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Noise Anisotropy in $YBa_2Cu_3O_{7-\delta}$ Thin Films

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Anisotropy of voltage noise in $YBa_2Cu_3O_{7-\delta}$ thin films was investigated using (103)/(013) oriented films. Normalized noise in the normal state does not depend on the direction of current flow, while in the superconducting state the noise is anisotropic. The difference stems from different origins of noise. Normal state noise is due to random motion of charge carriers while in the superconducting state it arises from fluctuations of density and/or velocity of flux vortices.

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1. Introduction

Effective mass of charge carriers in materials with anisotropic crystalline structure depends on the direction of their motion in a crystal. Anisotropy of superconducting parameters manifests itself in anisotropic properties of vortex matter. Therefore, not only the normal state resistivity ρ_n is anisotropic but also the dissipation caused by vortex motion is anisotropic. High-T_c superconducting cuprates are strongly anisotropic layered superconductors in which superconducting copper oxide planes coincide with $a-b$ planes of the perovskite structure.

Vortices induced by magnetic field applied perpendicular to the superconducting planes have form of pancake vortices. For fields applied at an angle to the crystalline c-axis, a nonzero component of the magnetic field in the direction parallel to the planes penetrates in the form of coreless Josephson vortices. For fields applied at an arbitrary angle to the c-axis, the crossing sublattices of pancake and Josephson vortices with markedly different pinning and viscosity properties coexist in the sample. Pinning anisotropy is strongly enhanced by the layered nature of high-T_c materials. The Lorentz force of bias currents flowing in $a-b$ planes forces vortices directed perpendicular to the c-axis to move across strong intrinsic pinning centers formed by weakly superconducting zones between $a-b$ planes. Motion of vortices in $a-b$ planes is hindered only by much weaker extrinsic pinning centers associated with various defects [1].

Current flow in high-T_c superconductors is naturally restricted to $a-b$ planes. Therefore, anisotropy is studied experimentally by varying the direction of applied magnetic field. Only in few experiments, by placing contacts on the top and the bottom of the sample, bias current could have been flown also along the c-axis. Directing the current at an arbitrary angle to the c-axis is nevertheless possible by employing properly patterned films with strong in-plane anisotropy. We have exploited this idea in our previous papers in which we have investigated anisotropic properties of vortices in layered (103)/(013) oriented thin $YBa_2Cu_3O_{7-\delta}$ (YBCO) films [2].

Anisotropic properties of high-T_c superconductors and their influence upon vortex dynamics is well documented in the literature, see [1], and references therein. In the light of this it is quite surprising that relatively little is known about anisotropy of the noise. In the known experiments, using a set of two distinct samples with contacts placed on the top and bottom of the specimen, the noise was measured at zero applied field conditions only for current owing either parallel or perpendicular to $a-b$ planes. Alternatively, the noise was measured for currents owing along $a-b$ planes under various direction of applied magnetic field. In such experiments one can change the nature and properties of the vortex system but cannot force the current to ow at an arbitrary chosen angle with respect to the crystalline axes. In this paper we report on noise properties in patterned anisotropic (103)/(013) oriented YBCO thin films as a function of the direction of current flow in zero applied magnetic field.

2. Experimental

Epitaxial YBCO high-T_c films typically grow with c-axis perpendicular to the substrate plane. By proper choice of the orientation of substrate and deposition parameters it is possible to grow films with strong in-plane anisotropy. Since a-axis oriented films are plagued by low stability and poor contact properties, we decided to use (103)/(013) oriented films for noise measurements. In such films the superconducting $a-b$ planes are tilted by 45° with respect to the direction normal to the film surface and unidirectional c-axis projection in the surface plane. Vortices may be directed to flow at any angle to the direction of copper planes by suitable patterning of the film that enforces chosen direction of the current flow.

YBCO (103)/(013) films were fabricated by dc inverted cylindrical magnetron sputtering in two-temperature growth process described in more detail in [2]. The orientation of the films was verified by X-ray ϕ-map and micro-Raman spectroscopy. The films were patterned into five 20 μm wide and 100 μm long strips, positioned at an angle of 30° to each other, as shown schematically in Fig. 1. Current in each stripe flows at a specific angle

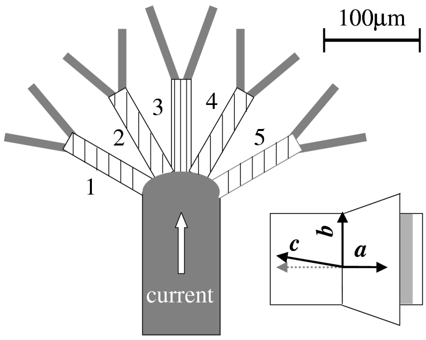

Fig. 1. Schematic top view of the patterned (103)/(013) sample.

with respect to YBCO crystalline structure. As shown in our previous papers, transport properties of YBCO depend in a systematic way on this angle [2].

3. Results and discussion

As a first step we have identified directions of strips with respect to YBCO crystalline axes by measuring the resistance at $T = 100$ K as a function of the angle θ between the projection of c-axis on the substrate plane and the stripe axis and fitting $R(\theta)$ dependence to the twofold symmetry equation, as described in detail elsewhere [2]. As expected, the maximum of the resistivity coincides with $\theta = 0°$. Voltage noise was measured by biasing strips with dc current from a high output impedance current source, amplifying the resulting voltage signal by home-made low noise preamplifier and processing the signal by a commercial digital signal analyzer. To eliminate instrumental and background noise from the data, for each data point the noise measured at $I = 0$ was subtracted from the spectra measured at finite current. Voltage noise, within the experimentally investigated range of temperature and currents, was always of the $1/f$-type. The power spectral density (PSD) of the noise fits well the power law $S_V(f) = Af^{-\alpha}$, with $\alpha \approx 1$.

Figure 2a shows an example of noise spectra measured in different directions of current flow at $T > T_c$. The intensity of the normal state voltage noise $A = S_V$ (1 Hz) scales with current I as $A = aI^{\beta}$. Exponent β was determined through fitting procedures to be $\beta = 2.0 \pm 0.1$. Quadratic dependence of PSD on current indicates that voltage noise in our sample originates from current independent resistivity fluctuations. The difference in the noise intensity at various θ stems only from different stripe resistances, since the normalized spectra $S_V/V^2 = S_R/R^2$ collapse to a single PSD, see Fig. 2b. Spectral exponent α in the normal state does not depend on the current direction.

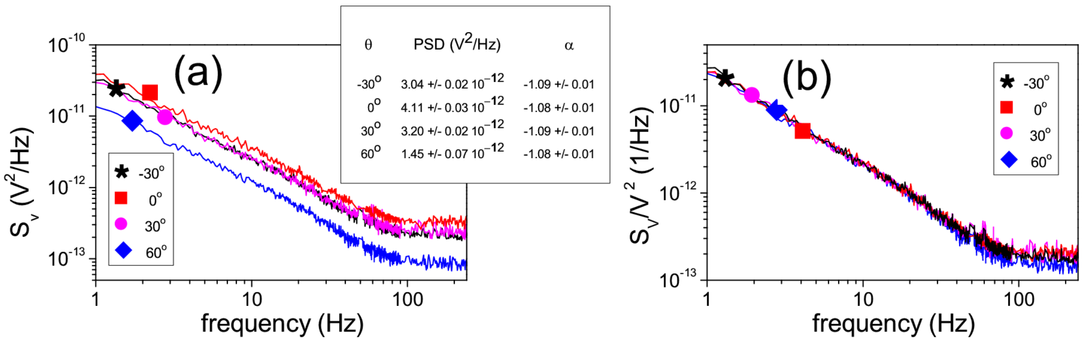

Fig. 2. (a) PSD of the voltage noise in the normal state; Inset: S_V (1 Hz) and α from fitting the PSD to $1/f$ form. (b) Normalized noise spectra.

The dependence of the noise on current direction in the superconducting state is shown in Fig. 3a. At $T = 55.6$ K and $I = 0.5$ mA all strips are biased in relatively low nonlinearity part of the respective $I-V$ curves, which allows us to normalize the measured PSD by the square of the mean voltage, as shown in Fig. 3b. In a difference to the normal state noise the absolute value of the spectral exponent α now systematically decreases with increasing angle θ. At $T < T_c$ also the intensity of the normalized noise depends on current direction and decreases with current direction getting closer to $a-b$ planes. Consistently, α and PSD in strips placed symmetrically (−30° and 30°) around the c-axis are identical.

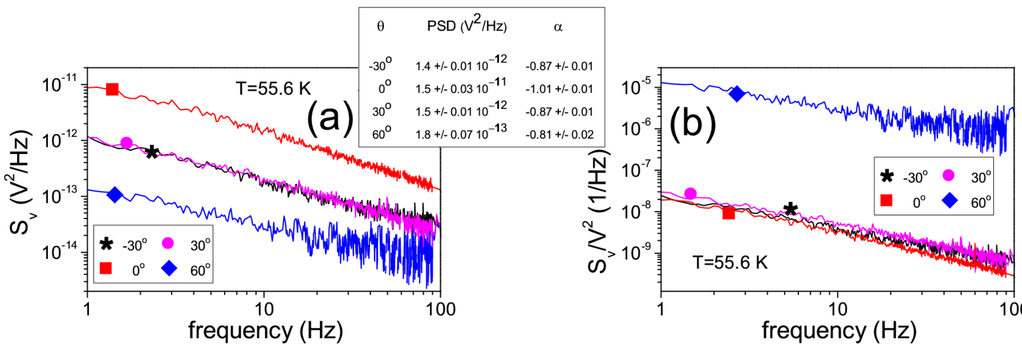

Fig. 3. (a) PSD of the voltage noise in the superconducting state at $T = 55.5$ K. Inset: S_V (1 Hz) and α from fitting the PSD to $1/f$ form. (b) Normalized noise spectra.

Contribution of intrinsic pinning to the strength of the pinning landscape decreases with decreasing θ. For a given current I the velocity of vortices and dc voltage V increase with decreasing θ. The normalized noise decreases with decreasing θ because increasing V has stronger effect on $S_{V(f)}/V^2$ than simultaneously increasing $S_V(f)$. Our experiments show that conductivity noise S_R/R^2 in the superconducting state is anisotropic.

Let us discuss the results using the Dutta–Dimon–Horn (DDH) model of $1/f$ noise, known to apply well to YBCO films in the normal and superconducting state [3, 4]. The model attributes $1/f$ noise to the action of an ensemble of elementary two-level fluctuators (TLF) undergoing thermally activated transitions between their energy wells and thus generating random telegraph signals with Lorentzian spectra [5]. When the distribution $D(E)$ of the activation energies in TLF ensemble varies slowly with respect to kT the noise PSD will be $1/f$-like. TLF in normal metals are usually associated with reconfiguring defects acting as charge traps, while in superconductors they influence the motion of flux vortices. DHD model relates, within the experimental frequency and temperature window, the spectral exponent of the noise $\alpha(T)$ to $D(E)$ $D(E) = \frac{\omega}{kT} S_V(\omega, T)$ as $\alpha(T) = 1 - \frac{1}{\ln \omega\tau_0}[\frac{\partial \ln S_V(\omega,T)}{\partial \ln T} - 1]$ [5]. Flat $D(E)$ gives pure $1/f$ noise with $\alpha = 1$ while $\alpha \neq 1$ indicates that $\partial D/\partial E \neq 0$.

The isotropy of α in the normal state implies therefore that the distributions of activation energies of TLF in various directions are the same, although fluctuator/defect density, and hence the resistivity, is obviously different. The difference in the noise anisotropy between the normal and superconducting state is due to fundamentally different origin of the noise. Randomness in scattering of the electrons by defects and phonons is the major source of the noise in the normal state. Voltage noise in the superconducting state arises from random motion of magnetic flux vortices and, in principle, has nothing in common with the normal state noise.

Finally, let us compare our results with the existing literature data [6, 7]. Our results agree with those of Taoufick et al. who found that the normalized noise increases when the direction of applied magnetic field gets closer to the c-axis direction. We see the highest noise for the strip with $\theta = 0°$. Let us observe that self-field of the current flowing along $a-b$ planes ($\theta = 0°$) is directed along the c-axis. On the other hand, our result contradict those of Song et al. who concluded that the normalized normal state noise of YBCO films is anisotropic. The difference may be due to a fact that their measurements were performed with a set of two distinct samples and only in two orthogonal current directions. Yet another source of discrepancy may be due to the fact that discussed experiments were performed using c-axis oriented YBCO films. It is known that transport properties of (103)/(113) films are strongly influenced by 90° twist domain boundaries and by tilt boundaries between (103) and (113) domains. These defects are absent in c-axis oriented films [8].

In conclusion, we have found that the normalized noise in the normal state of (103)/(113) oriented YBCO films is isotropic while the superconducting state noise is anisotropic. The anisotropy manifests itself both in the normalized noise intensity and its spectral properties. Although the general form of noise PSD is still $S_V \propto 1/f^{\alpha}$, the spectral exponent α depends on the direction of current flow.

Acknowledgments

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