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TWO–DIMENSIONAL VORTEX PLASMA IN $Bi_2Sr_2CaCu_2O_x$ SINGLE CRYSTALS IN THE VICINITY OF T_c

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Dedicated to Professor Mladen Paić on the occasion of his 90th birthday

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Quantitative analysis of results of measurements of magnetoresistance of Bi_2Sr_2-$CaCu_2O_x$ single crystals for magnetic fields 0.2–0.8 T, in the temperature interval 78.5–84 K has been made. For temperatures lower than 81 K the dissipation is predominantly determined by the suppression of the long-range superconducting order, whereas closer to T_c the flux-flow contribution becomes significant. We obtain very good agreement between the experiment and the model in which two dissipation mechanisms are additive.

1. Introduction

Although in the course of the past few years much effort has been devoted to find an explanation of the magnetoresistance of high-T_c superconductors, a satisfactory solution of this and other related transport phenomena has been elusive. It is clear, however, that the vortex-lattice dynamics in these layered compounds is governed by rather complicated mechanisms, which depend very much on a particular experimental arrangement. In the presence of a magnetic field higher than the critical field B_{cr}, the anisotropic three-dimensional (3D) vortex lattice becomes unstable with respect to the fully two-dimensional (2D) arrangement of vortices [1-4]. The lowering of the effective dimensionality can thus lead to some phenomena which are inherent to 2D-superconductivity. In addition, by investigating the properties of the isolated CuO_2 sheets, common to all high-T_c compounds, valuable information about the nature of high-temperature superconductivity can be provided.

Critical fluctuations are greatly enhanced in systems with lower dimensionality. An important consequence of such fluctuation phenomena is the creation of bound vortex-antivortex pairs, which dissociate above the Kosterlitz-Thouless (KT) temperature T_{2D} [5-7]. In such systems, the existence of the vortex plasma in the absence of any applied field makes the analysis of dissipation phenomena rather complicated. Strongly fluctuating vortices greatly influence the phase-coherence of the superconducting pairs and suppress the long-range superconducting order. Also, the density of free vortices, which contribute to the flux-flow, is determined not only by the magnetic field, but also by the thermally stimulated dissociation of the bound vortex-antivortex pairs.

In our previous article [1], we made a detailed analysis of the magnetoresistance curves of $Bi_2Sr_2CaCu_2O_x$ (BISCO) single crystals, for the magnetic field applied parallel to the c-axis, in terms of dissipation due to the suppression of the long–range superconducting order in decoupled double CuO_2 planes. From our results, we estimated T_{2D} at about 37 K and B_{cr} between 0.1 T and 0.2 T. This we did by interpreting the effective critical temperature of an isolated superconducting sheet as the T_{2D}, while the critical field value was deduced from the obvious discrepancy between the experimental results and the two-dimensional theory at low-field values. However, good agreement was achieved only at temperatures at least a few degrees below the mean-field transition temperature T_c, while closer to T_c the dissipation was found to be noticeably higher then that predicted by the theory of fluctuations alone. We made a tentative conclusion that in this temperature region the flux-flow takes considerable part in the total dissipation, and we based this assumption on the observed change of the sign of the Hall voltage in the proximity of T_c, which is commonly attributed to the flux-flow [8,9].

Here we report the continuation of our work on the data of Ref. 1. We find very good agreement with the model based on the assumption that the two dissipation mechanisms are additive, in which the flux-flow contribution is determined mostly by thermal dissociation of the bound vortex-antivortex pairs. Together with our previous results, we are now able to quantitatively describe the magnetoresistance curves in the temperature range from 78.5 K to 84 K (which is just below the point $R(H = 0) = 0$), and for applied fields 0.2–0.8 T.

2. Results and discussion

The experimental setup has been described in detail in the previous paper [1]. Briefly, the samples were produced by the KCl-method and the magnetoresistance was measured by a low-frequency (33 Hz) AC-method in a standard four-contact configuration, with the magnetic field applied parallel to the c-axis of the crystal. The critical temperature T_c was determined by linear extrapolation of the steep part of the transition curve in zero magnetic field to $R = 0$, and its value was found to be about 84.5 K. Special care was taken to determine the inclusions of the $Bi_2Sr_2Ca_2Cu_3O_x$ phase. Measurements of the magnetoresistance in the fully resistive state above 90 K showed that this phase is slightly present. But for the given temperatures ($T \leq 84$ K) and the magnetic field values ($H < 1$ T) its influence on the magnetoresistance can be considered negligible. However, if one wants to have very accurate extrapolated normal-state resistivity below T_c, which is essential in the flux-flow calculations, the normal-state resistivity has to be extrapolated from the linear part of the resistance curve below 105 K, where the higher-temperature phase mentioned above is in the superconducting state and does not contribute to the normal resistivity. This is the procedure we adopted in our present analysis. We note that our measurements ($I = 24$ μA) correspond to an ohmic dissipation, since we have found that in the above mentioned part of the $H-T$ phase diagram $V-I$ curves are linear at least up to 1 mA.

In our previous analysis, we did not succeed to describe quantitatively the dissipation above 81 K within the fluctuation model alone, the observed resistance close to T_c being higher than that predicted by the theory. We explained the apparent deviation of the phase-coherence-breaking-field H_φ from the exponential law $H_\varphi = H_0 \exp(-T/T_0)$ and its rapid fall above 81 K as the manifestation of an increased flux-flow contribution to the total dissipation [1]. The simplest model of the dual dissipation, i.e., due to the suppression of the long–range superconducting order and the vortex motion, is that these two contributions should be added. Thus, the total dissipation can be expressed as $R = R_c + R_f$, where R_c is the resistance due to the critical fluctuations above T_{2D} in the decoupled superconducting sheets and R_f is the flux-flow resistance. The flux-flow resistance can be written as $R_f = 2\pi\xi^2(n_+ + n_-)R_n$, where ξ is the coherence length, R_n the normal-state resistance, and $n_f = n_+ + n_-$ is the total density of free vortices (n_+) and antivortices (n_-).

When we extrapolate the dissipation due to the critical fluctuations in the region of the mixed dissipation (close to T_c) and subtract it from the total dissipation, we observe a remarkable thing: the additional dissipation depends mostly on the temperature, and very weakly on the magnetic field (Fig. 1). At a given temperature the field dependence of the additional dissipation for the fields 0.2–0.8 T is almost within the experimental error (because the total dissipation is still predominantly determined by the fluctuations of the superconducting order-parameter). So, in the first approximation, we neglect the field dependence of R_f.

This rather surprising observation indicates that the density of the free vortices is determined by some scaling that is strongly dependent on the specific properties of the thermally created 2D-vortex-plasma in the decoupled superconducting sheets. The density of the free vortices in the conventional 3D-superconductors is determined simply by the ratio B/Φ_0, where B is the magnetic field and Φ_0 is the magnetic flux quantum, which leads to the relation $R_f = (B/H_{c2})R_n$. Thus, in this simple model, the magnetic–field dependence of the flux-flow resistance is linear and its temperature dependence is given by the temperature dependence of the upper critical field H_{c2}. It seems that the situation in the high-T_c compounds is much more complicated.

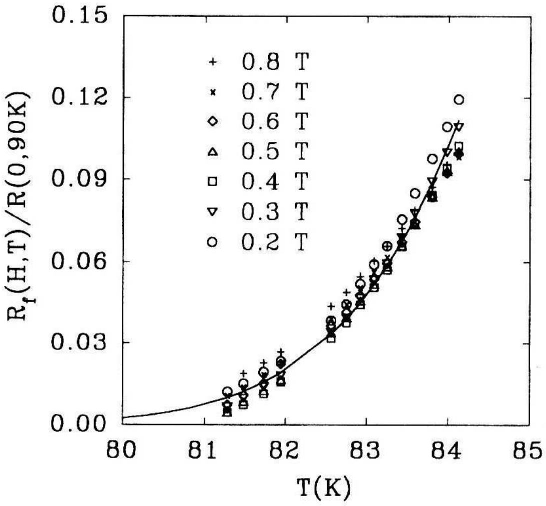

Fig. 1. Normalized flux-flow contribution $R_f(H,T)/R(0,90\text{ K})$ *to the total dissipation, for applied magnetic fields* 0.2–0.8 T, *extracted by subtracting the fluctuation resistance obtained in our previous work from the total resistance* $R(H,T)/R(0,90\text{ K})$. *Solid curve is the mean–temperature dependence of the flux-flow resistance, neglecting the small field dependence. Temperature dependence can be described by the law* $R_f(T) \approx R_n[exp(-\tilde{U}/T)]^{\nu(t)}$, *where* R_n *is the normal-state resistance,* $\nu(t) = 1/(t + xt^{\omega})$, $t = [(T/T_{2D}) - 1]$ *and* $T_{2D} = 37$ K.

Doniach and Huberman made a careful analysis of the statistical properties of the vortex plasma in two-dimensional systems which exhibit the Kosterlitz-Thouless behaviour [6]. Assuming that for fields higher than B_{cr} superconducting sheets in highly anisotropic high-T_c compounds, such as BISCO, are indeed 2D-systems with a Kosterlitz-Thouless transition, this approach could be applied to explain their properties. In the Doniach and Huberman model, the density of the free vortices and antivortices is determined by $n_{\pm} = \xi^{-2}\exp(-\beta U_{\pm})$, and $\beta = 1/k_B T$ and $U_{\pm}$ is the characteristic energy of creation of a free vortex (+) or antivortex (−). In the absence of the magnetic field $U_+ = U_- = U_0$, where U_0 is the sum of two parts. One is the chemical potential μ associated with the vortex core ($\mu = d\xi^2 H_c^2/8$, where d is an effective sheet thickness, ξ the in-plane coherence length, and H_c the thermodynamic critical field), and the other is the screened vortex-antivortex interaction U_S. With no applied field present, the density of the free vortices is determined by [6]:

$$n_f = 2\xi^{-2} exp[-\beta(\mu + U_S)]. \tag{1}$$

The exponential function has the following physical explanation: the term associated with μ describes the probability of a thermal creation of a vortex of any sign, and the term associated with U_S represents the probability of a thermally stimulated vortex-antivortex pair dissociation. Arguing that the vortex dielectric function in the vicinity of T_{2D} behaves as $\epsilon(t) = \epsilon(0)(1+xt^{1/2})$, where $t = [(T/T_{2D})-1]$ and x is a numerical constant, Doniach and Huberman found that n_f can be written as:

$$n_f = 2\xi^{-2}[exp(-\beta\tilde{U})]^{\nu(t)}. \tag{2}$$

Here $\nu(t) = 1/(t + xt^{1/2})$ and $\tilde{U} = \mu + C$, where C is a constant which depends on U_S and measures the strength of the binding energy. It has to be emphasized that μ is temperature dependent, since H_c and ξ are temperature dependent, and its dependence in the Ginzburg-Landau theory is approximately $(1 + \tau)(1 - \tau^2)$, where $\tau = T/T_c$. If we take that for BISCO $\xi(0) \approx 2 \times 10^{-9}$ m, $d < 1.5 \times 10^{-9}$ m (smaller than the distance between the superconducting sheets) and $H_c(0) \approx H_{c2}(0)\xi(0)/\lambda(0)$ (where $\lambda(0) \approx 3 \times 10^{-7}$ m is the in-plane magnetic penetration depth and $H_{c2}(0) \approx 40$ T), we obtain $\mu(0) \approx$ 20–30 K, which is rather small, and close to T_c it becomes even smaller. A small value of μ indicates that $\tilde{U}$ in its major part represents the binding energy of the vortex–antivortex pairs. Also, one should expect a slight temperature dependence of the probability $\exp(-\beta\mu)$ in the temperature region of our investigation. However, the strongly temperature dependent flux–flow resistance (Fig. 1) is mostly due to the thermal dissociation of vortex-antivortex pairs.

The presence of the applied field introduces the paramagnetic splitting term U_H, so that $U_\pm = U_0 \mp U_H$. The result is a net imbalance in the density of vortices parallel (+) and antiparallel (−) to the field. The splitting term U_H is basically equal to mH, where m is the paramagnetic moment of the vortex (there is also an additional term in U_H, which describes the "charging" effects and it is proportional to $(n_+ - n_-)$; see Ref. 6 for details). If we look at the energy scale, it is obvious that if the splitting term U_H is much smaller than the characteristic field-independent energy $\tilde{U}$, the influence of an applied magnetic field on the (anti)vortex density should be very weak indeed. The field-induced dissociation of the vortex-antivortex pairs is then low by comparison with the thermal dissociation, so that the influence of the magnetic field is mostly in making the (anti)vortices two-dimensional.

Since the observed R_f is really very slightly field dependent and strongly temperature dependent, we tried to represent all data for various fields ranging from 0.2 T to 0.8 T, with a single temperature-dependent curve of the form given in Eq. (2). We introduce an experimental exponent ω which should better describe the temperature dependence of $W = \nu\tilde{U}$ by replacing $xt^{1/2}$ with xt^{ω} (it is clear that the temperature dependence is much stronger than the predicted $t^{1/2}$-dependence). Thus, as the fitting parameters we use $\tilde{U}$, x and ω, for R_n we use the extrapolated linear resistance in the temperature region 100–104 K, and for T_{2D} we use the previously estimated value of 37 K [1]. We obtained the best results with the following values of the parameters: $\tilde{U} = 2800 \pm 300$ K, $\omega = 7 \pm 1$, $x = 1.4 \pm 0.2$.

Having this curve, we added the extrapolated resistance R_c to the computed R_f and obtained a predicted curve for the total dissipation. As the result of this procedure, we obtained a quantitative description of the magnetoresistance curves from 78.5 K to 84 K, i.e., in the region where there is no dissipation in zero field, and for the fields from 0.2 T (just above B_{cr}) [1] to 0.8 T (Fig. 2).

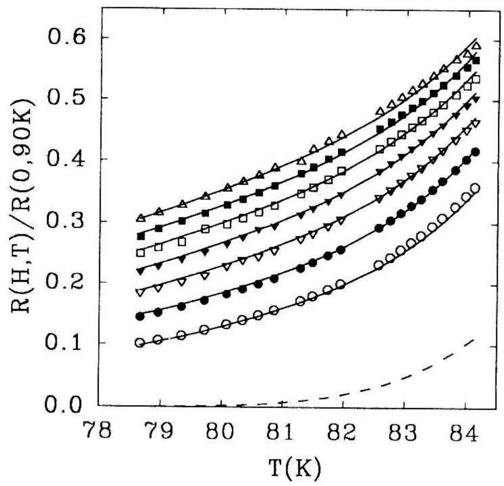

Fig. 2. Comparison of the experimental results and computed curves of the normalized magnetoresistance $R(H, T)/R(0, 90\text{ K})$ for various magnetic fields. The bottom fitted curve corresponds to H=0.2 T*, and each subsequent curve corresponds to the field increased by 0.1* T*, up to 0.8* T *(top curve). Dashed line is the flux-flow contribution to the total dissipation.*

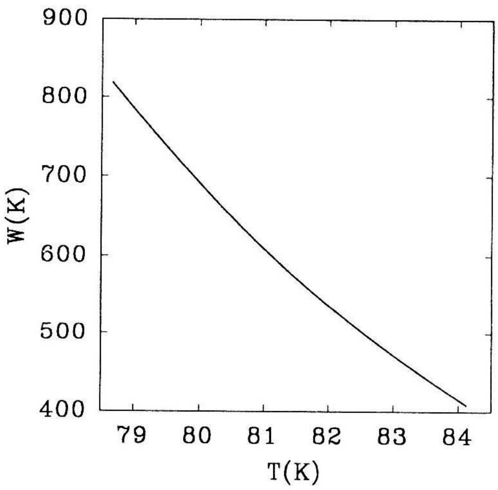

Fig. 3. Temperature dependence of the energy $W(T) = \tilde{U}\nu(T)$, which is mostly the binding energy of the vortex-antivortex pair. $W(T)$ rapidly increases with decreasing temperature.

Apart from the exact values of the fitting parameters ω and x, which describe the temperature dependence of R_f, and which are just phenomenological parameters, in our present model, the potential W should be very sensitive to the temperature (Fig. 3) in order that the theory fits well to experimental results, (Fig. 2); in the small temperature region investigated, the potential W changes by a factor of two. As mentioned before, this is mostly due to the strong temperature dependence of the vortex-antivortex dissociation.

The large value of $\tilde{U}$ and the strong temperature dependence of W set the energy scale which makes the small contribution of the magnetic field to the dissociation of vortex–antivortex pairs more understandable (the magnetic correction to the density of the free vortices is accounted for by introducing the factor $[\cosh(\beta U_H)]^{\nu}$) in the expression for n_f in Eq. (2) [6]. One should apply a relatively strong magnetic field to make its influence significant.

3. Conclusion

We have made a quantitative analysis of the magnetoresistance of single crystals of BISCO superconductors within the model of mixed dissipation due to the suppression of the long-range superconducting order and vortex motion, for magnetic fields 0.2–0.8 T (just above the critical field B_{cr} which separates 2D from 3D behaviour) and for temperatures 78.5–84 K. Above 81 K, the model of the fluctuations of the superconducting order-parameter has to be modified by the flux-flow contribution to the dissipation. The flux-flow contribution to the total dissipation is explained in terms of the Doniach-Huberman statistical model of 2D-superconductors which exhibit the Kosterlitz-Thouless transition. Our analysis shows that free vortices which contribute to the flux-flow are mostly produced by thermal dissociation of the bound vortex–antivortex pairs. The free-vortex density is weakly dependent on the magnetic field, due to the high value of the binding energy in comparison with the paramagnetic dissociation energy set by the magnetic field. This indicates that thermal creation and dynamics of the vortex plasma is a very important mechanism within the superconducting sheets in high–temperature superconductors with a high degree of anisotropy. A full description of the influence of the vortex plasma on the properties of these materials has to be elucidated by further extensive research, mostly by extending the measurements to lower temperatures.

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DVODIMENZIONALNA PLAZMA MAGNETSKIH VRTLOGA U MONOKRISTALIMA $Bi_2Sr_2CaCu_20_x$ U BLIZINI T_c

Izvršili smo kvantitativnu analizu magnetootpora monokristala $Bi_2Sr_2CaCu_2O_x$, za magnetska polja 0.2–0.8 T i u temperaturnom području 78.5–84 K. Na temperaturama ispod 81 K disipacija je uglavnom posljedica potiskivanja dugodosežnog supravodljivog uređenja, dok bliže T_c doprinos kretanja vrtloga postaje značajan. Ustanovljeno je vrlo dobro slaganje eksperimentalnih rezultata i modela u kojem su ta dva disipacijska mehanizma aditivna.