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$1/f$ noise in $Bi_2Sr_2CaCu_2O_{8+x}$ bicrystal grain-boundary Josephson junctions

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We have measured the low-frequency $1/f$ voltage noise of $Bi_2Sr_2CaCu_2O_{8+x}$ bicrystal grain-boundary Josephson junctions (GBJ's). The origin of the $1/f$ noise are fluctuations δI_c and δR_n of their critical current and normal resistance, respectively. The ratio p of the normalized fluctuations $|\delta I_c/I_c|/|\delta R_n/R_n|$ is found to be $p=1.9\pm0.25$ independent of temperature. The analysis of the noise data indicates that the critical current and resistance fluctuations are correlated. The measured noise properties can be consistently explained by the intrinsically shunted junction model based on an insulating layer at the grain boundary containing a high density of localized defect states.

There has been tremendous effort in understanding the nature of charge transport across grain boundaries in high-temperature superconductors (HTS's).[1] The electrical transport and noise properties of grain boundaries in $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin films have been studied intensively using artificially generated grain-boundary Josephson junctions (GBJ's) fabricated on bicrystalline substrates.[2] The critical current density J_c of YBCO GBJ's was found to decrease exponentially with increasing misorientation angle.[3] In contrast to Josephson junctions fabricated from low-T_c superconductors, for which the product of critical current density J_c and normal resistance times area ρ_n usually is independent of J_c and approximately equal to the gap voltage, it was found that $J_c\rho_n \propto (J_c)^q$ with $q \sim 0.5-0.6$ for YBCO GBJ's.[4,5] Recently, the study of low-frequency excess noise,[6] oxygen migration,[7] the magnetic-field dependence of the critical current,[8,9] and high-frequency electromagnetic properties[10] provided additional information on the charge transport in YBCO GBJ's. However, to our knowledge there is no conclusive evidence concerning the nature of the grain-boundary interface. In particular, it is still unclear whether the Josephson current is restricted to narrow superconducting filaments in a weakly conducting medium[7,8] or whether it has to pass through a dielectric barrier of finite thickness containing a high density of localized defect states.[1,3] Furthermore, it is not known whether grain boundaries in the other cuprate superconductors behave similarly to those in YBCO.

In this paper we report on the investigation of the low-frequency $1/f$ voltage noise of individual [001] tilt GBJ's in c-axis-oriented $Bi_2Sr_2CaCu_2O_{8+x}$ (BSCCO) thin films and compare our results to those obtained for YBCO GBJ's. The superconducting properties of both YBCO and BSCCO are determined by their CuO_2 double layers, which are rotated with respect to their in-plane orientation on both sides of [001] tilt grain boundaries. Therefore, comparing the $1/f$ noise behavior of BSCCO and YBCO GBJ's yields valuable information on the general nature of grain boundaries in the HTS's and thus may help to narrow down the possible mechanisms responsible for their weak-link behavior. In particular, the question whether the noise properties of HTS GBJ's are intrinsic properties, i.e., independent of the HTS material, can be clarified. We also note that in many applications such as superconducting quantum interference devices (SQUID's) the substantial amount of low-frequency $1/f$ noise in GBJ's and other types of HTS Josephson junctions is perturbing. To overcome the limitations due to the $1/f$ noise it is crucial to arrive at a detailed understanding of this low-frequency noise contribution.

There have been several studies of $1/f$ noise in YBCO GBJ's.[6,11–15] Kawasaki *et al.*[6] explained the $1/f$ noise in bicrystal GBJ's in terms of correlated fluctuations of the junction critical current and normal-state resistance. In analogy to the explanation of $1/f$ noise in conventional low-temperature tunnel junctions,[16] these fluctuations were attributed to the trapping and detrapping of charge carriers into localized states within an insulating barrier layer at the grain boundary and an adequate distribution of trapping times. The presence of an insulating barrier layer containing a high density of localized defect states originally was proposed to explain the $J_c\rho_n \propto (J_c)^q$ scaling observed for YBCO GBJ's.[3,1] Whereas the transport and noise properties of YBCO bicrystal GBJ's can be well explained by transport through an insulating grain-boundary layer,[1] Miklich *et al.*[12] suggested that the observed transport and noise properties of biepitaxial GBJ's are related to the fact that the total supercurrent across the grain boundary is carried only by a small number of filamentary paths. In order to further clarify these differences and the question whether grain boundaries behave similarly in the different cuprate superconductors, investigations of the low-frequency excess noise of GBJ's fabricated from BSCCO are of significant interest.

The GBJ's were fabricated by laser deposition of c-

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axis-oriented $Bi_2Sr_2CaCu_2O_{8+x}$ films on 24° [001] tilt $SrTiO_3$ bicrystals. Details of the deposition and patterning process have been reported elsewhere.[17] The films had a zero-resistance temperature well above 87 K. The critical current density of the GBJ's typically was $J_c \simeq 5\times10^5$ A/cm^2 at 4.2 K and $\simeq 2\times10^4$ A/cm^2 at 77 K. The data presented below were obtained with a 5-μm-wide GBJ patterned into 320-nm-thick BSCCO film. The current-voltage characteristic (IVC) and its derivative are shown in Fig. 1 for $T=60$ K. The inset shows the resistive transition of the junction. Both the IVC and the resistive transition, which shows the well-known foot structure caused by thermally activated phase slippage (TAPS),[18] are in perfect agreement with the resistively shunted junction (RSJ) model. The normal resistance $R_n \simeq 1.0\ \Omega$ of the junction was found to be independent of temperature.

The voltage noise of the GBJ was measured using a standard four-probe technique. The voltage across the current biased junction was preamplified using a low-T_c dc SQUID operated in the flux locked loop as a voltage amplifier and frequency analyzed using a HP3563A dynamic signal analyzer. A high sensitivity of 60 pV/$\sqrt{\mathrm{Hz}}$ down to 1 Hz was achieved. The sample temperature could be varied from about 10 to 150 K and precisely stabilized using an optical temperature control system. In order to reduce ambient magnetic fields the sample was shielded by a cryoperm shield. Furthermore, the cryostat and SQUID preamplifier were positioned inside an electromagnetically shielded room.

The measured voltage noise spectral density showed an unstructured $1/f^\alpha$ frequency dependence with $\alpha=1$ in the investigated frequency range (1 Hz–10 kHz) independent of bias current ($I_b > I_c$) and temperature ($T < T_c$).

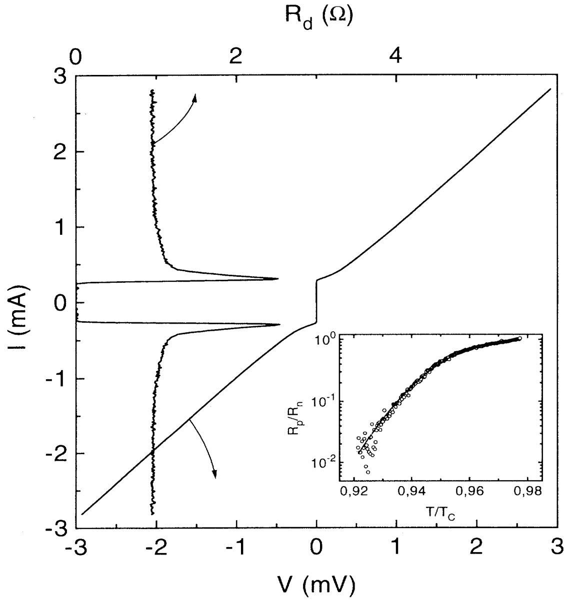

FIG. 1. Current-voltage characteristic and dynamic resistance versus bias current of a 24° [001] tilt $Bi_2Sr_2CaCu_2O_{8+x}$ GBJ at $T=60$ K. The inset shows the resistance versus temperature curve near the transition including a least-squares fit to the TAPS model (solid line) (Ref. 4).

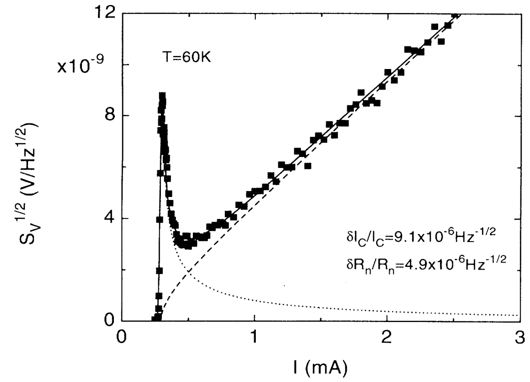

FIG. 2. Voltage noise $S_V^{1/2}$ at $f=63$ Hz vs bias current I_b. Data are obtained by averaging 20 power spectra and subtracting the amplifier noise level for every value of I_b. The solid line represents a least-squares fit based on the RSJ model assuming both critical current and resistance fluctuations. The dotted (dashed) line is calculated taking into account only critical-current (resistance) fluctuations.

Furthermore, time traces of the junction voltage did not show any random telegraph signals within the investigated range of temperature and bias current. Figure 2 shows the voltage noise $S_V^{1/2}$ at constant frequency ($f=63$ Hz) as a function of bias current for $T=60$ K. As shown in Fig. 3 we observed the $S_V(I_b)$ curves to behave similarly for all measurements taken at various temperatures. S_V first increases rapidly with increasing I_b and shows a sharp peak for $I_b \simeq I_c$. Then, after passing through a minimum S_V increases quadratically with increasing bias current. This behavior is very similar to that observed for YBCO GBJ's (Refs. 6 and 12) and seems to be universal for GBJ's fabricated from different HTS materials.

The measured low-frequency noise can be ascribed to the presence of fluctuations of both the critical current and normal resistance of the junction. In order to analyze the measured noise data quantitatively we extended the small signal analysis of Refs. 6 and 12 allowing for correlations between critical current and resistance fluctuations. Our analysis is based on the RSJ model, which perfectly fits the IVC's and the resistive transition of the

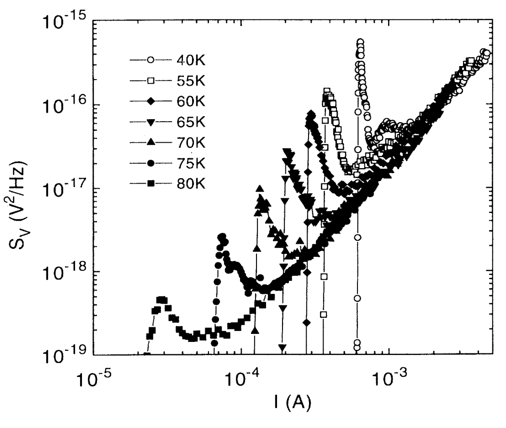

FIG. 3. Voltage noise spectral density S_V at $f=63$ Hz vs bias current at different temperatures.

BSCCO GBJ's. According to the RSJ model we have $V=R_n\sqrt{I_b^2-I_c^2}$ for $I_b \geq I_c$ and the voltage fluctuations can be expressed as $\delta V=(\partial V/\partial I_c)\delta I_c+(\partial V/\partial R_n)\delta R_n$, where δI_c and δR_n are fluctuations in I_c and R_n, respectively. In general, both δI_c and δR_n are fluctuations in I_c and R_n, respectively. In general, both δI_c and δR_n have to be regarded as complex numbers with a time-dependent phase thus incorporating a variable amount of correlation between δI_c and δR_n. The voltage-noise spectral density then is obtained to

$$S_V(f)=(V-R_dI)^2S_I(f)+V^2S_R(f)$$
$$+k(V-R_dI)VS_{IR}(f)\ . \qquad (1)$$

Here, $R_d=\partial V/\partial I$ is the differential resistance, $S_I=|\delta I_c/I_c|^2$, $S_R=|\delta R_n/R_n|^2$, $S_{IR}=|\delta I_c/I_c||\delta R_n/R_n|$ is the cross-spectral density of the fluctuations, and $k=2\langle\cos(\Delta\phi(t))\rangle$ is two times the time average of the cosine of the phase difference of the δI_c and δR_n fluctuations. For uncorrelated δI_c and δR_n fluctuations we have $k=0$, whereas we have $k=2$ and $k=-2$ for fully in-phase and antiphase correlated fluctuations, respectively. Equation (1) shows that S_V is dominated by fluctuations of the critical current and normal resistance for $I_b \simeq I_c$ and $I_b \gg I_c$, respectively. Fitting the experimental data to Eq. (1) we used the RSJ model IVC's including thermal noise rounding. The normalized fluctuations $|\delta I_c/I_c|$ and $|\delta R_n/R_n|$ and k were used as fitting parameters. The result of such a fit is shown in Fig. 2 (solid line). The fit yielded $|\delta I_c/I_c|=9.1\times10^{-6}$ Hz$^{-1/2}$, $|\delta R_n/R_n|=4.9\times10^{-6}$ Hz$^{-1/2}$, and $k\simeq-0.98$.

As shown in Fig. 3 for $I_b \gg I_c$ the noise data measured at different temperatures show a common asymptotic behavior. Since $S_V\simeq V^2|\delta R_n/R_n|^2$ for $I_b \gg I_c$ we can conclude that $|\delta R_n/R_n|$ is temperature independent. For $I_b\simeq I_c$ the voltage noise power can be approximated by $S_V\simeq R_d^2I_c^2|\delta I_c/I_c|^2$. Evaluating the $R_d(I_b)$ curves measured at different temperatures we obtain $R_d^{\max}\propto I_c^{0.35}$ for the maximum value of the dynamic resistance. Therefore, decreasing the temperature the peak of $S_V(I_c)$ at $I_b\simeq I_c(T)$ is expected to grow as $S_V^{\max}(I_c)\propto I_c^{2.7}|\delta I_c/I_c|^2$. Figure 4 shows the measured values of $S^{\max}(I_c)$. The linear fit to the data gives $S_V(I_c)\propto I_c^{2.56}$ close to the power of 2.7. That is, the normalized fluctuations of the critical current are approximately constant within the investigated temperature regime. The magnitude of $|\delta I_c/I_c|$ and $|\delta R_n/R_n|$ obtained at different temperatures by least-squares fits of the measured data is plotted versus temperature in Fig. 5. The ratios $|\delta I_c/I_c|\simeq9.5\times10^{-6}$ Hz$^{-1/2}$, $|\delta R_n/R_n|\simeq5\times10^{-6}$ Hz$^{-1/2}$, and $p=|\delta I_c/I_c|/|\delta R_n/R_n|=1.9\pm0.25$ are almost independent of temperature. These values are very close to those measured for YBCO GBJ's [$|\delta I_c/I_c|\simeq1.0\times10^{-5}$ Hz$^{-1/2}$, $|\delta R_n/R_n|\simeq4\times10^{-6}$ Hz$^{-1/2}$, $p\simeq2.5$ (Ref. 6)]. Although the spread is considerable for k we obtain $-1>k>-2$ suggesting that the δI_c and δR_n fluctuations in BSCCO GBJ's to a considerable amount are antiphase correlated.

Our experimental data demonstrate that the noise properties of BSCCO GBJ's are almost identical to those of YBCO GBJ's.[6] Furthermore, for both BSCCO and YBCO GBJ's the noise properties agree well with the observed scaling behavior of their I_cR_n products. For YBCO GBJ's the I_cR_n product was found to scale as $J_c\rho_n=I_cR_n\propto(J_c)^q$ with $0.5\leq q\leq0.6$.[1,4,5] According to this scaling relation one expects for the ratio of fluctuations $p=1/(1-q)$ and, hence, $2.0\leq p\leq2.5$ in agreement with the experimentally measured value of $p\simeq2.5$.[6] Our measurements on BSCCO GBJ's (Ref. 19) indicate a scaling relation $I_cR_n\propto(J_c)^{0.5}$ implying $p\simeq2.0$. This value perfectly agrees with that derived from our noise measurements. That is, the fluctuations δI_c and δR_n show the same scaling relation as the I_cR_n product. From this we can conclude that the microscopic origin of the low-frequency excess noise is the same as that for the scaling relation of the I_cR_n product. Furthermore, the close similarity of BSCCO and YBCO GBJ's gives strong evidence that the nature of the weak-link behavior of grain boundaries is independent of the HTS material. This may originate from the similar in-plane misorientation of the CuO$_2$ double-layer sheets present in both materials.

Our experimental findings namely the temperature-independent values of $|\delta I_c/I_c|$ and $|\delta R_n/R_n|$, the equivalent scaling of the fluctuations δI_c and δR_n and the I_cR_n product, as well as the antiphase correlation of critical current and resistance fluctuations support the following mechanisms responsible for the weak-link nature of

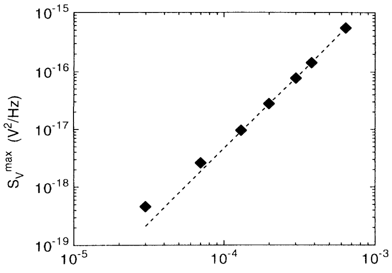

FIG. 4. Peak value $S_V^{\max}$ of the $S_V(I_b)$ dependencies at $I_b\simeq I_c$ for different temperatures at $f=63$ Hz vs the critical current. The dashed line represents a linear fit to the data.

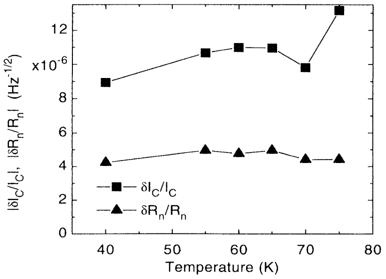

FIG. 5. Normalized fluctuations of the critical current and normal resistance vs temperature. The data are obtained by least-squares fit of the measured noise data to Eq. (1).

grain boundaries in the cuprate superconductors. Due to the layered structure of the cuprates with their narrow, quasi-two-dimensional conduction bands and small density of states, the cuprates are close to the metal-insulator transition.[20] Therefore strain, disorder, and oxygen deficiency are expected to render the HTS material insulating at the grain-boundary interface in agreement with high-frequency electromagnetic properties of GBJ's.[10] In order to explain our measurements consistently we adopt a superconductor-insulator-superconductor-type model, where the insulator is assumed to contain a high density of localized defect states. In addition to direct tunneling the localized states allow for a resonant tunneling channel. Resonant tunneling of Cooper pairs is strongly suppressed by Coulomb repulsion, that is, the pair current is transferred by direct tunneling. On the other hand, at a high density of localized states the normal current is dominated by resonant tunneling. That is, the localized states result in a large normal leakage current.[1,3,20] Following these arguments the GBJ can be viewed as an intrinsically shunted junction (ISJ), where the resistive shunt is provided by the resonant tunneling channel. The ISJ model naturally explains the small value and the scaling the I_cR_n product.[1] Trapping and release of charge carriers in the localized states results in fluctuations of the barrier height and, hence, of both the critical current and normal resistance. Here, an increase of the barrier height causes a decrease of the critical current and an increase of the normal resistance and vice versa. That is, δI_c and δR_n fluctuations are expected to be antiphase correlated. Moreover, the fluctuations should show a scaling behavior equivalent to that of the I_cR_n product, since they are related to the same physical origin. It has been shown elsewhere[1,3] that in the simplest case we have $I_cR_n \propto (J_c)^{1/2}$ and, accordingly, $(\delta I_c/I_c)/(\delta R_n/R_n) = -2$.[1,3] These predictions of the ISJ model are in very good agreement with our experimental observations.

We note that our results disagree with recent noise measurement on biepitaxial, 45° [001] tilt GBJ's.[12,14] For these junctions the normalized critical current fluctuations are much larger resulting in $p \simeq 5-50$ as compared to $p \simeq 2$ for bicrystal GBJ's. Miklich *et al.* proposed a model in which the junction consists of N parallel channels, where each channel has the same resistance but only one is carrying a supercurrent. With a suitable value for N this model well explains the large value of p. Furthermore, since the different channels are independent no correlation between δI_c and δR_n fluctuations is expected. This lack of correlation has been found experimentally.[14] The much larger normalized critical current fluctuations in biepitaxial GBJ's may be caused by the worse spatial homogeneity of the critical current density in this junction type as compared to bicrystal GBJ's.[21] It has been shown recently[13] that GBJ's with strongly inhomogeneous J_c can be viewed as multijunction arrays in which large δI_c fluctuations are caused by the switching between different quantum states of the multijunction structure. That is, the large value and considerable sample to sample variation of the δI_c fluctuations in biepitaxial junctions may be caused by the poor homogeneity of their critical current density. In general, the different noise behavior of biepitaxial and bicrystal GBJ's still needs further clarification.

In summary, we have shown that the noise properties of BSCCO GBJ's are very similar to those of YBCO GBJ's suggesting that the weak-link nature of the grain boundary is independent of the HTS material. The low-frequency noise in BSCCO GBJ's is caused by δI_c and δR_n fluctuations which seem to be antiphase correlated. The measured noise and scaling properties can be well explained by assuming an insulating layer at the grain boundary with a high density of defect states. Our experiments show that the density of localized states at the grain-boundary interface has to be reduced in order to obtain GBJ's with a high I_cR_n product and a low amount of $1/f$ noise.

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