Remanent nonlinear magnetic response in superconducting Y-Ba-Cu-O

A. Shaulov,[a] D. Dorman, and R. Bhargava
Philips Laboratories, North American Philips Corporation, Briarcliff-Manor, New York 10510

Y. Yeshurun
Department of Physics, Bar-Ilan University, 52 100 Ramat-Gan, Israel

(Received 9 April 1990; accepted for publication 15 June 1990)

We report a "memory" effect in the response of sintered Y-Ba-Cu-O to alternating magnetic fields. The application of a steady bias field, above a certain threshold, causes the generation of harmonic components in the response. These harmonics persist after the field is removed, exhibiting a logarithmic decay with time. We explain these phenomena in the framework of the Bean model, taking into account the granularity of the sample. The memory phenomenon offers a principle for a new recording mechanism which may allow extremely high storage capacity.

Harmonic generation in the alternating magnetic response of high-temperature superconductors has been the topic of many recent studies [1–6] Three basic models have been proposed to explain this phenomenon. The first one is based on Bean's critical state model[7] as recently extended by Ji *et al.*[4] According to this model, the origin of the harmonic generation is the hysteretic, nonlinear relationship between the magnetization and the external field. The second model, by Jeffries *et al.*,[1] relates to a granular material and views it as a collection of supercurrent loops with weak links. According to this model, the magnetic nonlinearity results from the nonlinear relationship between the Josephson current in these loops and the magnetic flux enclosed by the loops. The third approach[6] is based on the observed broadening of the resistive transition due to flux creep and it attributes the harmonic generation to the nonlinear magnetoresistance. These models have been used to explain some field and temperature dependence measurements of the harmonic components in the ac response of Y-Ba-Cu-O powders, ceramics, and crystals.

In this letter we describe a new aspect of the harmonic generation phenomenon in high-temperature superconductors, namely, the observation of a remanent nonlinear magnetic response induced by momentary application of a magnetic field, and the logarithmic decay of this response with time. These effects are not predicted by any one of the above models. We outline an explanation of the results within the Bean model by taking into account the internal field which is induced in the weak links by the flux trapped in the grains.

The experiments were performed on sintered disks of Y-Ba-Cu-O (9 mm diameter, 1.5 mm thickness). The material was prepared by ball-milling stoichiometric amounts of yttria, barium carbonate, and copper oxide powders. Calcination of the powders was performed at 900 °C in flowing oxygen (500 cc/min) for 16 h followed by a 10 h ramped cooling to room temperature. The calcined powders were ground and then pressed at 200 MPa into pellets and fired at 950 °C for 16 h in flowing oxygen (500 cc/min). An x-ray diffractogram of this material agreed with that of the superconducting "1-2-3-7" standard material.

The measurement circuit consisted of a primary coil coaxial with a pair of balanced coils, one containing the sample. The material's response was monitored by measuring the power spectrum of the off-balance voltage induced in the coil pair using an HP3585A spectrum analyzer. A nonlinear behavior of the magnetization was indicated by the appearance of harmonic components in the response.

The "memory" effect, namely, the remanent nonlinear response, is illustrated in Fig. 1. The traces in this figure show the power spectra of the magnetic response of the disk at 77 K, as a sinusoidal field of amplitude 0.04 Oe and frequency 20 kHz was applied perpendicular to its face. The upper trace shows the spectrum obtained at zero bias field after the sample was cooled to 77 K in zero field. This spectrum contains only the fundamental component at the driving frequency (20 kHz), indicating a linear magnetic behavior of the material. The middle trace demonstrates the generation of odd harmonics in the material's response as the alternating field was superimposed on a colinear steady bias field $H_{dc} = 170$ Oe. This field is larger than the lower critical field H_{c1} and smaller than the irreversibility field[8] H_{irr} of the material at 77 K. The appearance of harmonic components in the response indicates a nonlinear behavior of the magnetization. The lower trace in Fig. 1 shows the spectrum of the response after the bias field H_{dc} was removed. It is seen that the third-harmonic component in the response persists, although with somewhat reduced amplitude.

In Fig. 2 we demonstrate another phenomenon which is related to the memory effect. The traces in this figure show the spectra of the ac response of a sintered Y-Ba-Cu-O sample at 88.5 K. The upper trace shows the spectrum in the absence of a dc bias field. The proximity to the transition temperature $T_c = 90$ K, causes the appearance of the harmonic components in the response.[9] The application of a steady bias field larger than the irreversibility field H_{irr} (for this sample, we measured $H_{irr} = 310$ G at 88.5 K) suppressed the nonlinear behavior as shown in the middle trace of Fig. 2. Subsequent removal of the steady bias field caused the reappearance of harmonic components in the

[a]Now on a sabbatical leave at the Department of Physics, Bar-Ilan University, Ramat-Gan, Israel.

 0003-6951/90/330724-03$02.00

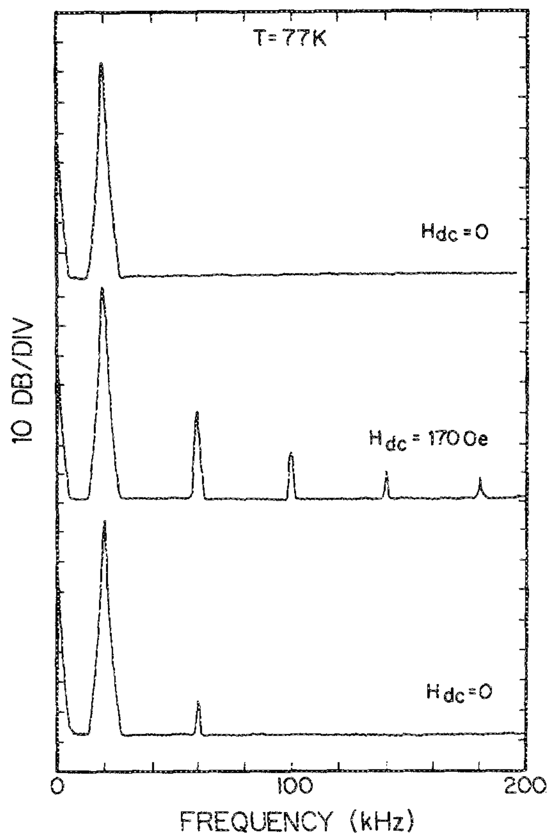

FIG. 1. Spectra of the ac response of sintered Y-Ba-Cu-O at 77 K without dc bias field (a), with a bias field of 170 Oe (b), and after the bias field is removed (c).

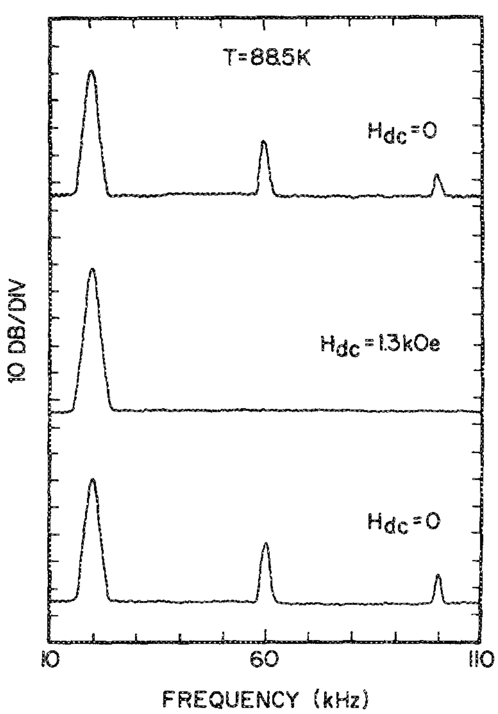

FIG. 2. Spectra of the ac response of sintered Y-Ba-Cu-O at 88.5 K without dc bias field (a), with a bias field of 1.3 kOe (b), and after the bias field is removed (c).

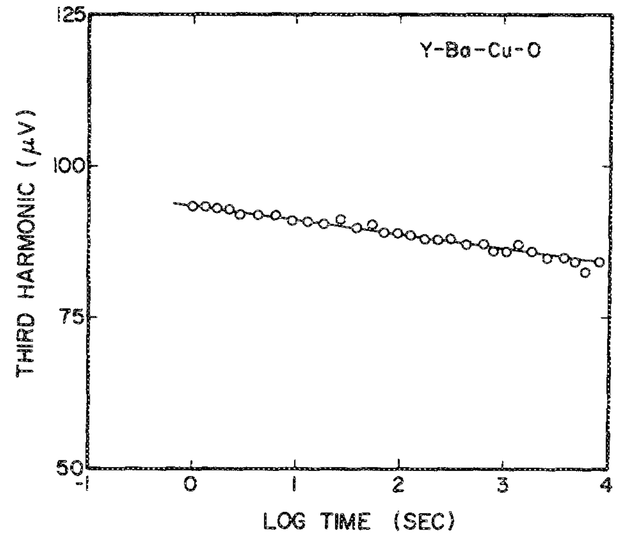

FIG. 3. Time decay of the remanent third-harmonic signal in sintered Y-Ba-Cu-O.

response as shown in the lower trace of Fig. 2. In this experiment, the amplitude of the remanent third-harmonic component is independent of H_{dc} up to our maximum field of 1.5 kOe. We note that the remanent magnetization itself is independent of field for fields above the irreversibility line.

The first experiment demonstrates that a change from a linear to a nonlinear magnetic behavior can be impressed in the material by momentary application of a magnetic field above a certain threshold. The induced nonlinear behavior decays slowly with time as indicated by the time dependence of the third component shown in Fig. 3. This logarithmic decay with time follows the well known behavior of the remanent magnetization.[10] Elimination of the nonlinear response was achieved by heating the sample above the transition temperature and subsequently cooling it to 77 K in zero field.

The memory effect and the logarithmic time decay seem to follow a pattern which is dictated by the irreversibility in the dc magnetization. However, irreversibility in the ac response is not predicted by either of the three models described above in the introduction. Moreover, we are not able to reproduce the memory effect in a Y-Ba-Cu-O crystal.[11] These suggest that the explanation to the memory effect is related to flux trapping and irreversibility in granular systems.[12,13] In the following we explain the experimental results in the framework of the Bean model, taking into account the effect of granularity on the flux profiles.

For $H_{dc} = 0$, the whole sample, grains and weak links, is shielded and the response to the ac field is linear; no harmonics are generated. On raising the bias field above the "effective" lower critical field, H_{c1}, of the medium, flux starts to penetrate the material and the magnetization induced by the sinusoidal field traverses hysteresis loops.[7] This irreversible, nonlinear behavior causes the generation of harmonic components in the response. When the external bias field is removed, some of the flux lines remain trapped within the grains, thus creating an internal bias field which, in the weak links, is above H_{c1}. As a result, the magnetic response of the material continues to be nonlinear. Following this interpretation, one can explain the logarithmic time decay of the third-harmonic signal on the basis of the dependence of the critical current upon the trapped flux.[13] According to the Bean model, for small ac fields, the amplitude V_3 of the third harmonic signal is inversely proportional to the critical current density.[7] The flux trapped within the grains produces an internal field in the weak links, which in turn, reduces the intergranular $J_c(B)$.[13] As the trapped flux creeps out of the grains, the internal field in the weak links decreases, and consequently, the intergranular $J_c(B)$ increases and V_3 decreases.

This memory effect may form a basis for a new recording mechanism which may allow extremely high storage density. Information may be stored on a thin layer of Y-Ba-Cu-O in a form of small domains with a nonlinear magnetic response in a matrix of superconducting material with a linear magnetic response. The size of these domains is expected to be of the same order as the diameter of flux tubes, namely, 0.01–0.1 μm. The density is determined by the Abrikosov lattice constant $a_0 = \sqrt{\phi_0/H}$. Thus, extremely high storage densities may be expected. In the recording or "writing" process, a focused electron beam may be used to cause local heating of the superconducting layer. In the presence of a magnetic field of strength H_0, lines of magnetic flux penetrate into the irradiated spot as soon as its temperature rises to a point at which H_{c1} becomes smaller than H_0. On cooling, some of the flux remains trapped within this spot, giving rise to a nonlinear magnetic response. In this way, a pattern of small domains with a nonlinear magnetic response is created in a superconducting matrix with a linear response. This pattern can be erased by raising the temperature of the superconducting layer above the transition point. Upon cooling, the whole matrix exhibits linear response and thus the system is immediately ready for storing a new information. In the reading process the film is scanned by an electron beam while an external sinusoidal field is applied to induce small oscillations in the magnetization of the material. The electrons moving in the field caused by the magnetization experience an oscillatory force perpendicular to their velocity. Thus, the reflected beam oscillates between two opposite directions. These oscillations are expected to be sinusoidal when the beam is reflected from a domain with a linear magnetic response and nonsinusoidal when the beam is reflected from a domain with a nonlinear magnetic response. Sinusoidal and nonsinusoidal deflections of the beam can be distinguished by using a detection system which is sensitive to the direction of the beam.

In summary, measurements of the remanent nonlinear magnetic response can be used as a tool for studying the metastable mixed state of high-temperature superconductors. Specifically, one can detect remanent magnetization and measure its time relaxation by monitoring the harmonic components in the ac response of the material. The potential application of the remanent nonlinear response as a principle for high-density recording should be further explored.

We would like to thank Shuki Wolfus and Ronen Hareuveni for helpful discussions. One of us (Y.Y.) acknowledges a partial support by the Basic Research Foundation administered by the Israeli Academy of Sciences and Humanities.

[1] C. Jeffries, Q. H. Lam, Y. Kim, L. C. Bourne, and A. Zettl, Phys. Rev. B **37**, 9840 (1988); C. D. Jeffries, Q. H. Lam, Y. Kim, C. M. Kim, and A. Zettl, Phys. Rev. B **39**, 11 526 (1989).
[2] A. Shaulov and D. Dorman, Appl. Phys. Lett. **53**, 2680 (1988).
[3] K. H. Muller, J. C. McFarlane, and R. Driver, Physica C **158**, 366 (1989).
[4] L. Ji, R. H. Sohn, G. C. Spalding, C. J. Lobb, and M. Tinkham, Phys. Rev. B **40**, 10 936 (1989).
[5] T. Ishida and R. B. Goldfarb, Phys. Rev. B **41**, 8937 (1990).
[6] D. G. Xenikos and T. R. Lemberger, Phys. Rev. B **41**, 869 (1990).
[7] C. P. Bean, Rev. Mod. Phys. **36**, 31 (1964).
[8] A. P. Malozemoff, T. K. Worthington, Y. Yeshurun, F. Holtzberg, and P. H. Kes, Phys. Rev. B **38**, 7203 (1988).
[9] A. Shaulov, R. Bhargava, and D. Dorman, to be published in the Proceedings of the Materials Research Society Meeting, Boston, 1989.
[10] See, e.g., M. Touminen, A. M. Goldman, and M. L. Mecartne, Physica C **153**, 324 (1988).
[11] A. Shaulov and Y. Yeshurun (unpublished). Experiments in a single crystal of Y-Ba-Cu-O ($T_c = 91$ K) were performed in the temperature range 77–91 K and dc fields up to 1.5 kOe. At 77 K no harmonic signals could be observed; presumably they are below the noise background level because of the large J_c in single crystals at this temperature. We do observe harmonic signals in close vicinity of T_c (i.e., in the range 89–91 K). However, in this temperature range, the crystal does not exhibit the memory effect.
[12] K. W. Blazey, A. M. Portis, and J. G. Bednorz, Solid State Commun. **65**, 1153 (1988).
[13] J. E. Evetts and B. A. Glowacki, Cryogenics **28**, 641 (1988).