Observation of two-gap superconductivity in SrFe$_{1.85}$Co$_{0.15}$As$_2$ single crystals by scanning tunneling microscopy and spectroscopy

Jewook Park$^1$, Seunghyun Khim$^2$, Gun Sang Jeon$^2$, Jun Sung Kim$^3$, Kee Hoon Kim$^2$ and K Char$^{1,4}$

$^1$ Center for Strongly Correlated Materials Research, Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Republic of Korea
$^2$ Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Republic of Korea
$^3$ Department of Physics, Pohang University of Science and Technology, Pohang 790-784, Republic of Korea
E-mail: kchar@phya.snu.ac.kr

New Journal of Physics 13 (2011) 033005 (12pp)
Received 23 October 2010
Published 2 March 2011
Online at http://www.njp.org/
doi:10.1088/1367-2630/13/3/033005

Abstract. Superconducting properties of SrFe$_{1.85}$Co$_{0.15}$As$_2$ single crystals and their parent material, SrFe$_2$As$_2$, were investigated by scanning tunneling microscopy and spectroscopy (STM/S). In the parent material, we modeled surface conditions on the in situ cleaved single crystals, based on the observation of $2 \times 1$ stripe patterns and $\sqrt{2} \times \sqrt{2}$ square-lattice patterns in the atomic-resolution topography images and with the help of local density of states measurements. In the STM/S studies on SrFe$_{1.85}$Co$_{0.15}$As$_2$, a robust superconducting gap ($2\Delta_{\text{large}} = 17.3\,$meV) was observed in the conductance spectra measured along a line on the SrFe$_{1.85}$Co$_{0.15}$As$_2$ surface. Moreover, an additional small gap-like ($2\Delta_{\text{small}} = 2.9\,$meV) structure was simultaneously observed. Our observation corroborates the two-gap structures in iron-based superconductors.

$^4$ Author to whom any correspondence should be addressed.
Since the recent discovery of iron-based superconductors [1], the origin of high-temperature superconductivity in iron pnictides has been an important research topic. Numerous experimental and theoretical studies have been conducted, and although our understanding of the physical properties of iron pnictide superconductors has advanced, it is still far from being complete [2]. One of the most important aspects of understanding the high-$T_c$ superconductivity of iron pnictides is the magnitude and anisotropy of the superconducting gap. After several early debates on the various possible types of superconducting gap symmetries, which range from conventional s-wave symmetry to d-wave symmetry, recent theoretical studies have proposed an extended s-wave pairing state with a sign change for different Fermi surfaces [3]–[6]. In contrast to the case of high-$T_c$ cuprates, the pnictides have several electronic bands. A strong interband coupling appears to be induced through nesting-related anti-ferromagnetic spin fluctuations with stripe-type correlations from the wave vectors connecting the hole and electron pockets in Fermi surfaces [7]–[10]. Such a multiband nature and strong interband coupling are believed to be crucial for producing high-$T_c$ superconductivity in the pnictides, and this suggests the possibility of multigap superconductivity in these systems.

Many experimental studies such as those employing point-contact Andreev reflection spectroscopy (PCAR) [11, 12], muon spin rotation ($\mu$SR) [13]–[16], angle-resolved photoemission spectroscopy (ARPES) [7]–[10] and optical spectroscopy [17] have presented evidence of two superconducting gaps with various magnitudes. In contrast, all of the scanning tunneling spectroscopy (STS) studies conducted so far have revealed single-gap superconducting behavior, for example, studies on SmFeAsO$_{0.85}$, (Ba,Sr)$_{1-x}$K$_x$Fe$_2$As$_2$ and (Ba,Sr)Fe$_{2-x}$Co$_x$As$_2$ [18]–[27]. As shown previously in the case of high-$T_c$ cuprates [28], scanning tunneling microscopy and spectroscopy (STM/S) has been known to be a powerful tool for providing a deeper understanding of the superconducting gap because it can be used to investigate the local density of states (LDOS) as well as the surface topography at the atomic level. Therefore, it is puzzling that a clear observation of two gaps has not been obtained using STM/S studies. Further investigation is highly desirable.

2. Experimental methods

Single crystals of undoped SrFe$_2$As$_2$ and Co-doped SrFe$_2$As$_2$ were grown using high-temperature solution growth techniques with a Sn flux. These undoped and Co-doped SrFe$_2$As$_2$
single crystals show clear signatures in both electrical resistivity and magnetization curves for the presence of a spin density wave (SDW) at 202 K and 120 K, respectively. The Co-doped SrFe$_2$As$_2$ sample shows superconductivity at 19.5 K, which indicates that superconductivity is coexistent with magnetism in single-crystal SrFe$_{1.85}$Co$_{0.15}$As$_2$.

In all our experiments, we cleaved samples under ultrahigh vacuum (<1 × 10$^{-10}$ torr) at liquid-nitrogen temperatures (∼80 K) and immediately transferred them to liquid-helium temperatures (∼4.3 K). We observed $ab$-plane topographies of the undoped and Co-doped SrFe$_2$As$_2$ single crystals with electrochemically etched tungsten tips or mechanically cut platinum–iridium tips. To obtain further information on both samples, we probed the LDOS using the tunneling conductance ($dI/dV$) spectra. For the acquisition of $dI/dV$ data, we fixed the tip position ($x$, $y$ and $z$) and used a lock-in technique with 2 kHz ac modulation.

3. Results

3.1. Undoped SrFe$_2$As$_2$ single crystals

Due to the strong covalent bonding between the (FeAs)$^-$ layers, cleaving occurs between the As layers of the SrFe$_2$As$_2$ single crystals. Both resulting surfaces were covered by half of the Sr layer. Several scenarios for surface reconstruction after cleaving have been reported. Boyer et al [20], who first reported STM/S studies on iron-based superconductors (Sr$_{1-x}$K$_x$Fe$_2$As$_2$ single crystals), reported clear patterns of 0.8 nm stripes of atoms. They suggested that these stripes come from the surface reconstruction of complete Sr layers. Hsieh et al [21] also reported 0.8 nm stripe patterns in undoped SrFe$_2$As$_2$ single crystals and suggested a similar dimerization scenario resulting from complete Sr layers. Yin et al [19] also reported similar 0.8 nm stripe patterns on Co-doped BaFe$_2$As$_2$ single crystals; however, they suggested an alternating-rows scenario, which results in half of each Sr layer remaining on each cleaved surface. In addition, Massee et al [26] reported a greater variety of reconstructions of cleaved surfaces using a combination of STM topography images and low-energy electron diffraction (LEED) studies. They modeled several reconstructions of half-layers of Sr atoms on an As layer, such as $2 \times 1$, $\sqrt{2} \times \sqrt{2}$ and a combination of these [26]. Chuang et al [27] also reported 0.8 nm stripe patterns on CaFe$_2$As$_2$ single crystals. In addition, their spectroscopy imaging-STM results confirmed that those stripes do not originate from bulk properties but from surface reconstruction [27].

In our STM studies of both undoped and Co-doped SrFe$_2$As$_2$ single crystals, we observed not only 0.8 nm stripe patterns, but also square-lattice-shaped surfaces. A representative topography image of the cleaved surface of an undoped SrFe$_2$As$_2$ single crystal (figure 1(a)) shows both features (regions A and B). We were able to observe detailed surface features from the magnified images of regions A and B as well as the two-dimensional fast Fourier transform (2D-FFT) image. The 0.8 nm periodicity of the stripe patterns and the 0.4 nm atomic modulation ($d_{As-As}$) are marked in each direction. In addition, the 0.56 nm modulation of the square lattice ($\sqrt{2} \times \sqrt{2}$) is visible in the 2D-FFT.

Based on the atomic-resolution topography images, we proposed that two types of surface conditions are made from the Sr half-layers and assigned each surface as $2 \times 1$ (figure 2(b)) and $\sqrt{2} \times \sqrt{2}$ (figure 2(c)). In the magnified images, the bright stripes are produced by alternating

This sample corresponds to the nominal doping $x = 0.4$ in a previous report [29]. Here, the Co content is estimated using energy-dispersive x-ray spectroscopy.
Figure 1. STM images of SrFe$_2$As$_2$ single crystals. (a) Topography image of SrFe$_2$As$_2$ single crystal (30 × 30 nm$^2$, 2 V, 200 pA). Stripe patterns and a square lattice are observed on the upper right side and lower left side of the image, respectively. Regions of A and B are magnified to give a detailed view of the atomic surface. (b) 2D FFT image obtained from (a). (c) Side view of the SrFe$_2$As$_2$ unit cell. Blue, yellow and red dots indicate Sr, As and Fe atoms, respectively. Black arrows show the anti-ferromagnetic spin ordering of Fe atoms. (d) Cleaving occurs between two (FeAs)$^-$ layers, with each resulting surface comprising half of the Sr layer. Blue, yellow and red dots also indicate Sr, As and Fe atoms, respectively. Open and closed yellow circles correspond to the top and bottom of the As layers in FeAs covalent bonding. In addition, different transparencies of the red dots indicate different spin directions of Fe atoms.

rows of Sr atoms (2 × 1, region A). The square-lattice patterns are made from diagonal next-nearest-neighbors ($\sqrt{2} \times \sqrt{2}$, region B), giving a lattice constant ($\sim 0.56$ nm) that is greater than the nearest Sr–Sr or As–As atoms (lattice constant $\sim 0.4$ nm) by a factor of $\sqrt{2}$. The cleaved surface also has several adatoms and deficiencies. Because the dark regions indicate a depth of almost 0.2 nm below the stripe surfaces, they could indicate the location of a Sr atom deficiency following surface reconstruction after cleaving. Similarly, the additional Sr atoms became attached to the reconstructed Sr layer during the cleaving process. The $\sqrt{2} \times \sqrt{2}$ surfaces are slightly higher than the 2 × 1 surface (0.01–0.02 nm), but the height difference is very small compared to that between the Sr layer and the As layer (\sim 0.2 nm). Therefore, these two types of reconstruction are made from the same Sr half-layers. However, we do not yet understand why the 2 × 1 and $\sqrt{2} \times \sqrt{2}$ surfaces have a slight height difference. More detailed theoretical calculations are required to answer this question.
Figure 2. Modeling of the cleaving mechanism. (a) $2 \times 1$ stripe pattern model of the Sr half-layer. (b) $\sqrt{2} \times \sqrt{2}$ square-lattice pattern model of the Sr half-layer.

Figure 3. Spectroscopy of SrFe$_2$As$_2$ single crystals. (a) Topography image of the newly cleaved surface of SrFe$_2$As$_2$ single crystals ($100 \times 50$ nm$^2$, 500 mV, 120 pA). (b) Magnified topography image of the black square region in (a) ($20 \times 20$ nm$^2$, 500 mV, 120 pA). (c) Averaged $dI/dV$ curve measured at the locations in (b) indicated by the different symbols.

We acquired $dI/dV$ spectroscopy data on the newly cleaved undoped SrFe$_2$As$_2$ surface. The same stripe-like surface pattern was obtained in the large flat terrace region (figure 3(a)). On the lower right side of figure 3(a), a square-lattice surface is also visible. The magnification of the black square region of figure 3(a) clearly shows the stripe patterns. This image also shows several dark and bright spots (blue circles (●) and red triangles (△), respectively, in figure 3(b)). We plot $dI/dV$, measured at three categories of surface conditions indicated by the symbols in figure 3(b). By comparing these $dI/dV$ spectra, we found that the conductance peak around 60 mV is observed only in the bright spots (△). Interestingly, the deficient dark spots (●) and the protruding bright spots (△) have a height of −30 and 100 pm, respectively. The difference in height between the dark and bright spots corresponds to the images in figure 1(b) and might...
be due to the difference in tip conditions. Therefore, we could guess that the $dI/dV$ data on the dark spots are similar to the stripe patterns, and the data on the bright spots are distinctively associated with the additional Sr atom. As in the case of high-$T_c$ cuprates, various conductance peaks are observed, which can be attributed to the presence of impurities. In this study, the additional Sr atoms on the surface appear to act as strong impurity sites.

3.2. Superconducting SrFe$_{1.85}$Co$_{0.15}$As$_2$ single crystals

Several early reports on iron-based superconductors indicate that superconductivity can be developed by applying pressure or charge carrier doping. In addition to the undoped SrFe$_2$As$_2$, we also studied electron-doped superconducting SrFe$_{1.85}$Co$_{0.15}$As$_2$ single crystals by using STM/S. As mentioned above, the SrFe$_{1.85}$Co$_{0.15}$As$_2$ sample shows coexistence of the SDW transition at $T_{SDW} = 120$ K and the superconducting transition at $T_c = 19.5$ K. These findings signify that this sample is under-doped. Figure 4(a) shows the topography images of the surface of the SrFe$_{1.85}$Co$_{0.15}$As$_2$ single crystal and figure 4(c) is a magnification of a $20 \times 20$ nm$^2$ square region of figure 4(a) under the same tunneling condition. Figure 4(d) is a topography image under reduced tunneling bias voltage conditions on the same region of figure 4(c). Like the undoped samples, stripe patterns of the topography images of the superconducting sample correspond to the $2 \times 1$ stripe patterns of a Sr half-layer. Additionally, dark points indicating

Figure 4. STM images of SrFe$_{1.85}$Co$_{0.15}$As$_2$ single crystals. (a) Topography ($100 \times 50$ nm$^2$, 1.0 V, 197 pA). (b) 2D-FFT image of (a). (c) Topography at 1 V ($20 \times 20$ nm$^2$, 1 V, 200 pA). (d) Topography at 100 mV ($20 \times 20$ nm$^2$, 100 mV, 200 pA).
Figure 5. Spectroscopy data along line A in figures 4(c) and (d). (a) dI/dV conductance curves along line A with varying bias voltage. Each dI/dV curve is offset for clarity. The red dotted central rectangle near zero bias is magnified for detailed investigation. Red arrows indicate coherence peaks of the superconducting gaps ($\pm \Delta_{\text{large}}$). After reducing the tip–sample distance, more detailed dI/dV data are obtained with even better energy resolution (right box). This corresponds to the blue dotted rectangle in the magnified center graph. Small blue arrows denote the small gap-like structures ($\pm \Delta_{\text{small}}$) inside the large superconducting gaps. (b) and (c) Re-drawn dI/dV conductance curves as a function of topography. The big arrow-shaped topography images correspond to the magnified line A region of figures 4(c) and (d). Blue dots on the big arrows are the data acquisition points for each dI/dV conductance curve. (d) The ninth dI/dV conductance curve of the $\pm 10$ meV range is magnified and its base line is numerically fitted for greater clarity.

the absence of atoms and bright points indicating atomic protrusion correspond to absent Sr atom positions and to additional Sr atoms on the stripe-patterned layer, respectively. The 2D-FFT image (figure 4(b)), obtained from figure 4(a), shows the same 0.8 nm periodicity of the Sr half-layers resulting from the $2 \times 1$ stripe pattern.

In the next set of figures, we acquired the local spectroscopy data for the SrFe$_{1.85}$Co$_{0.15}$As$_2$ sample along lines A and B in figures 4(c) and (d). Figure 5(a) shows dI/dV for line A with varying bias conditions. Each dI/dV curve is obtained from the blue dots in the arrow-shaped topography image of line A (figures 5(b) and (c)). The left box in figure 5(a) shows a clear gap,
which is a distinct result of superconductivity of this sample. The middle box in figure 5(a), which is the magnification of the curves in the low-bias region (dotted red rectangle) of the left box, shows this superconducting gap (2\Delta_{\text{large}} = 17.3 \text{meV}) more clearly. The two red arrows indicate the coherence peaks of the superconducting gap in the curves. The pairing strength of the gap, 2\Delta_{\text{large}} / k_B T_c = 10.2, suggests a somewhat strong coupling, nonetheless within the range of the reported values for iron-based superconductors [11]–[14], [30]. As can be seen in figure 5(b), which is the re-drawn color mapping of the curves and corresponds to each dI/dV curve in the ±100 mV range, the size of the distinct and robust gap is not varying with topographic condition. Moreover, the superconducting coherence peaks still exist in spite of the 60 mV conductance peak of the bright spot at the end point of line A. In order to investigate this superconducting gap in detail, finer energy resolution of dI/dV spectra was obtained by reducing the bias voltage sweep range and taking more data points in the curves. The right box in figure 5(a) is the detailed dI/dV data along line A of figure 4(d), which corresponds to the blue dotted rectangle of the middle box in figure 5(a). In this measurement of dI/dV spectra, we observed a small gap-like feature at 2\Delta_{\text{small}} = 2.9 \text{meV} inside the large superconducting gaps. The blue arrows indicate coherence peaks of the small gap-like structures. This small gap-like feature is also shown in the color-mapping image (figure 5(d)), which is re-drawn from the right blue panel of figure 5(a). The small gap-like feature does not change in size with varying topography; however, its existence is easily affected by surface conditions. The small gap-like feature is not clearly visible in the dI/dV curves of the right box in figure (a) near the bright spot at the top of line A, where the 60 mV bias conductance peak is observed in a larger bias range spectrum (the left box in figure (a)). In order to investigate the small gap-like structure in more detail, figure 5(d) shows a magnification of the ninth dI/dV curve in the ±10 mV range (dotted pink rectangle) and the base line of the conductance curves. Since we did not compare our two-gapped spectroscopy data with the non-superconducting states, we observed inevitably asymmetric coherence peaks between plus and minus bias condition. If the small gap-like feature is indeed a superconducting gap, this small gap indicates a very small pairing strength (2\Delta_{\text{small}} / k_B T_c = 1.7), which is even smaller than the Bardeen–Cooper–Schrieffer (BCS) limit of 3.53. Such a small gap (2\Delta_{\text{small}} / k_B T_c < 3) has been suggested in several reports, by PCAR on Ba_{0.55}K_{0.45}Fe_2As_2 (2\Delta_{\text{small}} / k_B T_c \sim 2.5–4) [11] and by \mu\text{SR} on Ba_{1-x}K_xFe_2As_2 (2\Delta_{\text{small}} / k_B T_c \sim 1) [13, 15], Ba(Fe_{0.93}Co_{0.07})_2As_2 (2\Delta_{\text{small}} / k_B T_c \sim 1.6) and SrFe_{1.75}Co_{0.25}As_2 (2\Delta_{\text{small}} / k_B T_c \sim 2.7) [13, 16].

In addition, the small gap-like feature was reproducibly obtained along line B from figures 4(c) and (d) under the same conditions as line A. Figure 6(a) shows another set of line spectroscopy data along line B, from which we deduce that this small gap-like feature is not a local property, but a uniform and robust feature of the SrFe_{1.85}Co_{0.15}As_2 single crystal. Interestingly, both dark and bright spots affect not only the existence of the small gap-like feature but also the sub-gap conductance of the large gap, indicating high sensitivity of the small gap-like feature to sample surface conditions. Therefore, the dI/dV spectra of several points in line B do not show the small gap-like feature, as in the data acquisition points near the bright and dark spots in the topography.

4. Discussions

In iron-based superconductors, several electronic bands are involved at the Fermi level and form two hole-like pockets (\(\alpha\) and \(\beta\)) at the \(\Gamma\) point (Brillouin zone center) and two electron-like pockets (\(\gamma\) and \(\delta\)) at the \(M\) points (Brillouin zone corners) of the Fermi surfaces. Early
Figure 6. Spectroscopy data along line B from figures 4(c) and (d). (a) Detailed d$I$/d$V$ conductance curves measured along line B of figure 4 over a smaller bias voltage range. The small blue arrows indicate coherence peaks of the small gap-like structures. Each of the d$I$/d$V$ curves are equally offset but the base lines of spectra change with topography, resulting in uneven spacing between the spectra. (b) Re-drawn d$I$/d$V$ conductance curves as a function of topography. In the same manner as in figure 5, the big arrow and blue dots indicate topography and acquisition points for the STS measurements.

_ab initio_ calculations [2, 5] predicted the two-gap superconductivity from such multiband nature of iron-based superconductors, and this was subsequently confirmed by many ARPES measurements and other experiments. We depict a schematic figure of the reported Fermi surfaces in figure 7(a).

According to ARPES data on Ba$_{1-x}$K$_x$Fe$_2$As$_2$ single crystals, the outer hole-like pocket ($\beta$) produces a small gap ($2\Delta_{\text{small}}/k_B T_c \sim 3.6$) while the inner hole-like pocket ($\alpha$) and the two electron-like pockets ($\gamma$ and $\delta$) create a comparably large gap ($2\Delta_{\text{large}}/k_B T_c \sim 7.2$–7.7) due to their significant nesting [7]–[9]. Based on the K-doped BaFe$_2$As$_2$ single-crystal ARPES studies, the hole pockets are expanded, the electron pockets become smaller, and the bottom of the electron Fermi surfaces approaches the Fermi energy when the hole doping level increases. Therefore, the Fermi surfaces of the iron-based superconductors are described within a rigid band shift model.

In the electron-doped case, the fact that BaFe$_{1.85}$Co$_{0.15}$As$_2$ has one hole-like pocket at the $\Gamma$ point and two electron-like pockets at the $M$ points seems to be relevant. Due to electron doping, the $\alpha$ Fermi surface appears to have shrunk, and the strong pairing strength ($2\Delta/k_B T_c \sim 6$) seems to have moved to the nested $\beta$ Fermi surface from the $\alpha$ Fermi surface, possibly due to changes in the nesting conditions [8]. In addition, PCAR experiments showed two-gap superconductivity in Ba$_{0.53}$K$_{0.47}$Fe$_2$As$_2$ [11, 12] and the results of $\mu$SR experiments on Ba$_{1-x}$K$_x$Fe$_2$As$_2$ can be better explained by a two-gap model than a single-gap model [13]–[16]. Optical spectroscopy also provides more evidence for the existence of two superconducting gaps [17].
Figure 7. Schematic figures of Fermi surfaces. (a) Fermi surfaces of two hole pockets ($\alpha$ and $\beta$) at the Brillouin zone center and two electron pockets ($\gamma$ and $\delta$) at the Brillouin zone corner. The shapes and locations of Fermi surfaces are based on reported ARPES studies [7]–[9]. (b) Shift of the two hole pockets relative to the Fermi energy ($E_f$) level according to a rigid band shift model. Black dotted and orange solid lines indicate $E_f$ of SrFe$_2$As$_2$ and shifted $E_f$ of SrFe$_{1.85}$Co$_{0.15}$As$_2$, respectively. The remnant $\alpha$ hole pocket in spite of the shift of $E_f$ is denoted as a yellow area.

In spite of the above evidence, the existence of multigap structures of iron-based superconductors has not yet been reported in many STM/S investigations. According to other groups, the relative contribution of different bands needs to be considered because the STM tip measures conductance spectra averaged in momentum space. Moreover, the matrix element that describes the coupling between states in the tip and the sample might be different for electron- or hole-like pockets. In addition, other gaps with weak coherence peaks may be hidden within the momentum-space-averaged spectra [18].

If we indeed observed two-gap superconductivity in SrFe$_{1.85}$Co$_{0.15}$As$_2$ in STM/S experiments, we propose a scenario to explain our observations of the two gaps in SrFe$_{1.85}$Co$_{0.15}$As$_2$. Like the Ba$_{1-x}$K$_x$Fe$_2$As$_2$ samples, a reduction in the sizes of the two hole-like pockets matches the nesting condition between the $\beta$ Fermi surface sheet and the electron pockets. Therefore, the large gap is more likely to result from the $\beta$ Fermi surface. If this is true, the small gap appears to be a result of the $\alpha$ Fermi surface in SrFe$_{1.85}$Co$_{0.15}$As$_2$, which survives despite electron doping. The yellow area of the schematic band structure in figure 7(b) indicates this survivability of the $\alpha$ hole pocket in the under-doped cases in spite of Co doping. In comparison to the apparent absence of the $\alpha$ Fermi surface in the ARPES study of BaFe$_{1.85}$Co$_{0.15}$As$_2$, the survival of the $\alpha$ Fermi surface might be due to the different doping dependences of the superconductivity in SrFe$_{2-x}$Co$_x$As$_2$ and BaFe$_{2-x}$Co$_x$As$_2$. It is likely that our SrFe$_{1.85}$Co$_{0.15}$As$_2$ is still under-doped, while the optimal doping of BaFe$_{2-x}$Co$_x$As$_2$ is achieved at $x = 0.15$ [31]. Therefore, the SrFe$_{1.85}$Co$_{0.15}$As$_2$ single crystal has two gaps of different size: the small superconducting gap from the $\alpha$ Fermi surface, and the large gap from the $\beta$ Fermi surface and the $\gamma$ and $\delta$ Fermi surfaces (electron pockets). While the $\alpha$ Fermi surface of the BaFe$_{1.8}$Co$_{0.2}$As$_2$ single crystal has shrunk with optimal doping, multiple gaps of similar size originate from the $\beta$ Fermi surface and the $\gamma$ and $\delta$ Fermi surfaces [19]. This could be one of the reasons why multiple gaps were detected in our STM/S studies.
We may speculate on the differences between our results and those of other groups as follows. No other groups have yet reported the existence of a small gap inside a larger gap, maybe because over-doped samples with single gaps, such as BaFe$_{1.8}$Co$_{0.2}$As$_2$, were used [19]. Another possibility is that it may be difficult to observe the small gap without detailed STS measurements over a small bias range. In order to obtain a small gap feature inside a larger gap, the tunneling resistance should be reduced sufficiently. In addition, the small gap-like feature was very sensitive to the sample surface conditions. Surface defects such as the 60 mV bias conductance peak or the Sr atom deficiency in the cleaved surface did not hinder detections of the larger gap, but the small gap-like feature was easily affected by surface defects, such as the bright and dark spots in the topography images.

Another interesting feature is the relatively large pairing strength of the measured large gap in SrFe$_{2-x}$Co$_x$As$_2$ as compared to BaFe$_{2-x}$Co$_x$As$_2$. By comparing the pairing strength of BaFe$_{1.85}$Co$_{0.15}$As$_2$ ($2\Delta/k_BT_c \sim 4.5$–$5.9$) and Ba$_{0.4}$K$_{0.4}$Fe$_2$As$_2$ ($2\Delta_{\text{large}}/k_BT_c \sim 7.2$–$7.7$) samples, it was suggested that Co substitution in the (FeAs)-plane causes stronger pair breaking [8]. However, our measurement of the large pairing strength ($2\Delta/k_BT_c \sim 10$) in SrFe$_{1.85}$Co$_{0.15}$As$_2$ is inconsistent with this picture. This may be because the increased pairing strength due to the nesting condition is sufficient to overcome the pair breaking by in-plane Co doping. The difference in the nesting conditions between BaFe$_{2-x}$Co$_x$As$_2$ and SrFe$_{2-x}$Co$_x$As$_2$ is supported by the SDW conditions of their parent materials because the nesting condition between hole pockets and electron pockets is connected to the SDW wave vector $Q \sim (\pi, 0)$ of the parent materials. The strong pairing strength of the large gap of SrFe$_{2-x}$Co$_x$As$_2$ might be related to the high SDW transition temperature of SrFe$_2$As$_2$ ($T_{SDW} \sim 205$ K) [17, 31]. This SDW transition temperature is higher than that of BaFe$_2$As$_2$ ($T_{SDW} \sim 140$ K) [32].

During the preparation of this paper, another STM group’s report about two-gap superconductivity was brought to our attention [33]. They presented well-defined two-gap feature in the spectroscopy data of BaFe$_{2-x}$Co$_x$As$_2$ single crystals. They reported different sizes of gapped features on the under-doped and over-doped samples. They defined each gapped feature as the larger gap originating from hole pockets and the smaller gap from electron pockets. Contrary to the previous ARPES results, the pairing strength of hole and electron pockets of their results turned out to be quite different in size in spite of nesting conditions between hole and electron pockets. Interestingly, Khasanov et al reported the presence of two superconducting gaps in SrFe$_{1.75}$Co$_{0.25}$As$_2$ using a $\mu$SR measurement; this sample is believed to be an over-doped region [16]. Normally, this over-doped region makes the existence of the $\alpha$ Fermi surface unfavorable. Therefore, we leave the origin of the small gap open for discussion.

5. Summary

In summary, we acquired topography images and LDOS data as a function of position on undoped and Co-doped SrFe$_2$As$_2$ single crystals. From the topography images of SrFe$_2$As$_2$, we revealed cleaving mechanisms including $2 \times 1$ stripe patterns and $\sqrt{2} \times \sqrt{2}$ square-lattice patterns. Through detailed investigations of LDOS in SrFe$_{1.85}$Co$_{0.15}$As$_2$ samples, we acquired two robust superconducting gaps: a small gap within a strongly coupled gap. We consider the possibility that the two-gap superconductivity is related to the momentum-dependent nesting conditions in electron-doped iron-based superconductors.
Acknowledgments

This work was supported by the NRF through the Acceleration Research Program (R17-2008-033-01000-0). This work was also partially supported by the National Research Lab program (M10600000238) and KICOS through a grant provided by MEST (K20702020014-07E200-01410).

References

[1] Kamihara Y et al 2008 Phys. Rev. B 77 214515
[2] Ishida K et al 2009 J. Phys. Soc. Japan 78 062001
[3] Parker D et al 2008 Phys. Rev. B 78 134524
[4] Bang Y et al 2009 Phys. Rev. B 79 054529
[5] Mazin V and Schmalian J 2009 Physica C 469 614
[6] Chubukov A V et al 2008 Phys. Rev. B 78 134512
[7] Ding H et al 2008 Europhys. Lett. 83 47001
[8] Nakayama K et al 2009 Europhys. Lett. 85 67002
[9] Terashima K et al 2009 Proc. Natl Acad. Sci. USA 106 7330
[10] Lin Z et al 2008 Chin. Phys. Lett. 25 4402
[11] Szabo P et al 2009 Phys. Rev. B 79 012503
[12] Samuely P et al 2009 Physica C 469 507
[13] Evtushinsky D et al 2009 New J. Phys. 11 055069
[14] Williams T J et al 2009 Phys. Rev. B 80 094501
[15] Khasanov R et al 2009 Phys. Rev. Lett. 102 187005
[16] Khasanov R et al 2009 Phys. Rev. Lett. 103 067010
[17] Hu W et al 2008 Phys. Rev. Lett. 101 257005
[18] Yin Y et al 2009 Physica C 469 535
[19] Yin Y et al 2009 Phys. Rev. Lett. 102 097002
[20] Boyer M et al 2008 arXiv:0806.4400v2
[21] Hsieh D et al 2008 arXiv:0812.2289v1
[22] Niestemski F et al 2009 arXiv:0906.2761v1
[23] Millo O et al 2008 Phys. Rev. B 78 092505
[24] Wray L et al 2008 Phys. Rev. B 78 184508
[25] Massee F et al 2009 Phys. Rev. B 79 220517
[26] Massee F et al 2009 Phys. Rev. B 80 140507
[27] Chuang T et al 2010 Science 327 181
[28] Fischer Ø et al 2007 Rev. Mod. Phys. 79 353
[29] Kim J et al 2009 J. Phys.: Condens. Matter 21 102203
[30] Evtushinsky D V et al 2009 Phys. Rev. B 79 054517
[31] Xu G et al 2008 Europhys. Lett. 84 67015
[32] Leithe-Jasper A et al 2008 Phys. Rev. Lett. 101 207004
[33] Teague M L et al 2010 arXiv:1007.5086v3