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Pinning energy in HTSC and its influence on electric and magnetic properties

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Abstract

We investigated the voltage-current (V-I) characteristics in polycrystalline, melt textured and epitaxially grown Bi-2212 superconductors, in Bi-2223 melt textured Ag tapes and in Y-123 films. In all samples the V-I curves are well described by a power law behaviour $V \propto I^p$ over many orders of magnitude in the voltage V. With increasing magnetic field and temperature the exponent p decreases with 1/B from a maximum at $p = 10$ -20 down to the ohmic limit $p = 1$. In a double logarithmic plot the V-I lines extrapolate to a common hinge point. These results are interpreted within the frame of thermally activated flux creep. From the measurements on thin films and bulk of $Bi_2Sr_2CaCu_2O_x$ we derive an expression for an effective activation energy $U_{eff}(B,T,j) = 60$ meV/B $(1-T/T_c)^{5/2}$ ln j_0/j. We show that a number of experimental observations are in accordance with this explicit result. In particular (a) exponential decay of the critical current density with field, (b) nonlogarithmic flux creep and (c) the irreversibility field $B_{irr}(T)$ emerge as consequences of the specific functional dependence of U_{eff}.

1. Introduction

Since the discovery of high temperature superconductors (HTSC) the nature of flux line pinning is a subject of intensive investigations. Proposed crystalline defects, acting as pinning centers, range from large precipitates of the 211-phase in YBaCuO [1] to small defects like oxygen vacancies [2] resulting in a collective pinning force.

In contrast to classical superconductors, the critical current density j_c is not only determined by the volume pinning force. At elevated temperatures, thermally activated depinning plays a crucial role, causing flux creep and dissipation far below the depinning critical current. These flux creep effects are a critical issue for the application of HTSC in magnet- and energy technology [3].

According to Anderson and Kim [4] the probability for a pinned flux line to escape a pinning potential well is given by exp -U/kT. The activation energy U is considered to be the elementary interaction energy between a defect and the flux line lattice. Thus flux creep experiments are an essential tool to investigate the individual pinning mechanism. The aim of this work is to investigate this effective interaction U as a function of temperature, magnetic field strength and current density in a variety of Bi-based materials over a broad range of temperatures and fields. Further we demonstrate, how U is correlated to electric and magnetic properties like critical current and magnetic irreversibility.

2. Voltage-current characteristcs

Dissipation due to thermally activated flux motion gives rise to a resistive voltage along the current path. The standard method is the observation of the irreversible magnetization, where the voltage gives rise to a nonlinear decay of the induced current with time. In the standard interpretation [4] the relative decay rate 1/M(0) dM/d lnt is quivalent to the quantity kT/U. From the M(t)-curve the underlying voltage-current (V-I) relation may be recovered [5-7]. As the observable time window is limited to typically 10^2-10^4 s in a SQUID-magnetometer, only a small section at a low level of the electric field $E \approx 10^{-12}$-10^{-14} V/cm can be covered. Using a torque magnetometer [6] or a vibrating sample magnetometer [7] the time window starts at 1 - 10 s and an accordingly larger part of the V-I curve may be observed.

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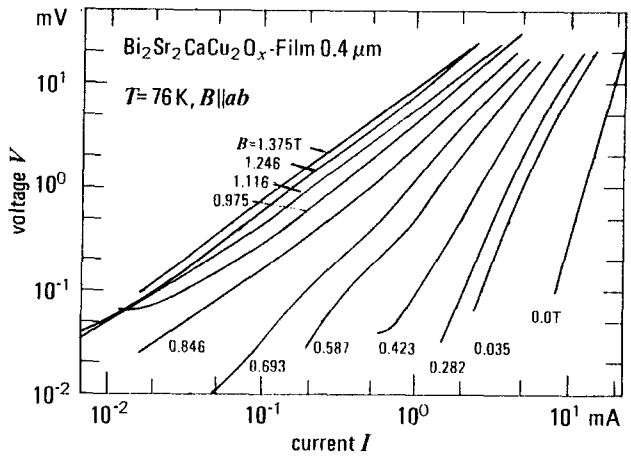

Figure 1: Voltage-current curves in Bi-2212 thin film on $SrTiO_3$

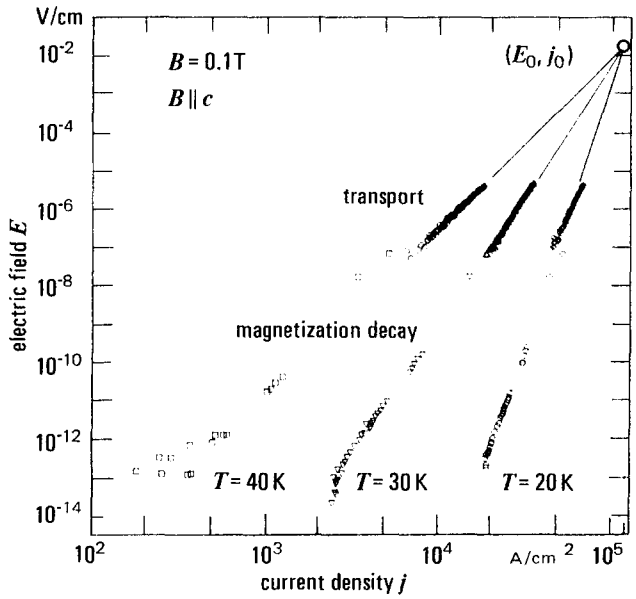

Figure 2: V-I curves in 12 μm layer of melt textured Bi-2212 on Ag-tape

This work is largely based on measurements of V-I curves and its interpretation in the light of flux creep theory.V-I curves on a number of rather different HTSC-materials have either been measured directly in four-terminal geometry or have been calculated from magnetization decay. Some examples are shown in figures 1-4. Fig. 1 is a 0.4 μm thick epitaxially grown Bi-2212-film [8] , fig. 2 a polycrystalline melt textured Bi-2212-layer prepared on an Ag tape by the Doctor's Blade method [9]. In fig. 3 the V-I curves for powder-in-tube tapes of Bi-2223 material are obtained by Hergt et al. [6] using torque magnetometry.

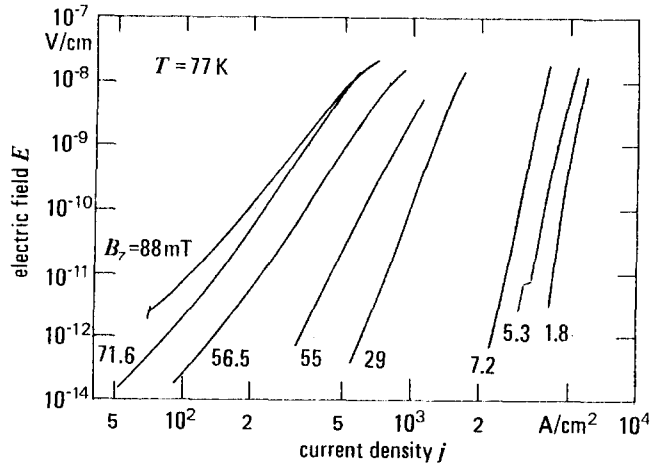

Figure 3: V-I curves from magnetization decay in Bi-2223 powder-in-tube sample

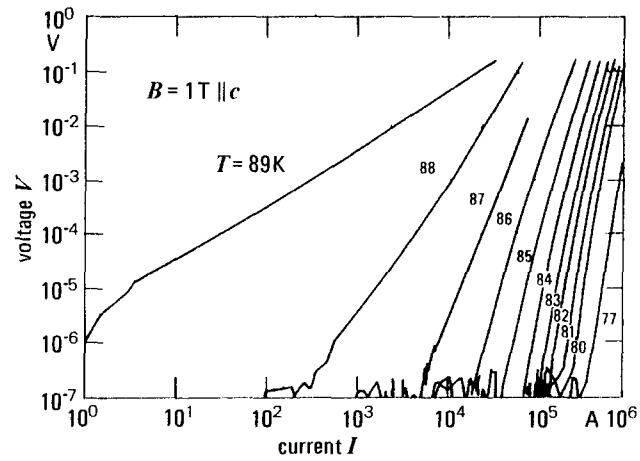

Figure 4: V-I curves in $YBa_2Cu_3O_7$- thin film

This method is particularly suitable to cover a large time window and in the range of very low voltages. It is appropriate for silver sheathed samples where current sharing does not allow to measure towards higher voltage drops. As an example for a Y-based material, fig. 4 shows V-I curves of a YBaCuO thin film on $SrTiO_3$. The example in fig. 2 contains data both from direct transport measurements as well as from flux creep in a VS-magnetometer. Both curves join nicely and are clearly parts of a common V-I curve covering 8 orders of magnitude in electric field. Obviously the nature of transport and magnetization currents is identical. This is also a proof that the sample, like all samples in this work, is not granular.

In the log-log representation of figs. 1-4 it is evident that in all samples the V-I curves follow closely a power law $V = I^P$. Two important features have to be noted: (1) As is explicitely demonstrated

in fig. 2, all curves extrapolate fairly well to a common "hinge" point, defined by an electric field E_0 and a current density j_0 and (2) the slope of the curves, representing the exponent p, decreases either if the field increases as in fig. 1 and 3 or the temperature as in fig.2 and 4. E_0 varies only little with B and T and is of the order 0.1 mV/cm in polycrystalline bulk and textured material and several mV/cm in films. j_0 is something like a upper bound for the critical current density and would be attained only for infinitely steep V-I curves.

This nonlinear resistive behaviour may be cast into a simple expression for the electric field:

$$E = E_0 \, (j/j_0)^p \qquad (1)$$

The hinge-point behaviour was first noted by King et al. [10] in a sintered Bi-2212 sample with very low current carrying capacity. We also found this behaviour in nontextured melt processed Bi-2212 material [11] and were able to explain differing enhancement factors of j_c and M_{irr} after O^+- ion irradiation by a change in the exponent p. In some cases, especially in YBCO-films, a change in the slope of the V-I curves at some value of voltage drop is observed. This gives rise to a positive or negative curvature which several authors regard as a signature of a vortex glass state [12]. In [5] we showed that the declining slope at high levels of electric field may equally well be explained by the onset of viscous damping in moving vortices.

With respect to applications of HTSC, the decrease of the exponent p with field and temperature means accordingly a marked reduction of the critical current density j_c which is defined by some fixed voltage criterion like 1 μV/cm. Figure 5 shows a collection of exponents p for different Bi-2212 materials as function of the applied field component parallel to the c-axis. For each temperature we find three regimes: (1) At the low field end p saturates at a value 10 - 20 independent of temperature. (2) At high fields, p approaches unity i.e. the sample becomes ohmic. This is the linear TAFF-regime [13] with a temperature dependent resistivity. (3) Between them p varies approximately with 1/B. Only here we observe the hinge-point behaviour of the V-I curves while in regimes (1) and (2) they shift parallel and do not extrapolate to the point (E_0, j_0). Surprisingly, single crystalline thin films and melt processed polycrystalline bulk show nearly the same behaviour of the exponent p(B,T). We suppose that despite the very different nature of the samples and a difference in critical current density of a factor of 100 the basic current limiting mechanism in both samples is the same. The value of j_0 characterizes the overall current carrying capacity and contains the effects of the microstructure on pinning. In the following, we will concentrate on the regime (3) with $p \propto 1/B$, as most of the specific electric and magnetic properties of HTSC are related to it.

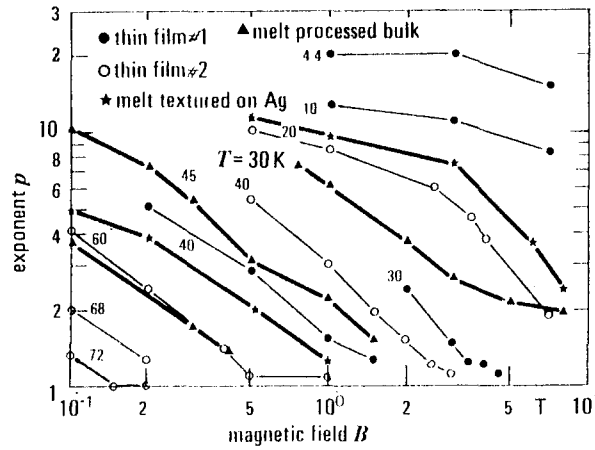

Figure 5: Exponent p of V-I curves in various Bi-2212 materials

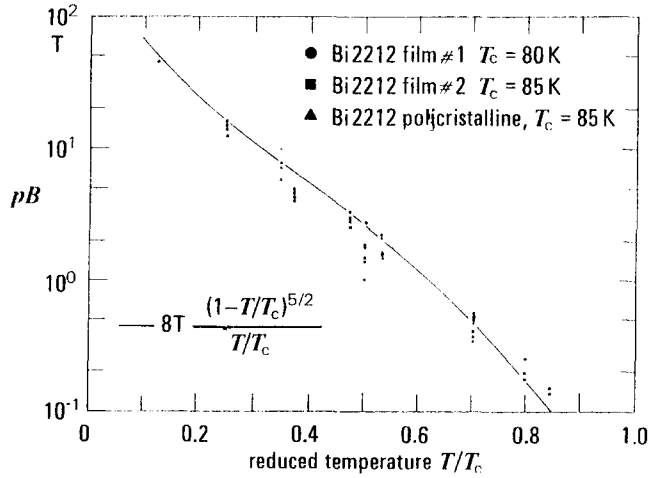

Figure 6: pB as function of reduced temperature

3. Parametrization of V-I curves

In order to extract the temperature dependence of p we have plotted the product pB in fig. 6 as versus the reduced temperature T/T_c. Here only the data with $1<p<10$ have been selected. We find that all entries are in the vicinity of a common curve which might be approximated by an

exponential function exp -T/11 K (Film #1 fits less but has a broad resistive transition and may be inhomogeneous). We propose however a more physically based expression which vanishes at T_c:

$$p \cdot B \approx 8\text{Tesla} \frac{(1 - T/T_c)^{5/2}}{T/T_c} \quad (2)$$

This function fits the data in fig. 6 equally well but allows an interpretation in terms of thermally activated flux creep.

4. Activation energy in Bi-2212

Up to now eqs. (1) and (2) represent a purely phenomenological description of the V-I behaviour of Bi-2212 superconductors. It is generally accepted that the broadening of the resistive transition with increasing field and temperature is the result of thermally activated flux motion. Indeed, it is the only conceivable physical process which could explain the pronounced temperature dependence seen in fig. 6. In the classical Kim-Anderson flux creep theory [4] the electric field E is given by

$$E = B f d \exp -U_{eff}/kT \quad (3)$$

where f is the attempt frequency for a hopping flux bundle and d the hopping distance. Linking this expression to the observed power law V-I characteristic eq. (1) using the empirically found dependence eq. (2) for the exponent p(B,T) we obtain an explicit expression for the effective activation energy in Bi-2212 superconductors:

$$U_{eff}(B,T,j) \approx 60\,\text{meV}/B\,(1-T/T_c)^{5/2} \ln j_0/j \quad (4)$$

This is the central result of this work. It comprises thermally activated behaviour in such different materials like films and bulk in a wide temperature range $0.1 < T/T_c < 0.85$. The electric field E_0 at the hinge point may be identified with the prefactor B f d in eq. (3). Assuming a hopping distance of one flux line lattice constant $d = (\Phi_0/B)^{1/2}$, we get a reasonable value for the attempt frequency $f \approx 10^6 - 10^7\ s^{-1}$.

The logarithmic current term in eq (4) is the origin of power law V-I behaviour in the flux creep scheme. It was first found on a YBaCuO film by Zeldov et al. [14] . These authors also proposed a microscopic model based on a long range pinning potential varying with the radius r like ln r/r_0. Van der Beek et al. [17] derived a barrier U(j) from magnetic relaxation in Bi-2212 single crystals. Interestingly the values for U_{eff}, obtained at different temperatures, fall on a single nearly logarithmic U(j)-curve if they are scaled by the same temperature factor $(1- T/T_c)^{5/2}$ as in our expression eq. (4).

Eq. (3) is not valid in the linear TAFF regime where U_{eff} is small enough to allow both forward and backward jumping of flux quanta under a driving force. As was demonstrated for our thin films [8] the resistivity follows here an Arrhenius behaviour with an activation energy $\propto B^{-1/2}$.

Up to now no microscopic pinning model exists which would explain our empirically found result for U_{eff}. The temperature factor $(1-T/T_c)^{5/2}$ might contain a yet unknown combination of superconducting parameters like critical fields and lengths which all scale with half or integer powers of $1 - T/T_c$. In particular the pronounced field dependence with 1/B has no obvious explanation in standard schemes of single flux line pinning. Tinkham [18] derived $U \propto 1/B$ from a flux line shear mechanism occupying an area Φ_0/B of one elementary cell of the flux line lattice. As we will demonstrate, this 1/B dependence has far reaching consequences both for electric and magnetic properties of HTSC.

5. Electric and magnetic properties

In the following we will show that the specific functional form of eq. (4) in the flux creep picture is in accordance with different measurable quantities. In particular electric as well as magnetic properties are treated on the basis of a common set of V-I curves eq. (1) which are defined by the hinge point data E_0 and j_0 and the functional dependence eq. (2) of the exponent p on B and T.

5.1 Field dependence of critical current

The critical current density is defined by some low voltage threshold $E = E_c$, e.g. 1 μV/cm. By inversion of eq. (3) and using the activation energy eq. (4) we obtain an exponential dependence of j_c on the magnetic field:

$$j_c(B,T) = j_0(T) \exp -B/B_0(T) \quad (5)$$

The "scaling field" $B_0(T)$ is given by

$$B_0(T) = 60\,\text{meV}\,(1 - T/T_c)^{5/2} / (kT \ln E_0/E_c) \quad (6)$$

This specific field dependence is commonly observed in BiSCCO film and bulk material [19] but also in YBCO-films [20]. Its origin is the inverse field dependence $U_{eff} \propto 1/B$ in eq. (4). As an example for the exponential decay of j_c with field we present in Fig. 7 the irreversible magnetization in samples of our non oriented melt processed Bi-2212 bulk material. The temperature dependence of the scaling field $B_0(T)$ evaluated in [19] is well represented by eq. (6).

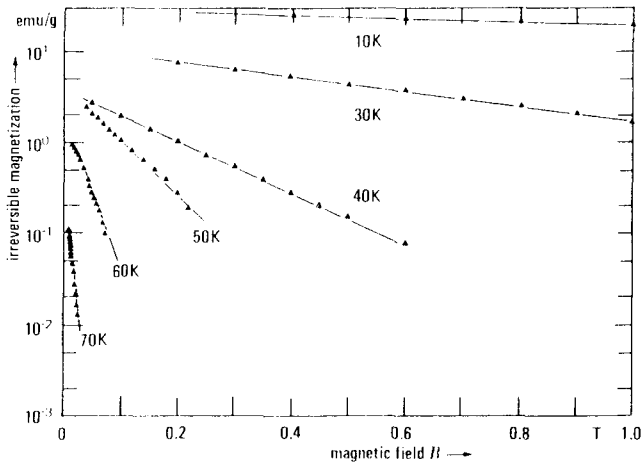

Figure 7: Magnetization of a polycrystalline melt processed Bi-2212 sample 120 s after field setting

Eq. (6) also implies a logarithmic dependence of B_0 on the voltage threshold E_c. It means a decreasing slope of the (ln j_c) vs. B curves with larger voltage criterion E_c . This behaviour was clearly demonstrated for our Bi-2212 films by Schultz et al. [21]. and is also responsible for the different scaling fields B_0 found in transport and magnetization critical currents in Bi-2212 bulk [19] due to differing voltage thresholds of 10^{-7} V/cm and 10^{-12} V/cm respectively .
Recently Gladun et al. [22] derived the same eq. (5) from an empirically found scaling of the resistivity in Bi-2223/Ag tapes on the basis of power law V-I curves.

5.2 Magnetic relaxation

In nongranular samples, decay of magnetization currents with time is controlled by the same V-I characteristics as those obtained in transport measurements. Hsu et al. [23] integrated the electromagnetic equations for a sample assuming a power law V-I characteristic eq. (1) and also obtained a power law decay with time for the magnetization

$$M(t) = M_0 (1 + t/t_0)^{-1/(p-1)} \qquad (7)$$

$M_0 = \mu_0 j_0 D/4$ is the initial magnetization of a slab of thickness D when the current density j_0 circulates in the sample. The effective time constant is $t_0 = D^2/[8\mu_0 (p-1)]\ E_0/j_0$ and contains the attempt frequency via the parameter E_0 . It can be shown that in the ohmic limit $p \rightarrow 1$ eq. (7) correctly approaches an exponential decay law.

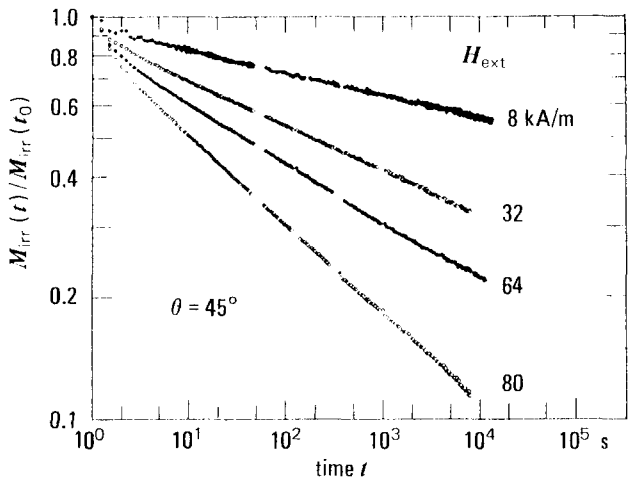

Figure 8: Magnetization decay from torque magnetometry on Bi-2223/Ag tape at 77 K [6]

Figure 8 shows the magnetic relaxation curves observed with a torque magnetometer on a textured Bi-2223 tape over four orders of magnitude in time [6]. The decay has been observed down to 10% of the initial value. The authors found that the logarithmic dependence $U_{eff} \propto \ln j_0/j$ fits the magnetization decay better than any exponent μ in the inverse power law barrier $U_{eff} \propto (j_0/j)^{\mu}$ which is predicted by collective pinning [15] or vortex glass theories [16]. The assumption of a logarithmic barrier is further confirmed by the V-I curves for this material in fig. 3 which are extracted from the decay curves in Fig.8. They demonstrate nicely that power law behaviour in magnetization decay and V-I curves are intimately linked.

5.3 Magnetic irreversibility line

Measuring magnetization loops M(B), it is commonly observed that HTSC samples become magnetically reversible beyond an irreversibility field B_{irr}. In the B-T-plane it defines an

irreversibility line [3]. We will show that this emerges in a natural way from the flux creep equation (7) and eq. (2) for the exponent p which we extracted from transport measurements.
Each data point of the magnetization loop is taken after a elapsed waiting time t_b where the observed magnetization $M(t_b)$ is only a part of the initial value M_0. From the inset in fig. 9 is obvious, that obtaining B_{irr} from the M(H)-loop is somewhat ambigeuous. A reasonable definition to describe the apparent merging of the two branches of the magnetization loop would be $M(t_b) / M_0 = 10^{-3}$. Note that M_0 is given by the value of j_0 and may be appreciably larger than the maximum of M at B=0. By inversion of eq. (7) we obtain an "irreversibility exponent" p_{irr} which defines the irreversibility line $B_{irr}(T)$ in the B-T plane:

$$p_{irr} = 1 + \ln(t_b/t_0) / \ln(M_0/M(t_b)) \qquad (8)$$

By extrapolation of the V-I curves only approximate values for the parameters E_0 and j_0 and their possible variation with field and temperature can be obtained. As they enter into eq. (8) only logarithmically via t_0, we may use estimated constants. Then eq. (2) can be rearranged to define the irreversibility line. For Bi-2212 it is given by:

$$B_{irr}(T) = \frac{8\,\text{Tesla}}{p_{irr}} \frac{(1 - T/T_c)^{5/2}}{T/T_c} \qquad (9)$$

For our melt processed bulk samples we found $E_0 \approx 0.5$ mV/cm and $j_0 \approx 5000$ A/cm^2. With D=0.03 cm we calculate $t_0 \approx 10^{-5}$ s and $p_{irr} \approx 3.3$.

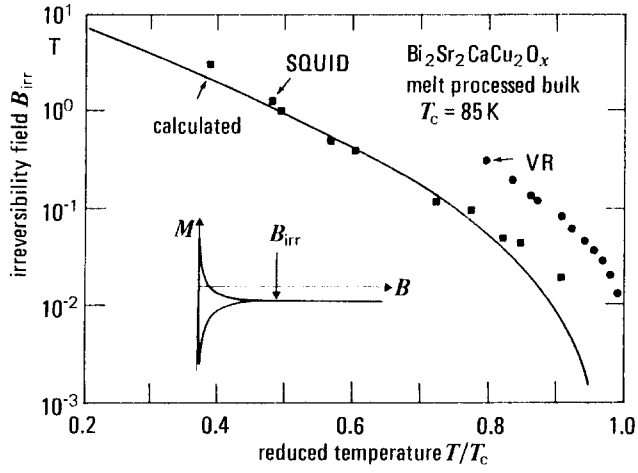

Figure 9: Magnetic irreversibility line in polycrystalline Bi-2212 bulk from SQUID-magneto-metry (t_b =120 s) and vibrating reed (f=1.3 kHz) [24]

In fig.9 the calculated irreversibility line is compared to measured values. We find excellent agreement over a large part of the temperature range. Weber [24] found about the same irreversibility line in Bi-2212 single crystals after neutron irradiation One should keep in mind that the curve is the result of an extrapolation over a very wide range from the quantities E_0 and j_0 at the hinge point down to nearly vanishing voltages and current densities present at the irreversibility field during the measurement of $M(t_b)$ .The result is an indirect proof that the underlying concept of power law behaviour for the V-I curves as well as the scaling of the exponent p in eq. (2) is valid over a very broad range of parameters. It is interesting to note that apart from a constant factor, $B_{irr}(T)$ measures the temperature dependence of the quantity U/kT. This may be a useful tool for investigating pinning in HTSC.
Fig. 9 includes some results of the damping maximum in a vibrating reed experiment at 1.3 kHz on the same material [25]. Here, the irreversibility line is shifted to higher fields. According to eq. (8) this effect is easily explained by the much smaller decay time $t_b \approx \omega^{-1} \approx 10^{-4}$ s entering in eq. (8). p_{irr} is accordingly reduced while the overall shape of the curve $B_{irr}(T)$ is maintained. The same arguments also apply to AC-susceptibility measurements where the logarithmic dependence of B_{irr} on the frequency is explicitely observed [26,27].

6. Conclusions

On a wide variety of HTSC-samples we found a number of common features in the electric behaviour. The voltage-current curves follow a power law $V \propto I^p$. In a double logarithmic plot all curves extrapolate to a hinge point. The exponent p decreases with increasing field and temperature in a definite manner which is specific for the class of material. Our interpretation within the flux creep scheme resulted in an explicit expression for the effective interaction energy U_{eff} in film and bulk samples of Bi-2212. It depends inversely on the magnetic field , logarithmically on current density and with $(1-T/T_c)^{5/2}$ on temperature. We demonstrated that this empirically found relation describes numerous electric and magnetic properties correctly. These results may be a step

towards a microscopic interpretation of the current limiting mechanisms in HTSC.

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