Flux flow excited by ultrasonic deformation of flux line lattice in high temperature superconducting ceramics

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Abstract

To investigate the flux pinning behavior in HTSC against various kinds of deformation of flux line lattice(FLL), the flux flow excited by ultrasonic deformation of FLL was measured for bulk sintered samples of $Bi_2Sr_2Ca_2Cu_3O_y$. The compressional, tilt and shear ultrasonic deformations, which are associated with the elastic moduli of C_{11}, C_{44} and C_{66} of FLL in isotopic superconductors, were applied to FLL. A peak of the flux flow resistivity was observed at a temperature T_p at which the dissipation of ultrasonic energy became the maximum. The differences in T_p and the peak height among the deformations were small differently from the theoretical prediction with the model of thermally assisted flux flow. The results suggest that most flux lines are bent due to the pinning at insulating layers and/or grain boundaries.

Key words: flux flow; flux pinning; irreversibility line; ultrasound attenuation

In high temperature superconductors (HTSC), the instability of flux line lattice(FLL) has been attributed to the large effect of thermal excitation and the weak flux pinning. Such instability is closely related to the dimensionality of the superconductivity[1] which originates from the layer structure of HTSC. The instability makes the state of FLL complicated. Accordingly, many kinds of FLL phases and their phase transitions have been predicted and confirmed experimentally[2].

By the ultrasonic method, it is expected that the elastic moduli of FLL can be determined by applying various ultrasonic deformation to FLL[3]. However, the ultrasonic energy dissipation due to the diffusive motion of flux lines is too small to detect by ultrasonic attenuation $\Delta\alpha$, in particular in low magnetic fields . In the previous papers[4,5], we proposed a new method measuring not $\Delta\alpha$ but the excess flux flow resistivity $\Delta\rho_\mathrm{us}$ excited by ultrasound.

In this paper, the flux flow excited by ultrasound was measured for bulk sintered samples of $Bi_2Sr_2Ca_2Cu_3O_y$ by applying compressional, tilt and shear deformations to examine the flux pinning behavior against various kinds of FLL deformation.

In the experiments, the Lorentz force F_L was generated by the current I and the magnetic field B, and the flux flow resistivity ρ_f caused by F_L was measured without ultrasound by the four-probe method. Next, the excess flux flow resistivity $\Delta\rho_\mathrm{us}$ caused by ultrasound was measured as follows: By applying the voltage V_in to a $LiNbO_3$ transducer (Y-36° or X-41° cut) attached on one end of a sample, the longitudinal or transverse ultrasound of the frequency f_rf was propagated. The frequency f_rf was chosen to resonate the sample so that flux lines were strongly vibrated by the standing waves through the coupling with pinning centers. When the wave vector $\boldsymbol{k}$ and the displacement vector $\boldsymbol{u}$ of the ultrasound are chosen to be $\boldsymbol{k} \parallel \boldsymbol{u} \perp \boldsymbol{B}$, compressional deformation is applied to FLL. The conditions of $\boldsymbol{k} \perp \boldsymbol{u} \perp \boldsymbol{B}$ and $\boldsymbol{u} \perp \boldsymbol{k} \parallel \boldsymbol{B}$ cause shear and tilt deformations, respectively. A small signal of $\Delta\rho_\mathrm{us}$ was detected by modulating the voltage V_in with the frequency of f_AM and by measuring the modulated component of ρ_f by a lock-in amplifier through a band-pass filter.

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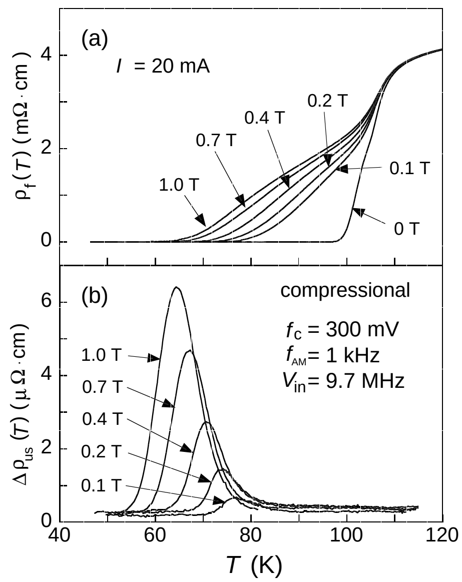

Fig. 1. Temperature dependence of (a) the flux flow resistivity ρ_f and (b) the excess flux flow resistivity $\Delta\rho_\mathrm{us}$ due to a compressional ultrasonic deformation in several magnetic fields.

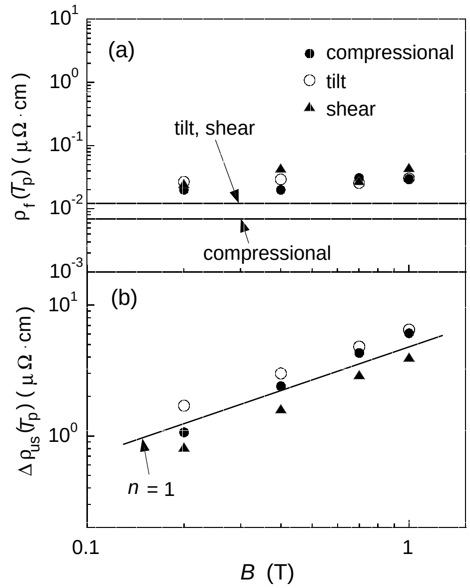

Fig. 2. Magnetic field dependence of (a) $\rho_\mathrm{f}(T_\mathrm{p})$ at the peak temperature T_p and (b) the peak height $\Delta\rho_\mathrm{us}(T_\mathrm{p})$. The solid line in (a) is the calculation using TAFF model.

Experimental results of ρ_f and $\Delta\rho_\mathrm{us}$ in several magnetic fields are shown in Figs. 1(a) and 1(b), respectively. A peak was observed in $\Delta\rho_\mathrm{us}(T)$ at a temperature T_p lower than the onset temperature, but slightly higher than the end temperature of the transition in $\rho_\mathrm{f}(T)$.

For the state of thermally assisted flux flow (TAFF) in an isotropic superconductor, the peak temperature T_p and the peak height $\Delta\rho_\mathrm{us}(T_\mathrm{p})$ can be estimated quantitatively from the following equations[5]:

$$\rho_\mathrm{f}(T_\mathrm{p}) = \frac{1}{2\pi}\mu_0 f_\mathrm{rf}\lambda^2, \tag{1}$$

$$\Delta\rho_\mathrm{us}(T_\mathrm{p}) = \frac{\rho_\mathrm{f}(T_\mathrm{p})}{2k_\mathrm{B}T_\mathrm{p}}\int \mathrm{d}V\frac{1}{2}C_{ij}{\epsilon_j}^2. \tag{2}$$

Here, λ is the wavelength of the ultrasound, and C_{ij} and ϵ_j are the tensors of elastic modulus of FLL and applied strain, respectively. The elastic energy of FLL is integrated over the volume of the sample.

In Fig. 2(a) the values of $\rho_\mathrm{f}(T_\mathrm{p})$ determined from the experiments of $\rho_\mathrm{f}(T)$ are compared with those obtained from eq. (1) by substituting the experimental parameters: $f_\mathrm{rf} = 9.2$ MHz and $\lambda = 260$ μm for compressional, and $f_\mathrm{rf} = 9.7$ MHz and $\lambda = 190$ μm for tilt and shear deformations. The experimental values of $\rho_\mathrm{f}(T_\mathrm{p})$ were independent of the magnetic field and the sort of the deformation, while they were slightly larger than the theoretical ones.

According to eq. (2) for an isotropic superconductor, $\Delta\rho_\mathrm{us}(T_\mathrm{p})$ is almost proportional to C_{ij}, therefore to B^2, when the change of T_p with B is considered to be small. However, $\Delta\rho_\mathrm{us}(T_\mathrm{p})$ changed with B^n ($n \sim 1$) as shown in Fig.2(b). Furthermore, since C_{11} and C_{44} are much smaller than C_{66} for FLL in conventional isotopic superconductors, $\Delta\rho_\mathrm{us}(T_\mathrm{p})$ of the shear deformation must be much smaller than that of the other ones. However, its difference among them was small.

The discrepancies suggest that most flux lines are bent due to the pinning at insulating layers and/or grain boundaries, and the contributions of C_{11}, C_{44} and C_{66} are averaged for the deformation generated by ultrasound. The decrease of the exponent n in B^n from 2 to 1 might be the evidence that the interaction between flux lines are weakened because of the bend of flux lines. Therefore, to investigate the anisotropic behavior of the instability of FLL in HTSC, it is necessary to use single crystals for the measurements. The measurements using epitaxial thin films are now in progress.

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