QUASI-TWO-DIMENSIONALITY AND KOSTERLITZ-THOULESS TRANSITION IN $Bi_2Sr_2CaCu_2O_x$ SINGLE CRYSTALS

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Nonlinear current-voltage characteristics $V \propto I^{a(T)}$ of single crystals BSCCO below T_c with a characteristic Nelson-Kosterlitz jump in a(T) at $T=T_c$ present evidence for a Kosterlitz-Thouless (KT) transition which may be explained by flux vortex unbinding inside the superconducting planes.

Introduction

Since high-T_c superconductors have layered structure it is interesting to study some features of 2D superconductivity in these materials, in particular, a possibility of KT transition which leads to thermal creation of the vortices inside 2D superconducting planes. The transition of this type is well known in thin films of common superconductors (for review see[1]). Some features of KT behaviour were observed in YBCO single crystals[2], YBCO ceramics[3] and in BSCCO system[4,5,6] also. Here we report on the observation of the Nelson-Kosterlitz universal jump[1] in single crystals of BSCCO, which can be considered as a direct evidence of KT transition in high-T_c materials.

Sample Preparation

Single crystals with T_c=80-85 K and conductivity anisotropy σ_{ab}/σ_c=5 10^4 near T_c were grown by flux methods using excess CuO as a flux and in KCl flux. The samples dimensions were of the order of 1 mm in the *ab* plane and 1-20 μm along the *c* axis. Contacts (with resistance $\approx 10^{-4}$ Ohm cm^2) where made using fired silver paste with oxygen treatment at 600°C. The resistivity ρ of the crystals at 300 K was 0.2 mOhm cm, residual resistance being 5% of R(300).

Resistivity Near the Transition

The dependence of R on T near T_c has a form $R(T) \propto \exp(-C/\sqrt{T-T_c})$ typical for KT transition (see inset to Fig 1). At higher temperature R(T) is well described by Aslamazov-Larkin theory for a fluctuation contribution to a conductivity of a 2D superconductor of the thickness $d_o \approx 10$ Å (Fig 1). Ginzburg -Landau temperature T_{co} is by 3 K higher than KT transition temperature T_c.

In the temperature region, where resistivity $\rho \ll \rho_n$, current is carried mainly by superconducting electrons. Thus, if the vortices created near KT transition move in different planes independently, current flows in the layer of thickness λ_L(λ_L is a penetration length for a field H$\|$*c*). So, in contrast to a normal state and to a case of 3D vortices, in which the resistance is determined by the whole volume of a sample, the resistance near the low

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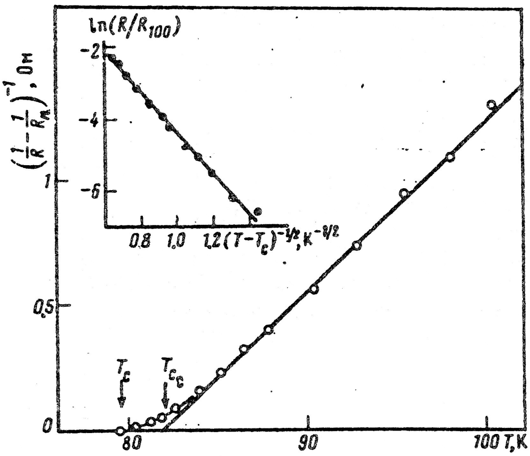


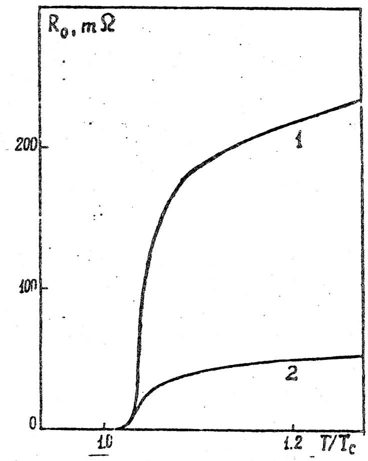


Fig.1. A comparison of resistivity behaviour near the transition with 2D Aslamazov-Larkin theory. Inset: Fit of resistance to the KT scaling.

Fig.2. Temperature dependence of sheet resistance for two samples with different thickness h: 1 - h=3 μm, 2 - h=15 μm.

temperature tail of R(T) should be independent on the crystal thickness h. The R(T) curves presented in Fig.2 for the crystals of different h agree with this statement well.

Nonlinear I-V Characteristics

It is known[1)] that in superconducting thin films with a KT transition at $T<T_c$ a critical current $j_c=0$ and I-V curves are nonlinear, $V\propto I^{a(T)}$. The reason for this behaviour is a lowering of the vortex-antivortex attraction energy by the current I acting on the vortex and antivortex in opposite directions. As a result the coupling energy has a maximum at a distance

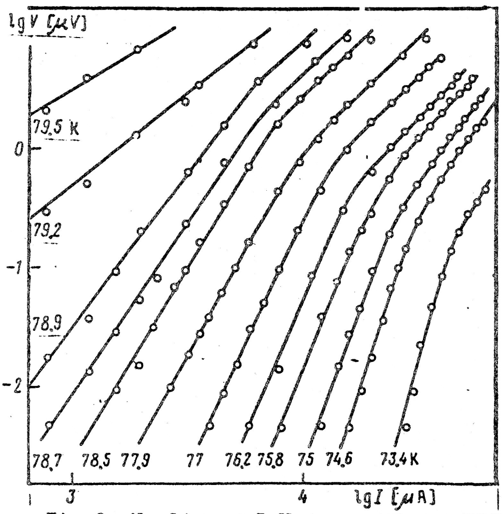
$$r_o \approx c\Phi_o/4(2\pi)^3\Lambda j\varepsilon_o \qquad (1)$$

between the vortices, where j is the current in a 2D superconductor per unit width of a sample, Φ_o is the flux quantum, $\Lambda=\lambda_L^2/d_o$, ε_o describes the weakening of the vortex interaction by bound vortex pairs. Therefore, thermal creation of vortices at a distance r_o takes place, the vortex concentration being $n \propto j^{a-1}$, where [1)]

$$a(T)=[\Phi_o^2/(4\pi)^2\Lambda T\varepsilon_o]+1 \qquad (2)$$

Since resistivity $\rho \propto (n\xi^2)\rho_n$, where ξ is the correlation length in the superconducting plane, $V\propto I^{a(T)}$. At $T>T_c$ $\rho>0$ even in the absence of the current, hence a=1, and there is a Nelson-Kosterlitz jump in a(T) from 1 to 3 at $T=T_c$.

I-V curves for different temperatures are shown in Fig.3. At lower currents they obey a power-low behaviour. Corresponding a(T) curve, presented in Fig.4, contains Nelson-Kosterlitz jump at $T=T_c$. Linear dependence of a(T) for $T<T_c$ means that $\Lambda \propto \lambda_L^2 \propto 1/(T_{co}-T)$ as in the BCS theory. Comparing a(T) in Fig.4 with eq.(2) yields $\Lambda\approx 100$ μm at $T=T_c$, and for $d_o=10$ Å we get $\lambda_L \approx 0.3$ μm.



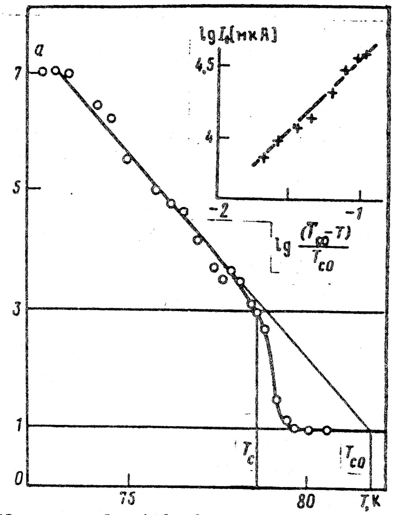


Fig.3. Nonlinear I-V curves for a BSCCO crystal with dimensions 1.1 x 0.5 x 0.0015 mm^3 at different temperatures.

Fig.4. Temperature dependence of the exponent in nonlinear current-voltage curves. Inset: Temperature dependence of the characteristic current I_1, for which a decrease of the exponent occurs.

At larger currents a form of V(I) dependences changes. At some characteristic value $I_1(T)$ a decrease of the exponent in V(I) curves occurs. In our opinion, the explanation of this behaviour is that the current j_1 per a plane reaches the value corresponding to distance $r_0 \approx \xi$ between created vortices (see eq.1), the value j_1 being of the order of Ginzburg-Landau depairing current. The order of magnitude of I_1 and its temperature dependence agree with the data in the inset to Fig.4 provided $\xi \propto \lambda_L \propto 1/\sqrt{T_{co} - T}$ as in BCS model.

KT transition takes place in 2D superconductors because the intervortex attraction for $r<\Lambda$ is determined by logarythmically dependent kinetic energy of superconducting currents $W_k=[\Phi_0^2/(4\pi)^2\Lambda\varepsilon_0]\log(r/\Lambda)$. In the quasi-2D superconductors 3D effects tend to prevent KT transition. The energy of magnetic interaction of vortices in different layers at a distance $z<<\Lambda$ is small, $W_m=[\Phi_0^2 z/2(4\pi)^2\Lambda^2\varepsilon_0]\log[(z+(z^2+r^2)^{1/2})/\Lambda]<<W_k$. Josephson interaction between layers gives a contribution to the intervortex interaction too: $W_J=[\Phi_0^2/(4\pi)^2\Lambda\varepsilon_0](\sigma_c/\sigma_{ab})(r/d)^2\log(r/\Lambda)$. For materials of BSCCO type with large conductivity anisotropy W_J is rather small. The estimation for our crystals yields that $W_J<W_k$ at $r<0,3$ μm. Comparing this value with the characteristic distances involved in our experiment we conclude that 3D effects may be neglected everywhere with the exception of a region $T-T_c<0,1$ K.

Influence of Magnetic Field

V-I curves obey power-low character in magnetic field under investigation

H<300 Oe. Fig.5 illustrates the influence of magnetic field H‖c on a(T) dependence One can see that universal jump of a(T) tends to be smeared at

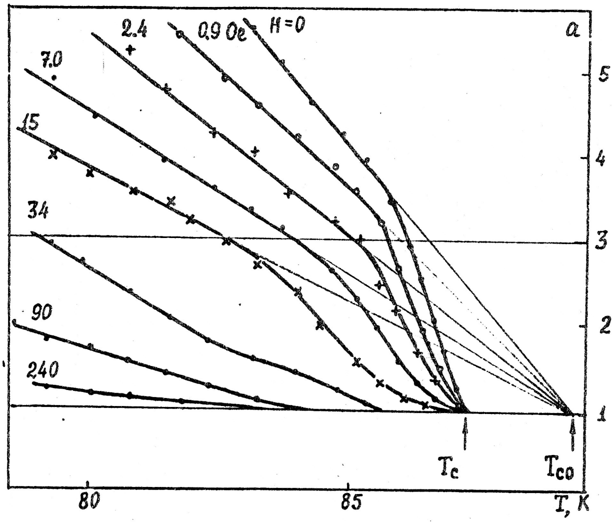


Fig.5. Temperature dependence of the exponent in nonlinear current-voltage curves at various magnetic fields H ⊥ *ab*.

fields H<1 Oe and is suppressed completely at H≈30 Oe. At higher H a(T) dependences change their curvature. So the scale of characteristic H suppressing jump is 1-10 Oe.

Conclusion

Thus, we may conclude that quasi 2D nature of high-T_c materials provides an opportunity of thermal creation and of independent motion of 2D flux vortices in different planes. The weakness of coupling of vortices in different planes may be the reason for the weakness of pinning in these materials.

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