Purely viscous motion of the vortices in semiclassical d-wave superconductor

Y. Matsuda [a,1], K. Izawa [a], A. Shibata [a], H. Ikuta [b], M. Hasegawa [c] Y. Kato [d]

[a] *Institute for Solid State Physics, University of Tokyo, Kashiwanoha, Kashiwa, Chiba 277-8581, Japan*

[b] *Center for Integrated Research in Science and Engineering, Nagoya University, Furo-cho,Chikusa-ku,Nagoya 464-8603, Japan*

[c] *Institute for Materials Research, Tohoku University, Sendai 980-8577, Japan*

[d] *Department of Basic Science, University of Tokyo, Komaba 3-8-1, Meguro-ku, Tokyo 153-8902, Japan*

Abstract

We report the free flux flow (FFF) resistivity associated with a purely viscous motion of the vortices in moderately clean d-wave superconductor Bi:2201 in the strongly overdoped regime (T_c=16 K) for a wide range of the magnetic field in the vortex state. The FFF resistivity is obtained by measuring the microwave surface impedance at different microwave frequencies. It is found that the FFF resistivity is remarkably different from that of conventional s-wave superconductors.

Key words: flux flow, surface impedance, d-wave

The problem of the energy dissipation associated with the viscous motion of the vortices in a type-II superconductor has continued much attention of researchers for years [**?**]. To gain an understanding on the energy dissipation, the experimental determination of the free flux flow (FFF) resistivity is particularly important . Hereafter the term FFF will refer to a purely viscous motion of the vortices, which is realized when the pinning effect on the vortices is negligible. In fully gapped s-wave superconductors, a rather good understanding on the the energy dissipation processes has been achieved by now. On the other hand, the microscopic mechanisms of the energy dissipation associated with the viscous vortex motion in unconventional superconductors is still far from being completely understood. Thus it is particularly important to clarify whether the arguments of the energy dissipation are sensitive to the symmetry of the pairing state.

High-T_c cuprates in strongly overdoped regime are particularly suitable for the above purpose because it appears that the semiclassical description of the electronic structure of the vortex core is adequate in strongly overdoped materials. In fact, many experiments have revealed that in the overdoped regime the electron correlation and antiferromagnetic fluctuation effects are much weaker than those in optimally doped and underdoped materials. We here report the FFF resistivity ρ_f of Bi:2201 in the strongly overdoped regime (T_c=15 K) [2,3]. This system is an excellent choice for studying the FFF resistivity. It has a comparatively simple crystal structure (no chain, single CuO_2 layer) and hence the band structure is simple. H_{c2} is within laboratory reach over a very broad range of temperatures [4,5]. A major cause of difficulty in obtaining the FFF resistivity in high-T_c cuprates was the strong pinning effect. To overcome this difficulty, we have measured the microwave surface impedance $Z_s = R_s + iX_s$ at different frequencies, where R_s and X_s are the surface resistance and surface reactance, respectively. The surface impedance were measured by the standard cavity perturbation technique [6–9]. High frequency methods are suitable for this purpose because they probe vortex response at very low currents when the vortices undergo reversible oscillations

[1] Corresponding author. E-mail: ym@issp.u-tokyo.ac.jp

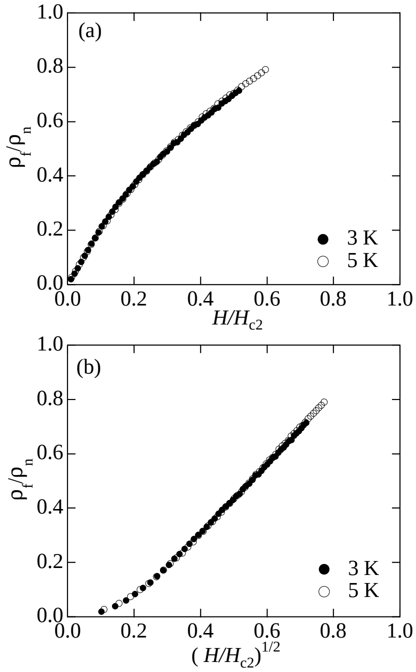

Fig. 1. (a) The flux flow resistivity at T =3 K and 5 K as a function of H/H_{c2}. We assumed H_{c2}=19 T at 3 K and 17 T at 5 K. The flux flow resistivity is normalized by the normal state value. (b) Same data plotted as a function of $\sqrt{H/H_{c2}}$.

and they are less sensitive to the flux creep [11]. The resonance frequencies of these cavities were approximately 15 GHz, 30 GHz, and 60 GHz. In Bi:2201, the pinning frequency is in a few tenth GHz region. We therefore measured the frequency dependence of R_s and X_s to obtain the FFF resistivity in the pinned free regime [10].

In Fig. 1(a), we plot ρ_f/ρ_n as a function of H/H_{c2} at 3 K, where ρ_n is the normal state resistivity. The field dependence of ρ_f is convex. We found that the there are two characteristic regimes in the H-dependence of ρ_f. In the low field region (H/H_{c2} <0.2), ρ_f increases linearly with H as

$$\rho_f = \alpha \frac{H}{H_{c2}} \rho_n \tag{1}$$

with $\alpha \simeq 2$. A deviation from H-linear dependence is clearly observed at higher field. In Fig. 1(b), ρ_f/ρ_n is plotted as a function of $\sqrt{H/H_{c2}}$. We found that ρ_f increases as

$$\rho_f \propto \sqrt{\frac{H}{H_{c2}}} \tag{2}$$

at H/H_{c2} >0.2. Since the linear extrapolation of ρ_f/ρ_n in Fig 7(b) points to $\rho_f/\rho_n = 1$ at H/H_{c2}=1, it is natural to expect that the relation of Eq.(2) continues all the way up to H_{c2}.

It has been revealed that the FFF resistivity in both dirty and clean s-wave superconductors is expressed by the Bardeen-Stephen relation expressed as $\rho_f = \rho_n H/H_{c2}$ almost throughout the whole Abrikosov phase; $H_{c1} < H < H_{c2}$ [**?**]. Therefore It is obvious from Figs. 1(a) and (b) that the field dependence of ρ_f expressed as Eqs.(1) and (2) is markedly different from that of conventional s-wave superconductors.

According to the theory by Kopnin and Volovik, the FFF resistivity in d-wave superconductor is governed by the quasiparticles with larger momentum localized near the vortex cores [12,13]. As a result, the reduction of the number of quasiparticles available for the energy dissipation in d-wave superconductors gives rise to the enhanced flux flow resistivity. Although this argument explains the low field ($H < 0.2H_{c2}$) behavior expressed as (1), it gives no account for the $\sqrt{H}$-dependence of ρ_f expressed as Eq.(1) observed in the almost whole regime at higher field ($0.2H_{c2} < H < H_{c2}$). A detailed numerical calculation for the energy dissipation especially when each vortex overlaps with its neighborhood would be necessary.

In summary, the microwave surface impedance measurements in the vortex state of overdoped Bi:2201 demonstrate that the free flux flow resistivity in the moderately clean d-wave superconductor with gap nodes is remarkably different from that in conventional fully gapped s-wave superconductors. These results indicate that the physical mechanism of the energy dissipation associated with the purely viscous motion of the vortices are sensitive to the symmetry of the pairing state.

References

[1] J. Bardeen and M.J. Stephen, Phys. Rev. **140**, A1197 (1965).

[2] Y. Matsuda *et al.* to appear in Phys. Rev. B.

[3] T. Nagaoka *et al.*Phys. Rev. Lett. **80** (1998) 3594.

[4] I. Chong, *et al.* Physica C **290** (1997) 57.

[5] Y. Matsuda *et al.*, Phys. Rev. B **40** (1989) 5176.

[6] Y. Tsuchiya, *et al.*, Phys. Rev. B **63** (2001) 184517.

[7] Y. Matsuda *et al.*, Phys Rev. B **49** (1994) 4380.

[8] T. Hanaguri, *et al.* Phys Rev. Lett. **82** (1999) 1273.

[9] K. Izawa *et al.*, Phys. Rev. Lett.**86** (2001) 1327.

[10] M.W. Coffey and J.R. Clem, Phys. Rev. Lett. **67** (1991) 386.

[11] Y. Matsuda *et al.*, Phys Rev. Lett. **75** (1995) 4512.

[12] N.B. Kopnin, and G.E. Volovik, Phys. Rev. Lett. **79** (1997) 1377.

[13] M. Eschrig, J.A. Sauls, D. Rainer, Phys. Rev. **B 60** (1999) 10447.