. The presence of superlattice reflections confirms the periodicity of the multilayers. For the films whose diffractograms are shown in figure 1, the YBCO layer thickness is ~ 80 Å, whereas the PBCO thickness varies from ~ 90 to ~ 40 Å from curve 'a' to 'c'.

The measurements of radio frequency penetration depth in the films were carried out using a tunnel diode oscillator set up as described earlier [2]. In this case the change in magnetic penetration depth, $\lambda(H, T)$, is related to the shift in frequency (δf) of the oscillator as $\delta\lambda(H, T) = G \times \delta(f)$, where G is a constant determined by the geometric configuration of the sample and inductive coil [3].

Figure 2a shows the temperature dependence of the shift in resonant frequency of the oscillator in zero field as well as when a dc field of strength 500 and 2000 G was applied perpendicular to the plane of a superlattice consisting of ≈ 80 Å each YBCO and PBCO layers. The onset of superconducting transition in zero field is at ~ 78 K. This is comparable to the results obtained in earlier studies on ≈ 100 Å thick YBCO films [4]. The large width of transition can be attributed partly to the partial isolation of YBCO layers by insulating PBCO layers, and partly, to the imperfections in film morphology at the interfaces of YBCO and PBCO layers [5,6]. The superconducting transition broadens and shifts to the lower temperature with the increasing field. Inset of figure 2a shows the frequency shift as the external magnetic field is rotated with respect to the plane of the superlattice. The angle dependent frequency shift shows sharp cusps at 0 and 180° angles where the magnetic field becomes parallel to the plane of the superlattice.

The small angular width of the cusp also suggests clean interfaces between YBCO and PBCO layers, indicating a large anisotropy of the system. The variation of $\lambda(H, T)$ as a function of external dc field strength was studied at a few temperatures below the onset of superconductivity. Two distinct regions of flux dynamics are evident from figure 2b. The low field regime (below the arrow in the figure) where δf shows sharp variation, corresponds to elastic response of the vortices. The penetration depth in this regime varies as $\sim \sqrt{B}$. The slope of δf vs. B curve becomes smaller but remains constant above the arrows. This change in behavior of δf suggests a crossover to the flux flow regime. Here also δf varies as $\sim \sqrt{B}$. The field at which crossover takes place essentially marks the

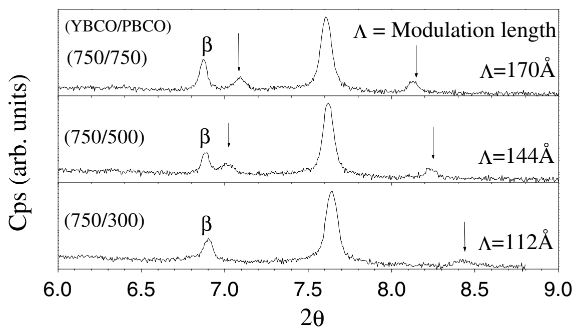

Figure 1. Low angle θ–2θ X-ray scan of three multilayers with different PBCO layer thickness. The number of laser pulses used to ablate the targets for each period are listed in the figure. The modulation lengths calculated from the position of superlattice reflections are $\sim$ 170 Å, 144 Å and 112 Å.

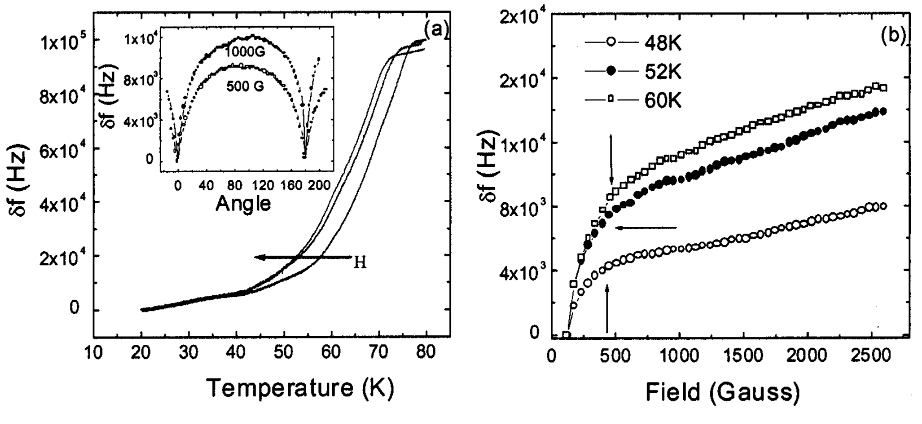

Figure 2. **(a)** The frequency shift (δf) plotted as a function of temperature for a YBCO/PBCO superlattices of $t_{\rm YBCO} \sim t_{\rm PBCO} \sim 80$ Å. The data are for zero field as well as infield (500 G and 2000 G) measurements. Inset shows the isothermal measurement of δf when the external field was rotated with respect to the plane of the superlattice. **(b)** Isothermal measurements of δf as a function of applied field ($H \| c$ axis).

irreversibility field of the superlattice samples. $H_{\rm irr}$ of the multilayers is considerably lower than that of a high-quality YBCO film.

4. Summary

In summary, we have synthesized high-quality superlattices of YBCO/PBCO system. Measurements of rf-penetration depth as a function of temperature, field strength and angle with respect to ab-plane suggest $2d$ nature of vortices in these systems.

Acknowledgments

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