In-plane Anisotropic Quasi-particle Interference and Vortex Core in FeSe

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FeSe is a unique iron-based superconductor which has nodal superconducting gap [1]. FeSe has another interesting aspect in that superconductivity occurs in an orthorhombic phase which might be related to the orbital ordering. We performed low-temperature STM/STS on high-quality single crystals of FeSe to investigate the superconducting gap and the electronic states in the orthorhombic phase. STM topograph of cleaved surfaces exhibits clear Se atomic lattice with small amount of defects and twin boundaries. STM topograph of cleaved surfaces exhibits clear Se atomic lattice with small amount of defects. Quasi-particle interference (QPI) patterns are clearly observed in the Fourier-transformed conductance images. Unidirectional electron- and hole-like QPI branches are identified and they disperse in orthogonal directions. This anisotropic behavior may be related to the orbital ordering in the orthorhombic phase. We also found that the bottom and top of the electron and hole bands measured from the Fermi energy are only a few times bigger than the superconducting-gap energy. This result indicates that FeSe is close to the BCS-BEC crossover regime. In such a case, quantum-limit behavior is expected in the vortex core. Indeed, we observe signatures of quantum-limit vortex core, such as electron-hole asymmetric spectrum at the vortex center and a spatial oscillation of the tunneling conductance.

Electric double layer transistor on oxide: device development and control of superconductivity

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Charge carrier density is a crucial parameter that governs physical properties of materials. Many superconductors have been discovered with targeting insulating mother materials and donating carriers by a chemical doping. However, maximum carrier density is limited by chemical solubility of a donor element to a mother material. Electrostatic field-effect approach is an alternative tool to induce charge carriers to an insulator. An electric double layer transistor (EDLT), a sort of field-effect transistor with a liquid electrolyte gate, recently attracts considerable attention due to its capability to induce high charge carrier densities. Charge carrier density can be reversibly modulated with changing gate bias from zero to above $10^{14} \text{cm}^{-2}$. High carrier density enables us to induce phase transition from insulator to superconductor on SrTiO$_3$, followed by a discovery of new superconductor KTaO$_3$ [1,2]. Electric field-effect tuning of superconductivity has been also reported on (La,Sr)$_2$CuO$_4$ and MoS$_2$ [3,4].

In this presentation, we will show recent studies of electric double layer transistor both on oxide semiconductors and superconductors. First, we will show peculiar superconductivity emerging on an insulator SrTiO$_3$. EDLT on SrTiO$_3$ shows superconductivity with almost constant $T_c$ of 0.4 K with various gate biases [1], while EDLTs on other systems shows decrease in $T_c$ around insulator-superconductor transition[3,4]. In order to examine phase diagram of SrTiO$_3$ around insulator-superconductor transition, we fabricated double gate device on SrTiO$_3$, which has a top electrolyte gate and a back-gate electrode on the backside of the SrTiO$_3$ substrate. As SrTiO$_3$ has high dielectric constant at low temperature, transport properties are electrostatically tuned by the back gating below 1 K. We observed insulator-superconductor transition modulated at low temperature by back-gating. Electron mobility largely suppressed at the insulator state, indicating that localization of charge carriers occurs at the insulator state. $T_c$ showed almost a constant value of around 0.4 K for a sheet resistance $R_s$ from 100 $\Omega$ to 10 k$\Omega$, which is around the quantum resistance of $h/e^2$. In addition, large residual resistance at superconducting state and decrease of critical current density was observed around the transition. This suggests that superconductivity in SrTiO$_3$ around the transition is similar to a granular thin film superconductor in spite of homogeneous carrier distribution on SrTiO$_3$ surface. Next, we will focus on another peculiarity of SrTiO$_3$ EDLT: two dimensional superconductivity. Electric field-induced carriers behave as two dimensional electron gas in semiconductor at the normal state. From angular dependence of critical magnetic field, we observed that carriers also behaves as ideal two dimensional superconductor following to the two dimensional GL equation [5].

Finally, we will present recent studies of EDLT on wide-gap oxide semiconductor Ga$_2$O$_3$, which has large band gap of 4.9 eV. An EDLT device on Ga$_2$O$_3$ bulk single crystal and ionic liquid electrolyte showed typical n-type FET characteristics. Device fabrication without exposing air is crucially important for making a good device. In addition, low temperature annealing of a Ga$_2$O$_3$ EDLT of around 200 deg.C improved device performance. We suggest that adsorbed water molecules or oxygen atoms on the surface makes high density interface defects at an electrolyte/oxide interface and suppresses device performance, similar to conventional FETs.

This work was conducted in collaboration with H. Aoki, Y. Iwasa, M. Kawasaki, N. Kimura, Y. Maeno, S. Nakamura, T. Nojima, A. Ohtomo, H. Shimotani, S. Yonezawa, H. T. Yuan.

References
Magneto-elastic coupling in detwinned SrFe$_2$As$_2$ by inelastic x-ray scattering

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The discovery of superconductivity at $T_c$’s up to 55 K in iron-pnictides has attracted considerable attention due to the possible novel physics in this class of materials. Early work strongly suggested that conventional electron-phonon coupling cannot explain the observed high-$T_c$ in Fe-pnictide superconductors. However, these materials do display a remarkable sensitivity of superconductivity and magnetism to the lattice. Therefore, it is interesting to investigate the phonon structure in order to shed light on the magneto-elastic coupling in these materials.

Here, we report the first inelastic x-ray scattering (IXS) study of single crystals of SrFe$_2$As$_2$ that have been detwinned by application of in-plane uniaxial stress. This allows us to clearly identify the change in phonon dispersion induced by the onset of magnetic order (e.g. Fig.1). Comparing these results against LSDA calculations we find rough agreement on average, but that the calculations fail to predict the right magnitude of the splitting, or even sometimes, the right sign. We will discuss the current state of our analysis relating magnetism to the phonon dispersion.

Fig.1 Phonon scans at tetragonally-equivalent Q positions showing anisotropy below $T_{s,m}$. 
Iron chalcogenide FeTe$_{1-x}$Se$_x$ attracted much attention due to its simple structure, which is favorable for probing the superconducting mechanism. Its less toxic nature compared with iron arsenides is also advantageous for applications of iron-based superconductors. By intercalating spacer layers, superconducting transition temperature has been raised over 40 K. On the other hand, the presence of interstitial Fe is almost unavoidable in FeTe$_{1-x}$Se$_x$ single crystals, which causes strong controversies over its fundamental properties, as well as its phase diagram. While Liu et al. reported that bulk superconductivity resides only in the range of $x > 0.29$ [1], it was observed in the range of $0.1 \leq x \leq 0.5$ by Noji et al. [2]. Our previous reports prove that the content of interstitial Fe can be controlled by O$_2$ annealing, and the well-annealed FeTe$_{0.6}$Se$_{0.4}$ single crystal shows bulk superconductivity [3].

In this report, we carefully annealed FeTe$_{1-x}$Se$_x$ single crystals ($0 \leq x \leq 0.4$) in O$_2$ atmosphere to remove the interstitial Fe. Systematic measurements on structure, transport, magnetism, and heat capacity were performed on crystals with and without interstitial Fe to construct an intrinsic doping phase diagram. The bulk superconducting region is proved to exist from $x = 0.08$ to 0.4 in the well-annealed crystals different from the filamentary superconductivity observed in all the doping levels in crystals before annealing. Antiferromagnetic transition in the phase diagram of crystals with interstitial Fe extending to $x = 0.3$ is suppressed to the region of $x < 0.08$ after removing the interstitial Fe. The above results show that the interstitial Fe enhances the antiferromagnetism, and suppresses the superconductivity. Heat capacity, Hall effect and magnetoresistance measurements were also applied to reveal the main effect of interstitial Fe.

Substitution Effect of Ba/Sr, Sr/Ca in $AFe_2(As_{1-y}P_y)_2$ ($A$=Ba, Sr, Ca)

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In iron pnictides, there is a general relationship between $T_c$ and local structures of FeAs tetrahedra [1,2]. Another viewpoint of structural relationship with $T_c$ is the Fermi Surface topology linked to the nesting condition. Then, we investigated how the electronic phase diagrams change when changing the crystal structures in $AFe_2(As_{1-y}P_y)_2$ where $A$=Ba/Sr or Sr/Ca. We expect that the change of A-atom site varies the anisotropy or dimensionality of the electronic system.

In this study, we synthesized the single crystals of $Ba_{1-x}Sr_xFe_2(As_{1-y}P_y)_2$ ($x=0.5$) and $Sr_{1-x}Ca_xFe_2(As_{1-y}P_y)_2$ ($x=0.08,0.16$), measured the resistivity and carried out the single crystal X-ray structure analysis using synchrotron X-ray for their optimum doped crystals, then elucidated their electronic phase diagrams and detailed crystal structures. The electronic phase diagram of $A$=Ba$_{0.5}$Sr$_{0.5}$ systems is similar to those of $A$=Ba and Sr ones. On the other hand, we got the different electronic phase diagram as for $A$=Sr/Ca systems ($x=0.08,0.16$) where the superconducting phase appears at a smaller P content as compared with $A$=Sr system, but $T_c$ at the optimum dope of those systems are almost the same in all systems. From the single crystal X-ray structure analysis, it has been revealed that in the optimum doped crystals, while the dimensionality of the crystal structures that are described as lattice constant rate $c/a$ systematically changes, the local structures of FeAs tetrahedra such as pnictogen heights or As-Fe-As bond angles are almost the same.


Figure 1. The electronic phase diagram of $AFe_2(As_{1-y}P_y)_2$ ($A$=Ba,Sr,Ca)