Low-frequency voltage noise and electrical transport in [100]-tilt $YBa_2Cu_3O_{7-x}$ grain-boundary junctions

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We have fabricated [100]-tilt $YBa_2Cu_3O_{7-x}$ grain-boundary junctions with high characteristic voltages I_cR_n and studied their low-frequency voltage noise. The intensities of normalized resistance and critical current fluctuations have been found to be equal in these junctions and a complete antiphase correlation between these two fluctuations has been demonstrated. These results show that quasiparticles and Cooper pairs in the [100]-tilt junctions tunnel directly through the same parts of the barrier. The band-bending model with charge fluctuations at the structural interface is indicated to be adequate for understanding current transport and voltage noise in high-T_c grain-boundary junctions. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2193307]

In recent years, much efforts has been applied to understand the mechanisms of electrical transport and noise in grain boundaries (GBs) in high-temperature superconductors.[1] Even low-angle GBs limit the critical current density of polycrystalline high-T_c samples, and large-angle high-T_c GBs behave like Josephson junctions. Many mechanisms, like a predominant *d*-wave symmetry of the order parameter in high-T_c grains, structural disorder, oxygen deficiency and localized states in a GB barrier, as well as space charge layers and band bending at the interface between the boundary and the high-T_c grains, have been suggested to account for electronic transport properties of GBs.[1,2] High-T_c GBs demonstrated intensive $1/f$ voltage noise, which decreased after annealing in oxygen[3] and was ascribed to trapping and detrapping of charge carriers in the insulating barrier.[3,4]

The main experimental results have been obtained for artificial [001]-tilt high-T_c GB bicrystal junctions, fabricated by epitaxial growth of the *c*-axis high-T_c thin films on bicrystal substrates. Due to island growth, a real GB in the *c*-axis film meanders around the substrate bicrystal boundary in a scale of a film thickness and consists of facets of various local misorientations.[5] These circumstances result in inhomogeneous current distributions,[6] large parameter spread[7] and low values of the characteristic voltages I_cR_n[1,2] of the [001]-tilt high-T_c junctions and might be considered as main obstacles in an understanding of the current transport in these junctions.

Recently, [100]-tilt high-T_c GB junctions with mutually tilted *c* axis's have been fabricated and demonstrated an order of magnitude less meandering, better current homogeneity and a threefold increase of the I_cR_n values, when compared with those of conventional [001]-tilt junctions.[8,9] Due to geometry reasons, the *d*-wave symmetry of the order parameter should have the diminishing effect on the electrical properties of these [100]-tilted junctions. In an attempt to clarify further the mechanisms of current transport in high-T_c junctions, we have studied the low-frequency noise in the [100]-tilt high-T_c junctions.

The low-frequency voltage noise δV in high-T_c junctions is associated with fluctuations of the critical current I_c and the normal-state resistance R_n of the junction and may be written as $\delta V = \delta I_c(\partial V/\partial I_c) + \delta R_n(\partial V/\partial R_n)$, where δI_c and δR_n represent fluctuations in I_c and R_n, respectively.[3] The critical current and resistance fluctuations might be correlated[10] and a standard formalism for the calculation of the spectral density of the sum of two random processes δI_c and δR_n can be applied.[11] Using the current-voltage characteristic $V(I) = R_n(I^2 - I_c^2)^{1/2}$ in the resistively shunted junction (RSJ) mode at dc currents $I \geqslant I_c$,[12] the spectral power density $S_V(f)$ of the low-frequency voltage noise has been found as

$$S_V(f,I) = [I_c^2 R_d(I)/I]^2 S_i(f) + V^2 S_r(f) - 2k(f) V_c^2 [S_r(f) S_i(f)]^{1/2}, \tag{1}$$

where $R_d(I) = \partial V/\partial I$ is the differential resistance, $S_r(f) = S_R(f)/R_n^2$ and $S_i(f) = S_I(f)/I_c^2$ are normalized spectral densities of fluctuations δR_n and δI_c, respectively, $k(f) = |\gamma_{ri}(f)| \mathrm{Cos}\, \theta_{ri}(f)$ is a correlation coefficient, γ_{ri} is the magnitude of the coherence function, θ_{ri} is the phase angle of the cross-spectral density $S_{ir}(f)$, $\gamma_{ri}^2(f) = |S_{ir}(f)|^2 / S_i(f) S_r(f)$.[11] Equation (1) is not valid at low voltages, where thermal rounding of the *I-V* curve is large.[10] The correlation coefficient *k*, introduced here, takes the values +1 and −1 for completely in phase and antiphase correlated fluctuations, respectively. In the case of equal spectral densities $S_r = S_i = S$, Eq. (1) gives a minimum value of $S_V = 2V_c^2(1-k)S$ at the voltage $V = I_cR_n$.

The [100]-tilt $YBa_2Cu_3O_{7-x}$ GB junctions with characteristic voltages I_cR_n up to 8 mV have been fabricated on $NdGaO_3$ bicrystal substrates.[13] The $2\times14°$ [100]-tilt junctions with moderate values of critical current density j_c were chosen for this study in order to get such values of the Josephson penetration length $\lambda_j \propto j_c^{-1/2}$, that the junction width *w* did not exceed $4\lambda_j$ in an extended temperature range. The junctions were patterned with widths in the range of 1–2 μm from 60-nm-thick $YBa_2Cu_3O_{7-x}$ films. Each junction was annealed in an ozone-oxygen mixture at a temperature of 140 °C in the presence of UV radiation. The annealing resulted in a twofold decrease in the normal-state resistance R_n and a corresponding twofold increase of the critical current I_c, independently on the junction widths. The characteristic voltage I_cR_n of the junctions only increased for a few percent after annealing. Maximum reduction of spectral densities $S_V(f)$ after annealing was from around three

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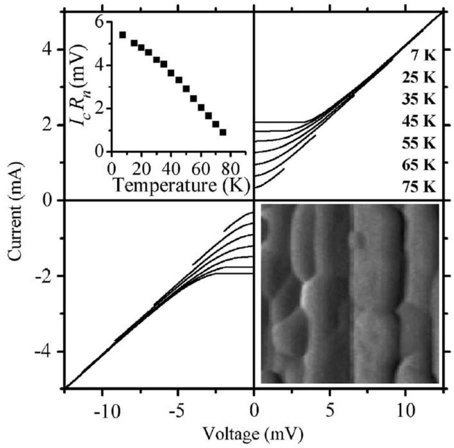

FIG. 1. Current-voltage characteristics of a 1-μm-wide $2\times14°$ [100]-tilt $YBa_2Cu_3O_{7-x}$ grain-boundary junction at temperatures from 7 to 75 K. Inset (left): characteristic voltage I_cR_n vs temperature. Inset (right): $1.5\times1.5\ \mu m^2$ atomic force microscopy image of unpatterned [100]-tilt $YBa_2Cu_3O_{7-x}$ grain boundary.

times at voltages $V \geq I_cR_n$ to up to seven times at low voltages.

The junctions were placed on a variable-temperature stage of a liquid-helium cryostat. The $I(V)$ curves and spectra $S_V(f)$ of voltage noise were measured with current bias using a four-probe technique. A liquid-nitrogen-cooled preamplifier with an input noise of $2.3\cdot10^{-10}\ V/Hz^{1/2}$ and a signal bandwidth of 150 kHz has been developed for the noise measurements. $S_V(f)$ spectra were measured by a SR780 signal analyzer in the frequency range of 100 Hz–25.6 kHz. The cryostat was placed in an Al-shielding box with two cascades of feedthrough filters and the junctions placed inside the cryostat were surrounded by cryoperm and copper shields.

The *I-V* characteristics of a $2\times14°$ [100]-tilt $YBa_2Cu_3O_{7-x}$ GB junction are shown in Fig. 1 at various temperatures from 7 to 75 K. The *I-V* curves demonstrate a good agreement with the RSJ model in the temperature range of 45–75 K. At lower temperatures of 7–25 K, the *I-V* curves go below the corresponding RSJ-like *I-V* curves with the same values of R_n and I_c. As can be seen from the left inset in Fig. 1, the I_cR_n values increase linearly with the temperature decrease in the range of 75–35 K and at lower temperature the curve slope becomes smaller. The right inset in Fig. 1 shows an atomic force microscope image of the [100]-tilt $YBa_2Cu_3O_{7-x}$ GB before patterning. Our estimate for the meandering of the $YBa_2Cu_3O_{7-x}$ GB in this junction is in the limit of ±20 nm, which is around one order of magnitude less than in [001]-tilt GB junctions fabricated by the same technique. Due to a more simple GB geometry, we should expect a better homogeneity of current flow in these junctions. The λ_j values were estimated to be 0.15 μm for 7 K and 0.4 μm for 77 K. Therefore, the junction width w of 1 μm might be less than $4\lambda_j$ at liquid-nitrogen temperatures. At temperatures below 40 K, where $w \geq 4\lambda_j$, a Josephson vortex can enter junction at $I > I_c$, thus resulting in a nonuniform spatial distribution of the superconducting current in the junction.[12]

Typical spectra $S_V(f)$ of voltage noise, measured at the dc voltages $V=I_cR_n(T)$ and temperatures from 7 to 75 K for 1-μm-wide junction, are presented in Fig. 2. The measured spectra were of $1/f^{\alpha}$ type with $\alpha=0.7-1.0$. Alternatively, the spectra might be fit to a superposition of $1/f$ background and Lorentzian components.[14] Spectra measured at 75 and 7 K were closer to a $1/f$ dependence than spectra at other temperatures. With a temperature decrease from 75 to 45 K and a corresponding increase of the I_cR_n values, the $S_V(f)$ values, measured at $V=I_cR_n$, scale proportional to $(I_cR_n)^2$.

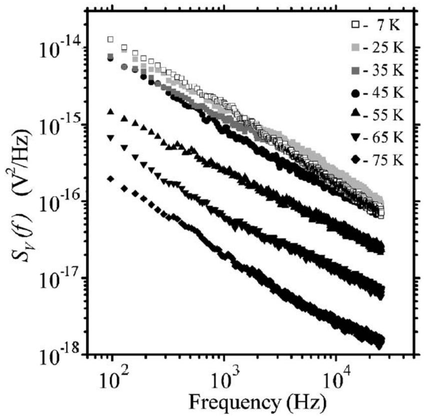

FIG. 2. Voltage noise as a function of frequency for 1-μm-wide [100]-tilt $YBa_2Cu_3O_{7-x}$ grain-boundary junction at temperatures from 7 to 75 K. Junction voltages V were set equal to the characteristic voltages I_cR_n for each temperature.

To get a quantitative comparison of experimental data with Eq. (1) with good accuracy, we took only data at temperatures above 45 K, where our [100]-tilt junctions were shown to be close to the RSJ model and superconducting currents are less probable to have nonuniform spatial distribution due to Josephson vortex formation. The $S_V(f)$ values at the frequency f of 3.2 kHz as a function of the square of dc voltage V are presented in Fig. 3 for three temperatures. All curves S_V vs V^2 show the same functional behavior, when S_V goes down to a minimum value at the voltages V close to the $I_cR_n(T)$ at this temperature, and then goes up as V^2. The $S_V(V^2)$ data in Fig. 3 do not coincide and go parallel at high voltages $V > I_cR_n$. The last observation is in contrast to bias dependencies of S_V for conventional [001]-tilt junctions at various temperatures,[3,15] which practically coincide at high biases. This behavior of $S_V(V^2)$ at $V > I_cR_n$ for [100]-tilt junctions might be explained, if resistance and critical current fluctuations are correlated.

Using the nonlinear curve fitting procedure[16] and Eq. (1), we were able to retrieve the set of parameters S_r, S_i, and k from the experimental data $S_V(V)$, $R_d(V)$, and $I(V)$. We reduced the voltage range of $S_V(V)$, taking off data at low

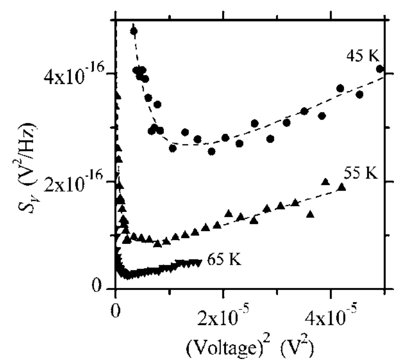

FIG. 3. Voltage noise S_V at a frequency of 3.2 kHz vs square of the dc voltage V for [100]-tilt $YBa_2Cu_3O_{7-x}$ grain-boundary junction at temperatures ranging from 45 to 65 K. Dashed lines are the fitting curves according to Eq. (1).

TABLE I. Summary of noise data for $2\times14°$ [100]-tilt $YBa_2Cu_3O_{7-x}$ bicrystal junctions at temperature $T=55$ K.

Sample	R_n (Ω)	I_cR_n (mV)	S_i(3.2 kHz) $\times10^{-12}$(Hz^{-1})	S_r(3.2 kHz) $\times10^{-12}$(Hz^{-1})	$p=(S_i/S_r)^{1/2}$	k
524_1	2.3	2.5	3.7±0.2	3.4±0.2	1.05±0.1	−1.1±0.15
325_1	3.3	1.9	3.4±0.1	3.5±0.2	1.0±0.1	−1.0±0.1
525_2	5.7	1.9	12±1	10±0.6	1.1±0.1	−1.15±0.15

voltages, where Eq. (1) is not valid, to get minimum deviations of the fitting curve from the experimental data. The best fitting curves are shown in Fig. 3 by dashed lines. The parameters S_i, S_r, and k in the fitting curves varied from $(6.1\pm0.4)\cdot10^{-12}$ Hz^{-1}, $(4.3\pm0.4)\cdot10^{-12}$ Hz^{-1}, (-1.1 ± 0.2) at 45 K to $(2.4\pm0.1)\cdot10^{-12}$ Hz^{-1}, $(2.4\pm0.1)\cdot10^{-12}$ Hz^{-1}, (-1.0 ± 0.1) at 65 K, correspondingly.

A similar fitting procedure was taken for several [100]-tilt junctions with various resistances. The resulting set of parameters S_r, S_i and k is shown in Table I for three [100]-tilt GB junctions at 55 K. The values of ratio $p=(S_i/S_r)^{1/2}$ within an accuracy of 10% were found to be equal to 1 for our [100]-tilt junctions. This value is in a disagreement with corresponding p values found for conventional [001]-tilt high-T_c junctions, ranging from 2 to 3.8.[3,4,15,17] The values of the correlation coefficient k were found to be equal to −1 with an accuracy of 15% for [100]-tilt $YBa_2Cu_3O_{7-x}$ GB junctions. Limited data on correlation between resistance and critical current fluctuations in conventional [001]-tilt high-T_c GB junctions are available.[15,17] If we use our definition of the correlation coefficient, a k value of 0.25 has been reached for [001]-tilt $YBa_2Cu_3O_{7-x}$ GB junctions[17] and $k\cong0.5$ has been reported for [001]-tilt $Bi_2Sr_2CaCu_2O_{8+x}$ GB junctions.[15] Thus, our data, for the first time, confirm a complete antiphase correlation of resistance and critical current fluctuations in high-T_c GB junctions. Complete antiphase correlation ($k=-1$) and $S_i/S_r=1$ are expected for uniform flow of currents through a tunnel junction,[10] or, at least, both quasiparticles and Cooper pairs should tunnel directly through the same part of the tunnel barrier.

Among various types of mechanisms suggested to explain the properties of high-T_c grain boundaries,[1,2] only few were developed to a degree, which allows a comparison with experimental transport and noise data.[4,10,18] A channel model describes an inhomogeneous grain boundary as a large number of conducting parallel channels, only one of which supports a supercurrent.[10] The ratio p in this model is much larger than one[10] and the fluctuations of I_c and R_n are expected to be uncorrelated with $k\approx0$. Our data with $p=1$ and $k=1$ are not consistent with this model.

The electrical transport and low-frequency noise characteristics of studied [100]-tilt junctions also contradict with the results of the intrinsically shunted junction (ISJ) model.[4] In the frame of the ISJ model, a dielectric barrier contains a high density of localized states and the quasiparticle current is dominated by resonant tunneling via these localized states. The Cooper pairs tunnel directly through the barrier. Trapping and release of charge carriers results in fluctuations of the barrier height. According to this model, the p values should be larger than two and it is in a contradiction with the experimental values of $p=1$ for the [100]-tilt junctions. Furthermore, the [100]-tilt junctions show no scaling of the I_cR_n values with critical current density j_c after oxygen annealing, which is also in a contradiction with the results of the ISJ model, where $I_cR_n\propto j_c^{1/2}$.

Our experimental data are more consistent with a model, where both quasiparticles and Cooper pairs tunnel through the same barrier, formed by band bending at the superconductor-boundary interface.[18] Recently, it was shown, that the barrier heights in the $YBa_2Cu_3O_{7-x}$ GBs are much lower than appropriate values for intrinsic insulators, and a band bending is a plausible mechanism for current suppression at GBs.[19] The GB is considered as consisting of three layers: the structurally distorted interface in the middle and two adjacent charge-depleted layers of undistorted material.[19] To include low-frequency voltage noise into this band-bending model, the fluctuations of trapped charge at the structural interface should be considered like in semiconductor GBs.[20]

In summary, we have studied the noise properties of [100]-tilt $YBa_2Cu_3O_{7-x}$ GB junctions with high characteristic voltages I_cR_n. The intensities of resistance and critical current low-frequency fluctuations have been found to be equal in these junctions and a complete antiphase correlation between these two fluctuations has been demonstrated. These circumstances allow us to conclude that quasiparticles and Cooper pairs tunnel directly through the same parts of the barrier in [100]-tilt junctions. Among various GB models, the bend-bending model with charge fluctuations at the structurally distorted interface might be a more adequate instrument for understanding of current transport and voltage noise in high-quality high-T_c GB junctions.

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