SOFT MAGNETIC PROPERTIES OF HIGH T_c SUPERCONDUCTING
THIN FILMS AS PERPENDICULARLY MAGNETIZING MEDIA

Shin-ichiro HATTA, Yo ICHIKAWA, Shigenori HAYASHI,
Hideaki ADACHI and Kiyotaka WASA

Central Research Laboratories, Matsushita Electric
Industrial Co., Ltd., Moriguchi, Osaka 570, JAPAN

The magnetic properties of high T_c superconducting thin films were discussed as the perpendicularly magnetizing media. In a weak field region below H_{c1} , every specimen film is very soft diamagnetic along the perpendicular direction to the film plane. This effect is caused by the shape anisotropy of thin films. The magnetic linear response is so excellent that an inductance curve is flat up to 70 MHz. Once the magnetic fluxoids are trapped in the films, it is unstable with showing the strong magnetic relaxation. Considering such properties, possibilities of magnetic application of the films at 77 K would be helpful.

INTRODUCTION

Since the transition temperature (T_c) of oxide superconductor exceeded the liquid nitrogen temperature, the superconducting devices operating at 77K were strongly investigated. Specially, the superconducting film devices seemed to be more helpful than those of bulk, because the films were dense and flat with the high critical current density (J_c). Therefore, the possibilities of the film devices in application were largely discussed on SQUID, superconducting transistor, etc.

Considering the magnetic properties of the superconductors, the application as magnetic materials seemed to be very possible. In particular, the superconducting films were perpendicularly magnetizing to the film plane with a giant apparent moment. By using such properties, lots of ideas on the film magnetic devices were presented.

In this paper, we will report the magnetic properties of the high T_c superconducting thin films in the technical field region, and discuss the possibility in the magnetic application.

EXPERIMENTAL

Our specimen films were prepared by an rf magnetron sputtering with the single target in the same conditions as $\text{ErBaCuO}(1)$, $\text{BiSrCaCuO}(2)$, $\text{TlBaCaCuO}(3)$ and $\text{NdCeCuO}(4)$ system. In these specimens, the n type superconductor is only NdCeCuO system. Every crystalline structure was highly oriented with c axis perpendicular to each film surface. These films were thought to have much better quality than bulk, because the resistivity in the normal state was in the order of $10^{-4} \Omega\text{cm}$ and J_c at 4.2K, was estimated to be about 10^6 A/cm^2 . Magnetization was measured by an rf SQUID susceptometer up to 100 K.

INITIAL MAGNETIZATION PROCESS

Most remarkable properties of the superconducting films are that there exists a perpendicularly magnetizing axis, and that they are very soft diamagnetic along the axis. The properties are quite different from those of usual magnetic materials. When initial magnetization curves are measured with changing angle (θ) between the film surface and the external field direction at 4.2K for the BiSrCaCuO film, the diamagnetization is strongly dependent on θ (Fig. 1). If the field is parallel to the film surface, the diamagnetization signal is too small to be detected below 200 Oe. The absolute value of susceptibility (χ) increases with increasing θ up to 90° . The maximum χ at 90° is about -100 (cgs unit). The apparent permeability ($\mu^* = 4\pi\chi = -1300$) is comparable to that of silicon steel. In the reversible magnetization process, where the film can exclude the magnetic fluxoid perfectly, the film is considered as a simply connected superconductor. Within weak field below 1 Oe, this physical situation may be reasonable. In this region, diamagnetization is written by

$$M = -H_{ex} / (4\pi(1-n)),$$

where n is a demagnetizing factor and H_{ex} is the external field. With the perpendicular direction of H_{ex} , n is about 1. Since the film is not perfect two dimensional plane, a correcting factor $\delta (>0)$ is necessary as $n=1-\delta$. In this case, δ is very small below 0.01. In the magnetic anisotropy for the films, the shape anisotropy is considered to be

relatively dominant, compared to the crystal magnetic anisotropy. When the higher quality film will be prepared to be much thinner, μ^* is possibly increased. Since the origin of the magnetization is not magnetic moment but superconductivity, there should not be any eddy current loss for the films. This was confirmed by the inductance measurement from 500 kHz up to 70 MHz. The high frequency properties were estimated to be flat over 100 MHz region(5).

IRREVERSIBLE MAGNETIZATION PROCESS

When H_{ex} is larger than H_{cl} , the magnetic fluxoid invades into the film. In Fig.2, an initial magnetization curve of TlBaCaCuO film is shown. At $H_{ex}=140$ Oe, the curve takes the minimum, however, H_{cl} is estimated to be much smaller than the field at the minimum. Each hysteresis loop of the specimen shows an imperfect rhombic shape with H_{ex} perpendicularly to the film plane. The maximum remanence becomes very large above 10^4 emu/cc

Fig. 1. Initial magnetization curves with changing angle(θ) between the external field and the film surface for BiSrCaCuO film at 4.2 K.

for BiSrCaCuO film, with the size of $1 \text{ mm} \times 2000 \text{ \AA}$, compared with usual ferromagnetic materials. The magnetization M (emu/cc) is proportional to the effective radius of the specimen, according to the Bean model(6).

A number of the invading fluxoids seem to be much more unstable, with comparing to bulky ceramics. These films exhibit significant magnetic relaxation due to the flux creep. The relaxation strength is highly anisotropic. When the fluxoids invade perpendicularly to the Cu-O basal plane, the strong relaxation takes place, while it is too small to be detected with H_{ex} parallel to the plane. All of our specimens reveal the temperature dependent relaxation with the logarithmic time

dependence. The magnetic relaxation can be approximated as,

$$x = (kT/a) \log(t/\tau + 1),$$

where $x = (M(T,0) - M(T,t))/M(T,0)$, τ is the time at which the extrapolation of linear curve crosses the $x=0$ line. Generally, the relaxation strength ($dx/d \ln t$) looks to be proportional to temperature except in the critical region. The experimentally determinable parameter, a , is considered to be the activation energy in the classical flux creep model(7). Such magnetic parameters are listed up in Table I.

For the NdCeCuO film, the relaxation takes place even at very low temperature. In Fig. 3, the time dependence of remanence of NdCeCuO film is shown. Also, the relationship of the relaxation strength vs temperature is indicated in Fig. 4. The activation energy, a , is estimated to be 0.02eV, which is only about 20 % as large as those of other p type films. In such high J_c films, it seems that the significant flux creep might be inevitable.

POSSIBILITY OF PERPENDICULAR MAGNETIZING DEVICES

As described in this paper, the magnetic application of the superconducting films seems to be very helpful. In particular, the films will be useful as soft magnetic materials in the very high frequency region to produce a new inductor or a part of magnetic recording head operating at liquid nitrogen temperature. When these films are treated as type II superconductor, with the magnetic

Fig. 2. The initial magnetization curve for TlBaCaCuO film at 4.2 K with $\theta=90^\circ$.

fluxoids trapped perpendicularly to the film plane, it is possible to produce the fluxoid memory of which memory density is estimated to be very large. In order to read out the information from the memory, a micro-magnetic head or an optical detector might be used. If we would use the light beam with a relatively long wave length above $100\text{ }\mu\text{m}$, the surface reflection is perfect in the superconducting state, while it is decreased in the normal state(8). When the film traps a number of magnetic fluxoids or excludes any fluxoid, the two state can be used as the memory unit. The reflectivity difference will be applied in a detecting operation like magneto-optical memory.

In these devices, the significant drawback is the time dependent properties due to the flux creep. In order to suppress the instability, we might need an artificial pinning barrier for the application.

REFERENCES

- (1) H. Adachi, K. Hirochi, K. Setsune, M. Kitabatake and K. Wasa: Appl. Phys. Lett. 51(1987)2263.
- (2) Y. Ichikawa, H. Adachi, K. Hirochi, K. Setsune, S. Hatta and K. Wasa : Phys. Rev. B38(1988)765.
- (3) Y. Ichikawa, H. Adachi, K. Setsune, S. Hatta, K. Hirochi and K. Wasa: Appl. Phys. Lett. 53(1988)919.
- (4) S. Hayashi, H. Adachi, K. Setsune, T. Hirao and K. Wasa: Jpn. J. Appl. Phys. 28(1989) No.6.
- (5) S. Hatta, K. Hirochi, H. Adachi, T. Kamada, Y. Ichikawa, K. Setsune and K. Wasa: Jpn. J. Appl. Phys. 27(1988)1646.
- (6) C. P. Bean: Phys. Rev. Lett. 8(1962)250.
- (7) M. R. Beasley, R. Labusch and W. W. Webb: Phys. Rev. 181(1969)682.
- (8) G. A. Thomas, A. J. Millis, R. N. Bhatt, R. J. Cava and E. A. Rietman: Phys. Rev. B36(1987)736.

Fig. 3. The time dependence of remanence of NdCeCuO film with logarithmic time scale.

Fig. 4. The relaxation strength in a logarithmic time scale vs temperature for NdCeCuO film.

Fig. 5. The hysteresis curve of BiSrCaCuO film at 4.2 K with $\theta=90^\circ$.

Table I

	ErBaCuO	BiSrCaCuO	TlBaCaCuO	NdCeCuO
type of carrier	p	p	p	n
$T_c(K)$	80	102	97	22
effective radius(mm)	0.45	1.0	0.87	0.5
$M_{max}(emu/cc)$	1400	11000	4000	1200
$a(eV)$	0.19	x	0.12	0.02