Thermally Activated Depinning in Polycrystalline Bi-Based High-T_c Superconductors

A. Gupta, P. Esquinazi, and H. F. Braun
Physikalisches Institut, Universität Bayreuth, D-8580 Bayreuth, West Germany

H.-W. Neumüller
Siemens AG, Research Laboratories, D-8520 Erlangen, West Germany
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With the vibrating-reed technique we have studied the coupling of the flux-line lattice (FLL) to the atomic lattice between 4.2 and 100 K at constant applied fields 0.014 T$\leq B_a \leq$4 T in three different Bi-based polycrystalline samples. Depinning of the FLL is observed at temperatures above T_D where a peak occurs in the damping of the vibrating sample. With increasing temperature, the FLL dissipation changes at T_D from a hysteretic to a viscous regime. The depinning temperature $T_D < T_c(B_a)$ follows a logarithmic magnetic field dependence which is similar to the dependence of the depinning temperature T^* obtained from measurements of the electrical resistivity due to thermally activated flux motion.

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Recently published work indicates large dissipation effects due to thermally activated flux motion in high-temperature superconductors.[1,2] In addition, the flux-line lattice (FLL) dissipation observed in the $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ superconductor is not only larger but of different character than in $YBa_2Cu_3O_7$. That the FLL behaves differently in different high-T_c superconductors has also been observed by mechanical measurements[3] where drastic changes in the oscillator response occur at tempertures lower than $T_c(B_a)$. The features observed in Ref. 3 have been interpreted as melting of the FLL. The melting of the FLL is a property of the lattice itself independent of pinning. Since mechanical measurements are sensitive to the coupling of the FLL to the atomic lattice via pinning it is not clear whether the observed effects are a manifestation of melting or a pinning effect. Therefore, a more careful study of the phenomena is necessary to test whether a correlation with pinning, if any, exists. We will show that the observed decoupling[3] of the FLL to the atomic lattice very likely is an effect related to the thermally activated motion of the flux lines and does not imply flux lattice melting.

We have performed vibrating-reed measurements in three polycrystalline samples with different T_c's and mass densities (ρ_m) and prepared by different techniques. We have observed an abrupt drop in the coupling strength of the FLL to the atomic lattice accompanied by dissipation peaks which shift to lower temperatures when the applied magnetic field is increased. Our measurements taken in a wide field range (0.014 T $\leq B_a \leq$ 4 T) reveal a logarithmic field dependence for the depinning temperature T_D which tends to $T_c(B_a)$ for $B_a \rightarrow 0$.

The vibrating-reed technique has been used to study the elastic response of the FLL to the pinning centers in amorphous and ceramic superconductors.[4,5] The advantage of this technique in comparison with other mechanical oscillators[3] lies in its sensitivity to small and high fields; the flexural vibration of the reed and its well determined movement relative to the external field permits a complete theoretical treatment of the field and pinning-strength dependence of the resonance frequency and damping (see Ref. 4 for more details). In our experiment the reed is driven resonantly by means of a phase-locked loop and its maximum amplitude was kept below 150 nm. We have observed a linear response in zero field even at amplitudes 10 times greater. The FLL movement relative to the reed in the nonzero-pinning region is very small; for example, at B_a = 0.4 T and T = 50 K it is of the order of 0.5 nm.

We have measured three samples with nominal compositions $Bi_2Sr_2CaCu_2O_8$ (sample 1), $Bi_{1.5}Pb_{0.5}Sr_2CaCu_2O_y$ (sample 2), and $Bi_1SrCaCu_3O_y$ (sample 3). Sample 1 was prepared through a melt process[6] and had ρ_m = 5.96 g/cm^3. The other two samples with ρ_m = 4.9 and 4.2 g/cm^3 were prepared by solid-state reaction. The samples were characterized by ac susceptibility, resistivity, x-ray analysis, and metallographic and microprobe analysis. Samples 1 and 2 were single phase ($\simeq$97%) with T_c = 83 and 70 K, respectively. Sample 3 contains different phases with a $T_c \simeq 62$ K corresponding to the main superconducting phase.[7]

It is important to note that the vibrating-reed technique probes the pinning of intragranular vortices in polycrystalline materials. This can be understood if we take into account the following: (1) The intragranular vortex spacing is typically much smaller than the grain diameter in our samples; (2) the grain boundaries represent a negligible part of the sample volume, and thus the dissipation due to the relative displacement of the FLL comes obviously from the bulk of the sample; (3) the possible energy dissipation across grain boundaries is not the main dissipation process in the reed. The superconducting surface currents[4] are extremely small, and they shield a very small field component[4] of the order of 0.1 μT at 0.01 T and 10 K. These currents are even smaller

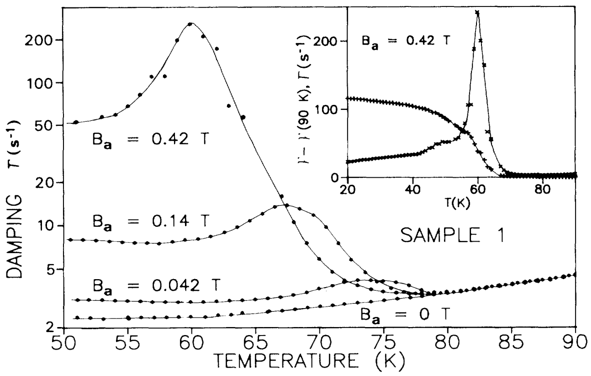

FIG. 1. Damping Γ as a function of temperature T for sample 1 [$T_c(B_a=0)=83$ K] at different applied fields. Note the semilogarithmic scale. Inset: Damping and resonance-frequency change as a function of temperature at $B_a=0.42$ T; ν (90 K) $=1.26$ kHz.

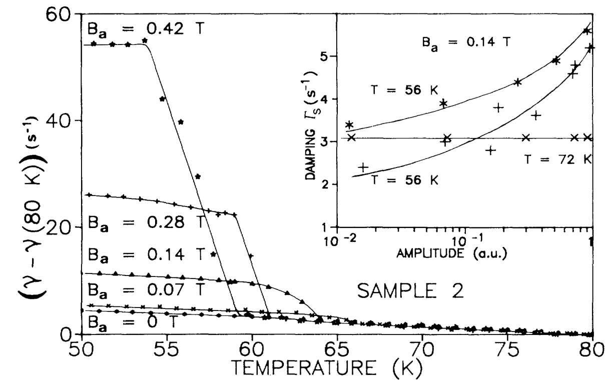

FIG. 2. Change of the resonance frequency for sample 2 ($T_c=70$ K) as a function of temperature at different applied fields; ν (80 K) $=1.39$ kHz. Inset: Amplitude dependence of the measured damping Γ_s [$=\Gamma-\Gamma(B_a=0)$] at $T=56$ K for samples 1 ($*$) and 2 (+). At $T=72$ K ($\times$) (above the peak in Γ, sample 1) Γ_s is amplitude independent. The other two samples show the same behavior. No amplitude dependence is measured at $B_a=0$; thus there is no contribution from the clamping of the reeds to the observed behavior.

near the depinning temperature and in higher fields due to the lower reed amplitudes and the depinning of vortices. The similarities of the measured properties described below between sample 1 (which is not a ceramic[6]) and the ceramic samples 2 and 3 with completely different microstructure, mass density, and superconducting properties show clearly that the response of the vibrating reed is governed by the intragranular FLL-to-atomic-lattice coupling. This is also confirmed by recent vibrating-reed measurements on ceramics and a single crystal of the Gd-1-2-3 phase.[8]

In Fig. 1 we present the damping Γ for sample 1 as a function of temperature at different applied fields. Γ increases monotonically from low temperatures below 50 K. Each peak in Γ is accompanied by a decrease in the resonance frequency (see inset) which indicates a decrease in the pining force.[4] Figure 2 shows in more detail the resonance-frequency change measured for sample 2 ($T_c=70$ K). We note that above a certain temperature T_D the FLL is completely decoupled from the reed. In conventional superconductors these phenomena occur at $T_c(B_a)$ or at $B_{c2}(T)$ if the field is increased at constant temperature.[4] In our measurements, however, the shift in the temperature of the peak of Γ or the temperature where the pinning force is zero does not follow the expected critical temperatures $T_c(B_a)$; for example, in sample 1 the peak in Γ shifts 15 K to lower temperatures when B_a is increased from 0 to 0.42 T whereas $T_c(B_a)$ should only shift by less than $\simeq 0.5$ K due to this field change. Sample 3 showed the same kind of behavior.

The features we observe in the resonance frequency and damping are qualitatively similar to those observed in the mechanical measurements reported recently.[3] But our data provide more information about the origin of the damping. For $B_a>0$ the contribution of the flux motion to the damping Γ_s [$=\Gamma-\Gamma(B_a=0)$] can be hysteretic or viscous: $\Gamma_s=\Gamma_h+\Gamma_v$.[4] Hysteretic damping has been proven to be the main dissipation process in amorphous materials for typical reed amplitudes.[4] The characteristic features of the hysteretic damping are its amplitude and frequency dependence. In the inset of Fig. 2 we show the measured amplitude dependence of Γ_s for samples 1 and 2 obtained at $B_a=0.14$ T and $T=56$ K, i.e., below the peak in Γ. The amplitude dependence of Γ_s suggests a power law $\Gamma_s \propto u(1)^n$ [$u(1)$ is the amplitude at the top of the reed] with $0.2 \le n \le 0.4$ in agreement with the theoretical expectation.[4] Quantitative estimates of Γ_h and of Γ_v, which is always present, are underway. We should note that a semiquantitative approach has been used successfully to estimate Γ_h in granular superconductors.[7]

Even more remarkable is the observation of total amplitude independence of Γ at temperatures above the peak; see inset of Fig. 2. This result indicates that in this temperature range the damping is mainly due to the viscous movement of the FLL in a zero-pinning regime. In this case the FLL remains parallel to the applied field and according to the theory[4] $\Gamma_v \le 0.4\eta/2\rho_m$, where η is the viscosity of the flux lines ($\eta \simeq B_a B_{c2}\sigma$ with σ the normal conductivity of the reed[9]). With $\delta B_{c2}/\delta T \simeq 0.5$ T/K and using the measured resistivity for sample 1 ($\rho=400$ $\mu\Omega$ cm) as an upper bound of the intragranular resistivity, we obtain $\Gamma_v(B_a=0.14\text{ T}, T=70\text{ K}) \le 11$ s^{-1} in very good agreement with the experiment; see Fig. 1. Since the viscosity of the flux lines decreases with increasing temperature[9] the damping should decrease after reaching some maximum value. Within this picture it is now possible to understand at least qualitatively why the damping decreases even when no pinning force is active.

In Fig. 3 we show the field dependence of the depinning temperatures T_D defined in two fashions: at the peak in Γ and at the temperature where the resonance frequency reaches its normal ($B_a = 0$) value. All the samples show a logarithmic field dependence with similar prefactors for T_D over a wide range of field. The data from sample 2 also indicate that $T_D \rightarrow T_c(B_a)$ when $B_a \rightarrow 0$.

It was shown that the electrical resistivity in the Bi-based and Y-based compounds can be described, at least for $\rho \leq 1$ $\mu\Omega\,\text{cm}$, by the universal function $\rho \propto \exp(-U_0/T)$, where U_0 is an activation energy.[1,2] This thermally activated dissipation can be understood in terms of flux creep.[1,2] With this simple law we obtain the field dependence of the temperature T^*, in some sense also a "depinning" temperature, at which the dissipation reaches some value ρ^*, i.e., $T^* \propto U_0$. For the Bi-based superconductor and for $\mathbf{B}_a \perp \mathbf{a},\mathbf{b}$ the experiments indicate that $U_0 \propto -\ln(B_a)$.[10] In Fig. 3 we have plotted the values of T^* at different applied fields at which $\rho^* = 10^{-3}$ $\mu\Omega\,\text{cm}$ taken from the $Bi_{2.2}Sr_2Ca_{0.8}Cu_2O_{8+\delta}$ data (Fig. 2 of Ref. 1). The striking similarity points out that the same thermally activated process responsible for the anomalous dissipation observed in the resistivity causes the thermal depinning of the FLL in our mechanical measurements.

Within the context of the thermally assisted flux flow (TAFF) model,[11] the "depinning" or "irreversibility" line obtained from the peak in ac susceptibility represents the solution of an implicit equation where the diffusion constant of vortices $D_0(B_a,T)$ equals a constant which depends on the measuring frequency and a characteristic sample dimension.[11,12] Since the peak in the damping observed in the vibrating reed and the peak of χ'' have the same origin,[12] and since the flux-flow resistivity is related to $D_0(B_a,T)$,[11] taking a fixed ρ^* is equivalent to taking a fixed value $D_0(B_a,T^*)$ which defines a depinning line $T^*(B_a)$. The similarities of $T_D(B_a)$ and $T^*(B_a)$ shown in Fig. 3 support the TAFF model.

In Fig. 3 we have also plotted the values of the "melting" temperatures obtained in Ref. 3 for the Bi-based and the Y-based superconductors when $\mathbf{B}_a \perp \mathbf{a},\mathbf{b}$. The higher melting temperature obtained in Ref. 3 for the Y-based superconductor, its B_a dependence, and even the observed anisotropy[13] just reflect the higher and anisotropic activation energies[2] or, within the TAFF model, smaller (and anisotropic) diffusion constants. In Fig. 3 we show the values of T^* for the $YBa_2Cu_3O_7$ superconductor taken at $\rho^* = 10^{-3}$ $\mu\Omega\,\text{cm}$ and for $\mathbf{B}_a \perp \mathbf{a},\mathbf{b}$ (Fig. 2 of Ref. 2). The similarities are evident. Whether the FLL melting occurs just at depinning or higher temperature cannot be answered by mechanical measurements

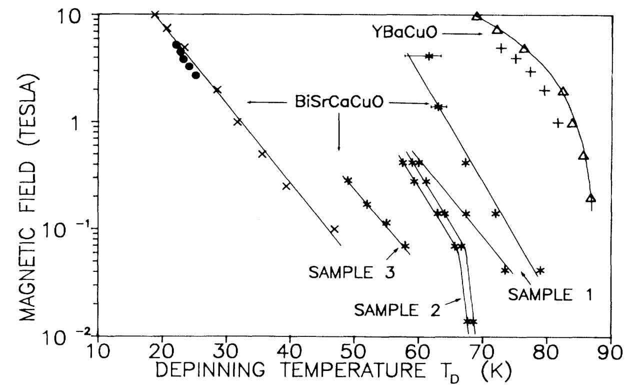

FIG. 3. Field dependence of the depinning temperature as defined in the text for the three measured samples (✱). (×) Temperatures T^* at which the resistivity has a value of 10^{-3} $\mu\Omega$ cm for different applied fields $\mathbf{B}_a \perp \mathbf{a},\mathbf{b}$, obtained from single-crystal data in the Bi-based superconductor (Ref. 1); (Δ) the same but for the Y-based superconductor (Ref. 2). (●, +) "Melting"-temperature data taken from Ref. 3.

alone. But it is worth noting that, in principle, one would expect an increase in the averaged pinning force, i.e., an increase in the resonance frequency, if melting occurs.[14] The dependence of the various characteristic temperatures on the applied field strongly suggests a correlation of the observed phenomena with pinning and thermal activation of flux lines.

In conclusion, we have studied the depinning of flux lines in polycrystalline Bi-based high-T_c superconductors. The observation of a crossover between two different dissipative regimes explains the measured peaks in the damping. The field dependence of the depinning temperature is logarithmic in a wide field range and resembles the magnetic field dependence of the depinning temperature T^* taken from electrical resistivity measurements. We should note that due to the diffusion nature of the thermally activated vortex motion the depinning lines shown in Fig. 3 depend on a characteristic sample dimension and on the measuring frequency.[12]

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