Intrinsic high-T_c Josephson junctions in random-telegraph-noise fluctuators

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Bias current and magnetic field strongly influence the switching rates of random-telegraph signals by stressing the two-level fluctuator energy structure. Symmetric-telegraph noise is observed when the stress due to current flow is compensated by the magnetic-field-induced stress. The dependence of the measured symmetrizing magnetic field on current flow enables one to infer the symmetry characteristics of a fluctuator. The symmetry characteristics in granular films were found to be strongly nonlinear. It has been shown that current flow across the intrinsic Josephson inductance is responsible for the observed nonlinearity. A fit of the experimental data to the proposed model has revealed that a Josephson element enclosed in a superconducting loop is likely involved in the random-telegraph voltage noise generation. The evaluated area of the loop is consistent with the free space between average grains in the sample investigated.

The fluctuating component of a voltage drop across dc current biased high-T_c superconducting (HTSC) thin films frequently takes the form of a random-telegraph signal (RTS).[1–3] In the presence of RTS fluctuations the voltage randomly jumps between two fixed levels, referred to as ''up'' and ''down'' levels, while the times during which it remains at each of the two levels are exponentially distributed. Generation of RTS noise can generally be traced to an action of a two-level fluctuator (TLF) consisting of two energy wells separated by a barrier. RTS signals in high-T_c superconducting films were found to originate from thermally activated random flux jumps.[3] Spontaneous RTS flux noise, for a recent review see Ref. 4, may be converted into observable voltages by means of an intrinsic flux to voltage conversion mechanism.[5] The generation of low-frequency random telegraph voltage noise in HTSC thus constitutes an indirect process involving two distinct mechanisms. The fluctuator mechanism is responsible for the kinetics of random movements of flux between two level fluctuator potential wells, while the detector action couples these fluctuations to the observable voltages.

Insight into the detector action can be obtained through the analysis of histograms of RTS switching amplitudes. We have recently shown that such analysis leads to the conclusion that the detection mechanism in granular HTSC films is associated with the autodetection of flux changes by intrinsic Josephson quantum interferometers.[5] The search for the fluctuator mechanism may be based on a statistical analysis of RTS wave forms in time domain. For thermally activated switchings between TLF wells the logarithm of the average lifetime is directly proportional to the activation energy. Changes of average lifetimes with changing current flow, magnetic field, or temperature provide a direct information about the activation energy dependence on experimental parameters. In this paper we demonstrate that the RTS fluctuator in granular HTSC films also involves the action of intrinsic Josephson junctions.

In the experiments we have employed YBaCuO granular HTSC films fabricated in a two-stage process: dc magnetron deposition from a stoichiometric target, followed by annealing in flowing oxygen. Electron microscope investigations revealed that the films were composed of densely packed needlelike grains with an average size of $20 \times 2\ \mu\text{m}^2$. Thin film samples were patterned into 0.4 mm wide and 4 mm long strips equipped with broad contact pads on both ends. Separate voltage and current contacts were subsequently fabricated on the pads using vacuum deposited silver films. Typical resistive critical temperature onset of our strips was 91 K and the transition width 1–2 K. Critical current densities were of the order of 10^3 A/cm^2 at 4.2 K. Details of the deposition procedure and film characterization were published elsewhere.[6]

For the noise measurements samples were biased with a dc current slightly above the value at which a measurable dc voltage appears. Simultaneously, a weak external magnetic field could be applied perpendicular to the strip surface. At temperatures below the transition temperature we detected several random-telegraph-noise signals emerging from the background noise. The background noise typically had the form of $1/f$-like fluctuations.[7] Clear telegraph signals persisted only within limited ''noisy window'' ranges of current flow and associated applied magnetic field; see also Refs. 2,3. We selected the temperature of the experiment, as well as the values of applied magnetic field and current bias, in such a way that a single RTS not contaminated with other telegraph signal manifestations could be monitored within a chosen noisy window. The fact that telegraph voltages were detected exclusively at temperatures below the critical temperature of the sample indicates that observed signals are

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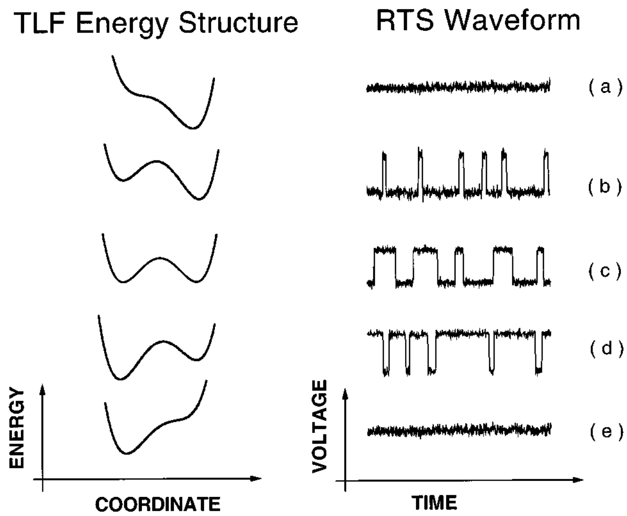

FIG. 1. Evolution of telegraph signal wave form with changing current and applied magnetic field. Bias current is increasing at a fixed magnetic field from (a) to (e) or, equivalently, magnetic field is increasing at a fixed current flow from (e) to (a). Left-hand side of the picture illustrates corresponding changes in two level fluctuator energy structure.

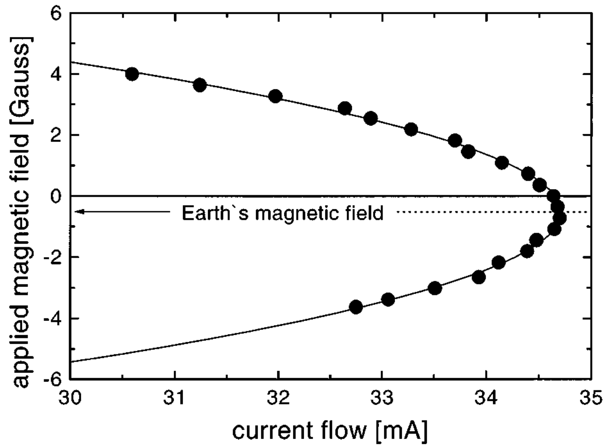

FIG. 2. Experimentally measured symmetry characteristic (full circles) for a TLF active in the granular YBaCuO thin film at 7.5 K. Solid line shows the best fit of the proposed Josephson model to the data. Note the vertical shift of the entire characteristic due to the presence of the Earth's magnetic field.

associated with superconducting properties of the film. Moreover, the fact that RTS appear only for current flow above the critical current of the strip entitles us to exclude the possibility that current carrying contacts may be the source of the observed signals.

Voltage signals were amplified by a low noise amplifier, acquired by room temperature processing electronics, and analyzed with a help of the desktop computer. The symmetry characteristic of an active TLF has been determined by finding the crossing points between the average up and down RTS lifetime dependencies on bias current at different fixed magnetic fields, or alternatively, on applied magnetic field at different fixed bias current flows. The average lifetimes in both RTS states were determined from decay rates of relevant Poissonian distributions of up and down lifetimes.

One of the most characteristic features of HTSC telegraph voltage noise is a strong influence of bias current and applied magnetic field on the shape of the RTS wave form.[3] In particular, when a noisy window is scanned by changing the bias current, or equivalently the magnetic field, the signal shape changes from an extremely asymmetric one on one edge of the noisy window, through a symmetric one, to an asymmetric signal of inverse polarity on the opposite edge of the noisy window. A typical example of the evolution of wave form shape with changing bias parameters is shown in the right-hand side of Fig. 1. Waveform changes can be attributed to the relevant changes in the TLF energy structure, as indicated schematically in Fig. 1. When the energy barrier heights seen from both TLF wells are equal, the average lifetime in the up level is the same as the average lifetime in the down level and the RTS is symmetric. Typically, this happens approximately in the center of a noisy window.[3] Any deviation of bias current and/or magnetic field from the values providing symmetric RTS signal, hereafter referred to as I_s and B_s, imposes a stress upon the TLF structure, shifting the bottoms of energy wells and making the telegraph signal asymmetric. When the stress becomes too strong the two-level structure ceases to exist and one gets out of the noisy window range, as is the case for the two outmost traces in Fig. 1. The ensemble of points $I_s(B_s)$ constitutes the symmetry characteristic of a TLF. All changes in an effective stress imposed on the TLF energy structure are directly reflected in the symmetry characteristics $B_s(I_s)$. We have employed this characteristic to obtain insight into the nature of processes involved in generation of RTS signals in YBaCuO granular thin films.

Experiments have demonstrated, as shown in Fig. 1, that transport current and applied magnetic field play competitive roles in stressing TLF energy structure. For any deviation of the current flow from I_s, provided that the noisy window limits have not been exceeded, one can tune the magnetic field to a value at which the stress imposed by the current will be compensated and RTS symmetry restored. Since the origin of the RTS signals can be traced back to hopping of flux vortices,[3] we attribute current and magnetic-field-imposed stresses on the TLF structure to the actions of Lorentz forces exercised by bias current and by screening currents due to the applied magnetic field, respectively. Magnetic field that compensates the stress imposed by current flow can be seen as a magnetic field that induces screening current whose Lorentz force, in the vicinity of a TLF, has the same value as the Lorentz force of the transport current but acts in the opposite direction. Equivalently, transport current that compensates stress imposed by applied magnetic field is a current whose self-field, in the vicinity of the TLF, has an equal value and the opposite direction with respect to the externally applied magnetic field.

Figure 2 shows a typical example of a symmetry characteristic determined for one of the TLF fluctuators that was detected in a granular YBaCuO sample. The symmetry characteristic is strongly nonlinear and not single valued. The nonlinearity in $B_s(I_s)$ can be formally attributed to the fact that the self-magnetic field is due to current flow in a nonlinear inductance. It is natural to think that in HTSC granular films, known to contain many intrinsic Josephson junctions, the nonlinear inductance may be identified with a Josephson inductance $L_J(I)$. The current I_s, as measured in the experiment, corresponds to the total current supplied from the external source to the sample. In a granular film the total current becomes divided between many paths inside the sample and only a fraction kI_s actually flows across the inductance involved in the fluctuator action. Therefore, the external magnetic field needed to compensate the self-field B_s of the current kI_s flowing in a nonlinear inductance L_J is

$$B_s(I_s)=\frac{L_J(kI_s)kI_s}{A}, \tag{1}$$

where A is the area of the investigated TLF in the plane perpendicular to the applied field. More precisely, A corresponds to the area containing currents capable of stressing the TLF energy structure.

Combining the well known Josephson equations, $V(t)=(\hbar/2e)(\partial\phi/\partial t)$, and $I(t)=I_c\sin\phi(t)$, one obtains

$$V(t)=\frac{\hbar}{2e}\,\frac{\partial \arcsin[I(t)/I_c]}{\partial t}. \tag{2}$$

On the other hand,

$$V(t)=-\frac{\partial}{\partial t}[L_J(I)I(t)]. \tag{3}$$

Equating (2) and (3), integrating both sides at current through the junction $I_B=kI_s$ and using (1) we get the symmetry characteristic in the form

$$B_s(I_s)=-\frac{\hbar}{2eA}\arcsin(kI_s/I_c)+\alpha, \tag{4}$$

where α is the integration constant. For the fluctuator depicted in Fig. 2 the integration constant α has to be nonzero. In fact, putting $\alpha=0$ in Eq. (4) imposes a fluctuator that is symmetric (unstressed) in the pristine state, $I_s(B_s=0)=0$. The experimental symmetry characteristic does not cross the origin, indicating clearly that the fluctuator is initially asymmetric. The value of the constant α can be easily calculated from the condition that Josephson inductance should cease to exist for current flow above the critical current I_c of the Josephson element in question, i.e., that $B(I_c)=0$. Taking this into account we finally obtain the following equation for the symmetry characteristic,

$$-B_s(I_s)=\frac{h}{8eA}\left[\frac{2}{\pi}\arcsin(kI_s/I_c)\pm n\right],$$

$$\text{where}\quad n=1,3,5,\ldots. \tag{5}$$

The solid line in Fig. 2 represents the best fit of Eq. (5) (setting $n=1$) to the experimentally measured characteristic. The fitting parameters are the Josephson critical current, normalized by k, and the fluctuator size. Note that since the data represented in Fig. 2 were taken while the external μ-metal screen had been temporally removed from the cryostat, the entire characteristic is shifted vertically by 0.51 G, the value corresponding to the Earth's magnetic field. The agreement between the proposed Josephson model and the experiment is excellent. The fluctuator area obtained from the fit is $A=0.36\pm0.01\ \mu\mathrm{m}^2$ while the junction critical current $I_c/k=34.7\pm0.03$ mA.

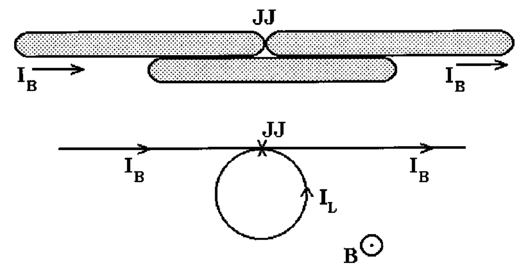

FIG. 3. Possible arrangement of three superconducting grains forming a loop with an intrinsic Josephson junction.

In order to ascribe a physical reality to the fluctuator model discussed above one should remember that a granular superconducting film constitutes a multiply connected superconductor. Screening currents due to a weak external magnetic field will flow along closed superconducting loops embracing the flux lines penetrating into nonsuperconducting spaces between the grains. As a rule such loops may contain Josephson junctions which are intrinsically formed between adjacent grains. The RTS will be symmetrical when the Lorentz force of the screening current is compensated by the action of bias current flowing through the Josephson element. Thus the symmetry characteristic described by Eq. (5) may be due to the action of a superconducting loop containing a Josephson junction with the phase controlled by the external bias current.

The simplest possible arrangement of three superconducting grains that will form a suitable loop is shown in Fig. 3. The current circulating in the loop so formed depends on both applied magnetic field B_{appl} and the phase of the Josephson junction, which is set by the bias current I_B. In fact, the fluxoid quantization equation for the intergrain loop of an inductance L and the area A reads

$$\Phi=B_{\mathrm{appl}}A+I_LL+\frac{\Phi_0}{2\pi}\arcsin\frac{I_B+I_L}{I_c}=m\Phi_0, \tag{6}$$

where $m=1,2,3,..,$ I_c is the critical current of the Josephson junction and I_L for the circulating current (see Fig. 3). If the fluctuator is stressed by the Lorentz force exerted by the circulating current I_L then we find straightforwardly that the $B_s(I_s)$ characteristic follows directly from the fluxoid equation as the condition for which the current circulating in the intergrain loop vanishes:

$$-B_s(I_s)=\frac{\Phi_0}{2\pi A}\arcsin\left(\frac{I_B}{I_c}\right)+m\Phi_0. \tag{7}$$

Writing the local bias current through the Josephson junction I_B as a fraction of the total current applied to the film from the external source, $I_B=kI_s$, we obtain the symmetry characteristic identical with Eq. (5), derived only from general considerations of a nonlinear inductance. Observe that the lowest quantum state of the fluxoid, $m=0$, corresponds to the fluctuator which is symmetric in the pristine state. In fact, for $m=0$ one gets the symmetry condition $B_s(I_B=0)=0$. Thus the equation describing the fluctuator which is initially asymmetric must assume the presence of trapped flux in the loop. In fact, for all $m\neq 0$ the circulating current does not vanish at zero applied field and zero bias current.

The physical meaning of the quantities in the proposed model is now transparent. The integration constant α corresponds to the trapped flux in the loop. The fluctuator area A corresponds to the size of the intergrain loop. Performing elementary geometrical calculation of the loop area in the arrangement depicted in Fig. 3, assuming grain tips to be circular, we find $A=\frac{1}{2}[D^2-(\pi D^2/4)]$. Putting in the average grain diameter $D=2$ μm we obtain $A=0.43$ μm^2, in an excellent agreement with the area provided by the fit procedure. The nonsingle valued symmetry characteristic reflects the quantum nature of the closed superconducting loop. For a given value of the bias current, which determines the phase of the Josephson junction, there are several possible values of external magnetic field, each providing different integer number of flux quanta in the fluxoid associated with the loop. In the experiment we were able to trace unequivocally only two branches corresponding to two adjacent quantum states. We have also observed several RTS characterized by symmetry characteristics that would fit well to Eq. (5) within other noisy windows at higher magnetic fields. Nevertheless, we cannot be sure that they are indeed extensions of the original process into higher quantum states because we were not able to continously monitor those RTS while they passed into another noisy window. The factor k can be estimated as the ratio of the cross section of an average grain to the total cross section of the film. We obtain k of the order of 10^{-2} and consequently, from the fitting procedures, we estimate the critical current density of the intrinsic junction to be of the order of 10^3 A/cm^2, a reasonable value for an intergrain Josephson junction.

In the proposed model the junction involved in the fluctuator action is biased below its critical current. On the other hand, the Josephson detector mechanism, as we discussed in Ref. 5, requires the action of junctions biased above the critical current. Therefore, although both the detector and the fluctuator mechanism involve intrinsic Josephson junctions, apparently the junctions are physically distinct. Considering the large number of junctions available in the film it is easy to think that fluctuator junctions are matched to the detector ones in a natural way, within appropriate bias parameter ranges. That is why in the experiments one has several noisy windows within which clear RTS voltages appear. An attractive and physically sound alternative to this approach may be a series-parallel Josephson quantum interferometer undergoing activated transitions between its different phase states.[8] The plausibility of such an approach has been recently demonstrated by numerical simulations.[9]

We have performed similar experiments with epitaxial and single crystal HTSC thin films.[2,3] Intrinsic Josephson junctions in materials with an ordered microstructure are located mainly between CuO planes and at twin faults. Although such intrinsic Josephson junctions influence many properties of oriented or epitaxial films, e.g., the dimensionality of the vortex systems,[10] we have found that they are not involved in the generation of RTS voltage noise. The symmetry characteristic measured for TLF's active in epitaxial and oriented films were strictly linear, implying that the response of such films to weak applied magnetic fields is linear and depends only on the geometry of the sample and on the quality of the patterning, as will be discussed by us elsewhere.

In conclusion, we have obtained an experimental evidence for intrinsic Josephson junctions involvement in random-telegraph-noise generation in granular high-T_c films. However, the detailed physical structure of the Josephson fluctuator remains still an open question. In the paper we have discussed only one of the simplest plausible arrangements of three superconducting grains constituting a loop with single Josephson junctions. Nevertheless one may find more complicated arrangements of junctions incorporated into closed superconducting loops that would also behave according to the predictions of the nonlinear Josephson inductance model.

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