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STUDY of the REMANENT MAGNETIZATION of $Bi_2Sr_2CaCu_2O_8$ SINGLE CRYSTALS by MEANS of a HALL PROBE

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Using a sensitive Hall probe, the remanent magnetization of $Bi_2Sr_2CaCu_2O_8$ single crystals has been measured accurately as a function of temperature. The interpretation of the results is based on the modified Kim-Anderson critical-state model. An explanation of some of the commonly observed history dependencies is proposed, as well as the finite value of the remanent magnetization. A fast and accurate method has been developed for characterizing the temperature dependence of the critical current density.

1. Introduction.

A special place among the new superconductors belongs to the Bi- and Tl- based compounds which are characterised by an exceptionally high anisotropy of their electronic properties, resulting in a quasi two-dimensional behaviour which manifests itself in the critical current density, in the critical fields, and in the irreversibility line. The initially reported $(T_c\text{-}T)^{3/2}$ temperature dependence of the irreversibility field in high-T_c materials is quite different from what later on is observed in $Bi_2Sr_2CaCu_2O_8$. Instead, at high temperatures, an exponential dependence is observed, $\ln(1/H_{irrev}) \sim T$. Below 20-30 K, H_{irrev} steeply increases from about 1 kG, up to huge field values[1]: at T=4K, the irreversibility field is not reached even at 40 T.

One of the consequences of the small values for the irreversibility field above 20 K is the experimentally observed rapid suppression of the critical current density by magnetic field. In this paper we analyze some of these properties, connected with the strong field suppression of the critical current density. We develop an easy and fast method of characterization of the superconducting properties by measuring the temperature dependence (during slowly heating) of the remanent magnetization. The critical state model is used for the analysis of the remanent magnetization. Despite the simplifications introduced into this model, it still remains a useful tool for a description of the magnetization process[2], as a first approximation to the quasi-static phenomena in the high-T_c superconductors. We find a simple argument for the observed independence of the remanent magnetization on the sample size: it is due to a suppression of the critical current by field.

2. Experimental details.

The results reported in this paper were obtained on two samples, prepared by a travelling-solvent-floating-zone technique and characterized by a sharp superconducting transition in the ac susceptibility. Sample No 1, of the size 2.8 x 3.6 x 1.35 mm^3, has a T_c value of 90 K, and sample No 2, of the size 4.8 x 6.6 x 1.75 mm^3, shows the superconducting transition at 87 K. The difference in the T_c values for both samples is probably due to a different oxygen stoichiometry. The crystallographic c-axis is perpendicular to the large surface of each sample and this was the direction of the applied magnetic field. In measuring the magnetization we use a commercial Hall probe (supplied by Lake Shore Cryotronics, Inc.) as a sensor of the magnetic field at a distance of 0.5 mm from the surface of the magnetized sample. Its sensitivity is 8 $\mu\Omega$/G and the size of the active area is about 1 mm in diameter. With the Linear Research resistance bridge LR-400, an excellent stability, linearity of response on field and an extremely small temperature dependence of the background signal is obtained. At certain conditions, we can easily reach a resolution of about 10 mG, which is comparable to that reported by other experimentalists[2,3,4]. The sensitive area of our Hall probe is comparable to the sample size and the measured stray field is related to the magnetization of the sample (this problem has been discussed widely in literature[5-7]). There is a good agreement between our results and those of the SQUID measurements in Ref. 8, which were performed under similar conditions. We made a calibration at low fields and low temperature, measuring the virgin magnetization curve in the Meissner state. If the magnetization is defined as H_s-H, where H_s is the field registered by the Hall probe and H is the externally applied field, we obtain $M=H_s\text{-}H=-0.39\cdot H$ for sample No 1. We are far from the case of perfect screening of the field by the sample, where $M=-H$ should be obtained. In order to have the actual magnetization, the quantity H_s-H should be normalized by 0.39. This is a very good approximation for higher fields, in case the flux distribution in the sample volume

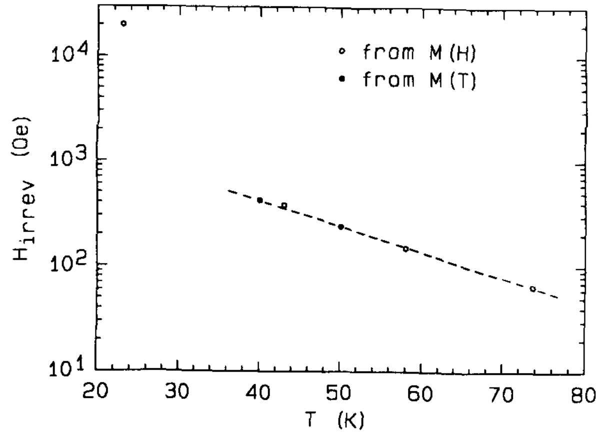

Fig. 1. A comparison between the values for the irreversibility field H_{irrev}, as determined from M(H) and from M(T) curves for sample No 1.

corresponds to the flux distribution in the Meissner state, i.e. when the supercurrent flow occurs within a thin surface layer of the sample. In case the magnetic induction changes across the sample in another way, this normalization can not be valid exactly but still it may be accepted as a good approximation.

We observe a very rapid decrease of the ZFC (zero-field cooled) magnetization at a temperature that is dependent on the magnetic field used. It is caused by a very fast drop of the critical current density at temperatures around 20-40 K. The point of coincidence between the FC (field cooled) and ZFC curves is a signature of the transition into the reversible region in the H-T plane. In Fig. 1, we compare the values for H_{irrev}, determined from M(H) and M(T) measurements. Both methods give similar results, which are close to those obtained in other reports[8]. Above 40 K, straight lines can be drawn through the data points in a plot of $\ln(H_{irrev})$ versus T, up to temperatures a few degrees lower than T_c. The irreversibility field H_{irrev} depends on temperature in a similar way as the critical current density[9].

3. Remanent Magnetization.

In Fig. 2. the remanent magnetization of sample No 2 is shown, measured after cooling the sample in field. At low temperature the field is removed, and the quasi-static remanent signal is measured during slowly heating the sample, with a temperature change rate of about 1K/min. At point A on curve b) the temperature starts to decrease, reaching point B, and then the temperature increases again, up to the point C, where a similar experiment is performed again. The results suggest that the shape of the flux profile after the decrease, and next at the increase of temperature between points A-B and C-D, is unchanged. We observe also that the remanent signal is initially different for a) and b), but there is a coincidence between both curves at higher temperatures. In Fig. 3 we present results of further studies of these effects.

One should consider the results in Fig. 3 together with the description of the experimental conditions for each data-set from a) to d) as contained in Table I.

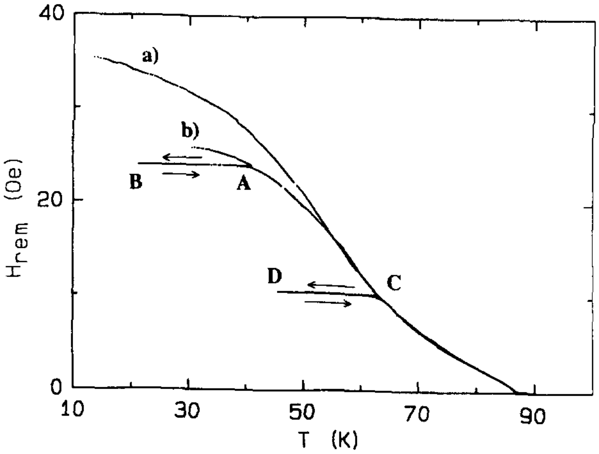

Fig. 2. The remanent magnetization (magnetic field at the sample surface) of sample No 2, measured after cooling the sample in field: a)-60 Oe, b)- 50 Oe. At low temperature the field is removed, and the quasi-static remanent signal is measured during slowly heating the sample. At point A on curve b) the temperature starts to decrease, reaching point B, and then the temperature increases again, up to the point C, where a similar experiment is performed again.

All measurements were performed after cooling the sample from temperatures above T_c, to $T < T_c$, without an external field. Then, at constant temperature T_{init}, given for each data-set in the Table I, the virgin magnetization curve has been registered, up to the field H_{max}. At fields exceeding the first critical field a departure of the signal from a linear dependence on field is observed, which is used for an estimate of the field for the first full penetration into the sample centre, H^*, as given in Table I. Next, the field has been removed. The quite fast initial decay of the remanent magnetization passes quickly to a very slow decay and changes occurring after, for instance, 1 min are not noticed at all in the scale of this figure. M_{rem} becomes quasi-static. Based on these and other not-shown data, we find a simple and clear tendency: M_{rem}

Table I. The measurement conditions for the results presented in Fig. 3. The H^* values in this table were determined approximately from analysis of the slope of $(4\pi M(H)+H)^{1/2}$ vs. H. This method gives an exact value for H^* only in case the critical current density is independent of the magnetic induction.

Data	T_{init}(K)	H_{max} (kOe)	H^* (kOe)	H_{max}/H^*
a)	21	1	15	0.07
b)	24.2	0.5	4	0.125
c)	18	26	20	1.3
d)	23	24	5	4.8

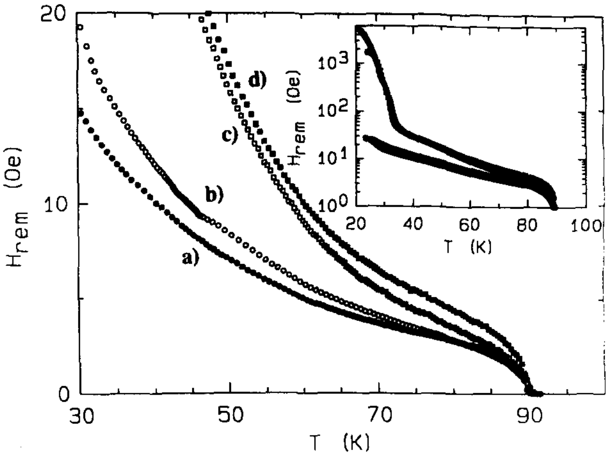

Fig. 3. The remanent field H_{rem} registered after the field H_{max} has been applied, and removed at temperature T_{init} for sample No 1. Table I contains information for all curves from a) to d) about the field H_{max}, temperature T_{init}, and H^* at the temperature, where the magnetic field was removed. Inset presents the same curves in a $\log H_{rem}$ vs. T plot in a larger temperature range.

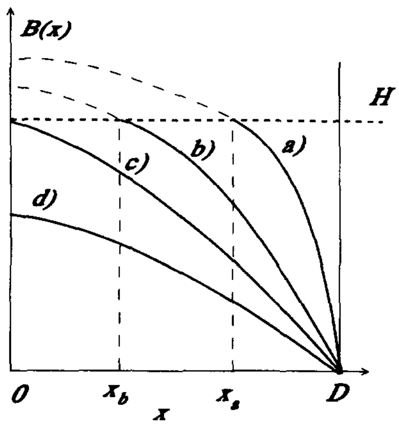

Fig. 4. The proposed evolution of the field profile in the sample, represented by the solid lines. For $x < x_a$ and $x < x_b$ for curves a) and b), respectively, the magnetic induction is constant. Curve a) is obtained when the magnetic field $H < H^*(T_1)$ is removed at $T = T_1$, after FC. Curve b) represents the changed field profile at $T_2 > T_1$. If temperature decreases from T_2 to T_1, then at T_1 the flux profile will remain the same as the one represented by curve b). Curves b), c) and d) are obtained when the field $H^*(T)$ becomes equal and subsequently higher than the field H removed at $T = T^1$, during temperature increase.

increases and finally saturates, when $H_{max}/H^*(T_{init})$ becomes larger than 1, independent of the initial conditions (temperature T_{init} and $H^*(T_{init})$). After a quasi-stable remanence is reached at low temperatures, we increased slowly the temperature and measured the curves a)-d) as given in Fig 3. We performed, without success, a few tests, whether it is possible to obtain larger values of $M_{rem}(T)$ than the ones represented by curves c) and d). The ratio of the registered $M_{rem}(T)$ to the maximal possible remanent magnetization at a given temperature, represented by curves c) and d), changes weakly with temperature, despite the tremendous change of the remanence itself. Near to T_c only, this rule does not work. We propose the following, simple model of these phenomena, illustrated in Fig. 4.

After switching off the magnetic field at $T = T_1$, in a part of the sample volume a critical current is induced. When temperature increases, the flux pinning is weakened, a certain number of vortices leaves the sample volume and the critical current density decreases, until a new, quasi-stable flux gradient is established. If, however, temperature is lowered, the repulsive inter-vortex force becomes lower than the pinning force, prohibiting vortex movement. The current density and the magnetization remains the same (Fig. 2). Then the current flowing in the sample volume is lower than the critical current density, which is possible of course, although not within the critical state model, where it can have only discrete values: 0 and $\pm J_c$.

The dependence of $M_{rem}(T)$ on the initial value of $H_{max}/H^*(T_{init})$, shown in Fig. 3, may be understood as due to the "stiffness" of the flux profile. Increase of temperature decreases its amplitude but has a rather weak effect on its shape. Deviation from this rule at higher temperatures should be considered as a possible result of weak, but still present relaxation effects, spreading out from the region with $J_c \neq 0$ into the sample centre.

4. Kim-Anderson Critical State Model.

In order to carry out a more quantitative analysis, we performed calculations of M(H) based on a modified Kim-Anderson formula for defining $J_c(B)$ by which a quite general class of situations can be obtained: $J_c = \alpha/(B+h)^n$, with $J_c(0) = \alpha/h^n$. For $n = 1$, the standard Kim-Anderson expression results, while for $n = 0$ the Bean critical state model is obtained.

We consider the simplest possible geometry: a slab of thickness 2D, with the external magnetic field H applied along the large surface of this slab (this geometry is chosen to simplify calculations and does not correspond to our experimental arrangement; it is known, however, that the result of this type of calculations depends mainly on a certain characteristic sample dimension and not so much on the geometry of the sample). For simplicity, we neglect the effect of the Meissner state, although the applied field should exceed the first critical field H_{c1} in order to achieve the critical state in the superconductor. However, more exact calculations[10] do not change significantly the obtained results for M(H). The details of our calculations and the comparison with experimental M(H) results will be reported elsewhere[11].

The following expression for the field H^*, corresponding to the first full penetration of the magnetic field into the centre of the slab, is used[11]:

$$H^* = \left(h^{n+1} + \frac{4\pi}{c}\alpha\cdot(n+1)\cdot D\right)^{\frac{1}{n+1}} - h \qquad (1)$$

From eq. 1, an expression for H^* in the classical Bean model (J_c independent on field, i.e. for $n=0$) is obtained: $H^*=4\pi/c\ \alpha D$, as well as an expression in the modified Kim-Anderson model, for $h \to 0$ and $n=1$: $H^*=(4\pi/c\ 2\alpha D)^{1/2}$, in agreement with other results[12]. The remanent moment depends on the history of the sample. Let us cool down the sample in the FC procedure, in the field H. The magnetization is quite small in the FC state and we can assume that the magnetic induction inside the sample is uniform and equal to the applied external field H. Reduction of the magnetic field at a certain temperature results in the induction of a surface critical current. The shape of the flux profile will depend on the value of the field H. If this field in the FC procedure was smaller then H^*, the induction B in the sample region close to its centre remains unchanged and it starts to decrease at a certain position, $x>0$, reaching $B=0$ at the sample surface. If H was higher than H^*, B changes from the value H^* at the centre, to zero at the surface. It is interesting to note that the remanent magnetization is independent of the amplitude of the magnetic field H, if this field is larger than H^*. For that case[11], the positive remanent magnetization (average of the magnetic induction over the sample volume) is given (in the FC state) by:

$$4\pi M_{rem} = \frac{n+1}{n+2} \cdot \frac{(H^*+h)^{n+2}-h^{n+2}}{(H^*+h)^{n+1}-h^{n+1}} - h \qquad (2)$$

The same equation is obtained for the remanent magnetization in the ZFC state, but for applied and removed external fields larger than about $2H^*$ ($2H^*$ holds for the Bean case, while a little smaller maximal field sweep is required if $n>0$). It is easy to check, using eq. 2, that for $h \ll H^*$ the remanent magnetization $4\pi M_{rem}$ is close to $(n+1)/(n+2)H^*$, while for $h \gg H^*$ it becomes similar as in the Bean model, i.e. $4\pi M_{rem} \approx H^*/2$. If the magnetic field in the FC state is smaller than H^* at the temperature T where this field is removed, then the remanent magnetization will be smaller than that given by 2). The quite well defined value of the maximal remanent magnetization, $H^*/2 < 4\pi M_{rem} < (n+1)/(n+2)H^*$, gives a possibility to use the measurements of $M_{rem}(T)$ as a method for sample characterization. In the studied material, the n values fitting well the magnetization hysteresis curves in the intermediate fields (well above H_{c1} and well below H_{irrev}) range between 0.5 and 1.

We note that the temperature dependence of the remanent magnetization for the data points c) and d) in Fig. 3 follow very well the reported[9] exponential character of $J_c(T)$ at high temperatures and the steep increase at lower T. Just close to T_c, approximately a $(T_c-T)^{2/3}$ temperature dependence is obtained, observed by us for both samples (Fig. 2 and 3).

In the presented model, the field H^* and the remanent magnetization weakly depend on D if n is large (eq. 1). The n values observed in our experiment are rather low. However, it is possible to impose an even stronger, although less accurate restriction on the upper limit of the remanent magnetization. The here assumed critical current density, defined by the modified Kim-Anderson relation, is overestimated for fields close to H_{irrev}. If the existence of the irreversibility field is taken into account, the magnetic induction profile obtained after sweeping the field to a certain field $H>H_{irrev}$ and next to zero, has such a form that the maximal possible value for B inside of a sample volume never exceeds H_{irrev}. As a result, the remanent moment divided by the sample volume can never exceed H_{irrev}, independent of the function $J_c(B)$ and of the sample shape (in the Bean model it is of the order of H^*, which is proportional to the linear size of the sample): $4\pi M \ll H_{irrev}$. This is the simplest possible proof on the existence of an upper limit of the remanent magnetization, and also for the finite width of the magnetization hysteresis curves at large fields, for any sample size. As a result, the remanent magnetization is not scalable with the sample volume, in agreement with experimental observations in YBCO[13] and BSCCO[14] single crystals. The function $M_{rem}(D)$, initially linear for sufficiently small D, must become independent of D, for sufficiently large D. We do not need to introduce the concept of a hidden granularity of the single crystals[13] or the concept of a surface barrier for flux movement[14,15], in order to explain the independence of the remanent magnetization and the magnetization hysteresis width on the sample size.

5. Conclusions

We present an explanation of the reported independence of the remanent magnetization on the sample size, as an effect of a strong field dependence of the critical current $J_c(B)$. This is a result of the softening of the vortex pinning, which occurs at the irreversibility line, in fields below 1 kOe at temperature higher than about 30 K. Measurements of the remanent magnetization provide a simple and fast method for characterization of the superconducting properties of new materials. There is a possibility to use $M_{rem}(T)$ as a method for sample characterization: for a large range of parameters n and h in the Kim-Anderson formula, the maximal possible values of $M_{rem}(T)$ may be assumed to be proportional to $H^*(T)$, a quantity related to the critical current density.

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