Instabilities in the current-voltage characteristics of submicron BSCCO bridges

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Abstract. The influence of magnetic field and microwave irradiation on dynamical phase separation in submicron Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ bridges has been studied. Strong effect on the shape and metastable character of the step-like $I$-$V$ characteristics are found. Under a weak field $H < 2$ Oe and low level microwave irradiation the step-like structure of the $I$-$V$ characteristics smears out and disappears completely. The average frequency of switching between metastable states grows by 5 orders under increase of magnetic field by only 1 Oe. This behavior is explained in terms of the model of dynamical vortex lines.

1. Introduction
By the present time the resistive state with a dynamic phase separation is well investigated theoretically and experimentally for narrow one-dimensional superconducting channels $d,w < \xi$ ($d$-thickness, $w$- width, $\xi$ - coherence length). At currents $I$ above depairing currents $I_d$ phase slip centers (PSC) arise in one-dimensional channels [1]. Each such center represents a region of an oscillating order parameter with length equal to $\xi$, generating a flow of normal quasi-particles on the length of penetration of electric field into a superconductor ($L_q$). $I$-$V$ curves of such one-dimensional channel show regular voltage jumps, whose number is equal to the number of PSCs in the channel. For thin bridges or films of the intermediate sizes $\xi < w < \lambda_{\perp} \equiv \lambda^2/d$, where $\lambda$ - the depth of magnetic field penetration, situation is more complicated. For short bridges $l < w < \lambda_{\perp}$ ($l$ is bridge length) the theory predicts occurrence of separate vortices chains (trains) [2]. $I$-$V$ curve of such bridges at high currents $I > I_1$ ($I_1$ - the current of the first vortex entry) can consist of separate voltage jumps caused by the infill of the chain by vortices cores up to a normal state [3]. On the other hand, in thin two-dimensional films $d < \xi < w$ at currents $I > I_1$ the new resistive state – phase slip line (PSL), a two-dimensional analogue of PSC – is predicted [4]. In this case stepped $I$-$V$ curves should be also observed. There are several experiments reporting stepped $I$-$V$ curves on wide, $w > \lambda_{\perp}$ LTS and HTSC films [5-6], treated in terms of PSL. However, in [6] authors could not explain the too large values of $L_q >> 1$ µm found for HTSC films. It is necessary to note, that the region $\xi < w < \lambda_{\perp}$ is most topical for HTSC, since the coherence length in HTSC is about tens of angstroms and is unachievable for the up-to-date lithography. The search of coherent quantum effects for structures with $w \cdot \lambda_{\perp} \sim 1$ µm, can result in practical application of HTSC.

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2. Sample preparation

The bridges with width \( w = 0.2 - 1 \ \mu m \) and length \( l \) typically 2 - 3 times larger were fabricated from BSCCO (2212) single crystal whiskers of 15 - 30 \( \mu m \) width by the method of laser microevaporation (LC - laser constrictions) \cite{7,8} (fig. 1a) or with the focused ion beam (FIB) technique \cite{7} (fig. 1b,c). The whiskers represent ribbon-like crystals with thickness, width and length in \( c, b \) and \( a \) crystallographic directions correspondingly. The bridges were formed along \( a \) direction. The diameter of the laser beam was 1-2 \( \mu m \), which allowed to produce bridges with the sizes \( w = 0.2-1 \ \mu m, \ l = 1-3 \ \mu m \). The pulsed mode of the laser (~10 ns) allowed to create the bridges with sharp boundaries between crystal and amorphous phase (a fast solidified melt) without degradation of superconducting properties of the bridge. For the selected whiskers (\( d = 0.13 – 0.2 \ \mu m \)) \( \lambda_{\perp} \) is about 1 \( \mu m \). The low-ohmic contacts \( (10^{-5} - 10^{-6} \ \Omega cm^2) \) were prepared by laser deposition of gold in vacuum \cite{7,8}.

![Fig. 1. TEM photograph of a laser-constriction (LC) bridge (a) and photos of FIB etched bridges (b-c). The scale bar (1 \( \mu m \)) is common](image)

![Fig. 2. Typical I-V curves for two FIB and one LC bridges (Inset: an example of a time domain of voltage at \( I=\text{const} \)](image)

3. Stepped I-V curves

Typical I-V curves for one laser and two FIB bridges are shown in fig. 2. All the I-V curves show voltage steps regular in current. The steps are separated with regions of constant differential resistance \( R_d \) with the same residual current. The gain of differential resistance on each step is the same. Temperature evolution of the I-V curves is as follows \cite{7}: close to \( T_c \) waves can be distinguished; with temperature decreasing the waves transform into smooth steps; then the steps become more abrupt, and hysteresis develops. It is necessary to note, that the first step current \( I_1 \) is nearly independent of the bridge width (see the two FIB bridges with width 0.2 and 0.5 \( \mu m \) (fig. 2), etched on the same crystal).

The time-domain studies have shown, that at high temperatures \( T > 60 \ \text{K} \) at a fixed current the voltage shows sharp switchings between two metastable states of the random telegraph signal type \cite{9}. A typical view of the signal is shown in the inset to fig. 2. The telegraph signal is characterized by an average period \( \tau \) or average frequency of switchings \( f = 1/\tau \). The temperature dependence \( \tau(T) \) can be very abrupt: decreasing temperature by 1 K increases \( \tau \) by several orders of magnitude, which corresponds to activation energies > \( 10^4 \ \text{K} \) \cite{9}. At lower temperature the switchings disappear and the hysteresis develops at a back sweeping of \( V(I) \).

4. Influence of magnetic and microwave fields

I-V curves of LC3 bridge are shown in fig. 3a at different magnetic fields. The magnetic field is perpendicular to the \( ab \) planes of a crystal. It is visible that low magnetic field dramatically affects the I-V curves of the bridges. The stepped structure begins to disappear already at several Oersteds. The
wavy structure forms which then transforms into smooth continuous curves. The field of the steps disappearance is 5-8 times lower than the first critical field $H_{c1}$ (corresponding to appearance of resistance at a zero current). The process of switching very strongly depends on the magnetic field as well. The external magnetic field ~ 1 Oe increases the average switching frequency by 4 orders of magnitude (see inset to fig. 3a). A similar effect of steps disappearance is observed under irradiation of bridges in microwave (MW) fields. Fig. 3b shows $I$-$V$ curves of bridges irradiated by MW power at different attenuation levels (the power absorbed by the sample was not estimated). For comparison, in the figure we show a curve for the unirradiated sample, but at higher temperature. The switching frequencies also very strongly depend on MW power (inset to fig. 3b). 70 GHz microwave irradiation of ~ 100 mW power increased the average frequency by 5 orders of magnitude.

5. Discussion and Conclusions

The observations of dynamic phase separation in BSCCO microbridges allow to assume that it is a resistive state similar with the PSL. This is confirmed by stepped $I$-$V$ curves with periodic increase of $R_d$; the small sizes of the resistive nanodomain. For example, for the FIB 0.5 μm bridge with length 1 μm (fig. 2) the number of nanodomains is equal to about 27 (the number of steps) at the saturation. That is, the nanodomain size is about 370 Å. Then from the PSC theory [1] we can estimate the inelastic relaxation time for quasi-particles $\tau_i = 3L_i^2/v_F l_e$, $\sim 10^{-12}$ s, where $v_F \sim 10^7$ cm/s is the Fermi velocity, $l_e$ is the mean free path ($l_e \sim 100$ Å near $T_c$). This is quite comparable with $\tau_i$ known for HTSC [10]. However, small densities of critical currents $10^5$-$10^6$ A/cm$^2$, the independence of $I_1 \sim 1$ mA of the bridge width argue that the process is controlled by an edge barrier for entry of vortices. The non-Josephson noise of the random telegraph signal type is also consistent with the idea of edge barrier: the switching is associated with the low hopping rate over the edge barriers. In contrast to PSCs, at decreasing of temperature the residual current runs to zero, and differential resistance $R_d$ approaches the complete (chordal) resistance $R$. This indicates the quasihomeric character of the dissipative nanodomains [7] and allows to suppose, that the PSL-like nanodomains are quasinormal channels formed by high-speed vortices ($v > 10^7$ cm/s) overcoming the edge barrier under the action of current. A high-speed vortex leaves a tail of a suppressed superconducting order parameter. This tail can overlap with the following vortex forming the stable quasinormal channel. It is obvious, that the stability of the channel should be higher at decreased temperatures and for narrower bridges. We have also observed this in experiment [7]. The experiments under magnetic and MW fields give further support our hypothesis. Small levels of magnetic and MW fields destroying the dynamic state with
phase separation, the sharp dependences of switching time $\tau(T,H,P)$ support the idea, that PSL is a phase coherent state. It is natural to assume that these are pairs of Abrikosov vortices, which give rise to the PSLs, i.e., vortex chains. Earlier to explain the high velocities of vortices and the voltage jumps (switchings) on the $I$-$V$ curves, we used the model of Larkin-Ovchinnikov (LO) vortex instability which qualitatively and quantitatively explained our results [7]. For the LO instability it is not important, either one vortex or a vortex-antivortex pair forms a chain. The vortex critical velocity for the instability development is important only. The sensitivity of steps to $H$ and MW specifies, that the chains are formed by vortex-antivortex pairs. Really, at small external fields the vortex-antivortex symmetry breaks: the vortices begin to enter the bridge at one edge with higher probability, than at the antivortices at the other one. At the same time the level of dissipation practically does not change at such $H$ (see fig. 3a), but stable channels do not form. The MW field works similarly with $H$: small levels of radiation break the fine equilibrium of the vortex-antivortex pairs. The non bolometric nature of MW effect is obvious from Fig. 3b. Heating by 5.4 K gives the same shift of $I$-$V$ curves as the MW effect, but does not destroy the steps.

Thus, PSLs in HTSC are associated with specific dynamic instability of vortex-antivortex chains. The questions concerning the vortex-antivortex dynamics practically are not studied. We came across only one work (theoretical) considering the process of the vortex-antivortex annihilation in HTSC [11].

In conclusion, we have found the strong influence of external magnetic and MW fields on the shape and metastable character of $I$-$V$ curves in submicron bridges based on BSCCO (2212) whiskers. The non-stationary behaviour of PSLs resulting in non Josephson oscillations of random telegraph signal type is reported. The average frequency of switchings depends exponentially on magnetic and MW fields. The BSCCO bridges could be efficient detectors of microwave radiation and low magnetic fields. The studies of the dynamic phase separation have shown that the states of PSL type are associated with a new dynamic instability of chains formed by vortex-antivortex pairs. The instability results in formation of quasinormal channels - analogues of PSLs.

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