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Anisotropic energy dissipation in high-T_c ceramic superconductors: Local-field effects

D. López and F. de la Cruz
Centro Atómico Bariloche, S. C. de Bariloche, 8400 Rio Negro, Argentina
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In a recent communication Ji, Rzchowski, and Tinkham have interpreted the history dependence of the microwave surface resistance in polycrystalline $YBa_2Cu_3O_{7-\delta}$ in terms of granularity and flux flow. In this paper we show that the proposed model can be extended to understand the hysteretic dissipation, found in polycrystalline superconductors through I-V dc curves, for the case where the magnetic field lies parallel and antiparallel to the transport current.

Surface impedance measurements[1] of polycrystalline $YBa_2Cu_3O_{7-\delta}$ have shown that the dissipation in samples cooled below T_c in zero field (ZFC samples), is higher than the one obtained when the samples are cooled in an applied field, (FC samples). In this type of measurements for homogeneous type-II superconductors, where the number of vortices is greater in a FC experiment than in a ZFC one, the dissipation is expected to be proportional to the number of vortices locked in the sample. At the frequencies used in the measurements, (15 GHz), all vortices dissipate[1,2] energy as if they were unpinned. From this point of view the experimental results[1] in the $YBa_2Cu_3O_{7-\delta}$ ceramic contradict the above expectations. The explanation given by Ji, Rzchowski, and Tinkham[1] is based on the granular nature[3] of the superconductivity in the polycrystalline oxide superconductors. In granular superconductors the viscosity[4] for fluxons between grains[5] is much smaller than that of the vortices within the grains. As a consequence, the dissipation inside the grains can be neglected when compared to that between the grains. The larger microwave dissipation in ZFC experiments indicates[1] that there are more fluxons between grains in the zero-field-cooled samples than in the FC ones. According to Ref. 1, the reason for this is that in a ZFC experiment the grains are more diamagnetic, inducing higher flux concentration at the grain boundaries. Thus, despite the fact that magnetization measurements[6] show that ZFC samples have a smaller magnetic-flux fraction than the FC ones, the flux concentration between grains remains larger when the sample is zero field cooled.

It is concluded in Ref. 1 that surface impedance measurement is a unique technique for providing information on the local-field distribution in a granular material.

Prompted by the conclusions of Ref. 1 and by our own results[7] on zero field cooling, dc and very low frequency ($\simeq$ 150 Hz) I-V characteristics, we decided to measure the I-V curves in ZFC and FC superconducting samples.

Since in ceramic materials the above-mentioned characteristics are determined by the weak links between grains,[3,7] which are sensitive to the magnetic flux through them, we expect hysteretic effects in the I-V curve and we have found that this is the case, even when no Lorentz forces act on the intergrain fluxons. The results have been explained within the same picture proposed in Ref. 1.

We have measured the I-V curves of polycrystalline $La_{1.85}Sr_{0.15}CuO_{4-\delta}$. The advantage of using this material is that its H-T phase diagram has been determined in detail through magnetization measurements.[3,6] It was shown[3,6] that the granular behavior can be well described by a unique superconducting nucleation temperature at the grains, T_{c0}, and a single temperature T_c ,where superconducting coherence throughout the sample is established. The lower critical field H_{c1}, where vortices first penetrate into the grains, was also determined from remanent moment measurements.[3,6] These very well characterized samples are ideal to investigate the possible influence of the local-field distribution in the I-V characteristics.

The sample used for this work is a partially deoxygenated one with $T_{c0} = 37.1$ K and $T_c = 22$ K, prepared as described elsewhere.[8] It is thermally connected to the cold finger of a cryogenerator where the temperature can be controlled to within 0.1 K. A copper solenoid applies a field up to 50 Oe and a Helmholtz pair of coils is used to reduce the earth's magnetic field down to 0.05 Oe. The magnetic field can be rotated with respect to the direction of the transport current flowing in the sample. The I-V curves are measured by the conventional four-wire technique. The electrical contacts were made using silver paint on silver sputtered contacts. In this way the contact resistance was less than 1 Ω and the power dissipated in the measurements never heated the sample, within the experimental accuracy.

In the ZFC experiments the applied field H was kept below H_{c1} (T) of the superconducting grains.[3] In this case the grains are in the Meissner state and the magnetic field is concentrated in fluxons between grains. In the FC measurements the magnetic flux is distributed between vortices pinned inside the grains and fluxons located in the links between the grains.

Previous ZFC measurements[7] showed that the critical currents are typical of Josephson junctions as found in other ceramic superconductors.[9] It was found[7] that once the transport current exceeds a field- and temperature-dependent minimum value I_m, the voltage follows an expression of the form

$$V = \pm(I_T - I_m)^\alpha (A_1 + A_2 \sin^2 \theta), \qquad (1)$$

where A_1, A_2 are fitting parameters that depend on field and temperature, α is a fitting parameter weakly dependent on field and temperature, I_T is the transport current, and θ is the angle between the magnetic field and the transport current. Although the field and temperature dependence of A_1, A_2 and α are of relevance for a complete understanding of the granular behavior of these materials, we defer for a future work its discussion. In this paper we focus the attention on the hysteretic dissipation characteristics of the granular structure as a unique tool to detect the local magnetic field in materials where the metastability of the vortex state in the grains coexists with the dissipative behavior in the intergranular material. We wish to remark from expression Eq. (1) that the onset of voltage is characterized by a threshold current, independent of θ. After this value is reached there is extra dissipation associated with the movement of fluxons.

Figure 1 shows the I-V curves for $H = 20$ Oe in FC and ZFC experiments. In the figures we have plotted two FC curves. The first one is obtained just after cooling the sample in the applied field, for $\theta = 0°$, which we define as parallel orientation. The second is measured after cooling the sample in the field and then rotating the applied field by 180° and we call this the antiparallel direction. It is clear that the dissipation in the ZFC measurements lies between the other two. In the inset we show details of the FC curves, where the difference of the critical currents can be observed.

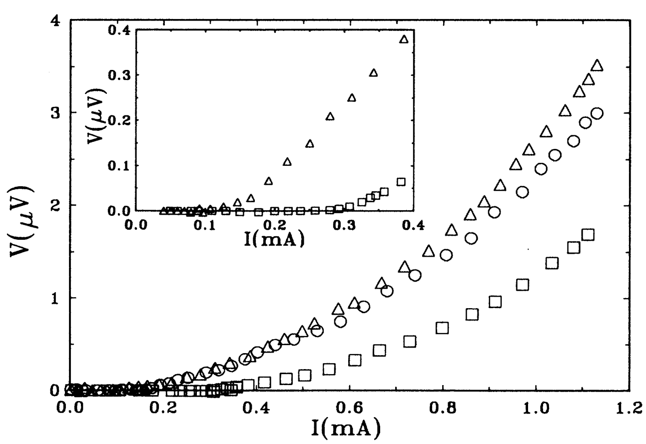

FIG. 1. I-V characteristic curve for ZFC and FC measurements, in $H = 20$ Oe and $T = 14$ K. (□), FC curve in the parallel orientation; (○), ZFC curve in the parallel orientation; (△), FC curve in the antiparallel orientation. The inset shows in an expanded scale the FC I-V curve when the voltage tends to zero.

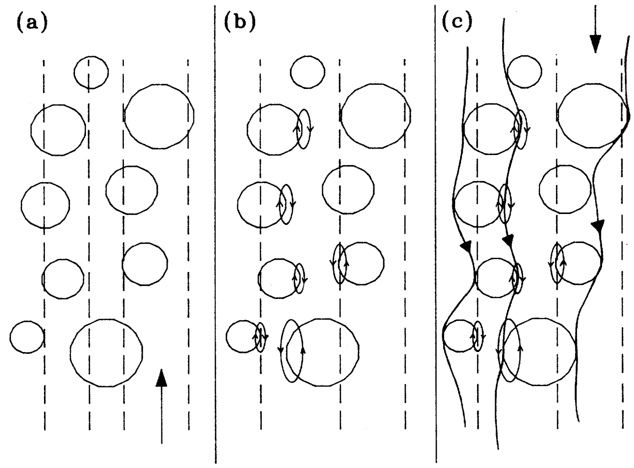

FIG. 2. Representative scheme of the local-field distribution in the (a) parallel FC configuration, (b) same as (a) after removing the magnetic field, and (c) antiparallel FC configuration. Note that the antiparallel FC case is equivalent to a FC experiment followed by a reduction of the applied field to zero, plus the field distribution of a ZFC experiment with $\theta = 180°$. Within this picture, the local-field distribution is higher in the antiparallel case.

The experimental situation described in Fig. 1 was not considered by Ji, Rzchowski, and Tinkham.[1] In our case there is no Lorentz force and, consequently, the dissipation is not associated[7] to flux flow. It can be argued that due to the superconducting granular nature of the material the vortices could bend to avoid the grains in the ZFC experiments, inducing a local Lorentz force even for $\theta = 0°$. However, it was previously shown[3,6] that the effective penetration depth for the intergranular fluxons is much larger (> 30 μm) than the size of the superconducting grains ($\simeq$ 2 μm); under this situation the fluxon

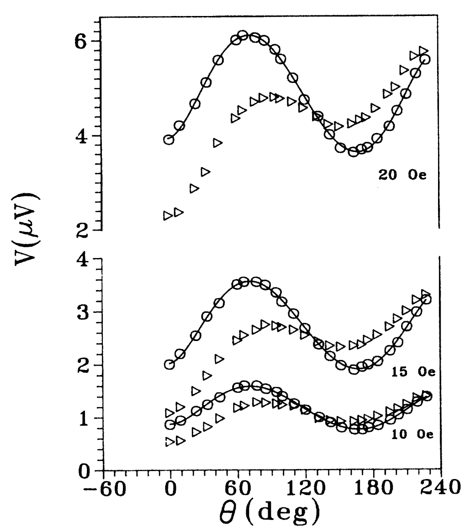

FIG. 3. Angular dependence of the voltage for a transport current of 1.1 mA and a temperature of $T = 14$ K. (△) is the FC experiment and (○) is the ZFC experiment. The solid line represents the fitting of Eq. (1) to the ZFC data.

should be taken as parallel to the applied field.

The results showing that the parallel FC curve with $\theta = 0°$ shows less dissipation than the antiparallel one, $\theta = 180°$, can be easily understood within the granular picture. Figure 2 shows a sketch of the field distribution in the parallel FC and antiparallel FC measurements. It is seen that the rotation of the field to $\theta = 180°$ increases the field induced between the grains by the vortices pinned inside the grains. As a matter of fact these results can be used to determine if the number of pinned vortices remains constant after rotation. In our experiments it was found that the measure voltage was reproduced after rotations of 360°, showing that at the temperatures and fields where the experiments were performed and within the typical time of the experiments, all vortices remain pinned. Thus the field-cooling results as those shown in Fig. 1 are quantitatively reproduced by FC the sample, then reducing the field to zero, and then increasing the field in the reverse direction to the same absolute value used when FC.

Figure 3 shows the complete angular dependence of the voltage, at constant current for FC and ZFC measurements. The results were obtained by a continuous rotation of the field at constant field magnitude. Similar results at other temperatures and fields, always at temperatures lower than T_c and fields below H_{c1}, were obtained.

The periodicity of the ZFC results with a period of π, indicates that the field distribution between the grains is determined by the external field and the demagnetization effects of the grains.

We conclude that measurements of I-V characteristics of the granular system are an excellent method to detect the local field in the links between grains. It is particularily interesting that the dissipation difference due to changes in the local-field distribution is detected even when the Lorentz force is zero. In this case the detection is possible due to the magnetic flux dependence of the Josephson critical currents of the links.

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