Journal of Optoelectronics and Advanced Materials Vol. 7, No. 6, December 2005, p. 3029 - 3032

ANOMALOUS SPLITTING OF THE FIRST PENETRATION PEAK IN THE LOCAL MAGNETIZATION OF $Bi_2Sr_2CaCu_2O_{8+y}$ SINGLE CRYSTALS

V. Mihalache*

National Institute of Materials Physics, 105 bis Atomistilor Str., Magurele, Bucharest, Romania, and Bilkent University, Ankara, Turkey

A scanning Hall probe microscope (SHPM) with an effective spatial resolution of ~1 μm has been used to study the local induction in high quality superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals at high temperatures and low magnetic fields. We observed, for the first time to our knowledge, an anomalous splitting of the peak of first full penetration of magnetic field. We discuss the observed splitting, which is connected to the effects of surface and geometrical barriers on the vortex lattice.

(Received October 12, 2005; accepted November 24, 2005)

Keywords: Superconductivity, $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals, Local magnetisation

The vortex matter in high-temperature superconductors (HTSC) and their interaction with pinning centres and surface and geometrical barriers is the subject of intense recent investigations. Local magnetisation measurements using high resolution Hall probes (~1 μm) can provide valuable information on this subject. At temperatures close to the critical one (T_c), in the mixed state of $Bi_2Sr_2CaCu_2O_y$ (Bi-2212) single crystals, all relevant energy scales (pinning, elastic, thermal and surface) are comparable [1,2] and the results of the measurements in magnetic fields comprise the contribution of different sources of irreversibility, making the interpretation of magnetic behavior very complicated. With the aim of separating the bulk, surface- and geometry-related contributions to the irreversible processes, some studies were performed [3-6] on single crystals having various shapes: platelet, ellipsoidal and prism. Since it is very difficult to separate the surface and geometrical barrier effects from bulk pinning, the investigations are usually made on "clean" single crystals in order to eliminate the contribution of bulk pinning. However, even the "cleanest" crystals contain a large number of structural defects.

In this paper, we present some local dc magnetisation measurements, using a high-resolution Hall probe, performed on several Bi-2212 single crystals, in the temperature range of 66K-87K, up to a maximum field of 200 Oe, with various sweeping rates up to 123 Oe/sec. Local magnetization studies were performed with the Hall sensor 'parked' just above the surface, at various locations, and on various samples. The results described below are qualitatively the same in most of the measurements. First of all, we emphasize that, with the increase of applied magnetic field sweeping rate (SR), the width of the magnetization loops increase significantly and become more symmetric; this Bean-type behavior originates from the bulk pinning. Apart from this, other sources of irreversibility are the geometrical barrier [7], which is a result of non-ellipsoidal sample geometry, and the Bean-Livingstone (BL) surface barrier [8,9], which is the result of the interaction between the Abrikosov vortex and its 'mirror image' near the surface. The presence of geometrical and surface barrier prevents the flux entering the sample at the lower critical field, until a higher field of first penetration is applied. A fingerprint of both geometrical and surface barriers is the asymmetric shape of the magnetization loop, *i.e.*, a sharp drop-off in magnetization above flux penetration on the ascending (increasing absolute value of the field) branch, and the nearly flatness of the descending

* Corresponding author: vmihal@infim.ro

(decreasing absolute value of the field) branch. Also, both surface and geometrical barriers results in magnetic hysteresis even in the absence of bulk pinning. However, the surface barrier acts on a microscopic scale whereas the geometrical barrier acts on a macroscopic scale and is no subject to thermal activation since such an extended barrier involves macroscopic energy of approximately $\epsilon_0 s$ (ϵ_0 being line energy of a non-interacting vortex and s being the sample thickness). In addition it is thought that the BL barrier is very sensitive to surface quality.

A typical 'local' magnetization loop taken at 77.3 K is shown in Fig. 1(a), while Fig.1(b) shows the most important details of the loop: the splitting of the sharp peak of 'first penetration' due to geometrical and surface barriers into *two* peaks (P_1^{GS} and P_2^{GS}) close to each other, and a third 'anomalous peak effect' (P^b) at higher field due to bulk pinning.

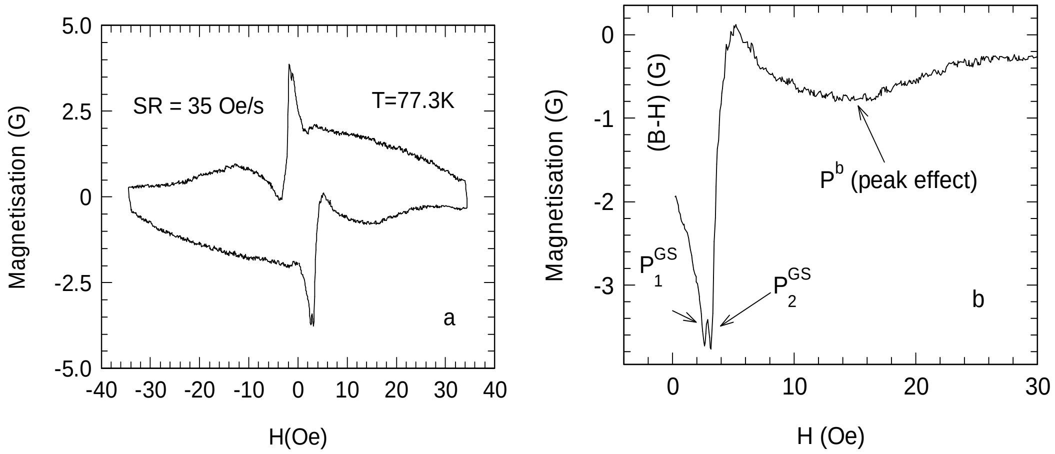

Fig. 1. Local magnetization loop measured at 77.3 K and the sweeping rate of 35 Oe/s (a) and a detailed view of part of the magnetization loop (b).

Fig. 2(a) shows the local magnetization loops at two sweeping rates (SR), 4.1 Oe/s and 123 Oe/s. It can be seen that the dependence of P^b on SR (position and height, determined from the descending branch of the magnetization loop where the contribution of geometrical and surface barriers to irreversibility is minimum) is much stronger that the corresponding SR-dependence of the two sharp low-field peaks, P_1^{GS} and P_2^{GS}. In the same time, as can be seen in Fig. 2(b), P^b shifts to higher field and become broader with decreasing temperature.

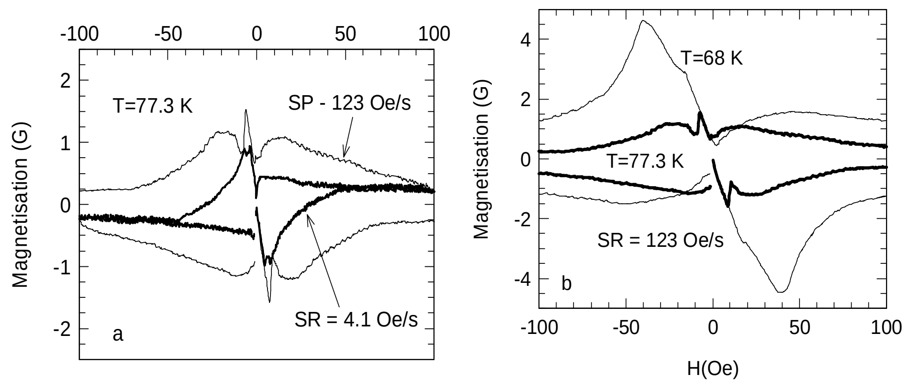

Fig. 2. Local magnetization loops measured at: *T*=77.3 K for two different values of SR (4.1 Oe/s and 123 Oe/s) (a); and for two different values of temperatures, 68 K and 77.3 K, and SR 123 Oe/s (b).

It was shown that, at high temperatures, bulk pinning is very weak [5,10] and the hysteresis is mainly due to geometrical and surface barriers. Regarding the time-dependence, Chikumoto *et al.*

[11] observed two regimes of relaxation at short and long timescales, respectively, in Bi-2212 single crystals, and explained the short timescale relaxation (at low temperatures) by the flux creep of pinned vortices, and the long timescale relaxation (at high temperatures) to the relaxation over surface barriers. These facts clearly demonstrate that the high-field, broad peak P^b is due to bulk pinning, while the small-field, sharp peaks P_1^{GS} and P_2^{GS} are due to geometrical and surface barriers.

For explaining the reason for the splitting of the peak of 'first penetration' we have studied in detail the dependence on timescale and temperature of the two peaks P_1^{GS} and P_2^{GS}. Fig. 3 shows details of magnetization loops at: (a) constant temperature of 76 K, for 3 and 45 Oe/s sweeping rates; and (b) constant SR of 45 Oe/s, for temperatures of 66 and 76 K, respectively. It can be seen that the position of P_2^{GS} is more time- and temperature-dependent than the position of P_1^{GS}.

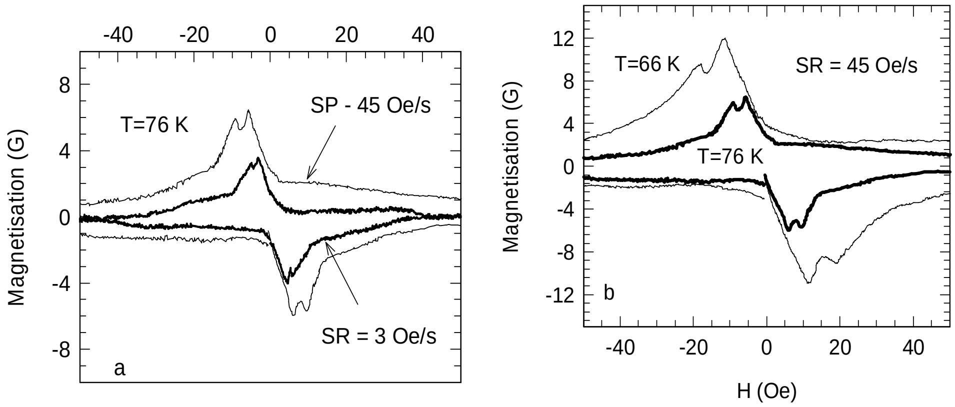

Fig. 3. Local magnetization loops measured at: 76 K for two values of sweeping rates, 3 Oe/s and 45 Oe/s (a), two different values of temperature, 66 K and 76 K, and the sweeping rate of 45 Oe/s (b).

From similar magnetisation loops at the same sweeping rate and various temperatures we determined the temperature dependence of the two sharp peaks, shown in figure 4.

At low temperatures, it was predicted theoretically [12,13] and proved experimentally [13] that the temperature dependence of the first penetration field due to surface barriers is exponential, while at higher temperature, about 70 K for Bi-2212, (where the exponential decay 'saturates') the geometrical barrier becomes dominant and the temperature dependence of the first penetration field is determined by the temperature dependence of H_{c1}. Therefore, the stronger temperature dependence of P_2^{GS} compared with that of P_1^{GS} means that the contribution of surface barriers to the occurrence of P_2^{GS} is larger than the contribution of surface barriers to P_1^{GS}.

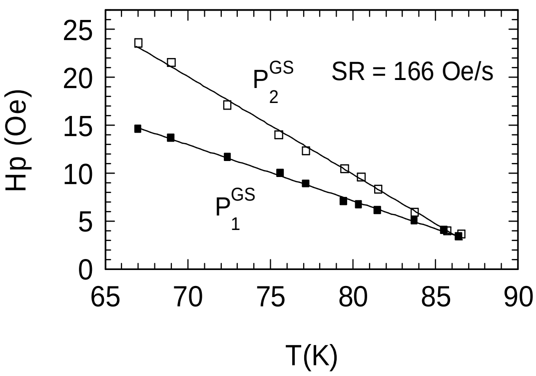

Fig. 4. The temperature dependence of the field at which the first penetration peaks P_1^{GS} and P_2^{GS} occur. The measurements were done with SR of 166 Oe/s, and the lines are guides to the eye.

At this point we can safely argue that the splitting of the field for first penetration (*i.e.*, the appearance of P_2^{GS}) is due mainly to the presence of *additional* surface barriers. To elucidate the origin of these additional surface barriers, complementary Atomic Force Microscopy and Scanning Hall Probe Microscopy studies are underway.

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