Ba$_{0.6}$K$_{0.4}$BiO$_3$ single crystal as a multiple Josephson system: new coherent effect?

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Abstract. The existence of space inhomogeneous superconductor insulator state (SISIS) found out earlier in polycrystalline samples of high-$T_c$ system Ba$_{0.6}$K$_{0.4}$BiO$_3$ ($T_c$~30 K) is confirmed on Ba$_{0.6}$K$_{0.4}$BiO$_3$ single crystal. At $T^*$ ($T^*<T_c$, $T^*$~17 K) the transition from the homogeneous superconducting state into the SISIS occurs. SISIS is characterized by the appearance of two gapes on the Fermi surface: semi- and superconducting, that are modulated in space in antiphase, the electric transport between superconducting regions being carried out due to Josephson tunneling. Thus the whole sample becomes a multiple Josephson system. Nonlinear I-V curves, depended on temperature and magnetic field, that are typical to a Josephson system, are observed on Ba$_{0.6}$K$_{0.4}$BiO$_3$ single crystal at temperatures below $T^*$. Besides, a step like peculiarity at the values of voltage of the order of one and two superconducting gaps shows up. These peculiarities are suppressed by magnetic field much earlier than critical current. Perhaps the last phenomenon is the consequence of "coherent" state of several successive Josephson junctions, appeared in the exfoliation state.

1. Introduction

High-$T_c$ system Ba$_{0.6}$K$_{0.4}$BiO$_3$ demonstrates anomalous behavior, being in the superconducting state [1-6]. Analogous anomalous of galvano-magnetic properties were for the first time found out and investigated in details in the related compound BaPbBiO [7-11], afterwards similar effects were observed in other high-$T_c$ systems: SrKBiO [12] and NdCeCuO [13]. In Ba$_{0.6}$K$_{0.4}$BiO$_3$, where the most wide spectrum of investigations [1-5] was carried out, the following phenomena observed attract attention: 1) the recovering of the resistive state from the superconducting one at temperatures below $T_c$, that depends on magnetic field and operating current through the sample (the resistivity reentrance), 2) nonlinear behavior at temperatures below $T_c$ – transition into superconducting state or “dielectric”- type enhancement of resistance in dependence of operating current through the sample and external magnetic field, with resistance value exceeding the residual resistance above $T_c$ by several orders of magnitude, 3) simultaneous suppression of “dielectric” rise of resistivity with temperature lowering, observed at “big” operating current, and resistive transition into superconducting state at “small” current at the same values of external magnetic field $H$, 4) the presence of large quantity of superconducting phase in the volume of sample, that stays in high resistive state at temperature below $T_c$, and it’s saving till the total destroying of resistive state by magnetic field, 5) hysteresis of voltage-current characteristics (VCC), depended on temperature and magnetic field, 6) nonmonotonic temperature dependence of critical current, determined from VCC,
with maximum at $T^* \approx 17$ K, 8) suppression of critical current by microwave radiation, 9) positive curvature of temperature dependence of critical magnetic field $H_{C2}(T)$, determined from the resistive transition curves in magnetic field, in the whole investigated temperature range down to relative temperature $T/T_C=0.08$ without any hint on saturation, 10) the properties of the sample are analogous to the properties of a 3-D Josephson net – nonstationary Josephson effect was observed on polycrystalline sample, 11) anomalous temperature dependences of the first critical magnetic field $H_{C1}(T)$ and residual magnetization $\Delta M(T)$ with a characteristic peculiarity – sharp bend at the same temperature $T^*$, were maximum of critical magnetic field is observed (point 6).

In work [7], where polycrystalline samples of BaPbBiO were investigated similar anomalies were found out. Phenomena observed were explained by the formation of Josephson contacts on the boundaries of granules and as a result the sample displayed the properties of a Josephson net. The most part of investigations in other high-$T_C$ systems was also carried out on polycrystals. However the nonmonotonic temperature dependence of critical Josephson current with maximum at $T^* \approx 17$ K, founded out in $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$ doesn’t agree with this scheme. More over the effect of resistance reentrance was observed in $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$ both on poly and single crystals. Magnetic measurements of $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$ single crystals also confirm the existence of peculiarity at $T^* \approx 17$ K. All anomalies mentioned above could be successfully and consistently explained with the help of model of space inhomogeneous state insulator-superconductor (SISIS) proposed in [14], according to which for a system being near the transition metal-isolator at specific conditions it occurs favorable to transit into a space inhomogeneous state that is characterized by two gaps simultaneously: superconducting and dielectric, both modulated in space in antiphase and mutually causing each other subsistence. The electric transport through the dielectric regions in this self-consistent state is carried due to Josephson tunneling. The phase state with lower free energy at given external conditions: temperature, magnetic conditions, operating current, is realized. While cooling at zero magnetic field the sample experience the transition into the homogeneous superconducting state at first ($T_C \approx 30$ K) and then into the space inhomogeneous (or exfoliated) state insulator- superconductor ($T^* \approx 17$ K). The fact of transition into the exfoliated state explains all the anomalies above except the positive curvature of $H_{C2}(T)$ dependence. To explain the last we are to make additional but quit logical supposition that this new state in its order changes with temperature further lowering, for instance, amplitude and/or period of superconductor and insulator gaps modulation increase. It should be noted that the question about exfoliation in connection with high-$T_C$ superconductors is widely discussed in literature, both theoretical models and different experimental data confirming its existence [15].

As for $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$, the whole picture looks quit complete: rather great number of various experimental results is consistently explained by one theoretical model. However up to now the most striking and convincing experiment in favor of SISIS – VCC with hysteresis depended on magnetic field and temperature was performed only on polycrystals. Hence to confirm the idea that self-consistent exfoliated state is a fundamental property of $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$ system and its Josephson properties don’t have any technological origin it is necessary to repeat this experiment on single crystals of $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$. The results of such measurements are produced in this work.

2. Samples
Single crystals of $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$, grown up by the method of chemical transport reactions, had dimensions of the order of 2x2x2 mm$^3$ (Fig.1).

Fig.1 The single crystals of $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$

3. Experiment. Results and discussion
Nonlinear behavior and the effect of resistance re-entrance depended both on the external magnetic field and the magnitude of the operating current is reproduced on single crystals of $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$ (Fig.2 a,b) just similar to the case of poly-crystals. The observed VCC (Fig.3 a,b) look quit analogous
to those found out earlier on polycrystalline samples of Ba$_{0.6}$K$_{0.4}$BiO$_3$ [1]. All peculiarities are repeated: qualitative difference between curves obtained at “high” (above $T^*$) and “low” (below $T^*$) temperatures, the dependence on magnetic field, huge hysteresis at low temperatures (Fig. 4), and what is especially important, nonmonotonic temperature dependence of critical current, determined from VCC (Fig. 4). All together it confirms the supposition that Josephson properties displayed by Ba$_{0.6}$K$_{0.4}$BiO$_3$ sample have fundamental but and not technological origin, and could be explained in the framework of SISIS model. Furthermore, as far as other high-$T_c$ compounds: BaPbBiO$_3$ [7-11], SrKBiO$_3$ [12], NdCeCuO$_3$ [13], - exhibit similar nonlinear behavior at temperatures below $T_c$, we can suppose that the reason of the phenomena observed is just the same and the model of space inhomogeneous state isolator-superconductor has a wider application for high-$T_c$ compounds.

Fig. 2 Temperature dependence of Ba$_{0.6}$K$_{0.4}$BiO$_3$ single crystal resistance: a - at different magnetic fields, amplitude of operating alternative current $I$=1 mA; b – amplitude of operating alternative current $I$ = 20 mkA, $B$=9 T.

Fig. 3 a – VCC of Ba$_{0.6}$K$_{0.4}$BiO$_3$ single crystal at different temperatures b – VCC of Ba$_{0.6}$K$_{0.4}$BiO$_3$ single crystal at $T$=2 K in different magnetic fields.

One more effect observed is worth discussion. On VCC of Ba$_{0.6}$K$_{0.4}$BiO$_3$ single crystal measured at “low” temperatures one may easily notice the step, at 2 K and 4.2 K step becomes S-like. The position of step on voltage axe depends on temperature and magnetic field. The step is suppressed by magnetic field of rather small magnitude in comparison with the field which suppresses critical Josephson current, simultaneously the S-type of the step disappears. One more point is to be noted. The magnetic field influence has a jump like character: the magnetic field of 0.1 T doesn’t produce any change in the
step position and/or form, while in H=1 T the corresponding location of step on the voltage axe changes for one third.

Fig.4. VCC of Ba$_{0.6}$K$_{0.4}$BiO$_3$ single crystal at T=2 K and different amplitudes of current

The nature of the phenomena observed is not quit clear. Perhaps it is the consequence of coherent state of few successive Josephson junctions appeared in the exfoliation state.

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