PCP4-1

^{31}P NMR studies of an optimally doped superconductor $Ba_{0.5}Sr_{0.5}Fe_2(As_{1-x}P_x)_2$ (x~0.4)

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We report ^{31}P NMR studies of an oriented polycrystalline superconductor of $Ba_{0.5}Sr_{0.5}Fe_2(As_{0.6}P_{0.4})_2$ (T_c = 29 K). The P-substituted $Ba_{0.5}Sr_{0.5}Fe_2As_2$ is one of the high-T_c superconductors as well as $BaFe_2As_2$and $SrFe_2As_2$ [1]. The ^{31}P nuclear spin-lattice relaxation rate $1/T_1$ shows an asymptotic behavior of $a+bT$ (a and b are constants) at higher temperatures than about 100 K and the minimum at 40 K with an upturn toward T_c. The a term in $1/T_1$ indicates the presence of two dimensional antiferromagnetic spin fluctuations. The negative Weiss temperature Θ = –15 K of the Curie-Weiss-type antiferromagnetic spin susceptibility $\chi(Q) \propto 1/(T+\Theta)$ in the analysis of $1/T_1T$ suggests a weakly antiferromagnetic ground state in the suppression of superconductivity. No spin pseudogap characterizes the weakly antiferromagnetic spin fluctuations above T_c.
[1] S. Adachi, Y. Murai, and K. Tanabe: Physica C **483**, 67 (2012).

Keywords: BaSr123, NMR

PCP4-2

Composition dependence of penetration depth in $FeSe_{1-x}Te_x$ films measured by superconducting resonators

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The relation between the structural (nematic) transition and superconductivity have attracted much interest in FeSe. Te-substituted $FeSe_{1-x}Te_x$ exhibits the rapid increase of the superconducting transition temperature, T_c, upon disappearance of the structural transition caused by the increase of x[1,2]. The rapid change of T_c may suggest a possible change in the superconducting properties. However, only thin-film growth techniques make it possible to obtain single crystalline samples of $FeSe_{1-x}Te_x$ in the composition region [1,2]. In this study, we measured temperature dependence and its magnitude of the penetration depth in $FeSe_{1-x}Te_x$ films to investigate the relation between superconducting gap structure and the structural transition, by the microwave transmission line resonator technique. [3]. We fabricated coplanar resonators of $FeSe_{1-x}Te_x$ films by using a sandblasting method and obtained the penetration depth from the resonant frequency. The merit of this technique is that the absolute magnitude of the penetration depth is obtained without the aid of any other measurement.

The measured penetration depth as a function of temperature was well represented by the power-law, $\lambda(T) = \lambda(0) + AT^n$ for $0.1 < T/T_c < 0.2$ which agrees with the so far established behavior[4]. Figure.1 shows the low-temperature-limiting $\lambda(0)$ and the power, n, as a function of Te content, x, together with T_c. It is remarkable that $\lambda(0)$ does not change largely when we crossed the orthorhombic-tetragonal boundary, which is in contrast to the T_c behavior. As for the power, n, the end material FeSe, exhibiting the structural transition, shows $n = 1.55$, whereas, other samples without structural transition shows $n > 2$. We will discuss the implications of these results, in terms of the change in the structure of the superconducting gap function as a function of Te substitution.

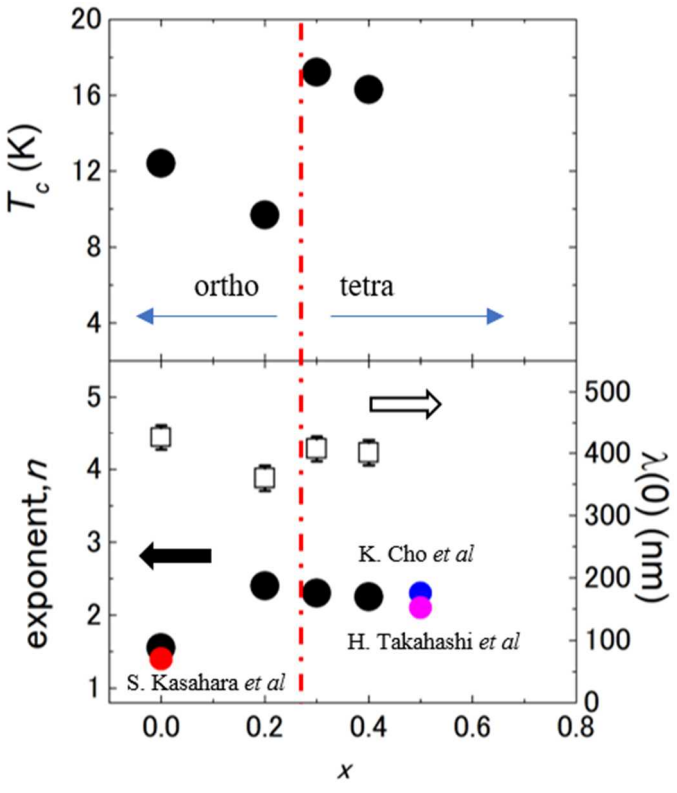

Fig1. x dependence of T_c, $\lambda(0)$ and exponent, n

[1] Y. Imai, *et al.*, Sci. Rep. **7**, 46653 (2017).
[2] Y. Imai, *et al.,* PNAS, **112,** 1937(2015).
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Keywords: iron-based superconductor, microwave, superconducting gap

PCP4-3

Transport properties of electron-doped $FeSe_{1-x}S_x$ and $FeSe_{1-y}Te_y$ films with electric double layer transistor

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FeSe shows the structural phase transition without an antiferromagnetic transition unlike other iron-based superconductors, and provides a unique playground to study the role of the structural phase (nematic) transition. We found that T_c of $FeSe_{1-x}S_x$ films monotonically decreases when the structural phase transition disappears [1], while that of $FeSe_{1-y}Te_y$ films jumps just after the structural phase transition disappears [2]. The contrastive behavior between $FeSe_{1-x}S_x$ and $FeSe_{1-y}Te_y$ may suggest that the structural phase transition does not play a universal role for T_c.

It is well-known that electron doping to FeSe increases its T_c up to 40-45 K [3]. It is of great interest to investigate the Tc behavior in such a high Tc electron-doped FeSe upon S/Te substitution, especially at the orthorhombic-tetragonal boundary. In this study, we fabricated the electric double layer transistor(EDLT) configuration of $FeSe_{1-x}S_x$ and $FeSe_{1-y}Te_y$ films on $LaAlO_3$ substrate, and measured transport properties under gate voltage to investigate the behavior of T_c of the tetragonal phase and orthorhombic phase for the electron-doped FeSe films.

Figure 1 shows the temperature dependence of the electron-doped $FeSe_{0.89}S_{0.11}$, $FeSe_{0.8}Te_{0.2}$ [4] and FeSe films. Electron-doped $FeSe_{0.89}S_{0.11}$ and $FeSe_{0.8}Te_{0.2}$ also show high T_c. Figure 2 shows the phase diagram of the electron-doped $FeSe_{1-x}S_x$ and $FeSe_{1-y}Te_y$ films. T_c's of electron doped $FeSe_{1-x}S_x$ and $FeSe_{1-y}Te_y$ films are lower than that of FeSe. Unlike the "bulk" $FeSe_{1-x}S_x$ and $FeSe_{1-y}Te_y$ films, T_c gradually decreases as x or y increases. We will discuss the origin of the difference in the behavior of T_c at the orthorhombic-tetragonal boundary between the "bulk" and electron-doped films.

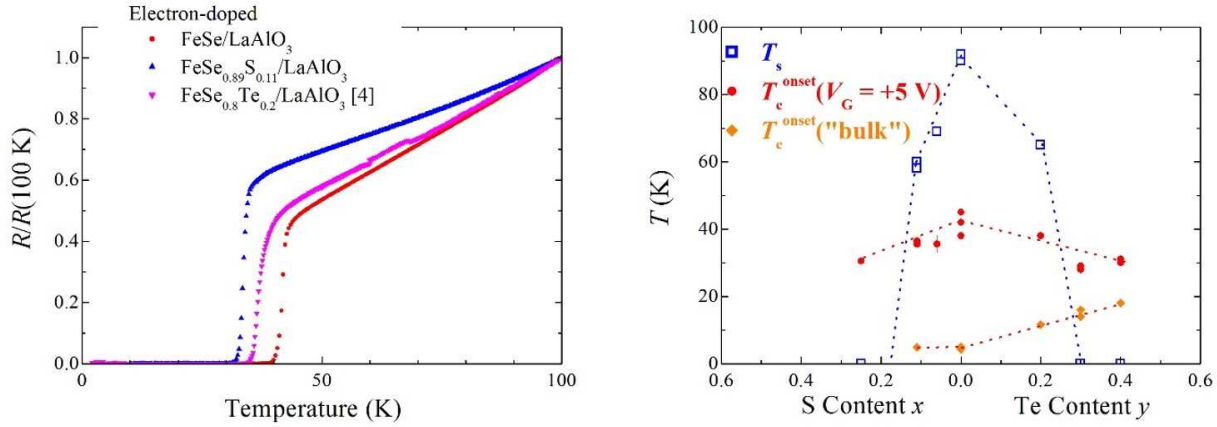

Fig. 1 Temperature dependence of resistivity of the electron-doped $FeSe_{0.89}S_{0.11}$, $FeSe_{0.8}Te_{0.2}$ [4] and FeSe under gate voltage V_G = +5 V.

Fig. 2 Phase diagram of the electron-doped $FeSe_{1-x}S_x$ and $FeSe_{1-y}Te_y$ films.

[1] F. Nabeshima *et al.*, J. Phys. Soc. Jpn. **87**, 073704 (2018). [2] Y. Imai *et al.*, Sci. Rep. **7**, 46653 (2017).
[3] J. Shiogai *et al.*, Nat. Phys. **12**, 42(2016). [4] S. Kouno *et al.*, Sci. Rep. **8**, 14731 (2018).

Keywords: iron chalcogenide, thin films, electric double layer transistor

PCP4-4

Effect of in-plane strain on transport properties of FeSe single crystals

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The band structure of iron-based superconductors is sensitive to the local crystal structure. A good example is a thin film of FeSe with epitaxial strain. From angle-resolved photoemission spectroscopy measurements, a systematic change of the band structure was observed according to the degree of in-plane strain [1]. Reflecting the band structure, superconducting transition temperature T_c also shows a systematic change with in-plane strain [2]. Although a study using thin films turned out to be effective, the quality of the film varies depending on substrate materials, and compounds to which such an approach is applicable would be limited. Here we report the electronic transport properties for FeSe single crystals with applying biaxial strain. FeSe single crystals were attached on two kinds of substrates (soda-lime glass and polycarbonate sheets) using cyanoacrylate adhesives. Since each substrate material has a different thermal-expansion coefficient, different compressive strain is imposed on FeSe at low temperatures, the magnitude of which is 0.38% for glass and 0.85% for polycarbonate. The compressive strain enhances T_c from 8.5 K for the strain-free sample to 13.1 K for the sample on polycarbonate, consistent with the study of the thin films [2]. We analyzed the magneto-resistance and the Hall effect at 30 K using a three-carrier model, in which one hole and two electron carriers are considered. The result for the strain-free sample is in agreement with the previous study [3]. For the samples on glass and polycarbonate, hole and electron carrier densities systematically increase with compressive strain, which means that we definitely succeeded in controlling the band structure of single-crystalline FeSe.

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[3] M. D. Watson *et al.*, Phys. Rev. Lett. **115**, 027006 (2015).

Keywords: iron-based superconductor, FeSe, in-plane strain, transport property

PCP4-5

Low-oxygen Annealing Process of FeSe Superconducting Materials

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Among various Fe-based superconducting materials, FeSe-based superconducting materials are considered to be ideal candidates for the exploring of superconducting mechanism due to their simplest crystal structure and tunable superconducting critical temperature. Besides, FeSe-based superconductors also can be adopted for practical applications based on their advantages, such as high upper critical field, high current capacity under high field, and low anisotropy. Therefore, it is necessary to optimize the fabrication process and superconducting performance of FeSe superconducting materials. Based on our previous study, with the introduction of high energy ball milling process and the change of initial Fe:Se ratio in the FeSe based superconductor, the content of tetragonal phase can be effectively improved. However, the existence of interstitial irons in the superconducting tetragonal phase β-FeSe can not be eliminated, which have obvious negative influence on the performance of the FeSe-based superconducting material. In this experiment, FeSe bulks with different Fe:Se ratios of 1.00, 1.05, 1.10, 1.15 and 1.20 were prepared with solid state sintering process. By comparing the superconducting properties of these sample both before and after annealing, the best Fe:Se ratio was determined to be 1.15. On this basis, many important parameters, including the annealing temperature, annealing time and oxygen partial pressure of the annealing atmosphere were systematically optimized. The phase composition and microstructure of the system were characterized after annealing, combined with the analysis of superconducting properties measurements. The results showed that during the low-oxygen annealing process, the interstitial irons inside the system was induced and diffused to the surface, which finally reduced the interstitial iron content of the tetragonal phase β-FeSe, thus increased the superconducting phase content and the critical transition temperature of the system. The optimum annealing process of 400 ^{o}C-5 %O_2-10 h for $Fe_{1.15}Se$ samples was obtained.

Keywords: Fe-based superconducting materials, FeSe, interstitial irons, annealing

PCP4-6

Critical current densities and superconducting properties for Fe $(Te_{1-x}Se_x)_{1-y}S_y$

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We have fabricated $Fe(Te_{1-x}Se_x)_{1-y}S_y$ high-quality bulk single crystals by the melting method with low heat treatment. First, three single crystals of x = 0.4, 0.45, and 0.46 were fabricated with the composition ratio of Fe $(Te_{1-x}Se_x)_{1-y}S_y$ as y = 0, and their superconducting properties were evaluated. Temperature dependence of magnetization showed that low-T_c region exists inside the crystals for x=0.4 and 0.45. The highest T_c of 14.4 K was obtained for x=0.45 crystal, and it decreased for x= 0.4 and 0.46. The highest J_c under the magnetic field parallel to the c-axis at 4.2 K was obtained for x=0.4 crystal, and achieved 0.15 and 0.05 MA / cm^2 at 0 T and 7 T respectively. At high temperature of 9 K, x=0.4 crystal had the highest J_c up to 3 T. To further improvement of superconducting properties we studied to fabricate single crystals in which the composition ratio of Fe $(Te_{0.6}Se_{0.4})_{1-y}S_y$ changes to y = 0.05, 0.1, 0.15 and 0.2.

Keywords: Single crystal, Fe (Te1-xSex) 1-ySy

PCP4-7

Effects of Point Defects Introduced by Co-doping and Proton Irradiation in $CaKFe_4As_4$

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Introduction of defects to superconductors enhances their critical current density (J_c). Recently, a new iron-based superconductor, $CaKFe_4As_4$, with a new type of structure is found [1], and its J_c is evaluated to be ~2 MA/cm^2 at 2 K and self-field [2].

To enhance J_c in $CaKFe_4As_4$, we introduced point defects by chemical and physical methods. In the chemical method, we have grown high-quality single crystals in which a part of Fe is replaced by Co up to 9 %. Co-doping is believed to make the inherently overdoped $CaKFe_4As_4$ closer to optimally doped one. Figure 1 shows J_c -H properties of $CaK(Fe_{1-x}Co_x)_4As_4$ up to $x = 0.09$ at $T = 5$ K. A relatively strong magnetic field dependence of J_c in the pristine $CaKFe_4As_4$ is weakened by modest Co-doping ($0.03 < x < 0.07$), leading to large J_c at high fields. It clearly demonstrates that the introduced Co work as point defects.

In the physical method, 3 MeV protons are irradiated into $CaKFe_4As_4$, which are known to produce point defects. In order to compare effects of two different kinds of point defects on J_c and get some insight into the effect of coexisting point defects, the pristine, 3% Co-doped, and 7% Co-doped crystals are irradiated. Figure 2 shows the irradiation dose dependence of J_c of these three crystals at $T = 5$ K and $H = 4$ T. J_c of all these three crystals is enhanced by the introduction of point defects by protons up to 0.1×10^{16} ions/cm^2. It means that proton-induced point defects cooperatively pin vortices with chemically induced point defects. Quantitative comparison shows that 7 % Co-doping has nearly the same effect as that induced by 0.1×10^{16} ions/cm^2 proton irradiation.

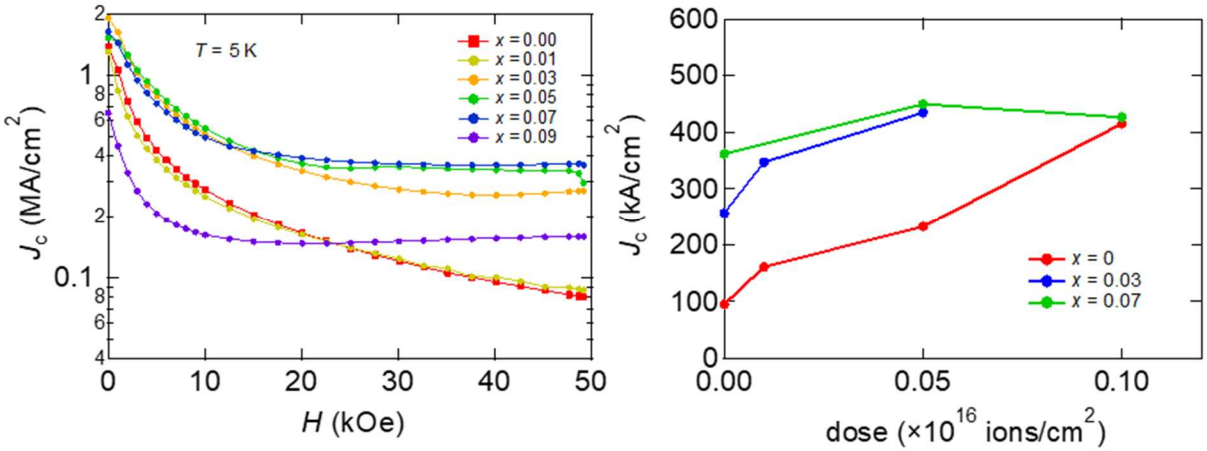

Figure 1: Magnetic field dependence of J_c in $CaK(Fe_{1-x}Co_x)_4As_4$ at $T = 5$ K.
Figure 2: Proton irradiation dose dependence of J_c in $CaK(Fe_{1-x}Co_x)_4As_4$ at $T = 5$ K and $H = 4$ T.

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Keywords: Iron-based superconductor, critical current density, particle irradiation, point defects

PCP4-8

Effects of Splayed Columnar Defects on Critical Current Density in $CaKFe_4As_4$

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Introduction of columnar defects to superconductors through particle irradiation enhances their critical current density (J_c) [1,2]. Further enhancement of J_c by dispersing the direction of columnar defects has been confirmed in cuprates $YBa_2Cu_3O_{7-\delta}$ [3] and iron-based superconductors (IBSs) $Ba_{1-x}K_xFe_2As_2$ [4] single crystals. Moreover, in such systems with splayed columnar defects, an anomalous peak effect in J_c at a certain magnetic field determined by the irradiation dose as well as an in-plane anisotropy of J_c between those parallel and perpendicular to the splay direction were observed [4, 5].

Here, we introduce splayed columnar defects to $CaKFe_4As_4$ single crystals, which was recently found as a new type of IBSs (1144-type IBS) [6], by irradiating 2.6 GeV U and 320 MeV Au ions and measure their J_c properties. J_c in $CaKFe_4As_4$ is also enhanced by splayed columnar defects at 5 K under zero field from 1.5 MA/cm^2 in the pristine crystal to 17 MA/cm^2 as shown in Fig. 1(a) for the case of $\theta_{CD} = \pm 20°$ and B_Φ = 4 T + 4 T. It should be noted that the anomalous peak effect at ~1/3B_Φ as observed in $Ba_{0.6}K_{0.4}Fe_2As_2$ (Fig. 1(b)) in the same irradiation condition disappears in $CaKFe_4As_4$. We interpret that the suppression of the anomalous peak effect in $CaKFe_4As_4$ is due to the presence of planar defects parallel to the *ab*-plane, which is unique to this material. We also compare the in-plane anisotropy of J_c in $Ba_{0.6}K_{0.4}Fe_2As_2$ and $CaKFe_4As_4$ with splayed columnar defects.

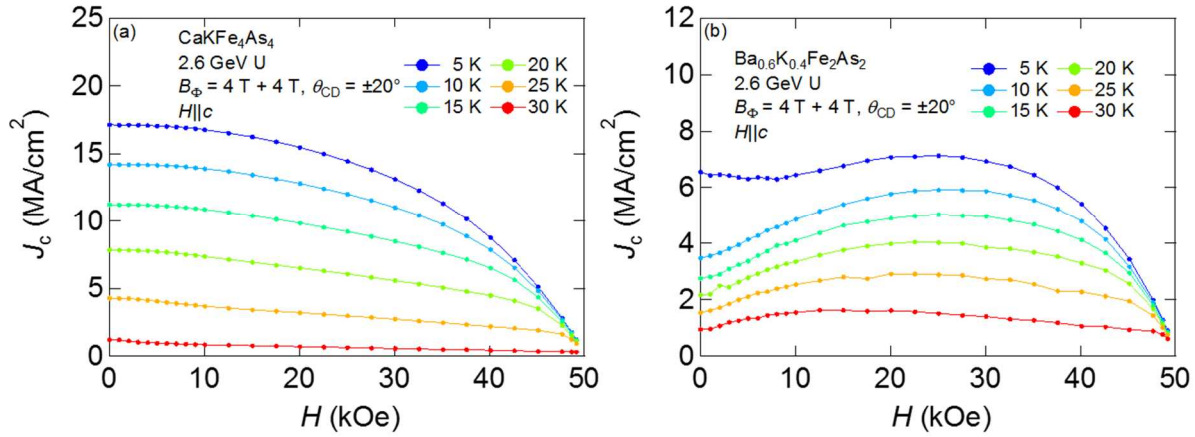

Fig. 1: Magnetic field dependences of J_c at various temperatures in (a) $CaKFe_4As_4$ and (b) $Ba_{0.6}K_{0.4}Fe_2As_2$ that are irradiated by 2.6 GeV U ions with B_Φ = 4 T + 4 T and $\theta_{CD} = \pm 20°$.

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Keywords: Iron-based superconductors, Particle irradiation, Critical current density, Columnar defect