Fluctuation Magnetoconductance in MgB$_2$

W. N. Kang, Kijoon H. P. Kim, Hyeong-Jin Kim, Eun-Mi Choi, Min-Seok Park, Mun-Seog Kim, Zhonglian Du, Chang Uk Jung, Kyung Hee Kim, and Sung-Ik Lee*

National Creative Research Initiative Center for Superconductivity and Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea

Mi-Ock Mun
Institute of Physics and Applied Physics and Department of Physics, Yonsei University, Seoul 120-749, Republic of Korea

(Received January 5, 2002)

We report fluctuation magnetoconductance in a MgB$_2$ superconductor prepared under a high pressure of 3 GPa. This excess magnetoconductance, $\Delta\sigma(H)$, follows the three-dimensional scaling function for the critical fluctuations proposed by Ullah and Dorsey. This feature is inferred to originate from the isotropic nature of the MgB$_2$ compound.

The recent discovery of superconductivity at about 40 K in MgB$_2$[1] brought about an avalanche of research. While the type of carrier was found to be hole-like[2], other properties have been reminiscent of conventional BCS superconductivity, and are significantly different from those found in the cuprate superconductors. These properties include a notable shift in the $T_c$ due to the boron isotope,[3,4] a stable metallic behavior with a higher carrier density,[5], and prominent bulk pinning.[5]

It is well-known that high-$T_c$ superconductors have a two-dimensional layered structure and a very short out-of-plane coherence length, which is quite different from conventional superconductors. Thus, a strong superconducting fluctuation effect around $T_c$ is evident for thermodynamic and transport quantities. In the MgB$_2$ system, various superconducting properties, including the electrical conductivity, are believed to be isotropic even though the boron planes are thought to act like the CuO$_2$ planes in the cuprate superconductors[6]. Thus, it could be very interesting to investigate the conductivity fluctuation effect in this compound.

In this paper, we present the magnetoconductance fluctuation in a MgB$_2$ polycrystal. The scaling functions for the critical fluctuations were employed to analyze the excess conductance of our sample. We found that the conductivity in the critical region scales with the three dimensional scaling functions.

A 12-mm cubic multi-anvil press was used for the high-pressure sintering. The pellet, which was made of a commercially available powder of MgB$_2$[7], was sintered at about 900°C after being subjected to pressures of up to 3 GPa. The zero-field resistivity transition temperature, $T_c$(0), is 38.3 K. A transmission electron microscope (TEM) study[8] showed that all grains were compactly connected and that no discernable empty space or impurities at the boundaries. The weak link behavior is expected to be less than that observed in to the high-$T_c$ superconductors. The details of the sample preparation and the properties of sample can be found elsewhere.[9]

The voltage noise was successfully reduced to a lower level by preparing a very thin and optically clean specimen polished from a strong, dense bulk pellet. The dimensions of the specimen were about $2.4 \times 4.0 \times 0.1$ mm$^3$. The standard photolithography technique was used to make electrical leads on the specimen. To obtain good ohmic contacts between the Au pads and the sample, we cleaned the surface using an ion beam before depositing Au-contact pads. The magnetic field was applied perpendicular to the sample surface and the current direction. The resistivity measurements were carried out in a cryostat with a superconducting magnet by using the standard 4-probe technique. A dc current source (model Keithley 220), two channel nanovoltmeters (model HP 34420A), and dc preamplifier (model EM electronics N11) with $J = 40 - 50$ A/cm$^2$ were used.

Figure[10] shows the temperature dependence of the resistance for applied magnetic fields of 0 T $\leq H \leq 5$ T. The gradual change in the resistance near the transition temperature is similar to the case of typical metallic superconductors. The resistance just above $T_c$ did not change with the applied field. It is clearly seen that the resistivity curves shift toward lower temperature as the field increases. The rate of decrease of $T_c(H)$ with respect to the field is significantly larger than that of the cuprates. The transition temperature $T_c(H)$ was estimated from the 90% drop of the normal-state resistivity, and the slope ($dH_{c2}/dT$)$_{T_c}$ was found to be about -0.54 T/K. This value of the slope is much smaller than the $dH_{c2}/dT$ of $\sim -2$ T/K observed in

*silee@postech.ac.kr
high-temperature superconductors such as YBa$_2$Cu$_3$O$_7$ and Bi$_2$Sr$_2$CaCu$_2$O$_8$. Using this slope, the estimated $H_{c2}(0)$ was found to be 13.9 T through the relationship $H_{c2}(0) \approx 0.7T_c(dH_{c2}/dT)_{T_c}$. This value is about ten times smaller than the value for cuprate superconductors. The coherence length $\xi(0) = [\phi_0/(2\pi H_{c2}(0))]^{1/2}$ was calculated to be 48.6 Å, where $\phi_0$ is the flux quantum.

In the strong-field region, since the quasi-particles are mainly confined to their lowest Landau level, an effective reduction of the dimensionality occurs, hence the fluctuation-induced conductance exhibits a critical behavior. Critical phenomena and scaling properties of the thermodynamic quantities near the transition temperature in a mixed state have been studied by a number of groups. Ullah and Dorsey proposed scaling functions for various thermodynamic and transport quantities within the Hartree approximation. The quartic term $|\psi|^4$ in the Ginzburg-Landau free energy was included which was in contrast to the free fluctuation theory where the quartic term is neglected. The scaling functions for the excess conductance are given by

$$\Delta\sigma(H)_{2D} = \left[\frac{T}{H}\right]^{1/2} F_{2D} \left[ A \frac{T - T_c(H)}{(TH)^{1/2}} \right] \quad \text{for 2D}, \quad (1)$$

$$\Delta\sigma(H)_{3D} = \left[\frac{T^2}{H}\right]^{1/3} F_{3D} \left[ B \frac{T - T_c(H)}{(TH)^{2/3}} \right] \quad \text{for 3D}, \quad (2)$$

where $F_{2D}$ and $F_{3D}$ are unspecified scaling functions, and $A$ and $B$ are field and temperature-independent coefficients. In these equations, the Aslamazov-Larkin(AL) term of the fluctuation conductance was taken into account.

To obtain the excess conductance $\Delta\sigma(H)$, we subtracted the extrapolated normal conductance from the total conductance by using a normal fit at temperatures far above $T_c(H)$ for each magnetic field. The correct determination of the $T_c(H)$ is critical for obtaining the best scaling behavior. For $T_c(H)$, we used the refined temperature around the 10% resistive superconducting transition point for each field. The excess conductance scaled excellently with the 3D form. Figure 2(a) shows $\Delta(1/R)/(T^2/H)^{1/3}$ versus the scaling parameter $(T - T_c(H))/(TH)^{2/3}$. All the data for the various fields collapse into a single curve while the 2D scaling plot gives a poor result, as shown in Fig. 2(b), for whatever value of $T_c(H)$. The values of $T_c(H)$ for the best fits were 34.9, 32.8, 31.0, 28.8, and 27.2 K for $H = 1, 2, 3, 4,$ and 5 T, respectively, which slightly deviated from linearity in $H$ but agreed with the generalized prediction by Maki.

FIG. 1. Magnetic-field dependence of resistitance of MgB$_2$ sintered under 3 GPa.

It is quite surprising to find 3D scaling behavior in a polycrystalline sample. A compactly connected morphology with no discernable empty space was observed using a TEM, thus, the weakly linked grain boundary effect is negligible. The high degree of isotropy is another feature for this 3D scaling behavior. The spreadout of the scaled conductance at low temperatures, indicated by the arrow in Fig. 2(a), is not unusual for the scaling behavior in the fluctuation conductivity. Several results obtained from high-$T_c$ superconductors as well as $\text{RNi}_2\text{B}_2\text{C}$ materials have commonly given the same broadening due to the vortex motion at the tail of the transition line.

In summary, we observed magnetoconductance fluctuations in MgB$_2$. With critical fluctuations included, the scaling behavior of MgB$_2$ was better explained by the 3D theory rather than by the 2D theory. Even though the
grains in the sample are randomly oriented, the excess conductance follows the 3D scaling function for critical fluctuations. This feature may indicate that MgB$_2$ is nearly isotropic. However, more rigorous studies of the suggested 3D nature of MgB$_2$ require at least a grain-aligned sample such as a c-axis oriented film or a single crystal.

This work is supported by the Ministry of Science and Technology of Korea through the Creative Research Initiative Program.

[1] Jun Nagamatsu, Norimasa Nakagawa, Takahiro Muranaka, Yuji Zenitani, and Jun Akimitsu, Nature 410, 63 (2001).
[2] W. N. Kang, C. U. Jung, Kijoon H. P. Kim, Min-Seok Park, S. Y. Lee, Hyeong-Jin Kim, Eun-Mi Choi, Kyung Hee Kim, Mun-Seog Kim, and Sung-Ik Lee, cond-mat/0102338 (2001).
[3] S. L. Bud'ko, G. Lapertot, C. Petrovic, C. E. Cunningham, N. Anderson, and P. C. Canfield, cond-mat/0101463 (2001).
[4] J. Kortus, I. I. Mazin, K. D. Belashchenko, V. P. Antropov, and L. L. Boyer, cond-mat/0101446 (2001).
[5] Mun-Seog Kim, C. U. Jung, Min-Seok Park, S. Y. Lee, Kijoon H. P. Kim, W N. Kang, and Sung-Ik Lee, cond-mat/0102113 (2001).
[6] J. E. Hirsch, cond-mat/0102313 (2001).
[7] Alfa Aesar, A Johnson Matthey Company, Stock # 88149: magnesium boride, 98% (assay) MgB$_2$ (possible impurities are not specified).
[8] Gun Yong Sung, Sang Hyeob Kim, Junho Kim, Dong Chul Yoo, Ju Wook Lee, Jeong Yong Lee, C. U. Jung, Min-Seok Park, W. N. Kang, Du Zhonglian, and Sung-Ik Lee, cond-mat/0102498 (2001).
[9] C. U. Jung, J. Y. Kim, S. M. Lee, Mun-Seog Kim, Yushu Yao, S. Y. Lee, Sung-Ik Lee, and D. H. Ha, Physica C (to be published).
[10] N. R. Werthamer, E. Helfand, and P. C. Hohenberg, Phys. Rev. 147, 295 (1966).
[11] P. A. Lee and S. R. Shenoy, Phys. Rev. Lett. 28, 1025 (1972).
[12] A. J. Bray, Phy. Rev. B 9, 4752 (1974).
[13] D. J. Thouless, Phy. Rev. Lett. 34, 946 (1975).
[14] G. J. Ruggery and D. J. Thouless, J. Phy. F 6, 2063 (1976).
[15] Salman Ullah and Alan T. Dorsey, Phys. Rev. Lett. 65, 2066 (1990).
[16] L. G. Aslamazov and A. I. Larkin, Phys. Lett. 26A, 223 (1968).
[17] K. Maki, Phys. Rev. 138, 868 (1965).
[18] A. K. Pradhan, S. B. Roy, and P. Chaddah, Phys. Rev. B 50, 7180 (1994).
[19] M. O. Mun, S. I. Lee, and W. C. Lee, Phys. Rev. B 56, 14668 (1997).