Hall-array gradiometer for measurement of the magnetic induction vector in superconductors

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An experimental technique for measuring the distribution of the normal and planar components of the magnetic induction near the surface of a superconducting sample is described. This technique utilizes a design of a double-layered Hall sensor array fabricated from a GaAs/AlGaAs heterostructure containing two parallel layers of a two-dimensional electron gas. Applications of this technique are demonstrated in measuring the current density distribution and in characterizing the flux creep process in a thin $YBa_2Cu_3O_7$ crystal. [S0021-8979(99)31408-0]

Local mapping of magnetic fields, using, e.g., Hall-probe arrays[1] or magneto-optical indicators,[2] has been widely employed in the study of superconducting materials. Using such techniques, the distribution of the magnetic field component B_z, *normal* to the sensor surface is measured. In many cases it is important to measure not only B_z but also the in-plane component B_x. For example, determination of the current density distribution in thin samples requires knowledge of both B_z and B_x. Several mathematical methods have recently been developed to circumvent the lack of B_x data by inverting the measured distribution of B_z into a map of current flowing in the sample.[3] However, due to the highly nonlocal relation between current and magnetic field, such inversion schemes are quite complicated. In the present article we describe a novel local magnetic measurement technique which yields directly the two components B_z and B_x. We utilize this technique in measuring the current density distribution in a thin $YBa_2Cu_3O_7$ crystal magnetized by a field perpendicular to its surface. We also apply the technique in the study of the flux creep process in the same sample, realizing the role of both B_z and B_x in this process.[4]

Experimental methods for measuring B_x were previously described by Kvitkovich and Majoros[5] and by Vlasko-Vlasov *et al.*[6] The device of Kvitkovich and Majoros comprises three independent Hall sensors arranged in three mutually perpendicular planes, thus enabling measurement of the vector **B**. However, in this device the separation between the sample surface and the sensors' active area is quite significant. Also, measurement of the field distribution requires mechanical scanning of the device. Vlasko-Vlasov *et al.* utilize domain wall motion in a magneto-optic indicator to measure B_x. Application of this method is complicated because it requires an external source of magnetic field with variable intensity to match the local values of B_x. The device described in this work is a double-layer Hall-probe array[7] attached directly to the sample. The array elements can be scanned electronically to yield a real time map of both B_z and B_x as shown below.

A schematic diagram of the double-layer Hall-probe array, and its configuration relative to the sample, is shown in Fig. 1. The array consists of a GaAs/AlGaAs heterostructure containing two distinct two-dimensional electron gas (2DEG) layers, separated by about 1 μm of AlGaAs and GaAs. This device allows measurement of the distribution of B_z at two levels z from the sample surface, thereby allowing determination of the gradient $\partial B_z/\partial z$ at a series of x values, from which B_x can be calculated as follows. We assume an infinite long strip magnetized by a field perpendicular to its surface, i.e., $\mathbf{B}=(B_x,0,B_z)$. The Gauss law

$$\nabla\cdot\mathbf{B}=\partial B_x/\partial x+\partial B_z/\partial z=0 \qquad (1)$$

leads to

$$\int_0^x(\partial B_z/\partial z)dx'=-B_x(x)+B_x(0), \qquad (2)$$

where $x=0$ is the center of the sample and $B_x(x)$ is the value of the in-plane component of the field near the sample surface. For antisymmetric current density distribution, i.e., $J_y(x)=-J_y(-x)$, as is the case in magnetization measurements, the integration constant $B_x(0)=0$.

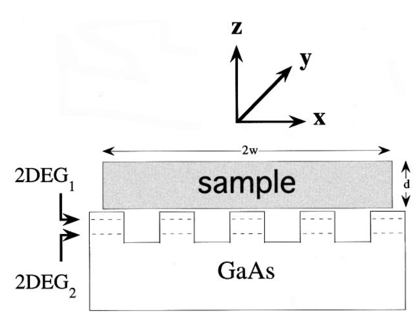

FIG. 1. Schematic diagram of the double-layer Hall-probe array and its position relative to the sample.

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In the present study, a double-layer Hall-probe array with five pairs of elements was fabricated, each element having an active area of $10\,\mu m\times 10\,\mu m$, separated by 40 μm between centers, yielding a spatial resolution of approximately 40 μm. For details of the fabrication process see Ref. 7. The upper and lower 2DEG layers had sensitivities of approximately 0.14 and 0.20 Ω/G, respectively. The noise level was approximately 0.5 G. Each layer was driven with 100 μA using two separate current sources, with the current in each source switched in polarity in order to eliminate offset potentials.

This device can be utilized in measurement of the current density distribution, and in characterization of the flux creep process in superconducting plates. In our configuration of an infinite long strip, the current flow can be approximated as one dimensional, $\mathbf{j}=(0,j\cdot sgn(x),0)$. The current density $J_y(x)$ is related to the gradients of B_x and B_z through the Maxwell equation

$$J_y=-(c/4\pi)(\partial B_z/\partial x-\partial B_x/\partial z). \quad (3)$$

For thin samples, in most of the sample bulk $\partial B_z/\partial x \cong B_z^*/w$, where B_z^* is the full penetration field and w is the half-width of the sample. The other derivative in Eq. (3), $\partial B_x/\partial z\cong 2B_x/d$, where $B_x\cong 0.5B_z^*$ is the planar field on the sample surface and d is its thickness. Thus, except for the center and the boundaries of the sample, where $\partial B_z/\partial x$ increases sharply and $\partial B_x/\partial z$ vanishes, $(\partial B_x/\partial z)/(\partial B_z/\partial x)\cong w/d$.[6] For thin samples this ratio may be as high as 10^5, consequently in such samples $J_y(x)$ is mainly determined by the tangential component B_x of the field on the sample surface, namely

$$J_y=(c/2\pi)(B_x/d). \quad (4)$$

Thus, in order to determine the current density it is sufficient to measure the in-plane component B_x.

Knowledge of both B_z and B_x is necessary for a complete description of the flux creep process. This point is clearly demonstrated in analyzing magnetic relaxation data in the remanent state. Ignoring the contribution of B_x leads to a one-dimensional continuity equation[9]

$$\frac{\partial B_z}{\partial t}=-\frac{\partial}{\partial x}(B_z\nu_x), \quad (5)$$

where ν_x is the average flux line velocity. At the neutral line[10] $B_z=0$ and $\partial B_z/\partial t=0$. Thus, at the neutral line Eq. (5) yields $\nu_x=\pm\infty$, leading to unphysical divergence of the activation energy U for flux creep, as $\nu=\nu_0\exp(-U/kT)$.

This problem is resolved when one considers both components, B_z and B_x. The differential equations governing the creep process are then[4]

$$\frac{\partial B_z}{\partial t}=-\frac{\partial}{\partial x}(B_z\nu_x-B_x\nu_z)=-\frac{\partial}{\partial x}(B\nu), \quad (6)$$

$$\frac{\partial B_x}{\partial t}=-\frac{\partial}{\partial z}(B_x\nu_z-B_z\nu_x)=\frac{\partial}{\partial z}(B\nu), \quad (7)$$

where $\mathbf{v}=(\nu_x,0,\nu_z)$ is the average flux line velocity, $v=\sqrt{\nu_x^2+\nu_z^2}$, and $B=\sqrt{B_x^2+B_z^2}$. Obviously, analysis on the basis of either equation should yield the same results for the flux creep parameters. At the neutral line one indeed has $B_z=\partial B_z/\partial t=0$, however $B_x\neq 0$ and $\partial B_x/\partial t\neq 0$, thus the relaxation process at the neutral line proceeds through relaxation of the in-plane component B_x which is normally neglected. The measurements described below provide the first experimental evidence for the important role played by B_x in the relaxation process.

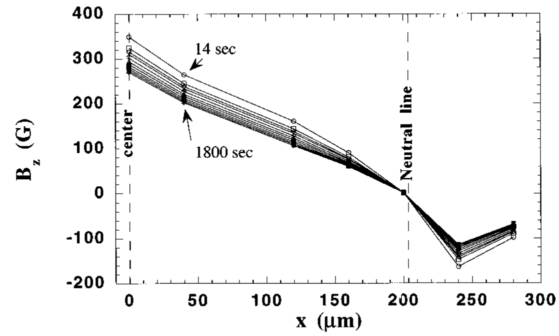

FIG. 2. Typical profiles of B_z, as measured by the lower Hall-probe layer, for thin $YBa_2Cu_3O_7$ crystal in the remanent state.

Measurements were performed on a detwinned thin $YBa_2Cu_3O_7$ single crystal of dimensions $1500\times 480\times 15\,\mu m^3$, at $T=50$ K. The sample was repeatedly positioned on the Hall-probe array in order to produce complete $B_z(x)$ profiles across half the width of the sample. The measuring procedure involved cooling the sample in zero field, then stabilizing the temperature at 50 K, subsequently magnetic field larger than twice the field H^* for complete flux penetration, was applied. Data were collected in the remanent state after turning the external field off.

Figure 2 shows typical field profiles of B_z in the remanent state, as measured at different times by the lower Hall-probe layer. The neutral line, at which $B_z=\partial B_z/\partial t=0$, is indicated in the figure. Figure 3 shows field profiles of B_x at different times as determined from the B_z profiles measured by both layers, using Eq. (2). Note that at the neutral line B_x is maximum and $\partial B_x/\partial t$ is large. According to Eq. (4) the B_x profiles also describe the current density profile $J_y(x)$, as indicated by the right hand side ordinate in Fig. 3.

In conclusion, the double-layer Hall-probe array can measure both the in-plane and the normal component of the

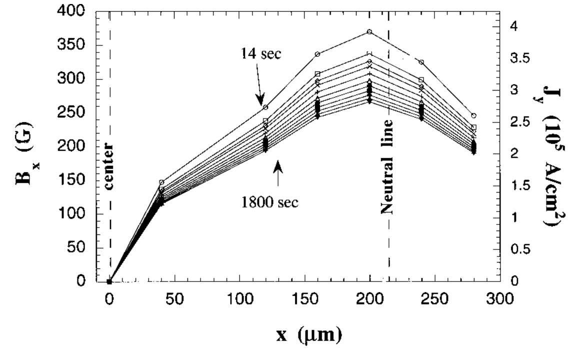

FIG. 3. Profiles of B_x determined from B_z profiles measured by the two Hall-probe layers. The same data points also represent the current density $J_y(x)$ as indicated by the right hand side ordinate.

induction field near the surface of a superconducting sample. This technique finds applications in measuring the current distribution across the sample and in characterizing the flux creep process in flat samples. Both applications have been demonstrated in a thin $YBa_2Cu_3O_7$ crystal in the remanent state. Additional applications can be found in, for example, determination of E-j curves and mapping of defects on a sample surface.

The authors thank D. Majer for his help in developing the gradiometer array. The analysis of magnetic relaxation near the neutral line was triggered by a comment by M. V. Indenbom, C. J. van der Beek, and G. D'Anna. This work was supported in part by the USA-Israel Binational Science Foundation, by the Heinrich Hertz Minerva Center, and by the Israel Science Foundation. One of the authors (M.M.) was supported by the Director for Energy Research, Office of Basic Energy Sciences through the Midwest Superconductivity Consortium (MISCON) DOE Grant No. DE-FG02-90ER45427 and in part by the Materials Research Science and Engineering Center (MRSEC) Program of the National Science Foundation under Award No. DMR-9400415.

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[10] The neutral line is the contour of points in the sample for which the z component of the induction field equals the external field H. For a platelet sample in a perpendicular field, the sample contribution to the induction field **B** is composed of components parallel (B_z) and perpendicular (B_x) to the applied field. As a result of demagnetization, ($B_z - H$) has a different sign at the edge and the center, and there exists a contour inside the sample where $B_z = H$ exactly. The neutral line has been observed in magneto-optic measurements (see Ref. 2), as well as in Hall-array measurements (see Ref. 4).