Research Institute for Solid State Physics and
Optics of the Hungarian Academy of Sciences

Némethné Pethes Ildikó

Dissipation in high-temperature superconductor $Bi_2Sr_2CaCu_2O_8$

Ph.D. Thesis Synopsis

Supervisor: Dr. Kriza György

2003.

Introduction

The discovery of high temperature superconductors in 1986 started a new chapter in solid state physics. Many aspects of their behavior have been understood since then, but they represent an important research area until now both in application and in basic research. It is not surprising, because these substances are already superconducting above the temperature of liquid nitrogen. It is very important to understand what kind of mechanism produces and influences the dissipation in these materials.

Laminar structure is a common property of high temperature superconductors; superconductivity is realized in the copper-oxide layers parallel to the *ab* face and by the Josephson-coupling of the layers. The conductivity is highly anisotropic, both in the normal and in the superconducting phases, because of the weak coupling between layers. This is largely responsible for the richness of the phase diagram of the vortices, induced by magnetic field.

Dissipation in superconductors results from motion of vortices and fluctuation of the order parameter phase between adjacent layers. Accordingly, it is very important to understand the behavior of vortices in the different parts of the magnetic field - temperature phase diagram.

Aims and experimental methods

In my Ph.D. thesis I have studied the dissipation caused by high transport current in single crystals of the strongly anisotropic high temperature superconductor $Bi_2Sr_2CaCu_2O_8$. To avoid Joule heating I used a specifically developed high current, short pulse technique to investigate the response of the system over a broad temperature (4.5-90 K) and magnetic field (up to 18 T) range. The measurements were made at the Research Institute for Solid State Physics and Optics of the Hungarian Academy of Sciences (MTA) and at the Commissariat à l'Energie Atomique at Saclay, France. The samples were prepared at the Ecole Polytechnique Federale at Lausanne, Switzerland and the contacts elaborated at the Research Institute for Nuclear Physics of the MTA at Debrecen and at Saclay.

After the initial measurements showing a threshold current for dissipation and the response at higher currents, it became evident that to understand in terms of basic superconductor properties it was essential to know the current and potential distributions in the samples. It had been accepted up to then that the current distribution in micron-thick samples was nearly homogeneous, but I was led to question this in such an anisotropic situation. It was very important to clarify this point, not only for basic understanding but also because it is of great importance in applications where it is necessary to maximize the critical current for dissipation. It was evident too that it was necessary to understand better the vortex phase diagram and the differences and stability of the phases arising from different field-temperature histories of this disordered system.

My short current pulse technique has enabled me to carry out the first reliable measurements in the free flux flow regime at low temperatures without significant heating. It has allowed me to show that, in contrast to classical type II superconductors, the dissipation by vortices is not well described in terms of the simple Bardeen-Stephen model where the vortex core is treated as a dissipative normal electron region.

The first results raised an issue too: what can we say about the stability of the vortex phases at differently prepared samples. Earlier it was established that the field cooled state is stable, but the mentioned measurements suggested the opposite. I have studied the stability of the vortex system carefully both in the field cooled and in the zero field cooled cases.

I have investigated the current-voltage characteristics. Several important parameters can be determined from these. One is the threshold current where the vortices start to move and a voltage response appears. Another is the high-current differential resistance which is seen to saturate with rising current. The high-current linear segment of the current-voltage characteristics extrapolates to a finite current at zero voltage, which I call second threshold current.

New results

I report in my Ph.D. Thesis the following results:

1. I have shown that in the solid phase below the T_p phaseline observed earlier, not just the threshold current but also the second threshold current is different in the zero field cooled (ZFC) and field cooled (FC) cases. In the FC case the second threshold

current is higher, similar to the threshold current reported earlier. As the temperature approaches T_p, the difference of the two value decreases to disappear at T_p. Above T_p there is no larger any difference between the current-voltage characteristics of the differently prepared samples. I have ascertained that below T_p the FC state is not stable as is traditionally thought. Below the T_p phaseline a small magnetic perturbation (some tens of milliteslas with optional sign) can change drastically the behavior of the FC state, causing that it becomes similar to the ZFC state. This effect can be observed both in the threshold and the second threshold current.

2. It had been shown earlier that below a certain temperature field line in the solid phase of the vortices, a small temporary field excursion of 2 mT was sufficient to convert a field cooled prepared sample into one which behaved in the same way as a zero field cooled sample. I have further shown, by means of experiments done over $\approx 10^6$ s, that on long timescales the ZFC state is stable, the FC state is metastable. The threshold current of the FC state at this timescales converges to the ZFC's one. The ZFC threshold current changes at short timescales (10^3 s) only, and its change is much smaller than the FC's one. This denotes that Bean-type density profiles do not play a significant role. At the same time a very small (2 mT) magnetic perturbation can catalyze the relaxation process but the interrogation pulse sequence does not induce relaxation.

3. My high-current measurements have shown that the liquid phase too is complex, between T_m melting line and T_c normal phase boundary there is a previously unobserved line, $T^\star$. Such that $T_m < T < T^\star$ the response of the system is non-linear correspondingly to the so called pinned liquid state and for $T^\star < T < T_c$ the current-voltage response is linear, corresponding to a classical liquid behavior. I have determined $T^\star$ as a function of magnetic field over two orders of magnitude.

4. I have shown that both in the classic *ab* and *c* measurement configurations the samples do not become resistive throughout. Rather, a resistive - non resistive front moves progressively out from the current contacts as the current increases. I have shown that the $I-V$ characteristics in the two configurations are essentially the same, and depend only on the value of the transport current and the smallest current to potential contact distance.

5. I have shown that the *ab* and *c* resistive breakdowns occur together along the resistive - non resistive front and it can be neither parallel nor perpendicular to the *ab* layer but has an angle Θ ($\neq 0$) with respect to it. With the aid of this, I have interpreted the results of point 4 on a model which gives a triangular-shape resistive region. I have determined Θ by measuring the threshold current on a special sample which has potential contacts on the top and on a terrace etched to a depth of 200 nm. I have estimated the anisotropy factor in the superconducting state, which proved to be much higher than in the normal state, leading to an effec-

tive penetration depth much smaller than the London penetration depth. With the help of this anisotropy factor and the measured threshold currents, I have estimated the critical current densities in the *ab* and *c* directions, whose values agree well with those obtained from magnetic hysteresis and from mesa experiments.

6. I have shown that at low temperatures, $5\ \mathrm{K} < T < T_m$, the magnetic field dependence of the high-current dissipation does not obey the Bardeen-Stephen law, and the differential resistance is two orders of magnitude higher than it would be expected on such a model. A possible interpretation of my results is that there is a new length scale $l \approx 20$ nm$\gg \xi$ the coherence length.

Applications of the results

My measurements belong to basic research. They can help to understand the behavior of high temperature superconductors, and to interpret other experimental results. The better understanding of dissipation, the determination of current and potential distribution in the bulk of the sample is also relevant to technical applications, such as superconductor magnets, detectors etc.

Presentations in the subject of the Thesis:

1. International Workshop on Electronic Crystals, La Colle sur Loup, France, 1999. (oral presentation)

2. International Workshop on Microscopic Structure and Dynamics in Unconventional Superconductors and Superfluids, Dresden, Germany, 2000. (poster)

3. International Conference on Science and Technology of Synthetic Metals, Bad Gastein, Austria, 2000. (poster)

4. Workshop on Vortex Dynamics and Dissipation in High-Tc superconductors, Budapest, 2001. (oral presentation)

5. Condensed Matter and Materials Physics Conference of the Institute of Physics, Brighton, United Kingdom, 2002. (oral presentation)

Publications:

B. Sas, L. F. Kiss, I. Pethes, S. Mészáros, K. Vad, B. Keszei, F. I. B. Williams, F. Portier and I. Puha : Metastability line in BSCCO phase diagram
J. Phys. IV France **9**, Pr10/73-75 (1999)

I. Pethes, B. Sas, G. Kriza, F. Portier, F. I. B. Williams, K. Vad, S. Mészáros: High-current differential resistance in $Bi_2Sr_2CaCu_2O_8$ single crystals
Synth. Met. **120**, 1013-1014 (2001)

F. Portier, G. Kriza, B. Sas, L. F. Kiss, I. Pethes, K. Vad, B. Keszei, F. I. B. Williams: Slow relaxation of low-temperature vortex phases in $Bi_2Sr_2CaCu_2O_8$
Phys. Rev. B **66**, 140511(R) (2002)

I. Pethes, A. Pomar, B. Sas, G. Kriza, K. Vad, Á. Pallinger, F. Portier, F. I. B. Williams: Potential and current distribution in strongly anisotropic $Bi_2Sr_2CaCu_2O_8$ single crystals at current breakdown
manuscript, submitted to *Phys. Rev. B*

I. Pethes, B. Sas, G. Kriza, F. Portier, F. I. B. Williams, K. Vad
Evidence for fast vortices from flux flow resistance in $Bi_2Sr_2CaCu_2O_{8+\delta}$
manuscript, submitted to *Phys. Rev. Lett.*