Conductance asymmetry in point-contacts on epitaxial thin films of Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$

M. Mehta, G. Sheet, D. A. Dikin, S. Lee, C.W. Bark, J. Jiang,
J. D. Weiss, E. E. Hellstrom, M. S. Rzchowski, C.B. Eom and V. Chandrasekhar

$^1$Department of Physics and Astronomy, Northwestern University, Evanston, IL 60208, USA,
$^2$Department of Materials Science and Engineering University of Wisconsin-Madison, Madison, WI 53706, USA,
$^3$Applied Superconductivity Center, National High Magnetic Field Laboratory,
Florida State University, Tallahassee, FL 32310, USA
$^4$Physics Department, University of Wisconsin-Madison, Madison, WI 53706

One of the most common observations in point-contact spectra on the recently discovered ferropnictide superconductors is a large conductance asymmetry with respect to voltage across the point-contact. In this paper we show that the antisymmetric part of the point-contact spectrum between a silver tip and an epitaxial thin film of Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$ shows certain unique features that have an interesting evolution with increasing temperature up to a temperature far above the critical temperature $T_c$. We associate this observation with the existence of a gap above $T_c$ that might originate from strong fluctuations of the phase of the superconducting order parameter.

Determining the order parameter symmetry is perhaps the most fundamental problem in understanding the nature of exotic superconductors. Point-contact spectroscopy (PCS), owing to its ability to provide both energy and momentum-resolved spectroscopic information, has proved to be an extremely powerful tool in determining the order parameter symmetry in unconventional superconductors. The list includes $d$-wave superconductors like the cuprates [1], multiband superconductors like MgB$_2$ [2] and the borocarbides [3]. Apart from determining the order parameter symmetry, PCS has also been applied to understanding important Fermi-surface properties in the heavy-Fermion superconductors [4]. Early PCS experiments on the recently discovered ferropnictide superconductors indicated the existence of a single BCS (Bardeen-Cooper-Schrieffer)-like superconducting gap [5]. More recent measurements reported the existence of features associated with multiple superconducting gaps possibly originating from the different regions of the disjoint Fermi surface of this class of materials [6, 7]. However, one of the common features in the majority of the point-contact spectra reported on the ferropnictides is a large asymmetry in the conductance with respect to voltage across the point-contact [3, 6]. In the past, a similar asymmetry was observed in point-contacts involving different complex superconducting systems. Such conductance asymmetry has been attributed to the Fano resonance in the case of heavy fermion systems [4] and unusual Fermi surface characteristics in the case of the ferropnictides [8]. However, a systematic study of the asymmetry in the ferropnictides is lacking.

In this Letter, we report on PCS of single crystalline thin films of the ferropnictide superconductor Ba(Fe$_{0.92}$Co$_{0.08}$)$_2$As$_2$. The films are epitaxially grown on a template of epitaxial SrTiO$_3$ grown on La$_{0.3}$Sr$_{0.7}$Al$_{0.35}$Ti$_{0.65}$O$_9$ crystals [9]. In the point-contact spectra, the features associated with Andreev reflection [10] at the point-contact are clearly seen, but other features including a strong asymmetry in the conductance with respect to the voltage across the point-contact are also observed. From a systematic analysis of the antisymmetric part of the spectra and its temperature dependence, we show that the asymmetry might provide useful information about the rich normal state properties of these superconductors.

In order to perform PCS the sample is mounted on a home-built low temperature scanning probe microscope adapted to perform spectroscopy in the point-contact mode. The point-contact is formed between the thin films and sharp metallic tips of silver. The microscope is equipped with a sophisticated coarse approach mechanism which gives us fine control on the size of the point-contact. The microscope with the sample is dipped in a liquid He storage dewar and the temperature is controlled by a heater and a diode thermometer mounted on the sample stage. The measurements are done by an ac-modulation technique using a lock-in amplifier. A representative spectrum captured at 10.4 K is shown in Fig. 1a. The raw data are clearly seen to be asymmetric about zero bias. For analysis we have extracted the symmetric and the antisymmetric (Fig. 1b) components of the differential resistance using the equation:

$$\frac{dV}{dI}_{s,as} = \frac{dV/dI(+V) \pm dV/dI(-V)}{2}. \quad (1)$$

The spectroscopic features arising in the symmetric component ($dV/dI_s$) and their temperature evolution have been discussed in another publication [11]. Here we concentrate on the antisymmetric component. At 10.4 K the antisymmetric component of the differential resistance is flat with its magnitude being almost zero at lower bias for $|V| < 12.5$ mV (Fig. 1b). Beyond this voltage range, the magnitude increases smoothly with $V$ and shows a linear dependence for $|V| > 20$ mV. The general shape of the curve changes with increasing temperature (shown by the color plot in Fig. 2a). The width of the flat region in voltage first decreases; then, close to a temperature of 27 K, the flat region disappears and the antisymmetric...
component changes sign near $V = 0$ (Fig. 2c). At still higher temperatures, the flat region reappears, reducing in range as the temperature is increased further, but remaining until our highest measured temperature. In this higher temperature range, the magnitude of the overall antisymmetric component (Fig. 2d) is much smaller [12].

An often-quoted explanation for conductance asymmetries in point-contacts is a contribution due to thermoelectric effects arising from a temperature gradient existing in the point contact. In order to understand this, it is important to briefly review the different regimes of electron transport in metallic point-contacts [13]. Depending on the size of the point-contact and the electronic mean free path of the materials forming the point-contact, electronic transport can take place in different regimes. A point-contact is in the thermal regime, the local temperature ($T_{eff}$) at the center of the point-contact can be considerably higher than that of the bath temperature $T_{bath}$. For a point-contact between two dissimilar materials, the temperature at the center of the point-contact is given by

$$T_{eff} = \sqrt{T_{bath}^2 + \frac{V^2 \rho_1 \rho_2}{(L_1 \rho_2 + L_2 \rho_1)(\rho_1 + \rho_2)}}$$

where, $L_1$ and $L_2$ are the Lorenz numbers corresponding to the two materials with resistivities $\rho_1$ and $\rho_2$ respectively. In both cases, $T_{eff}$ goes as $V^2$ for small voltages, as should be expected, since the effective temperature should not depend on the direction of the current flowing through the contact. Consequently, the contribution to the $I - V$ characteristic for thermoelectric effects is symmetric in bias, leading to a differential voltage characteristic $dV/dI$ arising from thermoelectric effects that is antisymmetric in the applied voltage. The corresponding asymmetry in $dV/dI$ can be represented by the antisymmetric component

$$(dV/dI)_{as} = (dT_{eff}/dI)(S_1(T) - S_2(T)) \approx (dT_{eff}/dV)(S_1(T) - S_2(T))$$

where, $S_1$ and $S_2$ are the Seebeck coefficients of the two materials respectively. Here we assume that the differential resistance $dV/dI$ does not change appreciably, so that we can replace $dT/dI$ with $dT/dV$ without significant error. This is clearly not true in the superconducting case, but the symmetry argument is not affected. The difference in the Seebeck coefficients between the two materials can be determined from the measured antisymmetric component of $dV/dI$ once $dT_{eff}/dV$ is known, which can be calculated from Eqn. (2). That is exactly what is seen in thermal point-contacts between two metals [13]. Since the ferropnictide materials are known to have rich thermoelectric properties [11], it is tempting to attribute our observation to the processes mentioned above.

However, our data are obtained from a point-contact that is either in the ballistic limit or close to the ballistic limit, but definitely not in the thermal limit. This is confirmed by the following observations for the symmetric component of the differential conductance ($dI/dV$) [see ref. [11]): (i) the general shape of the symmetric component of the spectrum clearly shows a conductance dip at zero bias which is the hallmark of a ballistic point-contact on a superconductor [10]; (ii) There is no conductance dip observed that could be related to the contribution of the critical current [15]; (iii) the normal state resistance of the point-contact is high ($R_{PC} \approx 82 \Omega$) and does not vary noticeably with increasing temperature and (iv) The approximate size of the point-contact is estimated to be $\sim 2.5$ nm by putting in the normal state contact resistance in Wexler’s formula [10] given by

$$R_{PC} \approx \frac{\rho l}{3\pi a^2} + \frac{\beta \rho}{a},$$

where $a$ is the contact diameter, $\beta \sim 1$, $\rho$ is the resistivity of the material in the normal state and $l$ is the mean free path. The estimated size of the point-contact turns out to be smaller than the typical mean free path in usual ferropnictide crystals (lower bound to the mean free path $\sim 3.5$ nm) [17].

In the ballistic limit of point-contacts, the above explanation for the conductance asymmetry is not valid as there is no dissipation of heat expected within the point-contact with $T_{eff} = T_{bath}$, and $T_{bath}$, is not $V$-dependent. A more sophisticated analysis would require the calculation of thermoelectric voltages from the nonequilibrium distribution functions that arise in the ballistic regime [15]. However, this has not yet been considered for point-contacts.
FIG. 2: Temperature dependence of the antisymmetric part of the point-contact spectra. (a) Color plot of the spectra between temperatures 5.8 K and 32 K. The black line indicates the spectrum at 23.7 K, just above the transition, (c) Spectrum at 23.7 K, the mid-point of the resistive transition of the point-contact spectra. (b) Spectrum at 23.9 K, just above the transition, (c) Spectrum at 27.6 K and (d) Spectrum at 31.7 K.

Therefore, the antisymmetric component \((dV/dI)_{as}\) does not appear due to conventional point-contact heating and consequent thermoelectric effect. However, a comparison of \((dV/dI)_{as}\) with \((dI/dV)\) at temperatures far below the superconducting transition temperature shows that the voltage range below which \((dV/dI)_{as}\) is flat is identical to the voltage that corresponds to the position of the conductance peak signifying the superconducting energy gap in \((dI/dV)\) (see ref. [11] and Fig. 1). Thus, the antisymmetric component is almost zero when the voltage across the point contact is less than the superconducting gap voltage, becomes finite just above the gap and varies linearly at higher voltages. The temperature evolution of \((dI/dV)\) clearly indicates that the superconducting energy gap decreases with increasing temperature, but does not vanish at the critical temperature of the superconducting film (23.7 K in this case), surviving to temperatures greater than 30 K. As discussed in [11], the superconducting critical temperature of the film is smaller than the temperature where pairing of the quasiparticles occurs without a global phase coherence. In such a case, phase-incoherent superconducting pairs in the normal state might cause a pseudogap to survive well above the critical temperature of the superconductor, and this pseudogap contributes to the thermoelectric effect in the same way as the conventional gap. It seems that this phenomenon is prominently exhibited by the antisymmetric component of the differential resistance \((dV/dI)_{as}\). Survival of the flat region even above 32 K, where features due to Andreev reflection have completely disappeared in \((dI/dV)\) indicates that the normal-state gap survives even above this temperature. We cannot resolve this feature in \((dI/dV)\) beyond 32 K [11].

In conclusion, we have observed significant conductance asymmetry in point-contact Andreev reflection spectra between metallic silver and epitaxial thin films of Ba(Fe0.92Co0.08)2As2. We show that the asymmetry observed in our ballistic point-contacts does not originate from the usual generation of local thermoelectric voltage for point contacts near the thermal limit. We argue that the antisymmetric component provides useful spectroscopic information about the Fermi surface of the material both in the superconducting and in the normal state and associate the unusual evolution of the antisymmetric component above \(T_c\) with the existence of the superconducting gap above \(T_c\) that might originate from strong fluctuation of the phase of the superconducting order parameter.

This work was supported by U.S. Department of Energy, Office of Basic Energy Sciences through grant No. DE-FG02-06ER46346 at Northwestern University and through grant No. DE-FG02-06ER46327 at University of Wisconsin-Madison. The work at the NHMFL was supported under NSF Cooperative Agreement DMR-0084173, by the State of Florida, and by AFOSR under grant FA9550-06-1-0474.

[1] G. Deutscher, Reviews of Modern Physics 77, 109 (2005).
[2] P. Szabo, P. Samuely, J. Kacmarcik, T. Klein, J. Marcus, D. Fruchart, S. Miraglia, C. Maremat, A. G. M. and Jansen, Phys. Rev. Lett 87, 137005 (2001).
[3] S. Mukhopadhyay, G. Sheet, P. Raychaudhuri, and H. Takeya, Phys. Rev. B 72, 014545 (2005).
[4] W. K. Park, J. L. Sarrao, J. D. Thompson, and L. H. Greene, Phys. Rev. Lett. 100, 177001 (2008).
[5] T. Y. Chen, Z. Tesanovic, R. H. Liu, X. H. Chen, and C. L. Chien, Nature 453, 1224 (2008).
[6] D. Daghero, M. Tortello, R. S. Gonnelli, V. A. Stepanov, N. D. Zhigadlo, and J. Karpinski, Phys. Rev. B 80, 060502 (2009).
[7] P. Samuely, Z. Pribulov, P. Szabo, G. Prists, S.L. Bud’ko, and P.C. Canfield, Physica C 469, 507 (2009).
[8] R.S. Gonnelli, D. Daghero, M. Tortello, G.A. Unmarino, V.A. Stepanov, R.K. Kremer, J.S. Kim, N.D. Zhigadlo, and J. Karpinski, Physica C 469, 512 (2009).
[9] S. Lee, J. Jiang, Y. Zhang, C. W. Bark, J. D. Weiss, C. Tarantini, C. T. Nelson, H. W. Jang, C. M. Folkman, S. H. Baek, A. Polyaniskii, D. Abraimov, A. Yamamoto, J. W. Park, X. Q. Pan, E. E. Hellstrom, D. C. Larbalestier, and C. B. Eom, Nature Materials 9, 397 (2010).
[10] G. E. Blonder, M. Tinkham, and T. M. Klapwijk, Phys.
Point-contact spectroscopy is known to be a surface sensitive probe. However, it is less surface sensitive than Scanning Tunneling Spectroscopy where only one atomic layer on the surface is probed. In our measurements we can probe several monolayers below the surface. Therefore, it is rational to consider our observation as a bulk property of the material.

[13] *Point-Contact Spectroscopy*, Yu. G. Naidyuk and I. K. Yanson, Springer New York (2005).