1-1-2010

**Fluctuation conductivity of single-crystalline BaFe1.8 Co0.2As2 in the critical region**

Soo Hyun Kim  
*Dept of Physics Sogang University Seoul*

Changho Choi  
*Dept Physics Sogang University Republic Korea*

Myung-Hwa Jung  
*Sogang University, South Korea*

Jung-Bum Yoon  
*Nano Materials Research Team Korea*

Young-Hun Jo  
*Nano Materials Research Team Korea*

*See next page for additional authors*

Follow this and additional works at: [https://ro.uow.edu.au/aiimpapers](https://ro.uow.edu.au/aiimpapers)  

Part of the Engineering Commons, and the Physical Sciences and Mathematics Commons

**Recommended Citation**  
Kim, Soo Hyun; Choi, Changho; Jung, Myung-Hwa; Yoon, Jung-Bum; Jo, Young-Hun; Wang, Xiaolin; Chen, X.H; Wang, X.F; Lee, Sung-Ik; and Choi, Ki-Young, "Fluctuation conductivity of single-crystalline BaFe1.8 Co0.2As2 in the critical region" (2010). *Australian Institute for Innovative Materials - Papers. 75.*  

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au
Fluctuation conductivity of single-crystalline BaFe1.8 Co0.2As2 in the critical region

Abstract
The magnetofluctuation conductivity, called excess conductivity, originated from the forming of the superconducting droplet near to the mean-field transition temperature, was measured for the optimally doped BaFe1.8Co0.2As2 single crystals with a critical temperature, $T_c$, of 24.6 K. This measurement of the excess conductivity for magnetic fields up to 9 T was compared with the thermodynamic scaling theory in the critical region, in which not only the Gaussian fluctuation but also fourth order terms of the order parameter are included. An analysis of the excess conductivity showed that the superconductivity followed three-dimensional scaling rather than two-dimensional scaling even though the sample had a layered structure.

Keywords
Fluctuation, conductivity, single, crystalline, BaFe1, Co0, 2As2, critical, region

Disciplines
Engineering | Physical Sciences and Mathematics

Publication Details

Authors
Soo Hyun Kim, Changho Choi, Myung-Hwa Jung, Jung-Bum Yoon, Young-Hun Jo, Xiaolin Wang, X.H Chen, X.F Wang, Sung-Ik Lee, and Ki-Young Choi

This journal article is available at Research Online: https://ro.uow.edu.au/aiimpapers/75
Fluctuation conductivity of single-crystalline BaFe_{1.8}Co_{0.2}As_{2} in the critical region

Soo Hyun Kim,1 Chang Ho Choi,1 Myung-Hwa Jung,1 Jung-Bum Yoon,2 Young-Hun Jo,2 X. F. Wang,3 X. H. Chen,3 X. L. Wang,4 Sung-Ik Lee,1 and Ki-Young Choi1,a)

1Department of Physics, National Creative Research Initiative Center for Superconductivity, Sogang University, Seoul 121-742, Republic of Korea
2Nano Materials Research Team, KBSI, Daejeon 305-333, Republic of Korea
3Department of Physics and Hefei National Laboratory for Physical Sciences at Microscale, University of Science and Technology of China, Hefei, Anhui 230026, China
4Institute for Superconducting and Electronic Materials, University of Wollongong, Wollongong, New South Wales 2522, Australia

(Received 29 December 2009; accepted 19 July 2010; published online 23 September 2010)

The magnetofluctuation conductivity, called excess conductivity, originated from the forming of the superconducting droplet near to the mean-field transition temperature, was measured for the optimally doped BaFe_{1.8}Co_{0.2}As_{2} single crystals with a critical temperature, T_c, of 24.6 K. This measurement of the excess conductivity for magnetic fields up to 9 T was compared with the thermodynamic scaling theory in the critical region, in which not only the Gaussian fluctuation but also fourth order terms of the order parameter are included. An analysis of the excess conductivity showed that the superconductivity followed three-dimensional scaling rather than two-dimensional scaling even though the sample had a layered structure. © 2010 American Institute of Physics. [doi:10.1063/1.3478716]

I. INTRODUCTION

The recent discovery of superconductivity in F-doped LaFeAsO (FeAs-1111) at 26 K (Ref. 1) has stirred interest in the community of strongly correlated electron systems and has accelerated further investigations to increase the superconducting transition temperature. In a similar structure, superconductivity was also discovered when La was replaced by Ln=Sm, Ce, Nd, Pr, Gd, Tb, or Dy (Refs. 2–7) with the highest T_c, up to 56 K, having been discovered for Nd substitution. Also, a T_c of 43 K was achieved by applying pressure to FeAs-1111. Soon after the discovery of these oxypnictides, oxygen-free iron pnictides, such as K- or Co-doped BaFe_{2}As_{2} and SrFe_{2}As_{2} (FeAs-122) (Refs. 10–12) with a T_c up to 38 K, were discovered. The common feature of these compounds is the possession of a FeAs layer that is similar to the CuO_{2} plane in high-temperature cuprate superconductors (HTSC). In fact, FeAs-1111 has one FeAs layer in a unit cell while the FeAs-122 phase contains two FeAs layers.

For conventional superconductors, superconductivity appears suddenly at the superconducting transition temperature, T_c, defined as the point at which the free energies of the superconducting and the normal states of a material become equal. However, for some superconductors, near the transition regions, thermodynamic fluctuations give rise to an anomalous increase in the superconducting properties even at temperatures above T_c. This fluctuation effect is very important because it may provide valuable information on the superconductivity once we measure physical quantities such as the conductivity, the magnetization, and the thermoelectricity. This is of theoretical significance in that it would provide a stringent test of scaling theories in phase transitions while approaching the critical region.

The quantity called the Ginzburg number, G_i, defines the order of thermal fluctuations in a superconductor. The derived Gi number is \[ \frac{8\pi^2k_BT_c\lambda_{ab}(0)/\xi_c\Phi_0^2}{2} \] for anisotropic superconductors, where \( k_B \) is the Boltzmann constant, \( \lambda_{ab}(0) \) is the London penetration depth along the ab plane, \( \xi_c \) is the c-axis coherence length, and \( \Phi_0 \) is the flux quantum. A value of \( \sim 10^{-2} \) for this quantity is known to be quite large for HTSC and indicates a quite enhanced fluctuation effect even for bulk single crystals. This number is several orders of magnitude larger than that, \( 10^{-9} \), for a conventional superconductor. This is the reason why the fluctuation effect has been observed for conventional superconductors only in the forms of thin films or one-dimensional (1D) wires not for these in a bulk form. Even though the \( T_c \) is lower than that of HTSC, a quite pronounced fluctuation effect is also observed in intermetallic superconductors, for example in YNi_{2}B_{2}C, and in the MgB_{2} superconductor. This can be understood from the magnitude of the Ginzburg number, Gi, which governs how strong the fluctuation effect is. This number is \( \sim 10^{-6} \) for YNi_{2}B_{2}C (Ref. 14) and for MgB_{2},\(^{15,16} \) which is between the value of \( \sim 10^{-9} \) for a conventional superconductor and \( \sim 10^{-2} \) for a HTSC.

Since both the Fe–As and the HTSC are characterized by a high T_c, a layered structure, and a short \( \xi_c \), an enhanced thermal fluctuation effect is also expected in Fe–As-based superconductors. It is well known that a quite large thermal fluctuation effect is observed in HTSC. However, so far, a conductivity fluctuation effect in the Fe–As superconductor has not been well documented.

One of the quantities related to the fluctuation effect that...
we like to investigate is the conductivity fluctuation in single-crystalline BaFe$_{1.8}$Co$_{0.2}$As$_2$. Since the Gi number is $\sim 10^{-3}$ for our single-crystalline BaFe$_{1.8}$Co$_{0.2}$As$_2$, which is higher than that of YNi$_2$B$_2$C, we expect to observe a conductivity fluctuation effect in our single crystals. Up to now, excess fluctuation conductivity has never been reported in Co-doped FeAs-122 superconductor although the Gi number of our sample is in a range comparable to that for the intermetallic superconductors mentioned above. The Gi number for another FeAs-based 1111 superconductor, NdFeAs (O and F) is reported to be $10^{-2}$, which is the same order of magnitude as the value for HTSC. On the other hand, (Ba and K) Fe$_2$As$_2$ shows Gi $\sim 10^{-4}$, which implies that even for the same family of Fe–As superconductors, the Gi number can vary by more than one order of magnitude.

In this paper, we present the fluctuations of the magnetococonductivity for optimally Co-doped BaFe$_{1.8}$Co$_{0.2}$As$_2$ superconducting single crystals with a $T_c$ of 24.6 K. The thermodynamic scaling functions of the magnetococonductivity, including the critical fluctuations, were analyzed. We found that the excess conductivity followed a three-dimensional (3D) scaling form quite well, but poorly matched the two-dimensional (2D) scaling form, so we conclude that this material is a 3D superconductor.

II. EXPERIMENTS

The single crystals of BaFe$_{2-x}$Co$_x$As$_2$ were grown by using the high-temperature self flux method. FeAs and CoAs were prepared by placing a mixture of As powder and Fe/Co powder in a quartz tube and reacting it at 600 °C for 10 h after it had been heated to 600 °C for 17 h. A mixture of FeAs/CoAs and Ba pieces was then placed in an alumina crucible. The whole assembly was sealed in a large quartz tube and heated to 1180 °C for 15 h, which was followed by a reaction at 1180 °C for 10 h. The detailed procedure of crystal growth is described in Ref. 18. The onset resistive transition temperature was 24.6 K. Several platelike crystals were used in this measurement.

The four-probe configuration was used to measure the magnetoconductivity for magnetic fields up to 9 T with the field direction parallel to the c-axis. The temperature for the resistivity measurement was varied up to 70 K, which is more than 2$T_c$. A temperature interval of 0.05 K was used for detailed measurement of the fluctuation conductivity.

III. THEORY

In Ginzburg–Landau (GL) theory, physical quantities are obtained with the assumption that the free energy has a minimum at $\Phi_0$. But the thermodynamic fluctuation allows the system to have another order parameter $\Psi(t)$ which considerably raise the free energy by $\sim k_B T$. Due to this fluctuation, the superconducting droplets are formed and annihilated near to the mean-field transition temperature and produce excess conductivity. To explain this, simple theory of the fluctuation, called Gaussian fluctuation theory, is suggested. In this theory, only square term, not fourth order term of the order parameter is included in the free energy. This theory works quite well for temperature above and below $T_c$ but poorly for temperature near $T_c$ in the critical fluctuation region. To overcome this disagreement, we should consider other theories that include square term and fourth order term, as well. When the fluctuation order parameter is comparable to the mean value of the order parameter, the fluctuations become critical. The boundary separating the critical fluctuation region from the Gaussian mean-field region is called the Ginzburg criterion. The critical region is related to the Gi number through the condition $\langle \Delta \Psi \rangle^2 \sim 1/T_c^{2/3}$. Ikeda et al. treated this fourth order term within the Hartree approximation and predicted the scaling form of physical quantities.

IV. RESULTS AND DISCUSSION

Figure 1 shows the dc resistivity of BaFe$_{1.8}$Co$_{0.2}$As$_2$ single crystals as a function of temperatures near $T_c$. Field values for this measurement were between 0 to 9 T. Figure 1 shows a broadening of the transition, which is quite different from a conventional superconductor and indicates the existence of a fluctuation effect. This broadening of the conductivity is not as large as HTSC but is still quite pronounced in this graph. The $T_c$, onset and the temperature of zero resistivity also decrease as the magnetic field is increased. From the graph, the fluctuation conductivity of this crystal in the presence of a magnetic field can be analyzed by including a...
critical fluctuation region in the framework of 2D or 3D scaling behaviors. First, we assume that the total conductivity, $\sigma$, is a sum of the normal conductivity, $\sigma_n$, and the excess conductivity, $\Delta\sigma$, $\sigma = \sigma_n + \Delta\sigma$. Then, the fluctuation conductivity can be calculated. The derivation of $\Delta\sigma$ within the scaling forms predicted by Ullah and Dorsey was adapted.

In Fig. 2, the scaled magnetoconductivity $\Delta\sigma$ for BaFe$_{1.8}$Co$_{0.2}$As$_2$ single crystals is given for the case of 3D scaling. For the correct form of the excess conductivity, the normal conductivity is subtracted from the total conductivity for each magnetic field. The total conductivity, with $\sigma_n$ of the form $1/(aT+b)$, was used while adjusting $a$, $b$, and $T_c(H)$ in the scaling functions for each magnetic field. To obtain the best 3D scaling function, we fitted the normal-state conductivity mentioned above. The obtained values of $a$ and $b$ were almost field independent and $a=(1.16 \pm 0.02) \times 10^{-6}$[cm/K] and $b=(4.75 \pm 0.02) \times 10^{-6}$[cm].

We also carefully obtained the $T_c(H)$ while varying the temperature in steps of 0.05 K to fit the excess conductivity to the scaling form. The obtained values of the $T_c(H)$ from the scaling analysis are shown in Fig. 1. The change in the upper critical threshold field per unit temperature, the slope $\Delta H_{c2}/\Delta T$, was about $-3.42$ T/K for the 3D scaling analysis. The excellent scaling behavior of the fluctuations is obtained for the 3D case. On the other hand, as is seen from the graph, the 2D scaling plot gives rather poor results, especially at low temperatures. Since Fig. 2 shows quite small excess conductivity, we redraw the fluctuation conductivity in log scale as shown in inset. Both of the linear and logarithmic scale, excess conductivity fit very well to the 3D scaling relation, but 2D scaling does not fit very well at the low and high-temperature region. The $T_c(H)$ is also measured from the $R(T)$ for the given $H$ with the criterion of $R=0.9$ $R$ (26 K) and found to be consistent from the value obtained from the scaling analysis. The Gi number of $10^{-5}$ was estimated from the value of $\lambda_{\text{tr}}(0) \sim 200$ nm (Ref. 24) and $\xi_c(0) \sim 2.08$ nm from $\xi_c(0)=[\Phi_0/(2\pi H_{c2}(1/\Gamma))]^{1/2}$ with our estimated value of $H_{c2} \sim 54$ T and anisotropic ratio of about $\Gamma \approx 2$. This upper critical field parallel to c-axis $H_{c2}(0)$ was estimated by using the formula of Werthamer, Helfand, and Hohenberg (WHH): $H_{c2}(0) = -0.69 T_c(dH_{c2}/dT)$. Since $\xi_c(T) > \xi_c(0)$ near $T_c$ and $\xi_c(0)$ is larger than that for a c-axis lattice constant of 1.3 nm, second distance 0.8 nm between two FeAs layers, it is quite natural, to expect the 3D scaling of the excess conductivity. We also expect any quantity related to the fluctuation effect to show a 3D behavior.

It is interesting to notice that the observed spread in the scaled conductivity for the low-temperature in the critical fluctuation region for a HTSC is almost not observed in the 3D scaling of BaFe$_{1.8}$Co$_{0.2}$As$_2$ single crystals, which implies that our scaling is quite remarkable. This spread is also not negligible in the 3D scaling for YNi$_2$B$_2$C (Ref. 14) or MgB$_2$ (Ref. 15) even though the Gi numbers of these two superconductors are in a range similar to that for our BaFe$_{1.8}$Co$_{0.2}$As$_2$ single crystals. In our BaFe$_{1.8}$Co$_{0.2}$As$_2$ single crystals, the broadening of the conductivity originating from the field-induced fluctuation conductivity in the critical region near the transition is quite pronounced.

V. CONCLUSION

In conclusion, in addition to cuprate HTSC and R (R = Y and Lu) Ni$_2$B$_2$C single-crystalline superconductors, we have observed fluctuation conductivity in BaFe$_{1.8}$Co$_{0.2}$As$_2$ single crystals. Including the critical fluctuation region, the scaling behavior for BaFe$_{1.8}$Co$_{0.2}$As$_2$ is well described by using a 3D theory, which is quite in contrast to the rather poor scaling for the 2D theory. Our sample’s Gi was $10^{-5}$. This value is between the value of $10^{-9}$ for a conventional superconductor and the value of $10^{-2}$ for a HTSC. The analysis of the excess fluctuation conductivity showed that the superconductivity followed 3D fluctuations rather than 2D fluctuations even though the superconductor had a layered structure.
ACKNOWLEDGMENTS

This work at SU was supported by MIST/KRF (Grant No. 2009-0051705) of Korea. We thank the A3 foreign program for initiating this project.