Giant phonon softening and strong-coupling superconductivity induced by copper/phosphorus doping of BaNi$_2$As$_2$

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The effects of chemical doping on the structural and superconducting phase transitions of BaNi$_2$As$_2$ 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$_x$)$_2$As$_2$ [2]. Specific-heat data suggested that doping-induced phonon softening was responsible for the enhanced superconductivity in the tetragonal phase [1, 2].


Keywords: BaNi2As2, chemical substitution, electron-phonon coupling, specific heat
Substitution effect of EuAF₄As₄ (A = Rb, Cs) superconductor with 1144-type structure

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Fe-based compound EuAF₄As₄ (A = Rb, Cs) with 1144-type structure exhibits the superconductivity with superconducting transition temperature: \( T_c \approx 35 \text{ K} \) and magnetic transition at 15 K, indicating the coexistence of the superconductivity and the magnetic ordered state.¹⁻³ We investigate the physical property of Ca-substituted samples of \((\text{Eu}_{1-x}\text{Ca}_x)\text{RbFe}_4\text{As}_4\) to clarify the competition between the superconductivity and the magnetic order in the 1144 system.

We succeeded in synthesizing the polycrystalline sample \((\text{Eu}_{1-x}\text{Ca}_x)\text{RbFe}_4\text{As}_4\) (\( x = 0, 0.25, 0.5, 0.75, 1.0 \)). \((\text{Eu}_{1-x}\text{Ca}_x)\text{RbFe}_4\text{As}_4\) 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.


Fig. 1 Temperature dependence of magnetic susceptibility of EuRbFe₄As₄. Inset shows the crystal structure of EuRbFe₄As₄.

Fig. 2 Temperature dependence of magnetic susceptibility of \((\text{Eu}_{1-x}\text{Ca}_x)\text{RbFe}_4\text{As}_4\) (\( x = 0.0, 0.5 \)).

Keywords: Superconductivity, Fe-based superconductor, 1144-type structure, EuRbFe₄As₄
P and Sb doping effects in LaFeAsO$_{1-y}$(F,H)$_y$ ($y$=0~0.3) system

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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$_x$O$_{1-y}$(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$_x$O$_{1-y}$(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$$<$0.14) of LaFeAs$_{1-x}$Sb$_x$O$_{1-y}$(F/H)$_y$, the nesting was improved by enlarging the $d_{xy}$ Fermi surface with Sb doping, stabilizing the superconducting state. In the heavy H doping region ($y$$>$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.


Keywords: iron based superconductor, 1111 system, P and Sb doping, H doping
Effect of Post-annealing on Physical Properties of BaFe$_2$As$_2$-based Superconductors

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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$_2$As$_2$-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$_2$As$_2$-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$_x$)$_2$As$_2$ 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$_2$As$_2$-based superconductors using as-grown and post-annealed single crystals. In the case of Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$, $T_c$ 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$_2$As$_2$-based superconductors.


Fig. 1 (left) Doping dependence of $T_c$ and $T_{N/s}$ for as-grown and annealed Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$. (right) Magnetic field dependence of $J_c$ for as-grown and annealed Ba(Fe$_{1-x}$Co$_x$)$_2$As$_2$ ($x$ = 0.06 and 0.08).

Keywords: iron-based superconductors, post annealing, superconducting transition temperature, critical current density
Anisotropy of Critical Current Densities in $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ and $\text{Ba(Fe}_{1-x}\text{Co}_x)_2\text{As}_2$ with Splayed Columnar Defects

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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 $\text{YBa}_2\text{Cu}_3\text{O}_7$ [5] and $\text{Ba}_{1-x}\text{K}_x\text{Fe}_2\text{As}_2$ [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. $\text{Ba}_{0.6}\text{K}_{0.4}\text{Fe}_2\text{As}_2$ and $\text{Ba(Fe}_{0.93}\text{Co}_{0.07})_2\text{As}_2$ 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.


Keywords: Iron-based superconductors, Critical current density, Columnar defects, Magneto-optical imaging
Direct Current Measurement of Hall Effect in the Mixed State for the Iron-Chalcogenide Superconductors

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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(Fe₁₋ₓCoₓ)₂As₂, shows the sign reversal below the transition temperature [2]. Moreover, a double sign reversal has been observed in some cuprates, such as Tl₂Ba₂CaCu₂O₈ [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 FeSe₁₋ₓTeₓ 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 FeSe₀.₅Te₀.₅ films, but FeSe₀.₈Te₀.₂ 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).

Effect of excess Fe in FeTe$_{0.6}$Se$_{0.4}$ on the flux pinning

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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: Fe$_{1+y}$Te$_{0.6}$Se$_{0.4}$, Single crystal, Excess Fe, Flux pinning
Gap Structure of FeSe Determined by Field-Angle-Resolved Specific Heat Measurements

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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 (Δ₁, Δ₂, and Δ₃). In the low-temperature and low-field region, the azimuthal-angle (ϕ) dependence of C shows a fourfold symmetric oscillation with sign change. In 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 Δ₁ is proved to have two vertical-line nodes or gap minima along the kₓ direction, and is determined to reside on the electron-type ε band. Δ₂ 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. Δ₃ 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 ΔC(φ)/T measured under various fields at 0.33 K. ΔC(φ)/T is defined as C(φ)/T - C(-45°)/T, and each subsequent curve is shifted vertically by 0.2 mJ/molK². Polar angle dependence of the specific heat ΔC(θ)/T measured under fields (b) below and (c) above 1 T at 0.33 K. ΔC(θ)/T is defined as C(θ)/T - C(0°)/T, and each subsequent curve is shifted vertically by 2 mJ/molK².

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