Irreversibility Lines and Pinning Force Density of Aligned $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ Single Crystals

Shaoyan Chu and Michael E. McHenry
Department of Materials Science and Engineering,
Carnegie Mellon University, Pittsburgh PA 15213

Abstract—DC Magnetic properties of aligned $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ single crystals have been measured for the first time using SQUID magnetometer in field up to 5 T and in the temperature range from 5 K to 150 K. The results confirm the existence of a broad temperature and field regime with completely reversible magnetization for these crystals. The temperature dependence of the irreversibility field H*(T) is determined from both M-H and M-T curves with fields oriented perpendicular to the ab plane of the crystal lattice. A strong field dependence of critical current density has been observed in these pristine single crystals with very weak pinning. These observations emphasize the importance of artificially introducing pinning sites in BSCCO material used for applications. Non-linear scaling models have been used to fit our experimental results to estimate the elemental pinning force density and the effective pinning potential.

I. INTRODUCTION

The temperature dependent irreversibility field H*(T), or irreversibility line (IL), is an important phase boundary in the H-T magnetic phase diagram of all layered high T_c superconductors. Below the IL a high T_c superconductor exhibits hysteretic response, while above the IL, the magnetic response is reversible and accompanied by a non-vanishing electrical resistivity. However, the physical interpretation of this phase boundary is still the subject of extensive theoretical and experimental studies. In some literature accounts, the IL is interpreted in terms of thermally activated flux flow or as a melting transition caused by thermally induced vortex/anti-vortex dislocation pairs. In explanation of very recent experimental data, it is claimed that the shapes of M-H curves as well as the vortex melting line reflect the field dependence of the pinning properties [1], [2]. Knowledge of the IL in HTSC materials can lead to new insights into the physics of the vortex state and materials limitations for applications.

Despite the large number of papers published on studies of the vortex state in the BSCCO system [3]-[7], there is still an open question as to the the equilibrium H-T phase diagram in Bi-2223 single crystals. Recent achievements in growing single phase Bi-2223 single crystals provided us with an opportunity to investigate this subject [8]. Further, using single crystal sample with weak pinning we can offer an important comparison with the apparently stronger pinning in tapes or wires containing the Bi-2223 phase. Here a standard determination of the IL is employed, which relies on M-H or M-T as is frequently reported in literature [9], [10]. At low temperature, H*(T) is determined using a scaling relation for the critical current and/or pinning force density. We also estimate the effective pinning potential, $U_{eff}(J)$, in our sample using linear and non-linear scaling models.

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II. EXPERIMENT

$(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ single crystals were grown using a fused-salt reaction technique [11]. The high-quality of the crystals has been confirmed by magnetization measurement, x-ray diffraction, TEM, SEM and EDX techniques [8]. A typical single crystal is shown in Fig. 1. The sample used in this paper consisted of a collection of 472 single crystals pressed in a piece of indium foil and aligned with the c-axes normal to the foil. Based on the x-ray diffraction pattern (shown in Fig. 2), the volume fraction of Bi-2223 phase in the sample is estimated to be above 97%. While some single crystals, checked individually, are shown to have a perfect Bi-2223 structure, a small fraction of the Bi-2212 phase persisted in the collection due to accidental selection. This small amount (less than 3%) of Bi-2212 phase crystals should not have an important effect on the magnetization measurements reported in this work.

DC magnetization measurements were carried out on the sample with magnetic field perpendicular to the ab plane of the BSCCO crystal lattice. The data shown in this work were obtained using a SQUID magnetometer (Quantum Design, MPMSR2) with a 3 cm scan length and an averaging of at least 6 scans to improve the statistics of the data. The raw SQUID signals were analyzed using a customized program which subtracts background signal from the recorded signal before calculating the magnetization of the Bi-2223 crystals.

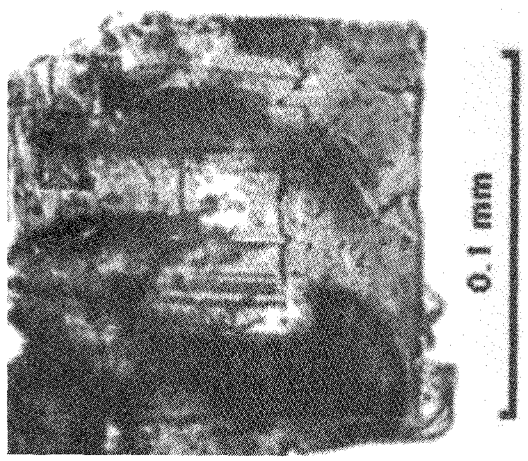

Fig. 1. Optical image of a typical $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ single crystal.

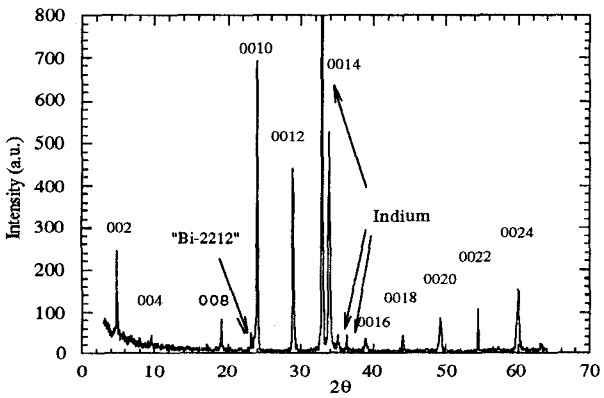

Fig. 2. X-ray diffraction pattern of the aligned Bi-2223 single crystals used in this work.

III. RESULT AND DISCUSSION

The temperature dependence of the DC magnetic moment of the aligned Bi-2223 single crystals is shown in Fig. 3. The Zero Field Cooling (ZFC) and Field Cooling (FC) data were taken at low field (~0.2 Oe). Using a linear extrapolation above the onset of the superconducting diamagnetic transition, T_C was determined to be 110 K. No visible contribution to the diamagnetic signal from the Bi-2212 phase is observed, consistent with the high quality of our sample.

We have determined the IL from DC magnetization data using two methods. In the first, we sweep the field at constant temperature and take the point were the hysteresis loop closes as the irreversibility field, $H_{irr}(T)$. In the second, we sweep the temperature at fixed field and take the point where the ZFC and the FC branches merge. Typical experimental data for both methods have been illustrated in Fig. 4. In the case of ZFC and FC branches, the irreversibility temperature $T_{irr}(H)$ was taken to be the temperature at which a magnetization difference between ZFC and FC branches, $\Delta M(T)$, becomes less than the value of the standard deviation in this temperature region. This corresponds to an upper bound of the critical current, J_c, of ~100 A/cm^2 calculated from the Bean model and depending on the average size of our crystals. In

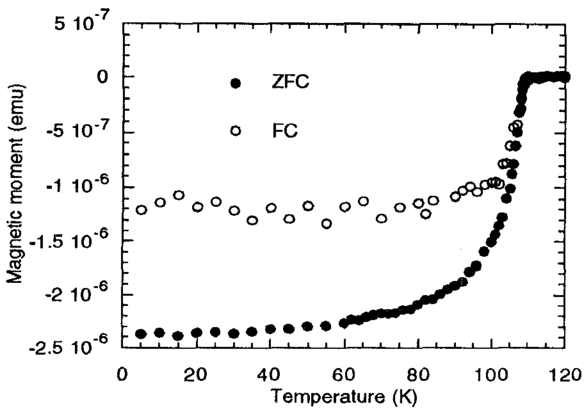

Fig. 3. Temperature dependence of DC magnetic moment (ZFC and FC curves) at low field (~ 0.2 Oe).

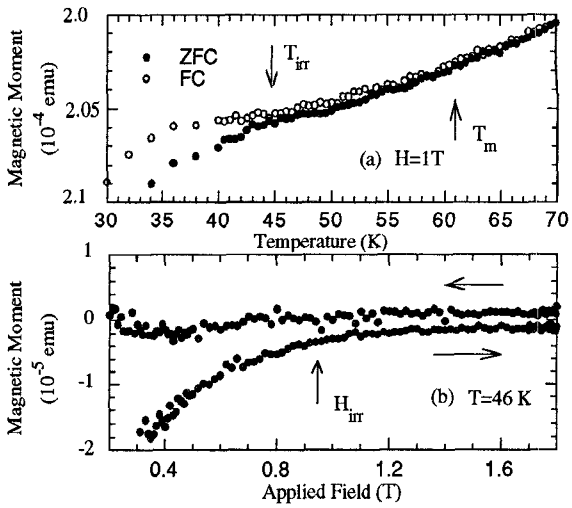

Fig. 4. Examples of the variation in the magnetic moment as a function of temperature (a) and a function of applied field (b) for defining $H_{irr}(T)$ and $T_{irr}(H)$ respectively.

principle, same sensitivity can be obtained using magnetic hysteresis loops at constant temperature. However, we found problems in this approach because of uncertainty in the remanent field trapped in the SQUID system's superconducting solenoid [10].

Fig. 5 shows the experimentally determined H*(T) irreversibility line, summarizing the results of study of the vortex state of our Bi-2223 single crystals. Just as for Bi-2212 single crystals [12], our data also show the $H_{irr}(T)$ and $T_{irr}(H)$ values to be nearly identical, implying that the determination of the IL is independent of the experimental method (magnetic loop or ZFC-FC branch). Equilibrium conditions for the vortex state in the BSCCO system may prevail in the both cases if the experimental artifact, field trapping, can be avoided. In comparison with polycrystalline Bi-2223 samples (wire [4], tape [7] and random orientation [6]) our data give a lower IL.

A sharp jump in the magnetization is observed in both M-H and M-T curves which is taken as evidence of vortex-lattice melting transition in the Bi-2223 phase similar to that observed in Y-123 and Bi-2212 single crystals [1], [2], [13], [14]. We have observed the vortex-lattice melting boundary in the H-T phase diagram for our Bi-2223 single crystals to be more than 10 K above Tirr(H) at an intermediate field (~1T) [15]. However, until now no observations of such a magnetic jump in polycrystalline samples have been made. These samples usually exhibit a higher IL masked by stronger pinning. It have been suggested that a high-quality crystal with low density of defects, providing weak pinning in the mixed state, offers a better system to observe the intrinsic IL. In pristine crystals one expects to see a vortex-lattice state below the vortex lattice melting temperature, T_m, rather than a vortex-glass state. It is therefore a better system to probe the first-order phase transition from the vortex-lattice to liquid state in passing through T_m. We should emphasize here, the flux pinning (caused by both bulk pinning and

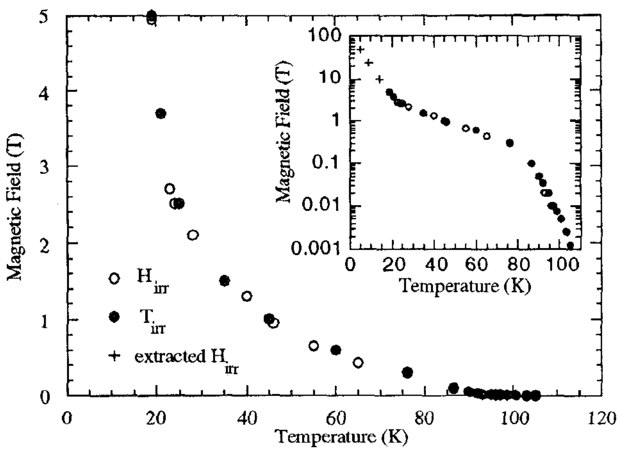

Fig. 5. The irreversibility field H* (H//c) in H-T phase diagram determined by both of M-H and M-T curves (circle and dot) and extracted from (1) with experiment results at high temperature (cross).

geometrical effects) has a strong influence on the IL, suggesting an alternative interpretation of the IL as a depinning line rather than a flux lattice melting.

Based on the critical state model, the critical current density, $J_c(H,T)$, is dependent on the reduced magnetic field, $b=H/H_{irr}\approx B/B_{irr}$, for field regimes where the magnetization is small compared with the applied field, H. The critical current density, J_c, (normalized by its value at H = 0, J_{c0},) for our crystals is shown in Fig. 6, where H* is determined from IL or its extrapolation. A steep field dependence of critical current density is again implicated in the weak pinning state of our sample.

The reduced critical current, J_c/J_{c0}, and pinning force density, $f_P=J_cB$, at low temperature fall on a universal curve. However, deviations from the universal curve can be seen for the data at higher temperature (T > 24 K). An interpretation of the higher temperature data requires a more detailed description of the relaxation of the critical state over experimental times due to flux creep.

The scaling of the hysterically determined J_c can be described as a function of the reduced field, $b = B/B_{irr}$, i.e. $J_c=F(B/B_{irr})$. This describes pinning behavior in hard type-II materials for conventional superconductors as well as high T_c superconductors [16], [17]. The scaling of the pinning force density is found to follow the field dependence $f_P \propto f_{P0}F(B/B_{irr})$ with the scaling function:

$$F(b)=b^p(1-b)^q \qquad (1)$$

Fits to the data shown in the inset of Fig. 6 yield the exponents $p\approx0.63$ and $q\approx2.04$ (T=19 K) which can be compared with $p\approx2$, $q\approx4$ for Y-123, $p\approx1$, $q\approx4$ for La-214, $p\approx1$, $q\approx4$ for Bi-2212 single crystals described in [3] and $p\approx0.5$, $q\approx2$ for Bi-2223 polycrystalline samples [4]. The difference in the exponents may imply a different pinning mechanism.

We note here, the scaling field, H* (for the data shown in Fig. 6) at low temperature (T<19 K) is chosen in such a way that the values of J_c fall on the same universal curve as the J_c data at higher temperature (T>19 K). H_{irr} can be directly determined by DC magnetic measurement as described in Fig. 3. Expression (1) can be transformed into a linear form for the given values of p and q, $B^{(1-p)/q} \propto 1-B/B_{irr}$. Plotting $B^{(1-p)/q}$ against B, an extrapolation to B axis yields $B_{irr}(\approx H_{irr}$, i.e. H*) for a given temperature.

The scaling of f_P can be understood appealing to a linearized model for relaxation of magnetization current as a result of flux creep [17]. In this model the magnetization current J(B,T) may expressed as:

$$J(B,T) \propto m(t)=m_o[1-(k_BT/U_o)\ln(t/\tau_o)] \qquad (2)$$

where m_o and U_o are magnetic moment (in the absence of thermal activation) and the volume pinning energy respectively. τ_o is the inverse of a flux hopping attempt frequency. Fig. 7(a) illustrates magnetic relaxation data in an applied field of 0.5 T. Using the linearized model (2), the values of k_BT/U_o shown in Fig. 7(b) could be used to estimate the pinning potential U_o. However such a description is limited. The relaxation phenomena in high T_c superconductors indeed is usually a nonlinear problem [17].

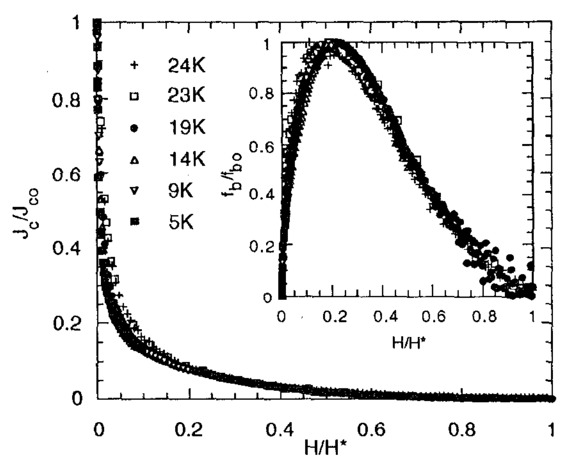

Fig. 6. Normalized critical current density and pinning force density (inset) versus reduced magnetic field.

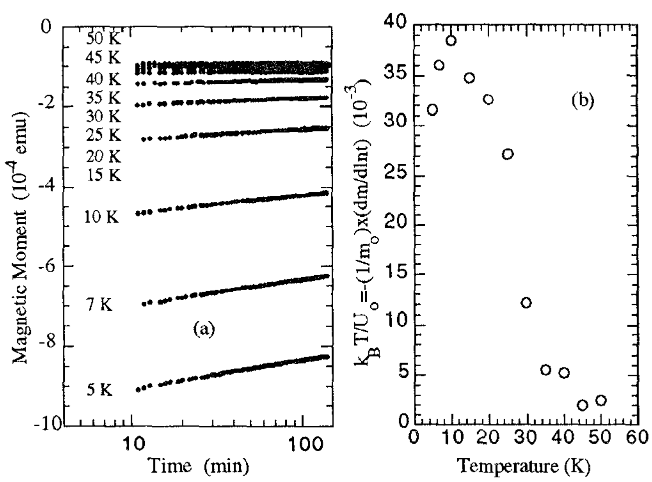

Fig. 7. (a) Magnetic moment relaxation data m(t) at H=0.5 T and (b) the values of k_BT/U_o determined by the linearized model (2).

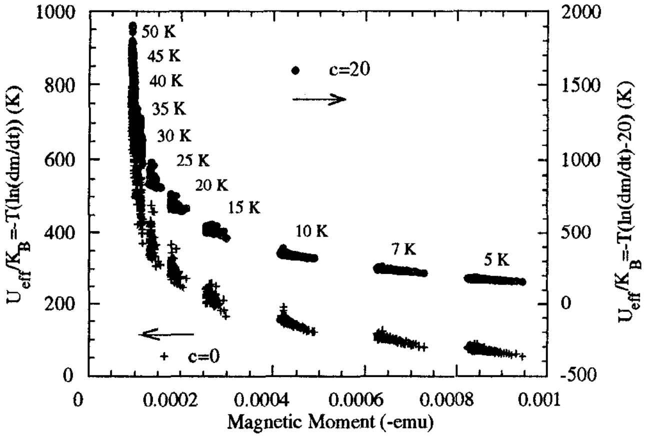

Fig. 8. Estimate of U_{eff} determined from the data in Fig. 7-(a) by using (3) with c=0 (cross) and c=20 (dot).

Following [17] and [18], the non-linear effective barrier energy to flux motion, U_{eff}, can be arrived at using the expression for a slab (of thickness d) geometry:

$$U_{eff} = -k_B T[\ln|dM(t)/dt| - \ln(Hv_o a/2\pi d) = -k_B T[\ln|dm(t)/dt| - \ln(Hv_o av/2\pi d)] \quad (3)$$

Where v_o, a and v are attempt frequency, the hop distance for fluxons (or flux bundles) and volume of the sample. Taking the constant $c=\ln(Hv_o av/2\pi d)$ as a temperature independent scaling constant to fit our data, we obtain $U_{eff}(J)/k_B$ as a function of magnetic moment in Fig.8. These data, as of yet uncorrected with an appropriate temperature scaling function, indicate that U_{eff} is a strongly non-linear function of $J_c(H,T)$. We will discuss this topic in further detail in the future.

IV. CONCLUSION

Magnetic hysteresis loop and magnetization branches curves for aligned Bi-2223 single crystals have been used to determine the irreversibility line, IL. Comparing with polycrystalline samples, our data show a weak pinning state. At low temperature, the scaling behavior of pinning force for this sample can be expressed as $\propto (B/B_{irr})^{0.63}(1-B/B_{irr})^{2.04}$. The magnetic relaxation data show the effective pinning potential to be a strongly non-linear function of current density, $J_c(H,T)$.

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