Giant Magnetostriction in $Bi_2Sr_2CaCu_2O_8$ Single Crystal in the Superconducting State and Its Mechanism

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Unusually large magnetostriction for a superconductor was found in a single crystal of the high-T_c cuprate $Bi_2Sr_2CaCu_2O_8$. The sample length change was measured along the *ab* plane under magnetic fields applied up to 6 T parallel to the *c* axis. The sample decreased in length during the field increasing process and with relative change exceeding 10^{-4} at 4.8 K. A quantitative model has been proposed which accounts for the magnetostriction in terms of internal forces arising from flux pinning. These observations show that magnetostriction measurement is a novel and unique technique to investigate the pinning effect and related phenomena in type-II superconductors.

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One of the most fundamental and interesting properties of real type-II superconductors is the existence of flux pinning and the associated irreversibility in the magnetization process. Although many studies have been devoted to this since the discovery of high temperature superconductors (HTSC's), the flux pinning behavior is not yet fully understood. For this reason, establishment of a novel method to investigate the flux pinning effect would obviously contribute to further research in this field.

The most often adopted experimental technique on the problem of the pinning effect is the magnetization measurement which measures magnetically the amount of the trapped or excluded flux lines. However, since the pinning force acts on the flux lines, an equal and opposite force must be exerted on the crystal. This means that a sample length change in an applied field, or magnetostriction, should be observed if the pinning force is strong enough.

It was already confirmed before the discovery of HTSC's that superconductors display magnetostriction [1]. However, its origin has been discussed in terms of thermodynamical arguments [1, 2], without the incorporation of flux pinning effects. To the best of our knowledge, the only work discussing the mechanism of magnetostriction in terms of pinning force is that by Isino *et al.* on V_3Si [3].

In this Letter, we report our observation of an unusually large magnetostriction in a $Bi_2Sr_2CaCu_2O_8$ single crystal in the superconducting state. The relative sample length change, $\Delta L/L$, was found to exceed the order of 10^{-4}. This value is much larger than those for HTSC's reported so far [4–7], except for polycrystalline $RBa_2Cu_3O_y$ (R=Dy, Ho) samples [8, 9]. These two exceptions are, however, rare-earth-ion-containing compounds, and the observations were discussed on the basis of local magnetic moments, which is not the case for $Bi_2Sr_2CaCu_2O_8$. We also formulate the above mentioned pinning-induced mechanism of magnetostriction. It will be shown that our observations can be fairly well explained by this model.

The single crystal used in this investigation was grown by the traveling-solvent-floating-zone technique described elsewhere [10]. The magnetostriction was measured with a capacitance dilatometer designed after Brändli and Griessen [11]. The sample length change is detected by capacitance change using a capacitance bridge, model 2500A of Andeen-Hagerling, Inc. Length changes of the order of 10^{-2} Å ($=10^{-12}$ m) can be detected. All the data reported here are transverse magnetostriction; the magnetic field was applied along the crystallographic *c*-axis direction and the length change was measured along the *ab* plane, i.e., perpendicular to the applied field. The sample size was $2.17\times2.50\times0.15$ mm^3, where the first number is the edge length along which the magnetostriction was measured and the last denotes that along the *c* axis. The magnetic field was swept with a constant cyclic rate, typically 10 mT/s, up to ±6 T after the sample was cooled under zero field (ZFC).

Figure 1 shows the magnetostriction curve measured at 4.8 K. An obvious feature of this curve is that the magnetostriction coefficient $\Delta L/L$ is surprisingly large, of the order of 10^{-4}. Another feature observed here is the large hysteresis. On first increasing the field, the sample was compressed: $\Delta L/L$ was negative and decreased monotonically. In the field decreasing stage $\Delta L/L$ crossed zero at around 4.3 T, the sample then expanded beyond its original dimension to a maximum near 2 T. $\Delta L/L$ then decreased but remained positive at zero field. The negative field region of the magnetostriction curve was completely symmetrical to the positive field region, except for the initial magnetization stage.

In Fig. 2, we show magnetostriction curves of the same sample measured at several temperatures. With increasing temperature, the magnetostriction becomes smaller for the same external field. Furthermore, the curves gradually change not only in magnitude but also in general shape. The inset of Fig. 2, showing the 20 K data on an

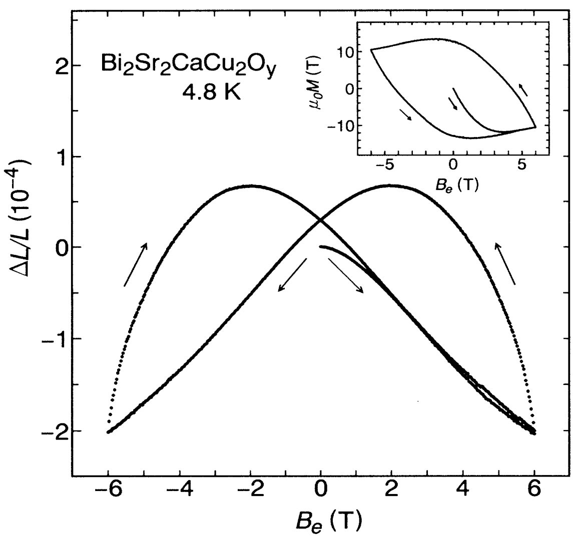

FIG. 1. Magnetostriction curve of a $Bi_2Sr_2CaCu_2O_8$ single crystal at 4.8 K. The field was applied along the crystalline c-axis direction and the sample length change was measured along the ab plane. The inset is the magnetization curve measured by a vibrating sample magnetometer on the same sample at 5.0 K.

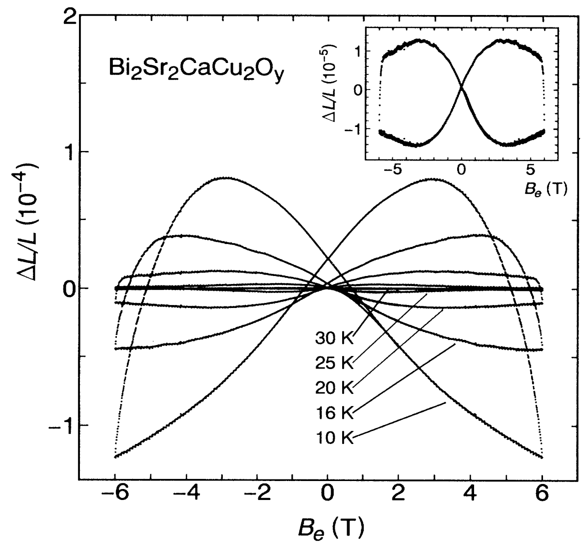

FIG. 2. Magnetostriction curves of the same sample as Fig. 1 measured at several temperatures. The field was applied along the crystalline c-axis direction and the sample length change was measured along the ab plane. The inset is a blowup of the magnetostriction curve at 20 K.

expanded scale, exhibits a minimum in the positive field region for field increasing process, a feature differing from the behavior at lower temperatures.

The linear thermal expansion coefficients of the a and b axes of $Bi_2Sr_2CaCu_2O_8$ are reported to be less than 1.5×10^{-5} at room temperature [12], and for physical reasons must be smaller at lower temperature. Therefore, sample length change of the order of 10^{-4} corresponds to temperature deviation of more than 10 K, and we can safely exclude the possibility of the sample length changes caused by temperature fluctuation. On the other hand, the present observations can be understood qualitatively in terms of a pinning-induced mechanism. During the field increasing process, a compressive force is exerted on the crystal, since the movement of vortices is restricted due to the flux pinning effect. In the field decreasing stage, the sample experiences an expansive force through the same mechanism. Since the flux motion is irreversible, the magnetostriction curve is expected to display a hysteresis. The sample will be in tension when the field is swept back to zero, due to the trapped vortices. Since it is known that the pinning force significantly decreases with increasing temperature in $Bi_2Sr_2CaCu_2O_8$, the magnetostriction should also decrease. These are all features observed in the present experimental results.

For a quantitative comparison between the above proposed model and the experimental results, we derive fundamental equations for the pinning-induced magnetostriction. For simplicity, we consider the one-dimensional flux penetration model and neglect the demagnetization effect. We also assume that the reversible magnetization is a small fraction of the total magnetization and that the critical state is achieved. Taking the strength of the pinning force of a flux line as f_p (N/m) per unit length, force of $-f_p$ is exerted on the specimen by each flux line. When we have n flux lines per area, the magnitude of the force exerted on the sample will be $-nf_p$ (N/m^3). Then the following equilibrium condition should hold:

$$\frac{\partial\sigma(x)}{\partial x}+\Big(-n(x)f_p\Big)=0, \tag{1}$$

where $\sigma(x)$ is the internal local stress.

We take the length of the sample L as $2d$. The local pinning force is expressed as $f_p=\Phi_0\mu_0^{-1}\partial B(x)/\partial x$, where Φ_0 is the flux quantum, μ_0 is the permeability of vacuum, and $B(x)=\Phi_0 n(x)$ is the local magnetic flux density [13]. Then $\sigma(x)$ can be obtained by integration as

$$\sigma(x)=-\frac{B_e^2-B^2(x)}{2\mu_0}, \tag{2}$$

where B_e is the applied external field.

If we assume that the ab plane of $Bi_2Sr_2CaCu_2O_8$ is elastically isotropic with c_{11} being the stiffness constant, we obtain the following expression for the relative sample length change in our experimental configuration:

$$\frac{\Delta L}{L}=\frac{1}{L}\int_{-d}^{d}\frac{\sigma(x)}{c_{11}}dx =-\frac{1}{2c_{11}\mu_0 d}\int_0^d\left\{B_e^2-B^2(x)\right\}dx. \tag{3}$$

It is now possible to calculate the magnetostriction curve once the local field distribution $B(x)$ is known. The simplest assumption for this is the original Bean model [14]. Calculations performed by assuming this model already reproduce many of the qualitative features of the measured 4.8 K curve. However, within this model, $\Delta L/L$ decreases monotonically by increasing the external field. This is due to its assumption of field independence of the pinning force. Since, however, it was observed experimentally that at higher temperature the $\Delta L/L$ curve has a minimum during the field increasing process (see the inset of Fig. 2), we have to incorporate some field dependence in the pinning force. For this purpose, we tentatively employ an exponential decay model for J_c [15]:

$$J_c(B) = \mp J_{c0}\exp(-|B|/B_0), \tag{4}$$

where $-$ $(+)$ stands for the field increasing (decreasing) process. $B(x)$ can be obtained by integrating this equation using the expression $J_c(x) = -\mu_0^{-1}\partial B(x)/\partial x$.

Some results of the calculations for various parameters are shown in Fig. 3. In these calculations we have used the value c_{11}=1.252×10^{11} N/m^2 deduced by Boekholt *et al.* at room temperature [16]. This value of c_{11} is also very consistent with the result of Wu *et al.*, 1.3×10^{11} N/m^2 [17]. We see from Fig. 3 that the overall shapes of the measured magnetostriction curves are well reproduced. In particular, the local minimum observed experimentally above 20 K is reproduced in the curve (c). These general agreements strongly support our picture

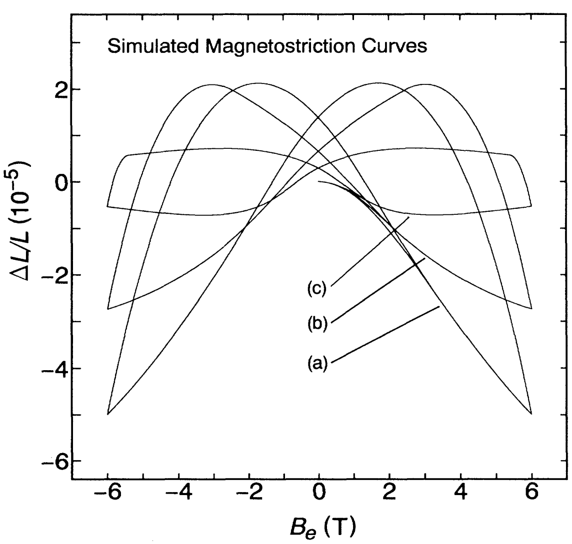

FIG. 3. Calculated magnetostriction curves by Eq. (3) and assuming the exponential decay model for the critical current J_c, Eq. (4). The parameters adopted are (a) J_{c0}=3.0×10^9 A/m^2, B_0=20 T, L=2.17 mm; (b) J_{c0}=2.0×10^9 A/m^2, B_0=10 T, L=2.17 mm; and (c) J_{c0}=1.5×10^9 A/m^2, B_0=3 T, L=2.17 mm.

of pinning-induced mechanism for the present magnetostriction phenomenon.

Nevertheless, the magnitude of the calculated magnetostriction is about 1 order smaller than the observed value at 4.8 K. This quantitative disagreement, however, seems not to be due to the applicability of the pinning-induced magnetostriction model, but rather ascribed to the large demagnetization effect expected for our sample. Indeed we see in the inset of Fig. 1 that the initial magnetization curve is much steeper than expected, which indicates a large demagnetization effect. While it is difficult to evaluate this demagnetization field precisely, we might assume for a rough estimation that the demagnetization effect can be described with a single demagnetization factor D [18, 19], keeping in mind that this is only justified for homogeneously magnetized samples. The effectively applied field $B_{\rm eff}$ is then expressed as $B_{\rm eff} = B_e - \mu_0 DM$, where M is the magnetization. If we approximate our sample by an ellipsoid [20] and use the magnetization data, the applied maximum effective field is estimated to be 15.5 T. Extending the magnetostriction calculation to this field, it is possible to obtain $\Delta L/L$ values of the order of 10^{-4}.

It is worthwhile to compare our observations with the previously reported magnetostriction measurements on HTSC's. Most of these are measurements for polycrystalline samples revealing much smaller values of $\Delta L/L$ [4–6]. However, these results are not inconsistent with our observations. According to Eq. (3), the pinning-induced magnetostriction depends on the difference of squares of the external field and the local field. Since the grain sizes of the polycrystals are much smaller than the single crystal dimensions and since the grain boundaries of HTSC's are known to have weak-linked nature, the polycrystals are much more easily magnetized than single crystals. Furthermore, the demagnetization effect is much more significant for flat single crystals with magnetic field applied along the shortest direction. It is not unreasonable, then, that the magnitude of magnetostriction measured on polycrystals are much smaller than our results for a single crystal.

The magnetostriction observed on RBa$_2$Cu$_3$O$_y$ (R =Dy, Ho) samples, on the other hand, were comparable in size to our results, even they were also measured on polycrystalline samples [8, 9]. However, the origin of large magnetostriction in this case seems to differ from our case as mentioned above. Indeed, the transverse magnetostriction was *positive* in these compounds, which is the opposite behavior expected for the pinning-induced mechanism.

Quite recently, Schmidt *et al.* reported 2 orders smaller values of magnetostriction for a $Bi_2Sr_2CaCu_2O_8$ single crystal [7]. The field was applied along the c-axis direction, similarly as in our case, but they measured the longitudinal magnetostriction: sample length change along the field direction. This should be a measure of shear deformation in our model and the reported smaller values of magnetostriction are reasonable.

In summary, we have observed giant magnetostriction in a $Bi_2Sr_2CaCu_2O_8$ single crystal. Fundamental equations are derived based on a model of the pinning-induced mechanism of magnetostriction. The proposed model qualitatively reproduces our observations very well; the quantitative discrepancy can reasonably be attributed to a large demagnetization effect.

The present observations have proved that measurement of magnetostriction is a novel technique for the investigation of the flux pinning and related phenomena. One of the potential advantages of this method is that the two transverse magnetostriction directions can be measured independently. By applying the field along the a-axis direction and detecting sample length changes along both the b- and c-axis directions, the anisotropy of the pinning effect can be studied. Such a capability renders magnetostriction a unique technique for elucidating the irreversible magnetic properties of HTSC's, in which the anisotropy is a critically important issue.

[1] G. Brändli, Phys. Kondens. Mater. **11**, 93 (1970); **11**, 111 (1970).

[2] H. Kronmüller, Phys. Status Solidi **40**, 295 (1970).

[3] M. Isino, T. Kobayashi, N. Toyota, T. Fukase, and Y. Muto, Phys. Rev. B **38**, 4457 (1988).

[4] E. du Tremolet de Lacheisserie, B. Barbara, and J. H. Henry, J. Magn. Magn. Mater. **71**, L125 (1988).

[5] J. Zieglowski, S. Blumenröder, A. Freimuth, H. Schmidt, E. Zirngiebl, D. Wohlleben, and H. J. Schmidt, Z. Phys. B **71**, 429 (1988).

[6] M. Braden, P. Böhm, F. Seidler, H. Kalenborn, and D. Wohlleben, Z. Phys. B **79**, 173 (1990).

[7] A. Schmidt, F. Stellmach, M. Boekholt, S. Ewert, K. N. R. Taylor, and D. Elefant, in Proceedings of the Third World Congress on Superconductivity, Munich, 14–18 September 1992 (to be published).

[8] A. del Moral, M. R. Ibarra, P. A. Algarabel, and J. I. Arnaudas, Physica (Amsterdam) **161C**, 48 (1989).

[9] A. M. Kadomtseva, N. P. Kolmakova, I. B. Krynetskii, R. Z. Levitin, V. V. Snegirev, and A. K. Zvezdin, Physica (Amsterdam) **162C–164C**, 1361 (1989).

[10] N. Motohira, K. Kuwahara, T. Hasegawa, K. Kishio, and K. Kitazawa, J. Ceram. Soc. Jpn. **97**, 994 (1989).

[11] G. Brändli and R. Griessen, Cryogenics **13**, 299 (1973).

[12] R. H. Arendt, M. F. Garbauskas, C. A. Meyer, F. J. Rotella, J. D. Jorgensen, and R. L. Hitterman, Physica (Amsterdam) **182C**, 73 (1991).

[13] P. G. de Gennes, *Superconductivity of Metals and Alloys* (Benjamin, New York, 1966).

[14] C. P. Bean, Rev. Mod. Phys. **36**, 31 (1964).

[15] P. Chaddah, K. V. Bhagwat, and G. Ravikumar, Physica (Amsterdam) **159C**, 570 (1989).

[16] M. Boekholt, J. V. Harzer, B. Hillebrands, and G. Güntherodt, Physica (Amsterdam) **179C**, 101 (1991).

[17] J. Wu, Y. Wang, H. Shen, J. Zhu, Y. Yan, and Z. Zhao, Phys. Lett. A **148**, 127 (1990).

[18] M. Wacenovsky, H. W. Weber, O. B. Hyun, D. K. Finnemore, and K. Mereiter, Physica (Amsterdam) **160C**, 55 (1989).

[19] F. M. Sauerzopf, H. P. Wiesinger, and H. W. Weber, Cryogenics **30**, 650 (1990).

[20] J. A. Osborn, Phys. Rev. **67**, 351 (1945).