PCP3-1

Giant phonon softening and strong-coupling superconductivity induced by copper/phosphorus doping of $BaNi_2As_2$

*Minoru Nohara[1], Masaya Takasuga[1], Kazutaka Kudo[1]

Okayama University, Japan[1]

The effects of chemical doping on the structural and superconducting phase transitions of $BaNi_2As_2$ were studied. We found an abrupt increase in the superconducting transition temperature T_c from 0.6 K in the triclinic phase with less doping to 2.5–3.3 K in the tetragonal phase with more doping at $x = 0.067$ for $BaNi_2(As_{1-x}P_x)_2$ [1] and at $x = 0.16$ for $Ba(Ni_{1-x}Cu_x)_2As_2$ [2]. Specific-heat data suggested that doping-induced phonon softening was responsible for the enhanced superconductivity in the tetragonal phase [1, 2].

[1] K. Kudo, M. Takasuga, Y. Okamoto, Z. Hiroi and M. Nohara, Phys. Rev. Lett. **109**, 097002 (2012).
[2] K. Kudo, M. Takasuga and M. Nohara, arXiv:1704.04854.

Keywords: BaNi2As2, chemical substitution, electron-phonon coupling, specific heat

PCP3-3

Substitution effect of $EuAFe_4As_4$ (A = Rb, Cs) superconductor with 1144-type structure

*Kenji Kawashima[1,2], Shigeyuki Ishida[2], Kunihiko Oka[2], Hijiri Kito[2], Nao Takeshita[2], Hiroshi Fujihisa[2], Yoshito Gotoh[2], Hiroshi Eisaki[2], Yoshiyuki Yoshida[2], Akira Iyo[2]

IMRA Material R&D Co., Ltd.[1]
National Institute of Advanced Industrial Science and technology (AIST)[2]

Fe-based compound $EuAFe_4As_4$ (A = Rb, Cs) with 1144-type structure exhibits the superconductivity with superconducting transition temperature: T_c = ~35 K and magnetic transition at 15 K, indicating the coexistence of the superconductivity and the magnetic ordered state[1-3] (Fig. 1). We investigate the physical property of Ca-substituted samples of $(Eu_{1-x}Ca_x)RbFe_4As_4$ to clarify the competition between the superconductivity and the magnetic order in the 1144 system.
We succeeded in synthesizing the polycrystalline sample $Eu_{1-x}Ca_xRbFe_4As_4$ (x = 0, 0.25, 0.5, 0.75, 1.0). $Eu_{1-x}Ca_xRbFe_4As_4$ shows superconductivity at around 36 K. The magnetic ordered state appears below 15 K and exhibits monotonous suppression by substituting non-magnetic Ca^{2+} for Eu^{2+} (Fig. 2). On the other hands, T_c value is always around 36K, does not exhibit appreciable change by the substitution. In this presentation, we will report the detail of these results.

[1] K. Kawashima *et al.*, J. Phys. Soc. Jpn. **85** 064710 (2016).
[2] Y. Liu *et al.*, Phys. Rev. B **93** 214503 (2016).
[3] Y. Liu et al., Sci. Bull. **61**(15) 1213 (2016).

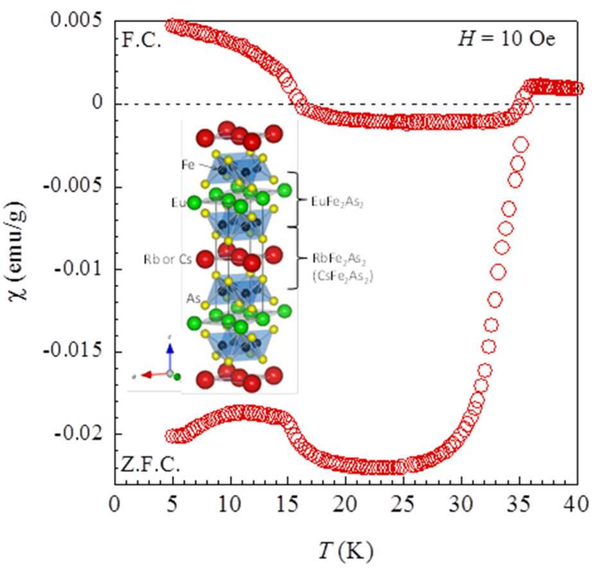

Fig. 1

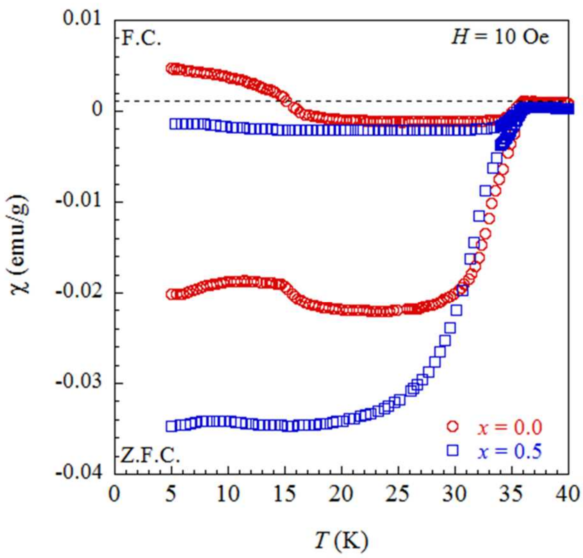

Fig. 2

Fig. 1 Temperature dependence of magnetic susceptibility of $EuRbFe_4As_4$. Inset shows the crystal structure of $EuRbFe_4As_4$.
Fig. 2 Temperature dependence of magnetic susceptibility of $Eu_{1-x}Ca_xRbFe_4As_4$ (x = 0.0, 0.5).

Keywords: Superconductivity, Fe-based superconductor, 1144-type structure, EuRbFe4As4

PCP3-4

P and Sb doping effects in $LaFeAsO_{1-y}(F,H)_y$ (y=0~0.3) system

*Hirokazu Tsuji[1], Masahiro Uekubo[1], Shigeki Miyasaka[1], Setsuko Tajima[1], Hajime Sagayama[2], Hironori Nakao[2], Reiji Kumai[2], Youichi Murakami[2]

Department of Physics, Osaka University, Osaka 560-0043, Japan[1]
Condensed Matter Research Center and Photon Factory, IMSS, KEK, Tsukuba 305-0801, Japan[2]

In LaFeAsO, electron doping level and local crystal structure can be controlled by substituting F or H for O, and P for As. Resultantly, Fermi surface topology is changed by these substitution effects, and three different superconducting states appears in $LaFeAs_{1-x}P_xO_{1-y}(F/H)_y$ system. [1,2] In these superconducting states, the nesting in LaFeAsO and LaFePO type Fermi surfaces and the next nearest neighbor interaction play an important role for stabilizing superconductivity. In the present work, we have investigated the transport properties and the crystal structure of $LaFeAs_{1-x}Sb_xO_{1-y}(F/H)_y$ (y=0~0.3) to clarify the correlation between the stability of superconductivity and the change of the Fermi surface accompanied by the Sb and F/H substitutions. In the system with Sb substitution, the result of structural analysis revealed that the lattice constants and the pnictogen height from the Fe plane (h_{Pn}) increase. These structural change with Sb substitution induces the expansion of the d_{xy} hole Fermi surface. In the low F/H doping region (y<0.14) of $LaFeAs_{1-x}Sb_xO_{1-y}(F/H)_y$, the nesting was improved by enlarging the d_{xy} Fermi surface with Sb doping, stabilizing the superconducting state. In the heavy H doping region (y>0.14), T_c is almost unchanged by Sb substitution due to the improvement of the next nearest neighbor interaction in the *xy* direction in real space, which is in sharp contrast to the P-substitution effect.

[1] S. Miyasaka *et al.*, Phys. Rev. B 95, 214515 (2017).
[2] H. Usui, K. Suzuki, and K. Kuroki, Sci. Rep. **5**, 11399 (2015).

Keywords: iron based superconductor, 1111 system, P and Sb doping, H doping

PCP3-5

Effect of Post-annealing on Physical Properties of $BaFe_2As_2$-based Superconductors

*Shigeyuki Ishida[1], Daniel Kagerbauer[2], Dongjoon Song[1], Hiraku Ogino[1], Masamichi Nakajima[3], Michael Eisterer[2], Hiroshi Eisaki[1]

AIST (Japan)[1]
TU Wien (Austria)[2]
Osaka University (Japan)[3]

In this study, we investigated the post-annealing effect on the superconducting properties, in particular, critical temperature (T_c) and critical current density (J_c) of the $BaFe_2As_2$-based superconductors. Iron-based superconductors have attracted much attention both from basic and application aspects. From the basic point of view, the relationship between high-T_c superconductivity and neighboring antiferromagnetic/orthorhombic (AFO) phase has been widely discussed. As for the application, improvement of J_c has been the main target, which is required for practical use of superconductors. It has been shown that T_c and the magneto-structural transition temperature ($T_{N/s}$) of $BaFe_2As_2$-based superconductors are significantly enhanced by the post-annealing process[1-3]. Recently, it was reported that J_c of $Ba(Fe_{1-x}Co_x)_2As_2$ is also largely enhanced by the post annealing[4]. This is interesting because the post-annealing process is considered to remove disorder, defects, strain, inhomogeneities, *etc.* which possibly act as pinning centers in the as-grown crystals. To understand the role of post annealing, we investigated the physical properties of $BaFe_2As_2$-based superconductors using as-grown and post-annealed single crystals. In the case of $Ba(Fe_{1-x}Co_x)_2As_2$, T_c was increased by 2-3 K after annealing in the entire doping range (x = 0.05 (underdoped) to 0.10 (overdoped)). Also, $T_{N/s}$ was increased by 5-10 K, hence the AFO phase persists to higher x after annealing. J_c was increased for the underdoped and optimally-doped samples, whereas it was decreased for the overdoped ones. These results indicate that the AFO phase is relevant to the enhancement of J_c. Similar changes on T_c, $T_{N/s}$, and J_c were observed after annealing $BaFe_2(As_{1-x}P_x)_2$ single crystals, suggestive of a common effect of post annealing on $BaFe_2As_2$-based superconductors.

1) K. Gofryk, *et al. Phys. Rev. B* **83**, 064513 (2011). 2) D.L. Sun, J.Z. Xiao, and C.T. Lin, *Journal of Crystal Growth* **321**, 55 (2011). 3) S. Ishida, *et al. J. Am. Chem. Soc.* **135**, 3158 (2013).
4) L. Li, *et al. Sci. Rep.* **7**, 949 (2017).

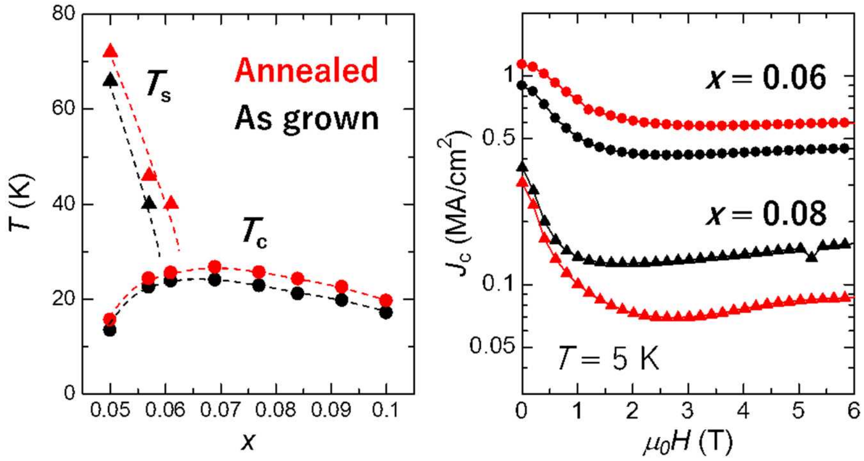

Fig. 1 (left) Doping dependence of T_c and $T_{N/s}$ for as-grown and annealed $Ba(Fe_{1-x}Co_x)_2As_2$. (right) Magnetic field dependence of J_c for as-grown and annealed $Ba(Fe_{1-x}Co_x)_2As_2$ (x = 0.06 and 0.08).

Keywords: iron-based superconductors, post annealing, superconducting transition temperature, critical current density

PCP3-6

Anisotropy of Critical Current Densities in $Ba_{1-x}K_xFe_2As_2$ and $Ba(Fe_{1-x}Co_x)_2As_2$ with Splayed Columnar Defects

*Nozomu Ito[1], Sunseng Pyon[1], Tadashi Kambara[2], Atsushi Yoshida[2], Satoru Okayasu[3], Ataru Ichonose[4], Tsuyoshi Tamegai[1]

Department of Applied Physics, The University of Tokyo, Hongo, Bunkyo-ku, Tokyo, Japan[1]
Nishina Center, RIKEN, Wako, Saitama, Japan[2]
Japan Atomic Energy Agency, Advanced Science Research Center, Tokai, Ibaraki, Japan[3]
Central Research Institute of Electric Power Industry, Electric Power Engineering Research Laboratory, Kanagawa, Japan[4]

Columnar defects in type-II superconductors serve as artificial pinning centers, which lead to enhancement of critical current density J_c [1, 2, 3]. It has been proposed that a further enhancement of J_c is possible by dispersing the direction of the columnar defects [4]. In such a system with splayed columnar defects, enhancement of J_c has been confirmed in $YBa_2Cu_3O_{7-\delta}$ [5] and $Ba_{1-x}K_xFe_2As_2$ [6] single crystals. Due to the competing effects of suppression of vortex motion by unequal lengths of vortex segments between splayed columnar defects and detrimental effect of misalignment of vortices, the optimal splay angles were found to be 5° in both of the above systems. However, since these results were obtained through magnetization measurement, the estimated J_c is a weighted average of J_c's along two directions in the *ab* plane. Since the splay direction and the direction perpendicular to the splay direction are distinguished in a system with bimodal splayed columnar defects, J_c's along these two directions can be different.
$Ba_{0.6}K_{0.4}Fe_2As_2$ and $Ba(Fe_{0.93}Co_{0.07})_2As_2$ single crystals used in this study were synthesized by FeAs flux method, and splayed columnar defects were installed into these crystals by irradiating them with 2.6 GeV U or 220-320 MeV Au ions. The distribution of magnetic field on the surface of the samples in the critical state was observed using magneto-optical imaging, and in-plane anisotropy of J_c was estimated. We investigate the dependence of in-plane anisotropy on the splay angle, the ion used for irradiation, and the material of the single crystals, and discuss the details of vortex pinning in systems with splayed columnar defects.

[1] L. Civale *et al.*, Phys. Rev. Lett. **67**, 648 (1991).
[2] Y. Nakajima *et al.*, Phys. Rev. B **80**, 012510 (2009).
[3] T. Tamegai *et al.*, Supercond. Sci. Technol. **25**, 084008 (2012).
[4] T. Hwa *et al.*, Phys. Rev. Lett. **71**, 3545 (1993).
[5] L. Krusin-Elbaum *et al.*, Phys. Rev. Lett. **76**, 2563 (1996).
[6] A. Park *et al.*, Physica C **530**, 58 (2016).

Keywords: Iron-based superconductors, Critical current density, Columnar defects, Magneto-optical imaging

PCP3-7

Direct Current Measurement of Hall Effect in the Mixed State for the Iron-Chalcogenide Superconductors

*Ryo Ogawa[1], Tomoya Ishikawa[1], Masataka Kawai[1], Fuyuki Nabeshima[1], Atsutaka Maeda[1]

Dept. of Basic Science, the Univ. of Tokyo[1]

The sign of the Hall resistivity in the mixed state are different from that in the normal state, for some high Tc superconductors and conventional superconductors, e.g. V and Nb [1]. Recently, it was reported that the Hall resistivity of the iron-based superconductor, $Ba(Fe_{1-x}Co_x)_2As_2$, shows the sign reversal below the transition temperature [2]. Moreover, a double sign reversal has been observed in some cuprates, such as $Tl_2Ba_2CaCu_2O_8$ [3]. Such anomalous behaviors of the Hall resistivity cannot be explained by basic vortex motion models, such as the Bardeen-Stephen model [4], in which the superconducting state and the normal state have the same Hall sign. So far, several theoretical approaches have attempted to explain the Hall sign change, and as the origin of sign reversal, the intensity of the vortex pinning in superconducting samples [5], the influence of the superconducting fluctuations [6], the vortex core charge [7], and other causes were pointed out. However, the origin of the Hall anomaly is still controversial, and consensus regarding this matter is not reached yet.

In order to clarify this problem, we measure the Hall resistivity for the iron-chalcogenide superconductor $FeSe_{1-x}Te_x$ films near the transition temperature, and investigate how the composition and the pinning strength affect the Hall effect in the mixed state. As a result of experiments, we observe the sign anomaly for $FeSe_{0.5}Te_{0.5}$ films, but $FeSe_{0.8}Te_{0.2}$ films do not show the sign reversal, as shown in figure. Those measurements suggest the pinning influence on the Hall resistivity behavior. In the symposium, we will report the details of those measurements and analyses.

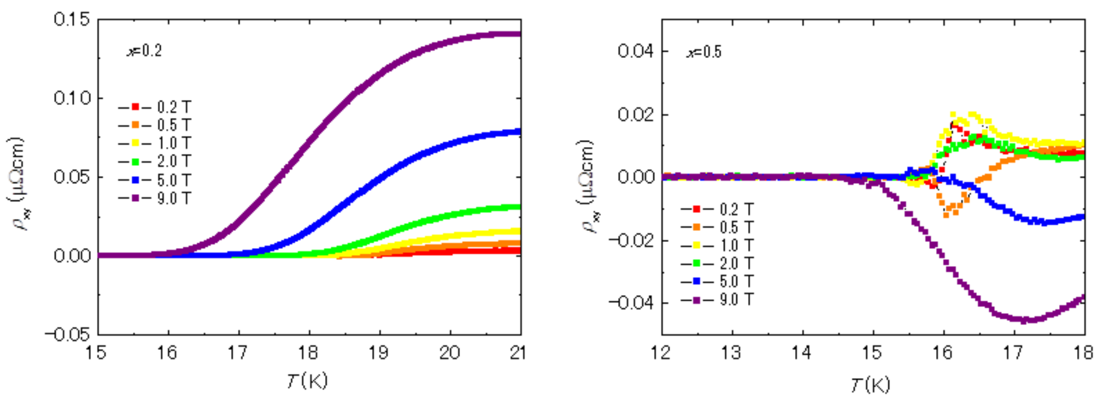

Fig. The Hall resistivity for *x*=0.2 (left) and *x*=0.5 (right).

[1] M. Galffy and E. Zirngiebl, Solid State Commun. **68**, 929 (1988).
[2] L. M. Wang, *et al.*, Phys. Rev. B **83**, 134506 (2011).
[3] S.J. Hagen, C.J. Lobb, and R.L. Greene, Phys. Rev. B **43**, 6246 (1991).
[4] J. Bardeen and M. J. Stephen, Phys. Rev. **140**, A1197 (1965).
[5] N. B. Kopnin and V. M. Vinokur, Phys. Rev. Lett. **83**, 4864 (1999).
[6] H. Fukuyama, H. Ebisawa, and T. Tsuzuki, Prog. Theor. Phys. **46**, 1028 (1971).
[7] D. I. Khomskii and A. Freimuth, Phys. Rev. Lett. **75**, 1384 (1995).

PCP3-8

Effect of excess Fe in $FeTe_{0.6}Se_{0.4}$ on the flux pinning

*Yuji Tanaka[1], Ibuki Wada[1], Osuke Miura[1]

Dept. of Electrical and Electronic Engineering, Tokyo Metropolitan University[1]

We have fabricated $FeTe_{0.6}Se_{0.4}$ large-size bulk single crystals with high critical current densities (J_c) under magnetic fields. $FeTe_{0.6}Se_{0.4}$ single crystals were prepared by the melting method with two stage heat treatments. Temperature dependence of magnetization showed that low-T_c region exists inside the crystals. The magnetization curves indicated the typical fishtail type, and the magnetic J_c under the magnetic field parallel to the c-axis at 4.2 K achieved 0.36 and 0.2 MA / cm^2 at 0 T and 5 T respectively. From the temperature scaling behavior of flux pinning properties we speculated that low-T_c regions near excess Fe moderately distributed inside the crystals are dominant pinning centers in high fields at low temperatures. We have studied effect of excess Fe in $FeTe_{0.6}Se_{0.4}$ on the flux pinning for crystals in which the amount of Fe is changed, and verified how excess Fe namely low-T_c region works for flux pinning. Increasing or decreasing the amount of Fe by only 1 %, the crystals become filamentary superconductors. Therefore, we carefully studied the superconducting properties when changing the amount of Fe by 0.1 - 0.5 %.

Keywords: Fe1+yTe0.6Se0.4, Single crystal, Excess Fe, Flux pinning

PCP3-9

Gap Structure of FeSe Determined by Field-Angle-Resolved Specific Heat Measurements

*Yue Sun[1], Shunichiro Kittaka[1], Toshiro Sakakibara[1], Koki Irie[2], Takuya Nomoto[3], Kazushige Machida[2], Jingting Chen[4], Tsuyoshi Tamegai[4]

Institute for Solid State Physics (ISSP), The University of Tokyo[1]
Department of Physics, Ritsumeikan University[2]
RIKEN Center for Emergent Matter Science (CEMS)[3]
Department of Applied Physics, The University of Tokyo[4]

Quasiparticle excitations in FeSe were studied by means of specific heat (C) measurements on a high-quality single crystal under rotating magnetic fields. The field dependence of C shows three-stage behavior with different slopes, indicating the existence of three gaps (Δ_1, Δ_2, and Δ_3). In the low-temperature and low-field region, the azimuthal-angle (ϕ) dependence of C shows a fourfold symmetric oscillation with sign change. On the other hand, the polar-angle (θ) dependence manifests as an anisotropy-inverted two-fold symmetry with unusual shoulder behavior. Combining the angle-resolved results and the theoretical calculation, the smaller gap Δ_1 is proved to have two vertical-line nodes or gap minima along the k_z direction, and is determined to reside on the electron-type ε band. Δ_2 is found to be related to the electron-type δ band, and is isotropic in the ab-plane but largely anisotropic out of the plane. Δ_3 residing on the hole-type α band shows a small out-of-plane anisotropy with a strong Pauli-paramagnetic effect.

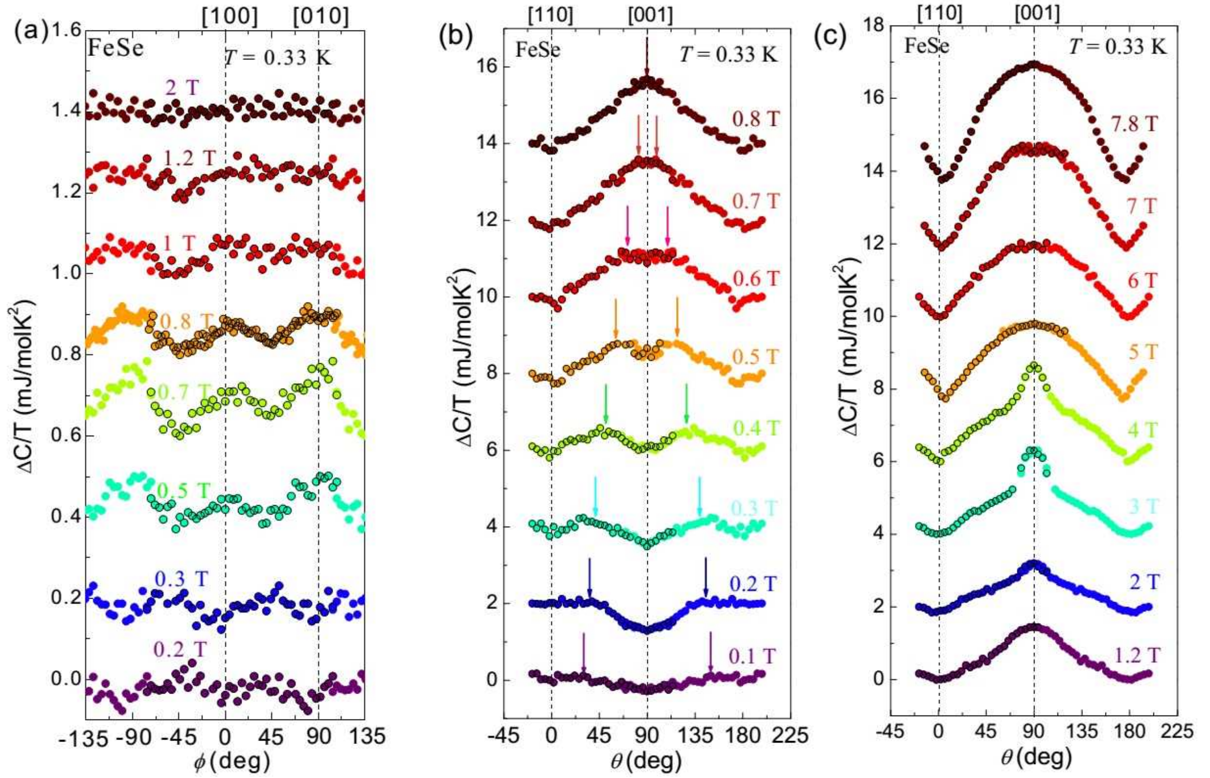

Fig. (a) Azimuthal angle dependence of the specific heat $\Delta C(\phi)/T$ measured under various fields at 0.33 K. $\Delta C(\phi)=T$ is defined as $C(\phi)/T - C(-45^{\circ})/T$, and each subsequent curve is shifted vertically by 0.2 mJ/molK^2. Polar angle dependence of the specific heat $\Delta C(\theta)/T$ measured under fields (b) below and (c) above 1 T at 0.33 K. $\Delta C(\theta)/T$ is defined as $C(\theta)/T - C(0^{\circ})/T$, and each subsequent curve is shifted vertically by 2 mJ/molK^2.

Keywords: FeSe, Field-Angle-Resolved Specific Heat, gap structure