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Time dependence of the magnetization in $Bi_2Sr_2CaCu_2O_{8+z}$

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Abstract

The Maley procedure has been applied to obtain $U_{eff}(j)$ of a Bi-n = 2 single crystal for $B < 4$ T//c-axis and $T < 20$ K from the time dependence of the non-equilibrium magnetization. Analyzing the resulting $U_{eff}(j)$ within the collective creep model it is found that for large current densities, flux creep of elastic small ($<\lambda$) flux bundles consisting of quasi 2-dimensional pancake vortices occurs. However, at large j better agreement is found with the logarithmic potential model. From the logarithmic $U_{eff}(j)$ dependence j_c in the absence of thermal activation has been derived. It has been found that $j > 10^{10}$ Am^{-2} for all fields investigated. These high values of j_c indicate that the pancake vortices are pinned independently and that oxygen vacancies in the CuO_2 planes are not the only pinning centers.

1. Introduction

The vortex dynamics in ceramic high-T_c superconductors has been analyzed frequently within the Anderson-Kim model [1] thereby assuming a linear relation between the current density j and the free energy barriers U_{eff} which separate different metastable configurational situations in the vortex lattice. However, indications of non-logarithmic magnetic relaxation in $Bi_2Sr_2CaCu_2O_{8+z}$ (Bi-n = 2) [2] make clear that for this system this model is not appropriate and consequently procedures to extract activation energies from it yield incorrect results. The deviations from logarithmic relaxation suggest a non-linear $U_{eff}(j)$. Maley et al. [3] reported a procedure to obtain $U_{eff}(j)$ from magnetic relaxation data only. Here we adopt this procedure and compare the resulting $U_{eff}(j)$ with predictions of the collective creep model [4] and the logarithmic potential model [5]. A similar approach has been reported recently by van der Beek et al. [6].

2. Experimental

The Bi-n = 2 crystal ($4.5 \times 1.5 \times 0.075$ mm^3) used in the present experiments has been grown by a TSFZ process. The typical composition was $Bi_{2.02}Sr_{2.00}Ca_{0.98}Cu_{1.99}O_{8+z}$ [7], i.e. very close to the model composition. The crystal has been given an additional heat treatment at T = 600 °C in a flowing O_2 atmosphere to reduce inhomogeneities of the oxygen content. The superconducting onset temperature $T_c = 87$ K has been determined by ac susceptibility. The homogeneity of the oxygen content is reflected by the sharpness of the χ_{ac} transition: $\Delta T_c = 1.7$ K (10%-90% of the χ_{ac} signal).

The magnetic moment m has been measured with a PAR Vibrating Sample Magnetometer and the applied magnetic field B along the c-axis. In order to relate the current density j to the magnetic moment correctly, j must flow uni-directional. This has been established by cycling the magnetic field with a ramping rate of 10^{-2} T/sec. prior to registration of m(t). After this cycling procedure, the magnetic field is stabilized in the persisting mode. Simultaneously, m is recorded every second up to 2000 seconds.

In this way, m(t) has been determined at various temperatures ($2.09 < T < 25$ K) and applied magnetic field (B = 0, 0.5, 1, 2, 3, 4 or 5 T).

3. Results and discussion

For B = 1 Tesla, a representative field value, the magnetic relaxation data are shown in fig. 1. Whereas at low temperature only minor deviations from logarithmic relaxation are present, at higher temperatures these deviations become pronounced. This indicates that the Anderson-Kim model and related models, such as the inversion scheme of Hagen and Griessen [8] can not be applied to obtain U_{eff}.

An alternative method to obtain values of U_{eff}

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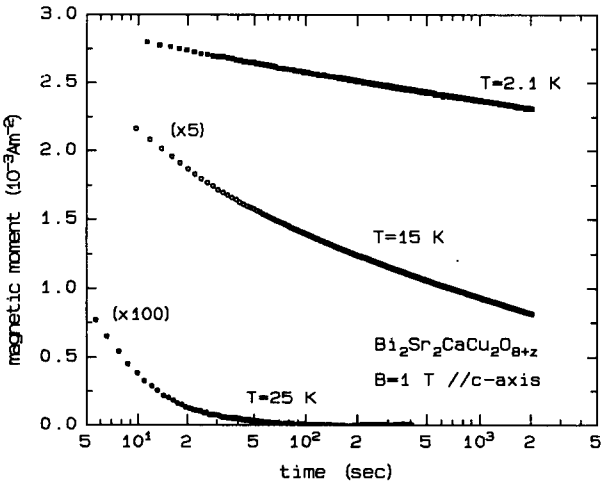

Fig. 1. Time dependence of the magnetic moment on a logarithmic time scale.

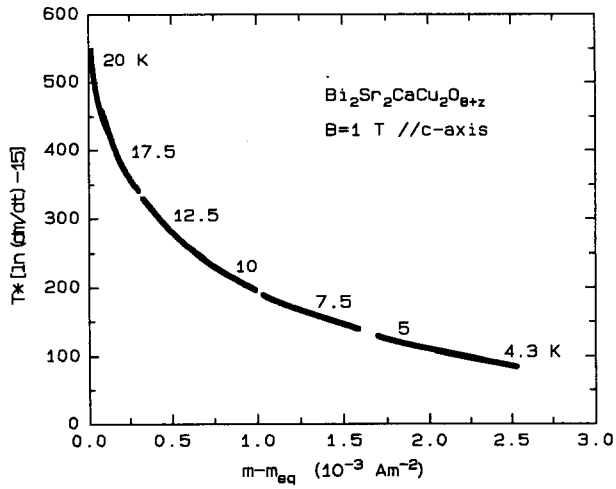

Fig. 2. Plot of $T\cdot[\ln(dm/dt)-\epsilon] = U_{eff}$ versus $m\text{-}m_{eq} \sim j$ for B = 1 T and ϵ = 15.

from the magnetic relaxation data only and without being affected by transient effects [9], is employed by Maley et al. [3]. This method is based on the fact that the time dependence of the magnetization of a sample in a constant applied magnetic field is related to the electric field at its circumference R [10], and yields

$$U_{eff}(j) = -T\cdot \ln\left|\frac{dM}{dt}\right| + T\cdot\epsilon, \qquad (1)$$

with $\epsilon = (2\cdot\rho_f\cdot j/\mu_0\cdot R)$ and ρ_f the flux flow resistivity. Under the assumption that ϵ is constant, eq. (1) indicates that $U_{eff}(j)$ is equivalent to within a additive constant $T\cdot\epsilon$ to $T\cdot\ln|dM/dt|$. A plot of $T\cdot\ln|dM/dt|$ versus $M\text{-}M_{eq} = (R/3)\cdot j$ (if $j \neq j(B)$) yields therefore information about the current dependence of U_{eff}.

In fig. 2 we have plotted $T\cdot\{\ln|dm/dt| - \epsilon\}$ versus $m\text{-}m_{eq}$ for B = 1 T and T <25 K on a linear scale. The equilibrium magnetization has been determined from the hysteresis curves. Clearly, with the addition of the constant ϵ, the data obtained from different temperatures collapse onto one universal curve representing $U_{eff}(j)$. In fact, for all fields investigated $U_{eff}(j)$ is non-linear, thereby proving the inadequacy of the Anderson-Kim model. In the subsequent discussion, we will concentrate on the exact current scaling. Two models will be considered: the collective flux creep model, and the logarithmic potential model.

In the collective creep model $U_{eff} \sim [(j/j_c)^a - 1]$, with the parameter a dependent of the dimension of the vortex lattice and the size of the vortex bundle. For a vortex system consisting of quasi 2 dimensional arrays of pancake vortices located in the superconducting CuO_2 planes, the exponent *a* has been calculated to be $a = 9/8$ or $a = 1/2$, depending on the size of the vortex bundle R_p perpendicular to the hopping direction and the field [11].

The current dependence of the activation energy on a double-logarithmic scale is revealed in fig. 3a for a representative field value of B = 1 Tesla. The overall scaling with current density of the effective flux creep activation barrier is in qualitative agreement with the predictions of the collective flux creep model for 2-dimensional vortex discs, i.e. *a* decreases for decreasing j and for large current densities $a = 1.1 \pm 0.1$ is found, close to $a = 9/8$. This suggests that the creep occurs through small bundles of 2D vortex pancakes. This result is in agreement with the recent analysis of van der Beek et al. [6].

Now we will discuss the $U_{eff}(j)$ dependence in terms of the logarithmic potential model [5]. This model predicts that for large driving forces, $F_l > 2\cdot U'/u_{hop}$, the effective barrier height drops logarithmically with increasing current density as $U_{eff} = U'\cdot\ln(j_c/j)$. To investigate whether the logarithmically shaped barrier describes the magnetic decay, $U_{eff}(j)$ is shown in fig. 3b on a logarithmic scale. Indeed, we find that for large driving forces, i.e. large values of j, the current scaling of the effective barrier height follows a logarithmic relation. By extending the logarithmic current dependence of the effective barrier height to $U_{eff} = 0$, the data offer the possibility to determine j_c, as summarized in table 1. J_c is rather large, exceeding 10^{10} Am^{-2}, and decreases monotonically as a function of the mag-

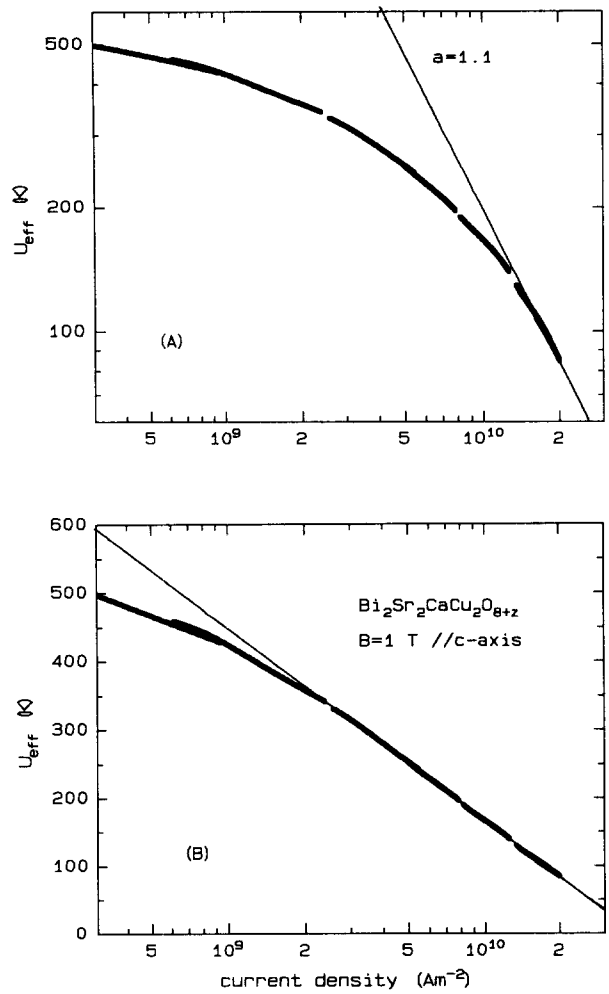

Fig. 3. (a) $U_{eff}(j)$ on a double-logarithmic scale for B = 1 T. The drawn line represent the data points at large current densities. The slope of the line is indicated. (b) $U_{eff}(j)$ on a semi-logarithmic scale for B = 1 Tesla. The line is a fit through the data points.

netic field, in close agreement with results of van der Beek et al. [6], obtained on a crystal with (non-model) composition $Bi_{2.17}Sr_{1.87}Ca_{0.99}Cu_{1.97}O_{8+z}$. This indicates that apparently the Bi/Sr ratio has no influence on j_c. We like to note, that the small decrease of j_c with B indicates that application of the Bean model [12] is formally not proper.

From j_c, the volume of the flux particles which are pinned independently can be estimated. Assuming 2D collective pinning theory to be valid (note that this implies that the longitudinal correlation length L_c should not exceed s, the distance between the CuO_2-Ca-CuO_2 blocks), the transverse correlation length R_p can be written as

$$R_p/a_0 = 9.8\times 10^9 \cdot B_c \cdot (B\cdot \xi/j_c \cdot B_{c2})^{\frac{1}{2}}. \qquad (2)$$

Substituting B_{c2} = 75 T [13], ξ = 2.1 nm, B_c = 0.37 T, and j_c from table 1, this yields $R_p/a_0 < 1$. Therefore, we may conclude that the pancake vortices are pinned independently for all fields investigated.

One of the key questions regarding the high-T_c superconductors is, what entities are responsible for the pinning of the vortex lattice. For Bi-n = 2, obvious candidates for pinning centers are oxygen vacancies in the CuO_2 planes. Knowing the size of the correlated volume, and assuming that these vacancies are responsible for pinning, we are now in the position to determine the density of pinning centers. For point defects with dimension $R_v \leq \xi$, the potential due to the interaction of a 2D vortex with a single point defect can be written as $U_0 = \frac{1}{\mu_0}\cdot B_c^2 \cdot V_p = \frac{1}{\mu_0}\cdot B_c^2 \cdot \frac{4}{3}\cdot \pi \cdot R_v^3 \cdot (\frac{\xi_0}{R_v})$. The effective pinning volume V_p is enhanced with respect to the volume of the defect by a factor ξ_0/R_v [14], where $\xi_0 = 1.35\cdot\xi$ is the BCS coherence length. The maximum pinning force is given by $f_p = U_0/r_p$, with $r_p = \xi$ the range of the pin potential. According to the collective pinning theory, the macroscopic pinning force density F_p is related to the fluctuation of the elementary pinning forces of n_a active pins inside V_c, and can be written as $F_p = j_c \cdot B = W^{\frac{1}{2}}\cdot V_c$, with $W = n_a \cdot < f^2 > \simeq \frac{1}{2}\cdot n_a \cdot f_p^2$ and $V_c = a_0^2 \cdot s = (\Phi_0 \cdot s)/B$ in our situation. The only unknown parameter is n_a. Notice that application of

Table 1. The critical current density j_c, obtained from the scaling of the effective activation barrier with ln(j), as a function of applied induction B.

B (T)	j_c (10^{10} A/m^2)
0	5.2
0.5	4.9
1	4.0
2	3.5
3	2.8
4	2.4

the collective pinning theory implies $n_a \gg 1$. If we combine all the expressions given above, n_a can be written as

$$n_a = 9.6\times 10^{-14} \cdot \left[\frac{j_c \cdot \Phi_o \cdot s}{B_c^2 \cdot R_v^2}\right]^2 . \qquad (3)$$

Oxygen ions in the CuO_2 layers have a two-fold coordination such that $R_v = 0.135$ nm [15]. For s we may take 1.5 nm, and j_c can be obtained from table 1. For the thermodynamic field B_c two values may be taken: (I) $B_c = 0.37$ T which is consistent with $B_{c2} = 75$ T [13] and $\lambda = 300$ nm [16], or (II) $B_c = 0.29$ T, consistent with $B_{c2} = 45$ T [17]. If these parameter values are inserted in eq. (3), we obtain $n_a(I) = 250$ and $n_a(II) = 660$, where the superscripts denote the used parameter set. Note that these large values of n_a justifies the application of the collective pinning concept. The oxygen vacancy concentration per CuO_2 layer n_v, can be estimated by $n_v = n_a/(2\cdot\pi\cdot\xi^2)$, because active pinning centers are predominantly present in the vortex cores. This yields $n_v(I) = 9\times 10^{18}$ m^{-2} and $n_v(II) = 1.4\times 10^{19}$ m^{-2}. If these values are compared to the oxygen ion concentration per CuO_2 layer, $n(O^{2-}) = 4/a^2$, with $a = 0.54$ nm the size of the unit cell in the ab-plane, we find $n_v(I)/n(O^{2-}) = 0.65$ and $n_v(II)/n(O^{2-}) = 1$. These values are rather unrealistic, and therefore we may conclude that oxygen vacancies in the CuO_2 layers are not the only pinning centers in Bi-n = 2. It must be remarked however, that the resulting value of $n_v/n(O^{2-})$ is rather sensitive to the choice of parameter values.

4. Conclusions

Using the Maley procedure, we obtained $U_{eff}(j)$ of nearly stoichiometric Bi-n = 2 single crystals from magnetic relaxation experiments with magnetic fields between 0.5 and 4 Tesla //c-axis. The resulting $U_{eff}(j)$ has been compared with predictions of the collective creep model and the logarithmic potential model.

The collective creep model predicts that $U_{eff} \sim j^{-a}$. Experimentally, we find $a = 1.1 \pm 0.1$ for large current densities and for all applied fields investigated, suggesting elastic flux creep of small ($<\lambda$) flux bundles consisting of quasi 2-dimensional pancake vortices. However, at large j better agreement is found with the logarithmic potential model.

Finally, the critical (depinning) current density in the absence of thermal activation has been derived from M(t). It has been found that $j_c > 10^{10}$ Am^{-2} for all fields investigated. The results suggest that: (1) the Bi/Sr ratio has no influence on j_c, (2) the pancake vortices are pinned independently and (3) oxygen vacancies in the CuO_2 planes are probably not the only pinning centers.

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