PC1-1-INV

High-Tc Research Over Thirty Years: Beyond The Common Knowledge of Superconductivity

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Thirty years have passed since the discovery of high Tc superconducting cuprates. So far a tremendous amount of efforts have been devoted to solve the mysteries of high Tc superconductivity. What we have learnt in these 30 years had been unexpected and beyond the common knowledge of superconductivity before the high Tc cuprates. In my talk, I will list up and revisit these issues that are different from the conventional superconductors. Some of them are important for practical application of this material. From the physical viewpoint, the strong electron correlation is a key issue causing various unusual properties such as the pseudogap and the precursor of superconductivity. It requires us a new picture beyond the BCS theory.

Keywords: unconventional superconductors, strong electron correlation, BCS-BEC crossover

PC1-2-INV

Scanning Tunneling Microscopy as a Tool for Superconductivity Research

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Scanning tunneling microscopy (STM) has been developed in the field of surface science as a tool to image atomic/molecular structures at the surfaces. Due to the capability to perform local tunneling spectroscopy with atomic spatial resolution and sub-meV energy resolution, STM can also be a powerful technique for analyzing the electronic states behind the novel functions of materials. Indeed, recent developments of STM technology are largely motivated by researches on unconventional superconductors. We will review electronic states of cuprate and iron-based superconductors revealed by modern STM techniques, especially spectroscopic-imaging STM combined with Fourier analyses. We will also discuss future directions of STM as a tool for superconductivity research.

Keywords: scanning tunneling microscopy, cuprate superconductor, iron-based superconductor

PC1-3-INV

Angle-Resolved Heat Capacity of Unconventional Superconductors

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Owing to a strong Coulomb repulsion, strongly correlated superconductors mostly have anisotropic gap functions which have nodes for certain direction in the momentum space. Since the nodal structure is closely related to the pairing mechanism, its experimental determination is of primary importance. Among various approaches, angle-resolved heat capacity measurements in a rotating magnetic field turns out to be quite useful in experimental determination of the gap structures. The basic idea is based on the fact that the field-induced density of states (DOS) of the vortex state in nodal superconductors exhibits characteristic field and orientation dependences. Zero-energy DOS (ZEDOS), in particular, rapidly increases roughly in proportional to $H^{1/2}$ at low fields. Importantly, this $H^{1/2}$ like increase of ZEDOS exhibits a weak anisotropy arising from the nodal structure, and in a low-field region $H<<H_{c2}$, minima occur when H is parallel to the nodal direction [1]. This field-angular dependence of ZEDOS can be detected by heat capacity measurements in a rotating magnetic field at low temperatures, and can be a powerful tool to probe the gap nodal structures [1,2]. An important point of this experiment is that the measurements need to be done at very low temperatures ($\leq 0.1T_c$) due to a sign-change issue [3]. In this presentation, recent advances in the angle-resolved heat capacity measurements on unconventional superconductors are discussed, including results on $CeCoIn_5$ [4], UPd_2Al_3 [5] and $CeCu_2Si_2$ [6].

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Keywords: Heat capacity, gap nodal structures, rotating magnetic field, angular oscillations

PC1-4-INV

What is the lowest possible vortex creep in superconductors, and how can we achieve it?

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Thermal and quantum fluctuations play only a minor role on the vortex properties of many low temperature superconductors (LTS). However, they dramatically influence vortex matter in high temperature superconductors (HTS) such as oxides and Fe-based, creating a proliferation of vortex liquid phases that occupy substantial portions of the phase diagram and fast dynamics of the metastable states (flux creep). This fascinating physics has been a topic of continuous interest for decades, but on the other hand is detrimental for applications. The strength of the thermal fluctuations is quantified by the Ginzburg number (Gi) that measures the ratio of the thermal energy to the condensation energy in an elemental superconducting volume. The combination of the small coherence length (x), large anisotropy (g) and high transition temperatures (T_c) in the HTS results in Gi values several orders of magnitude higher than in LTS. For instance, $Gi \sim 10^{-9}$ in Nb and $\sim 10^{-2}$ in $YBa_2Cu_3O_7$, naturally accounting for the much faster creep rate (S) in the latter. We have found that, for strong pinning superconductors in the Anderson-Kim (AK) creep regime, there is a universal minimum attainable $S \sim Gi^{1/2}(T/T_c)$. This lower limit has been achieved in a few materials including $YBa_2Cu_3O_7$, MgB_2 and our $BaFe_2(As_{0.67}P_{0.33})_2$ films and, to our knowledge, violated by none. This hard constraint has two important, broad implications: first, the creep problem in HTS cannot be fully eliminated and there is a limit to how much it can be ameliorated, and secondly, we can confidently predict that any yet-to-be-discovered HTS will have fast creep. On the other hand, many SC exhibit S values higher, sometimes orders of magnitude higher, than the lower limit. The reason is that Gi only sets the lowest limit for S, but in order to achieve it the pinning landscape must be optimized. I will show that S can be reduced by appropriate engineering of the pinning landscape, in some cases (such as in irradiated $Ba(Fe_{1-x}Co_x)_2A_2$ single crystals) dramatically so and all the way down to the lower limit imposed by Gi. Finally I will discuss some of our studies of creep outside the AK limit and in very clean (weak pinning) samples, where collective effects are relevant and different glassy and plastic dynamic regimes can be observed and tuned by methods such as irradiation and film thinning.

Keywords: vortex matter, vortex dynamics, flux creep

PC1-5

Detecting changes in the vortex configuration associated with dynamic ordering and disordering

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When many particle systems with a random initial distribution are periodically sheared and the number (n) of the shear cycle is increased, the particles gradually self-organize to avoid future collisions and transform into an ordered structure. This is called random organization or dynamic ordering [1]. We have shown that dynamic ordering reported in colloidal suspensions [1] also occurs in a periodically driven vortex system of amorphous Mo_xGe_{1-x} films with weak random pinning. This was detected from the time-evolution of voltage $V(t)$ that increases toward a steady-state value [2-4]. Quite recently, we have developed a new method to detect the vortex configuration using the similar $V(t)$ measurements, where after freezing the vortex configuration by switching off the ac driving current, we executed subsequent readout measurements of $V(t)$ in response to ac drive. Thus, we have made an unexpected, striking finding that the transient vortex configuration formed during the dynamic-ordering process is not microscopically homogeneous but consists of disordered and organized regions, and that the ration of the latter region increases with n [5].
We also know that, in the presence of random pinning, an initially organized vortex configuration becomes disordered when a small dc driving force is applied to the vortex system [2,3]. This process is called the dynamic disordering. Thus, an interesting question arises: how does the vortex configuration evolve associated with the dynamic disordering by the dc drive? In this work, we study this issue by using the same vortex system of amorphous Mo_xGe_{1-x} films driven by the dc current. The results show that the vortex configuration during the dynamic-disordering process is homogeneous, in contrast to the case of the dynamic ordering by ac drive [2-4]. Therefore, the origin of the coexistence regions found in [5] is attributed to the ac drive and/or dynamic ordering.

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Keywords: vortex dynamics, self-organized systems, nonequilibrium phase transition, pinning

PC1-6

Molecular Dynamics Simulations on Melting Transition of Vortex Matter in Nano-Sized Superconductors

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In the H-T phase diagram for bulk cuprate High-Tc superconductors, there is a melting line of vortex lattice. This melting behavior comes from weak pinning, large thermal and quantum fluctuations in the cuprate High-Tc superconductors.

Recently, Ooi et al. showed the melting temperature in a nano-sized superconducting cuprate square plate oscillates with increasing magnetic field. They explained this oscillation comes from the stability of configuration of n^2 vortices (n=1,2,3,4,…)[1].

Previously, in order to confirm this phenomenon, we studied the vortex lattice melting in nano-sized superconductors using the molecular dynamics method[2,3] for vortices. Temperature dependence of vortex dynamics comes from the fluctuation force and penetration dependence in the vortex-vortex interaction. Using the standard deviation of the positions of vortices, we determined the melting temperature. Changing the vortex numbers, we found the melting temperature oscillates with increasing the vortex number. But we used periodic boundary conditions [4].

In this presentation, we extend our method to fixed boundary condition case and show the size dependence and shape dependence of the vortex-melting curves.

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Keywords: Vortex matter, Melting Transition, Molecular Dynamics, High-Tc superconductor

PC2-1-INV

New iron-based superconductors with separate double FeAs Layers

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In the view of crystal structure, cuprate and iron-based superconductors contain quasi-two-dimensional CuO_2 planes and FeAs layers, respectively, which play the decisive role for high-temperature superconductivity. In iron-based superconductors, the FeAs/Se layers are either separated each other to form a single-layer compound (e.g., LaFeAsO), or connected by monatomic layer to form an "infinite-layer" material (e.g., $BaFe_2As_2$), or simply stacked together with van de Waals force (e.g., FeSe). Are there any analogs of double-CuO2-layer or multi-CuO_2-layer materials in iron-based systems?

In a paper published four years ago [1], we proposed an intergrowth structure which contains separate double-FeAs layers. Recently, motivated by the discovery of "1144-type" iorn-based superconductors [2], we succeeded in synthesizing the target compound ($KCa_2Fe_4As_4F_2$) for the first time [3]. The double FeAs layers are connected by K+, which are separated by the insulating Ca_2F_2 layers. The material itself is almost optimally hole doped, making it superconducting (at 33 K) without extrinsic chemical doping.

We also tried to expand this 12442-type family of iron-based superconductors. We find that the lattice match is crucial for the intergrowth structure. The tolerance of lattice mismatch is about 2% for the synthesis under ambient pressure. So far we have obtained 18 new superconductors in the 12442 family whose T_c values span from 28 to 37 K [4]. The possible structural correlations with T_c will be discussed in the talk.

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Keywords: Iron-based superconductors, Lattice match, Crystal structure

PC2-2-INV

X-ray fluorescence holography of $Ca_{1-x}Pr_xFe_2As_2$

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The state-of-the-art technique, x-ray fluorescence holography experiment [1], was performed in order to visualize the local 3D atomic configurations and positional fluctuations [2] of iron-based superconductor $Ca_{1-x}Pr_xFe_2As_2$. The compound has been reported to exhibit high superconducting transition temperature T_c = 49 K with a very small superconducting volume fraction of several percent [3,4]. STM/STS observed a large superconducting gap around the doped Pr atoms, but no superconducting gap was observed around Ca [5]. In order to investigate the reason why the high T_c superconductivity emerges around Pr, we performed x-ray fluorescence holography experiments using synchrotron radiation at BL13XU, SPring-8, Japan and reconstructed the atomic images around Ca and Pr atoms from the holograms.

The atomic images of As revealed that As positions fluctuated significantly even in the parent $CaFe_2As_2$ compound without Pr doping. For Pr-doped $Ca_{0.9}Pr_{0.1}Fe_2As_2$, we found that the positional fluctuations of As were almost unchanged around Pr atoms compared with $CaFe_2As_2$, but the positional fluctuations of As were significantly increased around Ca atoms, which were located far from doped Pr. These observations were consistent with the local superconductivity at T_c = 49 K around the doped Pr.

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Keywords: iron-based superconductors, chemical substitution, local structure, x-ray fluorescence holography

PC2-3

An X-ray Fluorescence Holographic Study on a Fe-based High-Temperature Superconductor $FeSe_{0.4}Te_{0.6}$

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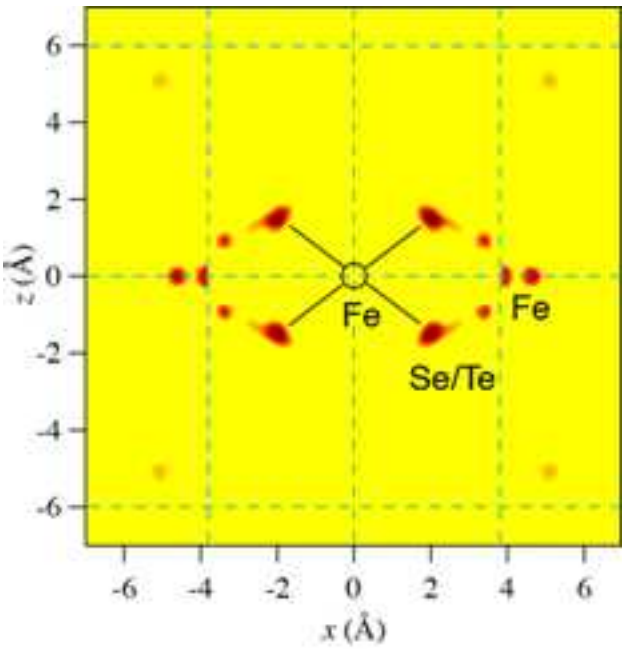
$FeSe_xTe_{1-x}$ is one of the simplest Fe-based superconductors, and has intensively been studied concerning the interplay between structural or magnetic degrees of freedom and superconductivity. $FeSe_{0.4}Te_{0.6}$ has a layered structure in which the layers of Fe atoms and Se/Te atoms overlap each other. To understand the superconductivity of $FeSe_{0.4}Te_{0.6}$, it is necessary to independently reveal the local structures around the Fe and chalcogen atoms.
The x-ray fluorescence holography (XFH) [1] is a newly developed technique that enables one to draw three-dimensional (3D) atomic images around a specific element emitting fluorescent x-rays. We have performed Fe and Se Kα XFH measurements on a $FeSe_{0.4}Te_{0.6}$ single crystal at 100K. Figure 1 shows the atomic image around the Fe central atom on the (010) plane. As seen in the figure, the images of the nearest-neighboring Se/Te atoms have an oval form with a tail towards the larger x direction. This observation is supported by x-ray absorption fine structure (XAFS) measurements, which have also been conducted at the same temperature. The XAFS results indicate that the Se/Te atoms are considerably displaced from their ideal position and exhibit large positional fluctuations. The x-ray [2] and neutron [3] diffraction results, on the other hand, indicate only slightly different z values for Se and Te, respectively. It should be also noted that the second neighboring Fe images are separated into four, suggesting a large lattice distortion in the crystal.



Keywords: High-temperature superconductor, Holography, Atomic image

PC2-4

Evolution of Physical Properties in FeSe Single Crystals with Different Qualities

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FeSe attracts a lot of attention because of its unique nature with nonmagnetic nematic state coexisting with superconductivity, close proximity to BCS-BEC crossover regime with its small Fermi energy, and possibility of extremely high superconducting transition temperature (T_c) [1]. This is backed up by recent developments of crystal-growth technique using KCl/$AlCl_3$ mixtures with a low melting temperature [2]. Using technique, we have successfully grown FeSe single crystals with a wide range of superconducting transition temperatures (T_c) between 9.1 K and 5.5 K. Systematic studies have been performed on their transport, magnetic, structural, and thermal properties. As the T_c is suppressed, residual resistivity increases and the magnitude of magnetoresistance decreases. On the other hand, crossover from low-field quadratic to high-field linear magnetic field dependence is observed in all FeSe crystals, indicating the presence of Dirac Fermions. In addition, specific heat measurements demonstrate the presence of multiple gaps in all FeSe crystals. The temperature dependence of specific heat can be well fitted by the combination of a large isotropic *s*-wave gap and a small anisotropic *s*-wave gap. In FeSe with the highest T_c, the anisotropy of the small gap becomes the largest. This is consistent with the recent angle-resolved specific heat measurements on the same piece of crystal showing a clear four-fold angular dependence [3].

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Keywords: FeSe, Specific Heat, Multi-gap Superconductivity, Dirac Fermion

PC2-5

Electrotransport and magnetic measurements on bulk FeSe superconductors

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The superconducting properties of bulk, polycrystalline FeSe samples were characterized through magnetic and electric transport measurements. In order to improve the superconducting properties, the sintering temperature was varied up to 900 °C and to improve the grain connectivity, silver was applied in low concentrations to the samples ranging from 0 to 7 wt.-%. The electric properties of the samples were investigated by the four point probe method (*R-T* measurements and *V-I* characteristics). Generally, the sample with 4 wt.-% Ag-addition showed showed the highest critical transition temperature among all the samples fabricated with the same preparation parameters. The critical currents were estimated from *V-I* measurements in various applied magnetic fields up to 6 T. Via Arrhenius plots, the pinning potential U_0 was determined for all samples studied. The magnetic properties (*M-T* and *M-H*) of the samples were measured using an extraction magnetometer in a Quantum Design PPMS with applied magnetic fields up to 7 T. The scaling of the normalized volume pinning force versus the reduced field indicated a peak position at 0.4 for the pure FeSe sample sintered at 900 °C, which points to a δT_c-pinning type. The improved flux pinning and the high critical current densities are attributed to the textured microstructure of the material.

Keywords: FeSe, I-V characteristics, pinning, critical current

PC2-6

Epitaxial NdFeAs(O,F) Films By Molecular Beam Epitaxy: Influence Of Film Thickness And Surface Morphology On Superconducting Properties

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The Fe-based superconductors, such as *Ln*FeAs(O,F) (*Ln*=lanthanide) and related compounds, represent a new class of superconductors exhibiting the highest critical temperature (T_c) apart from the cuprates. Due to relative high anisotropies of *Ln*FeAs(O,F) combined with the intrinsic pinning, the critical current density J_c in high magnetic fields exhibits a strong angular dependence with regard to the magnetic field orientation. These unconventional superconductors are interesting not only from a fundamental research point of view, but also with regard to possible sensor applications. For such applications, however, thin films with a smooth surface and high T_c are necessary. With this respect, we comparatively investigate the microstructure – transport property relationships of $NdFeAsO_{1-x}F_x$ thin films and NdFeAsO/NdOF compounds, grown with several thicknesses by molecular beam epitaxy (MBE) on MgO(001) substrates. The (micro) structure was investigated by X-Ray diffraction as well as atomic force and scanning electron microscopy and atom probe tomographyic. Superconducting properties were determined by electrical transport measurements. We show how film thicknesses, structure, surface morphology and growth defects influence the resistive transition and T_c as well as temperature, field and orientation dependencies of J_c. For a 20 nm thin $NdFeAsO_{1-x}F_x$ film with a root mean square roughness < 2nm a high transition temperature of $T_{c,0} = 44.7$K and $T_{c,onset} = 48$K could be observed which is close to values measured on single crystals.
The work was partly supported by the JSPS Grant-in-Aid for Scientific Research (B) Grant Number 16H04646.

Keywords: NdFeAsO1-xFx, MBE, surface morphology

PC3-1-INV

On the interfacial superconductivity of FeSe/STO

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Recently, interfacial superconductivity up to 75K has been discovered in FeSe/STO and FeSe/BTO interfaces [1,2]. We combine angle resolved photoemission spectroscopy (ARPES), scanning tunneling microscopy (STM) and molecular beam epitaxy (MBE) to study the superconductivity at interfaces and surfaces. Based on the impurity effects and quasiparticle interference behaviors revealed in our STM data, we found that the pairing symmetry of FeSe/STO is the plain *s*-wave type [3]. Moreover, with surface electron doping, the FeSe thick film exhibits an anomalous phase diagram with a correlated insulating phase and a superconducting phase with Tc up to 46K [4]. By placing such a heavily electron doped FeSe superconducting layer closer to the FeSe/STO interface, its superconducting gap increases exponentially to the single layer FeSe/STO value [5], which resembles the behavior of the STO phonon strength measured by EELS [6]. Our results demonstrate the critical role of interfacial electron-phonon interactions in the high Tc of FeSe/STO interface.

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Keywords: interfacial superconductivity, FeSe/STO, ARPES, STM

PC3-2

Effect of orbital ordering on charge dynamics in $FeSe_{1-x}Te_x$ studied by optical spectroscopy

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For most iron-based superconductors, the superconducting phase emerges in the vicinity of the antiferromagnetic-orthorhombic (AFO) phase. However, FeSe exhibits the tetragonal-to-orthorhombic structural phase transition at T_s ~ 90 K, below which the orbital ordering was observed, without accompanying the magnetic phase transition. Although the change in the band structure across T_s has been intensively studied, the effect of the orbital ordering on the charge dynamics remains unclear.

In this work, we performed optical spectroscopy for $FeSe_{1-x}Te_x$ thin films (x = 0, 0.1, 0.2, and 0.4) on CaF_2 substrates grown by the pulsed laser deposition method [1]. One of the advantages of using thin films is that the measurement can be carried out on Te-substituted compositions which are unstable for bulk samples. No abrupt change in the optical spectrum of FeSe was observed across T_s, in contrast with the case of iron pnictides showing the AFO phase, in which a clear gap feature is observed. Below T_s, the weight of a coherent Drude component decreases with decreasing temperature, indicative of a gradual suppression of the coherent carrier density [2]. This highlights a peculiar metallic state in FeSe that the Fermi surface gradually modified with temperature. For x = 0.2 and 0.4, the coherent Drude weight does not change for the whole temperature range investigated in the present study. This indicates that the orbital order is suppressed by Te substitution, consistent with a recent transport study [3].

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Keywords: Iron chalcogenide, Thin film, Optical spectroscopy

PC3-3

High-Resolution ARPES Study of Quasiparticle Band Dispersion in Electron-Doped FeSe Thin Films

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The recent discovery of high-temperature (Tc) superconductivity in one- monolayer FeSe thin films has attracted considerable attention [1-3] because the Tc value of ~65 K is the highest among iron-based superconductors despite the low Tc (<10 K) character of bulk FeSe crystal. One of the key ingredients to trigger high-Tc superconductivity in one-monolayer FeSe is electron doping [2-4] which results in unique Fermi-surface topology distinct from that in bulk iron-based superconductors. To understand the origin of Tc enhancement by electron doping, we have fabricated high-quality electron-doped FeSe thin films and investigated their electronic structure by high-resolution angle-resolved photoemission spectroscopy (ARPES). In this presentation, we report the evolution of the quasiparticle band dispersions as a function of temperature and discuss the relationship with the emergence of high-Tc superconductivity.

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Keywords: FeSe, Electronic structure, Angle-resolved photoemission spectroscop

PC3-4-INV

Superconductivity in the Noncentrosymmetric Iridium Phosphide ScIrP

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5*d* band metals of heavy elements such as Ir and Pt are promising candidate to show unconventional superconductivity caused by the strong spin-orbit interaction of heavy 5*d* atoms. Typical examples are platinum boride and arsenide superconductors Li_2Pt_3B and SrPtAs; the spin triplet pairing is reported to be dominant in the former, while the chiral *d*-wave or other unconventional pairings are theoretically predicted in the latter. Moreover, many Ir- or Pt-based superconductors have been discovered in recent years, indicating they are one of the hot spots for the search for novel superconductors.
Here we report the discovery of a bulk superconducting transition at 3.4 K in the ternary iridium phosphide ScIrP [1]. ScIrP crystallizes in the hexagonal ordered Fe_2P-type structure with a noncentrosymmetric space group of *P*-62*m* (left figure) [2]. We prepared polycrystalline samples of ScIrP by a solid state reaction method. As shown in the right figure, electrical resistivity and magnetization show a sharp drop to zero and a strong diamagnetic signal at 3.4 K, respectively, indicating a bulk superconducting transition occurs at this temperature. On the basis of heat capacity data in a zero magnetic field, ScIrP is suggested to be a weakly-coupled BCS superconductor. Alternatively, experimental results under magnetic fields indicate that this material is a type-II superconductor with an upper critical field H_{c2} above 5 T at zero temperature. This moderately high H_{c2} does not violate the Pauli limit, but it does imply that there is a significant effect from the strong spin-orbit interaction of 5*d* electrons in the noncentrosymmetric crystal structure. *The work has been done in collaboration with T. Inohara, H. Nagaso, Y. Yamakawa, A. Yamakage, and K. Takenaka (Nagoya University).
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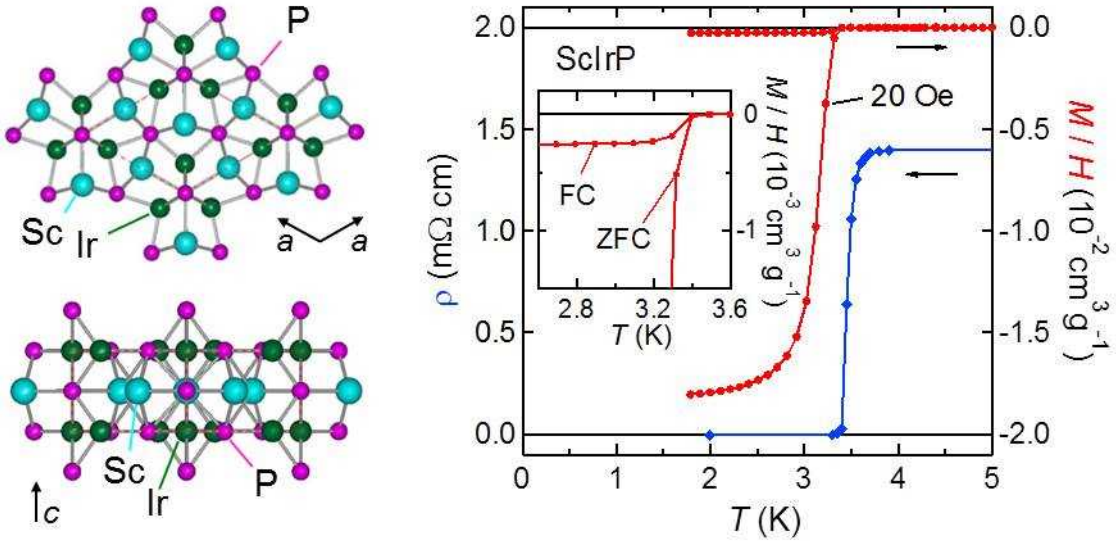

Fig. (left) Crystal structure of ScIrP. (right) Temperature dependence of electrical resistivity and magnetization of a polycrystalline sample of ScIrP.

Keywords: 5d electron system, iridium phosphide

PC3-5-INV

Nonlinear superconducting transport in noncentrosymmetric superconductors

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Symmetry breaking of crystal is known to affect the electric transport, offering a variety of novel properties and functionalities in solids. Among them, noncentrosymmetric superconductors have been studied as the basic platform and attracting much interest from both fundamental and technological view point. Nonlinear magnetotransport, in which magnetoresistance for forward and backward current are not equivalent, is one of the manifestations of the lattice symmetry breaking in electric transport. Although there have been several studies of such an asymmetric electric transport in chiral and polar materials [1,2], reports on the nonlinear transport in superconducting phase is elusive.
In this presentation, I will report the observation of the nonlinear superconducting transport in noncentrosymmetric superconductors. Such superconductivity without space inversion symmetry is realized in nanostructures of transition metal dichalcogenides via ionic liquid gating. In two-dimensional MoS_2, nonlinear second harmonic voltage signals are largely enhanced in electric-field-induced superconducting state, showing the characteristic selection rule (presence of absence of signals as a function of electric current directions) [3].
We also studied the electric-field-induced superconductivity in a chiral WS_2 nanotube[4]. **Second harmonic signals originating from the tube chirality also show the large enhancement in superconducting region and characteristic quantum oscillations due to the quantum interference of supercurrent along the circumference of the nanotube have been observed.**
These results imply the universality of unidirectional superconducting transport and also provide a powerful approach for probing the exotic superconducting state in noncentrosymmetric superconductors.

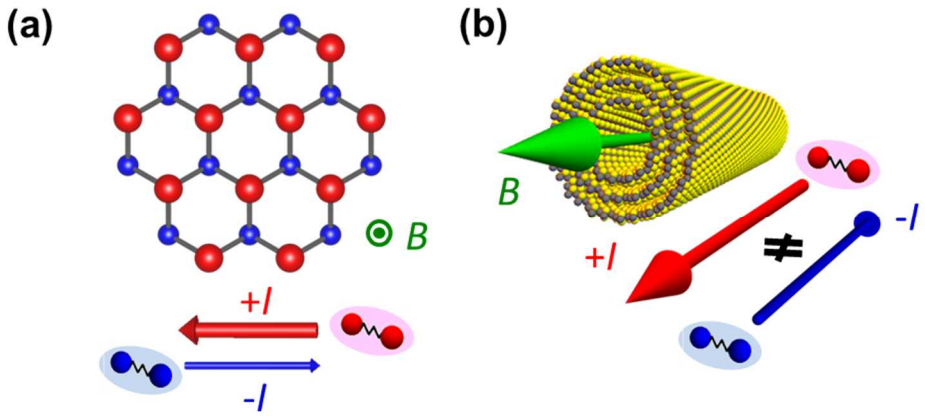

Fig.Nonlinear superconducting transport in (a) MoS_2 and (b) WS_2 nanotube

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Keywords: Noncentrosymmetric syperconductor, Nonlinear transport, Transition metal dichalcogenides, Ionic liquid gating

PC4-1-INV

Quasilinear quantum magnetoresistance in pressure-induced nonsymmorphic superconductor CrAs

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Linear magnetoresistance is a subject of high interest. The helimagnet CrAs undergoes a quantum phase transition to a nonmagnetic superconductor under pressure [1, 2]. We have measured the transverse magnetoresistance of CrAs under pressure [3]. In the pressure range close to where the superconducting transition temperature is maximised, our low-temperature magnetoresistance exhibits striking non-saturating, quasilinear magnetic field dependence up to 14 T (Figure 1a). Our bandstructure calculations reveal a subtle band crossing near the Y-point of the Brillouin zone (Figure 1b), which is protected by the nonsymmorphic crystal symmetry. In this presentation, I will show that the quasilinear magnetoresistance arises from an intricate interplay between the nontrivial band crossing and strong magnetic fluctuations.

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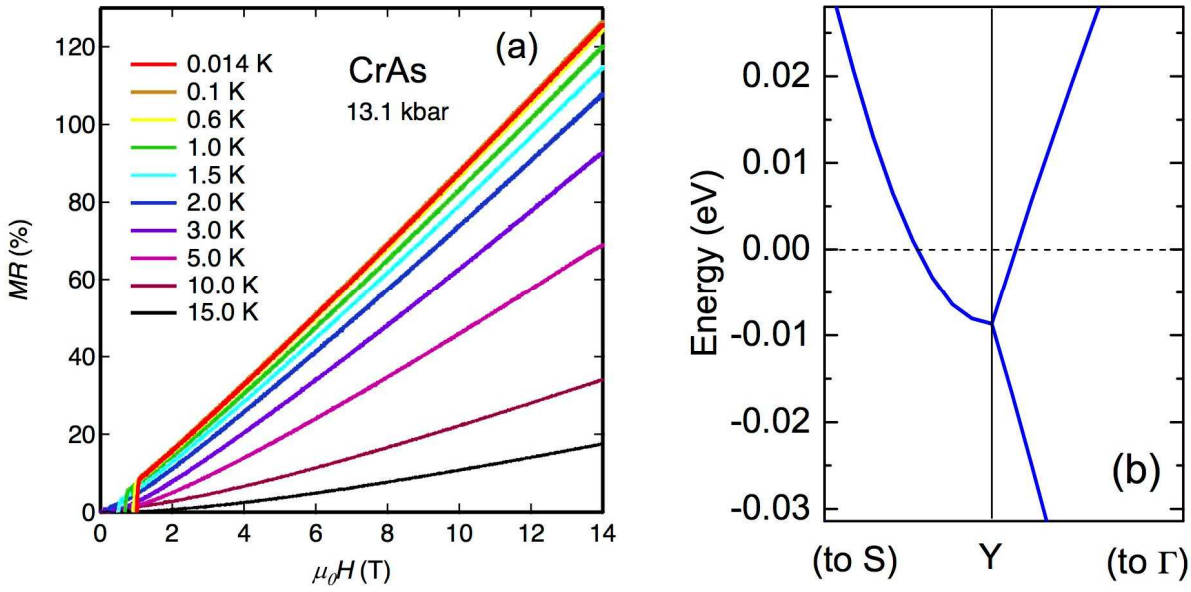

Keywords: CrAs, magnetoresistance, high pressure

PC4-2-INV

High Temperature Superconductivity and Quantum Phase Transitions in crytalline 2D Superconductors

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By direct transport and magnetic measurements, we provide fist direct evidence for high temperature superconductivity in the 1-UC FeSe films grown on insulating STO substrates with the onset Tc and critical current density much higher than those for bulk FeSe.[1] Furthermore, thickness dependent of superconductivity is carefully studied and interesting phenomena, such as superconductor-insulator transition and linear magnetoresistance, are observed.[2-5] These investigations may pave the way to enhancing and tailoring superconductivity by interface engineering.[4] Furthermore, quantum phase transition is one of most important topics in condensed matter physics. When we study the superconductor-metal transion in ultrathin cyrtalline Ga films grown on GaN substrate [6], we firstly discover quantum Griffiths singularity in two dimensional (2D) system and superconductors [7], which is a new quantum phase transition in 2D superconductors. This discovery is further revealed in LAO/STO(110) interface superconductors [8] and monolayer Ising superconductor $NbSe_2$ films[9].

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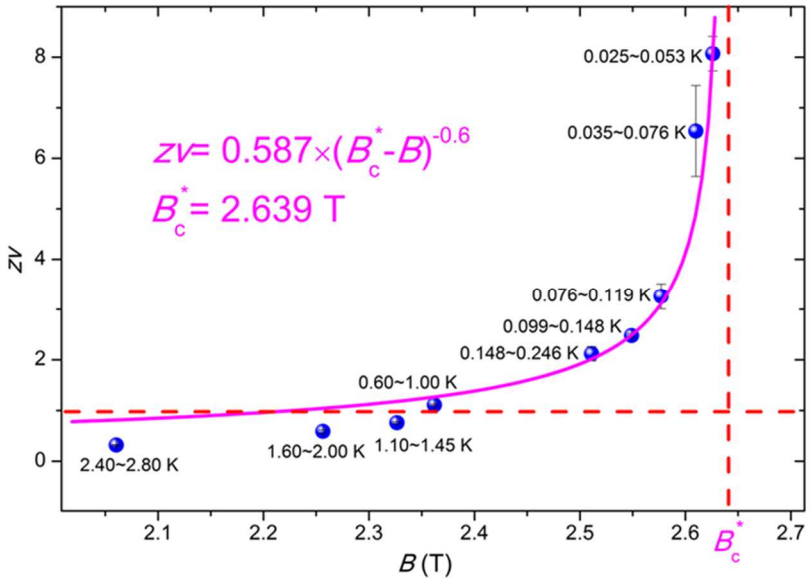

Keywords: High Temperature Superconductivity, Quantum Phase Transition, Crytalline 2D Superconductor, Quantum Griffiths Singularity

PC4-3-INV

Structural Phase Diagram and Anomalous Magnetic Properties in a Superconductor of $LnO_{1-x}F_xBiS_2$ (Ln: rare earth elements)

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Since the discovery of BiS_2-based superconductor, $Bi_4O_4S_3$ and $LnO_{1-x}F_xBiS_2$ (*Ln*: rare-earth elements) by Mizuguchi *et al.* in 2012[1, 2], we have studied physical properties of $LnO_{1-x}F_xBiS_2$ more precisely by using single crystals. Especially, we have focused on the relation between the emergence of superconductivity and crystal structure, and on the relation between the transport properties and the magnetism of the block layers, which contain *Ln* ions.

From our systematic structural investigations of $LaO_{1-x}F_xBiS_2$ by using a high-flux synchrotron X-ray diffraction, it has been revealed that $LaO_{1-x}F_xBiS_2$ has complex structural phase diagram in the x vs. temperature plane. Even for non F-doped compound (x=0), which was initially reported to have a tetragonal structure, a monoclinic structure with space group $P2_1/m$[3] is realized at room temperature. Recently we found that a structural phase transition to a tetragonal structure at ~ 550 K with increasing temperature, and the structure of this system is also very sensitive to x.

Recently we also succeeded to observing the anomalous behaviors related with magnetic freedom of *Ln* ion in $LnO_{1-x}F_xBiS_2$. For example, anomalous $-\log T$ divergence of specific heat in $CeOBiS_2$ at low temperatures[4] and a extremely heavy fermion like behaviour in C/T in Nd system as show in Fig. (b). Although these behaviors seems to be very similar to the typical heavy fermion systems such as $CeRu_2Si_2$, $CeCu_6$ and $CeNi_2Ge_2$, the mechanism should be different from ordinary one considering the electronic structure. In this presentation, we would like to present these data and discuss on the electronic structures of $LnO_{1-x}F_xBiS_2$.

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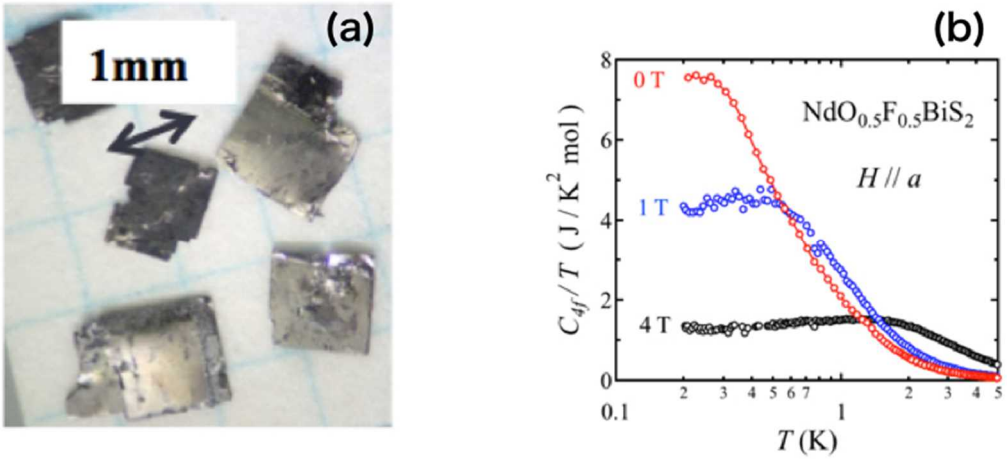

Fig. (a) Single crystals of $NdO_{0.5}F_{0.5}BiS_2$. (b) Temperature dependence of C_{4f}/T of $NdO_{0.5}F_{0.5}BiS_2$.

Keywords: BiS2-based superconductor, Single crystal, Structural phase transition, Heavy fermion like behavior

PC4-4

The superconducting anisotropy of La-$O_{0.5}F_{0.5}$-BiS_2 single crystal

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Being one of the most heavily studied members in the layered BiS_2-based superconductor family, the optimally fluorine doped La-$O_{0.5}F_{0.5}$-BiS_2 that grown under ambient pressure was found to be superconducting at transition temperature T_c ~3 K at ambient pressure [1]. Additionally, its T_c can be further enhanced to a maximum of 10 K with the application of pressure [2]. Band structure calculations have revealed a two-dimensional-like Fermi surface, implying a highly anisotropic normal state [3, 4]. In order to probe the anisotropy of the superconductivity experimentally, we measure the upper critical field of an as-grown La-$O_{0.5}F_{0.5}$-BiS_2 single crystal at ambient pressure by electrical resistivity measurement with a magnetic field oriented along the *c*-axis and the *ab*-plane, respectively. Our results show a very high superconductivity anisotropy factor γ which is also temperature dependent. Meanwhile, a pronounced upward curvature of the in-plane upper critical field $H_{c2}^{ab}(T)$ near T_c and an anomalously high $H_{c2}^{ab}(0)$ that exceeds single band Pauli limit are also observed in the H-T phase diagram. These features can be explained by two-gap model in dirty limit [5, 6], suggesting the La-$O_{0.5}F_{0.5}$-BiS_2 system to be a multigap superconductor.

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Keywords: BiS2-based superconductors, upper critical field, anisotropy, two-gap model

PC4-5

Nearly isotropic superconductivity in layered Weyl semimetal WTe_2 at 98.5 kbar

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Tungsten ditelluride WTe_2 is a layered transition-metal dichalcogenide. At ambient pressure, it exhibits no superconductivity but extremely large magnetoresistance. Superconductivity can be induced, along with the rapid suppression of the magnetoresistance, by application of a physical pressure (P) [1,2]. The superconducting phase emerges after ~30 kbar and the superconducting critical temperature (T_c) reaches a maximum at ~100–150 kbar before decreases again [1,2], thus forming a dome-shaped T_c(P). WTe_2 was originally considered to be electronically 2-dimensional because of the layered structure. Interestingly, subsequent experiments including transport [3] and spectroscopic measurements [4] reveal that the electronic structure is in fact a three-dimensional system at ambient pressure. Here, we present the angular and temperature dependence of the upper critical field of WTe_2 under 98.5 kbar down to 30 mK. Our results reveal a remarkably small and temperature-independent anisotropy factor ($=H_{c2//ab}/H_{c2//c}$), leading to our conclusion that the superconducting state in WTe_2 is nearly isotropic.

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Keywords: WTe2, High pressure, Upper critical field anisotropy

PC4-6

Strong Pauli Paramagnetic Effects in the Quasi-Two-Dimensional Superconductor Restacked TaS_2 Nanosheets

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Recently we reported an enhanced superconductivity in restacked monolayer TaS_2 nanosheets compared with the bulk TaS_2, pointing to the exotic physical behaviors of low dimensional systems. Here we tune the superconducting properties of this system with magnetic field along different directions. It is found that the present system bears a strong Pauli paramagnetic spin-splitting effects under high fields. Importantly, an unusual angular dependence of the upper critical field deviating from the Ginzburg-Landau model (GL model) and Thinkham model is observed, showing a strong evidence for the presence of triplet component of the superconducting order parameter in the mixed state. Moreover, with the vertical field fixed, we find that the superconducting transition temperature Tc can be enhanced by increasing the transverse field and forms a dome-shaped phase diagram. The present finding is significant in the viewpoint of fundamental physics and may also facilitate the applications of low-dimensional superconductors in the environment of high field.

Keywords: Pauli Paramagnetic Effects, Low-Dimensional Superconductors, Restacked TaS2 Nanosheets

PC5-1-INV

Critical-Current-by-Design

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We present a new paradigm, critical-current-by-design, that aims at predicting the optimal pinning landscape for maximum critical current in high temperautre superconducting (HTS) applications. This approach uses large scale time dependent Ginzburg-Landau simulations is to elucidate the vortex dynamics in complex pinning landscapes. On the experimental side, we use controlled particle irradiation to create defects of various morphologies in HTS coated conductors to enhance their critical current. We illustrate this new paradigm by predicting the critical current (J_c) and the non-additive pinning action of different defects in irradiated samples. An example of the latter is the recently discovered *reduction* of J_c at low fields in oxygen and copper irradiated HTS coated conductors which contain self-assembled BaZrO nanorods. In a new development, we discovered that off-angle irradiation can mitigate this issue. Furthermore, vortex creep studies in HTS coated conductors indicate that the J_c reduction could also be a consequence of faster creep in the presence of different vortex pinning sites. Another development is the discovery of double chain layer defects in HTS coated conductors, induced by high-energy, heavy-ion irradiation. These defects intersect the ion irradiation induced tracks and show a decrease in the oxygen and copper content at the interface, resulting in interfacial strain. These revelations directly demonstrate the extension of the electronic inhomogeneity following irradiation and the potential of strain-induced vortex pinning. We show that the combination of large scale TDGL simulations with bulk critical current and microstructural characterization provides the necessary ingredients for realizing the critical-current-by-design paradigm.

This work was supported by the Center for Emergent Superconductivity, an Energy Frontier Research Center funded by the U.S. D.O.E., Office of Science, Office of Basic Energy Sciences. The computational work was supported by the Scientic Discovery through Advanced Computing (SciDAC) program funded by U.S. Department of Energy, Office of Science, Advanced Scientic Computing Research and Basic Energy Science.

PC5-2-INV

RESONANT SCATTERING STUDIES OF CHARGE ORDER IN QUANTUM SOLIDS

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The spontaneous self-arrangement of electrons into static and periodically modulated patterns, a phenomenon commonly termed as charge order or charge-density-wave, has recently resurfaced as a prominent, universal ingredient for the physics of copper oxide high-temperature superconductors. Its antagonist coexistence with superconductivity, together with a putative connection to a quantum critical point beyond optimal doping, are symptomatic of a very fundamental role played by this collective electronic state for the physics of cuprates.

Resonant x-ray scattering (RXS) has rapidly become the technique of choice for the study of charge order in momentum space [1], owing to its ability to directly identify a breaking of translational symmetry in the electronic density. We have used RXS in Bi-, Nd, and Y-based cuprates to detect charge-density-waves even in presence of short-ranged order [2-3], exploring a realm previously accessible only by STM. Using the information available from the full two-dimensional momentum space, we have taken this experimental methodology further to reveal the local (intra-unit-cell) symmetry in the charge distribution [4,5].

To conclude, I will discuss recent results and future perspectives concerning the study of the nanoscale (10-100 nm) texture of electronic orders using coherent soft x-ray scattering in scanning (RXS nanomapping) and imaging (ptychography and holography) mode.

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PC5-3-INV

Nematic Phase Transition at the Onset Temperature of Pseudogap in High-T_c Cuprates

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A long-standing controversial issue in the quest to understand the high transition temperature (T_c) superconductivity in cuprates is the nature of the enigmatic pseudogap sate of the phase diagram, where anomalous electronic states, including Fermi arc, charge density wave and *d*-wave superconductivity emerge. Especially important is whether the pseudogap state is a distinct thermodynamic phase characterized by any kinds of broken symmetries below the onset temperature T^*. Electronic nematicity, a four-fold (C_4) rotational symmetry breaking, has emerged as a key feature inside the pseudogap regime. Here we report torque-magnetometry measurements of anisotropic susceptibility within the CuO_2 planes in clean single crystals of $YBa_2Cu_3O_y$ (YBCO) and $HgBa_2CuO_{4+\delta}$ (Hg1201) with exceptionally high precision. In YBCO, the in-plane anisotropy of susceptibility displays a significant increase with a distinct kink at the pseudogap onset temperature T^*, showing a remarkable scaling behavior with respect to T/T^* in a wide doping range. Our systematic analysis reveals that the rotational symmetry breaking sets in at T^* in the limit where the effect of orthorhombicity is eliminated. These results provide thermodynamic evidence that the pseudogap onset is associated with a second-order nematic phase transition, which differs from the recently reported charge-density-wave transition that accompanies translational symmetry breaking.

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PC5-4-INV

Hidden Fermionic excitation at the origin of high-temperature superconductivity and pseudogap in cuprates

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The quasiparticle dynamics in a superconductor reflects its pairing mechanism. In fact, in conventional superconductors, studies on the quasiparticle dynamics played an essential role in establishing the phonon-mediated pairing mechanism [1]. We studied this dynamics for cuprate high-temperature superconductors, whose pairing mechanism is still unknown: We calculated the frequency-dependent properties of the two-dimensional Hubbard model, which is a standard model of cuprates, with an unbiased numerical method called cluster dynamical mean-field theory.

By scrutinizing the frequency-dependent structure of the electron self-energy, we found that
i) a hidden fermionic excitation, which appears as a pole in the self-energy, emerges directly from the Mott physics when carriers are doped to the parent Mott insulator,
ii) the hidden fermion enhances the superconductivity considerably through a hybridization to quasiparticles [Fig. (b)], and
iii) the same hidden fermion generates a pseudogap above the superconducting transition temperature as a hybridization gap [Fig. (a)].
We thus obtained a unified view on the Mott insulator, pseudogapped metal, and high-temperature superconductivity in cuprates.[2]

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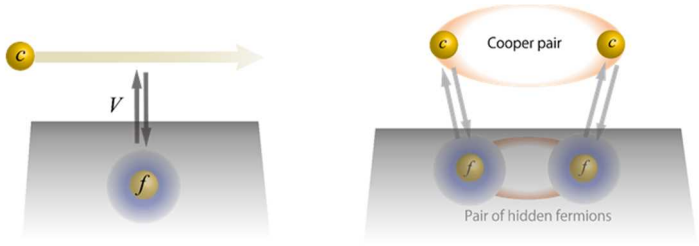

(a) $T>T_c$: Pseudogap state (b) $T<T_c$: Superconducting state
Figure: Hidden fermion (*f*) hybridizing with quasiparticles (*c*).

Keywords: cuprate superconductors, pseudogap, Hubbard model, hidden fermion

PC5-5-INV

Design of high-temperature topological superconductivity in curates and heavy fermions

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We propose topological superconductivity in strongly correlated d-wave superconductors. Although the gapless d-wave superconductors do not realize topological superconductivity, we find gapped topological superconducting states induced by spin-orbit coupling and electron correlation in recently-discovered two-dimensional heterostructures.

(1) 2D topological superconductivity in high-temperature cuprate supercoductors [1,2]
Search of gapped strong topological superconductivity has been one of the central subjects in the research field of topological science. We design the topological superconductivity based on familiar nodal d-wave superconductor heterostructures, such as high-Tc cuprates and heavy fermions [1]. Nonequilibrium topological superconductivity induced by circularly polarized laser-light is also proposed [2].

(2) Topological superconductivity in heavy fermion superlattices and reduction by electron correlation [3,4]
It is shown that the heavy fermion superlattice $CeCoIn_5$/$YbCoIn_5$ [5] realizes odd-parity superconductivity by spin-orbit coupling and it is a platform of topological crystalline superconductivity protected by mirror symmetry [3]. We also show the breakdown of topological classification by electron correlation, which can be experimentally realized by tuning the superlattice structure [4]. Material realization of similar odd-parity superconductivity in MoS_2 heterostructures is also proposed [6].

[1] A. Daido and Y. Yanase, Phys. Rev. B 94, 054519 (2016).
[2] K. Takasan, A. Daido, N. Kawakami, and Y. Yanase, Phys. Rev. B 95, 134508 (2017).
[3] T. Yoshida, M. Sigrist and Y. Yanase, Phys. Rev. Lett. 115, 027001 (2015).
[4] T. Yoshida, A. Daido, Y. Yanase, and N. Kawakami, Phys. Rev. Lett. 118, 147001 (2017).
[5] Y. Mizukami *et al.* Nat. Phys. 7, 849 (2011).
[6] Y. Nakamura and Y. Yanase, Phys. Rev. B 96, 054501 (2017)

Keywords: High-temperature cuprate superconductor, Heavy fermion superlattice, Topological superconductivity, Strong electron correlation

PC5-6

Electron backscatter diffraction analysis (EBSD) on superconducting nanowires

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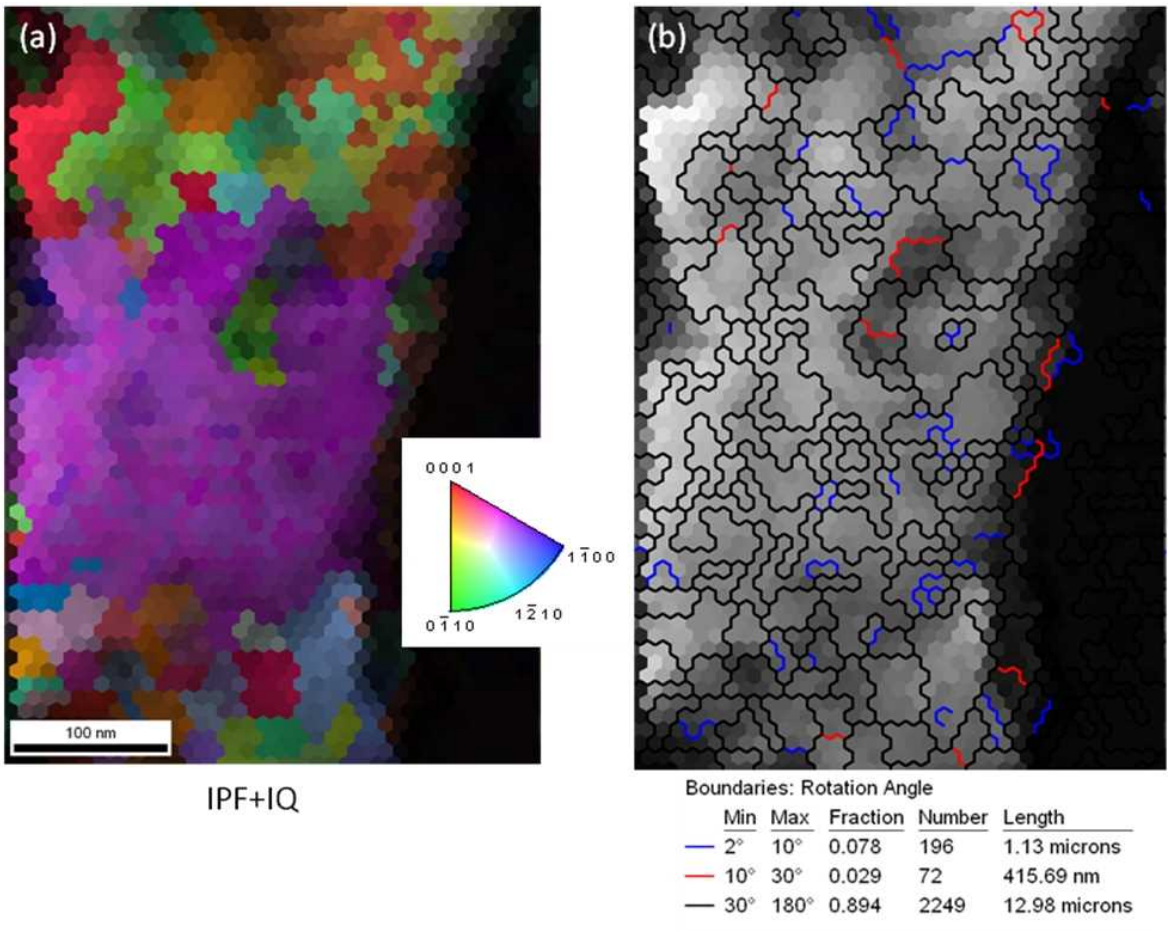
Electrospun, superconducting nanowires are characterized concerning the grain orientation, their texture and the respective grain boundary misorientations by means of electron backscatter diffraction (EBSD) analysis. The individual nanowires in such electrospun, nonwoven nanowire networks of $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) are polycrystalline, have diameters up to 250 nm and their grains are in the 20-50 nm range [1]. This requires a high spatial resolution for the analysis in the scanning electron microscope. However, the small diameter of the nanowires enables the application of the newly developed transmission EBSD (t-EBSD) technique without the preparation of TEM slices. Here, we present several EBSD mappings on Bi-2212 nanowires and compare their microstructure to those of filaments of the first generation tapes [2].

[1] M. R. Koblischka *et al.*, AIP Advances **6**, 035115 (2016).
[2] A. Koblischka-Veneva *et al.*, Physica C 468, 174 (2008).



Caption: EBSD mapping of a nanowire (a) and the determined misorientations.

Keywords: EBSD, Grain orientation, Nanowire, Bi-2212

PC5-7

Study of oxygen exchange kinetics of $YBa_2Cu_3O_{7-\delta}$ films to achieve high carrier concentration

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ICMAB - CSIC[1]

YBCO films are of great technological interest as they show exceptional good superconducting properties. As in all cuprate SCs these properties are governed by its oxygen content. Understanding how to achieve optimal oxygen doping of the oxygen deficient triple perovskite YBCO structure is still an open, critical issue and its optimization a main goal of this work. The oxygenation kinetics is strongly influenced by microstructural and morphological features, which strongly differ depending on the growth technique. The kinetic effects comprises of molecular oxygen absorption, dissociation and atomic bulk diffusion.

We show that in-situ techniques as electrical conductivity relaxation (ECR) and high temperature environmental XRD (HTXRD) are very useful tools to analyze the oxygen exchange processes. We monitor the mechanisms of oxygen in- and excorporation in standard and nanocomposite CSD and PLD YBCO thin films during post annealings of grown films by changing between oxidizing and reducing $p(O_2)$ atmospheres. This analysis allows us to determine the dependence of the oxygenation rate of in- and out-diffusion (bulk and surface) on several processing parameters, as the O_2 partial pressure and temperature and obtain time constants and activation energies for each case. Our results demonstrate that the oxygenation of the thin films studied, is limited by surface reactions. Catalytic agents deposited on the surface, strongly accelerate the oxygen exchange and allow lower oxygenation temperatures, leading to higher oxygen contents. Understanding the oxygen exchange allows to properly engineer the carrier concentration to the overdoped regime, as monitored by Hall effect and XRD measurements. Therefore we can study the correlation between the doping level and the critical currents, with the aim to maximize the latter.

Funding from from EU ERC-AdG-2014-669504ULTRASUPERTAPE, Severo Ochoa SEV2015-0496 program and MINECO MAT2014-51778-C2-1-R and FEDER project is acknowledged.

Keywords: YBCO thin film, Oxygen exchange, Overdoping

PCP1-1

Pb Substitution effect in La(O,F)BiSSe

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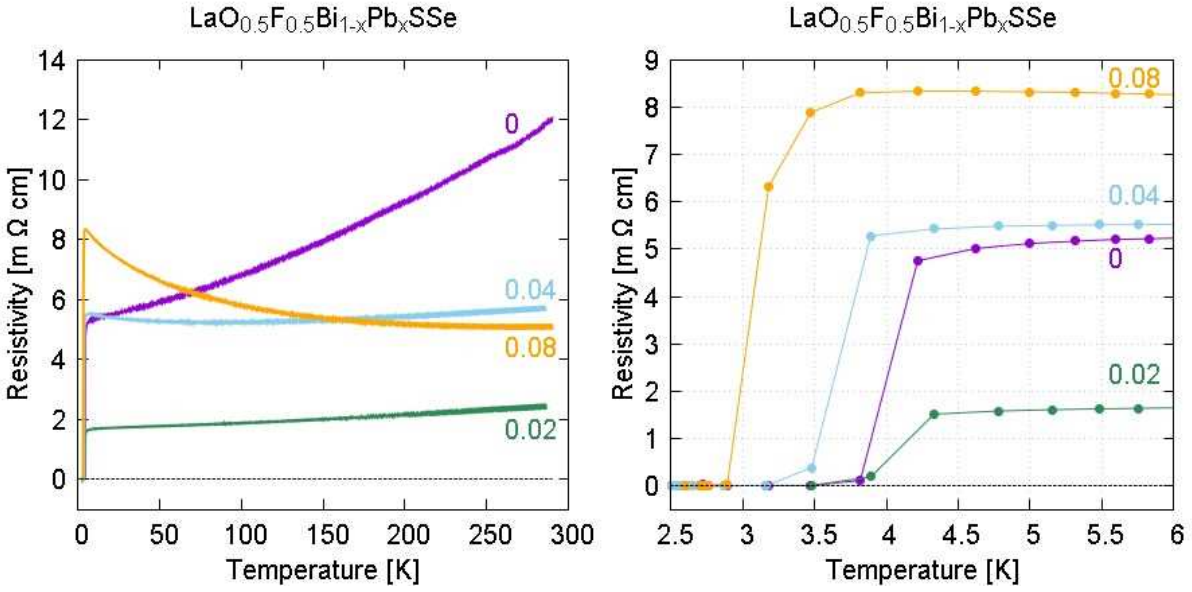
BiS_2-based superconductors *Ln*(O,F)Bi*Ch*$_2$ (*Ln* = La, Ce, Nd… , *Ch* = S, Se) have layered structure and these superconducting critical temperatures (*Tc*) change by doping carriers or applying chemical pressure by element substitution. For example, it is reported that the *Tc* were enhanced by Pb substitution in Nd(O,F)BiS_2[1]. Moreover, anomalous behaviors in temperature dependence of electrical resistivity were observed in Pb substituted La(O,F)BiS_2 single crystals[2]. It is interesting problem whether such Pb substitution effects occur inn other BiS_2- based materials. To verify this, we investigated Pb substitution effects in La(O,F)$Bi_{1-x}Pb_xSSe$ (x = 0, 0.02, 0.04, 0.08) single crystals because La(O,F)BiSSe has the highest *Tc* in La(O,F)Bi*Ch*$_2$ in ambient pressure[3].
From X-ray diffraction experiment, decrease of a-axis length was observed with increasing Pb concentration indicating successful Pb substitution. In contrast to the results in La(O,F)BiS_2, *Tc* decreases with increasing Pb concentration in both magnetization and electrical resistivity measurements. Furthermore, the anomalous behavior which has observed for La(O,F)$Bi_{1-x}Pb_xS_2$ in resistivity measurement was not observed in all Pb concentrations.

[1]S. Demura *et al.*, Solid State Communications 223 (2015) 40-44
[2]S. Demura (in preparation)
[3]T. Hiroi *et al.,* J. Phys. Soc. Jpn. **84**, 024723 (2015)



Keywords: BiS2-based superconductor, in-plane chemical pressure

PCP1-2

Unidirectional pressure effect on electrical resistivity in single crystal $La(O,F)BiS_2$

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$LaOBiS_2$ has a crystal structure composed of an alternate stacking of conducting layers (BiS_2 layers) and spacer layers (LaO layers). Carrier doping by partial substitution of F for O induces superconductivity with a transition temperature (T_C) of 3K [1]. According to preceding study, T_C in $La(O,F)BiS_2$ was enhanced by application of hydrostatic pressure[2]. T_C was also increased by partial substitution of S^{2-} by Se^{2-}, which induces in-plane pressure [3]. These reports indicate that T_C in $La(O,F)BiS_2$ is thought to be sensitive to structural perturbations, especially in-plane structural perturbation. The in-plane structural instability was also predicted theoretically.
We have tried to measure electric properties in $La(O,F)BiS_2$ under in-plane structural perturbation. We performed electrical resistivity measurements under application of uniaxial stress using a piezo actuator, which can expand the sample unidirectionally by application of voltage. We have succeeded to measure electrical resistance under the unidirectional stress at room temperature, liquid nitrogen temperature and liquid helium temperature. At the conference, we will discuss the results.

[1] Y. Mizuguchi *et al.*, J. Phys. Soc. Jpn 81 (2012) 114725
[2] H. Kotegawa *et. al.*, J. Phys. Soc. Jpn 81 (2012) 103702
[3] Y. Mizuguchi *et al.*, Sci. Rep. 5,14968 (2015)

Keywords: BiS2 based superconducor, in-plane chemical pressure

PCP1-3

F Substitution Effect on supermodulation in $LaO_{1-x}F_xBiSe_2$ Studied by STM

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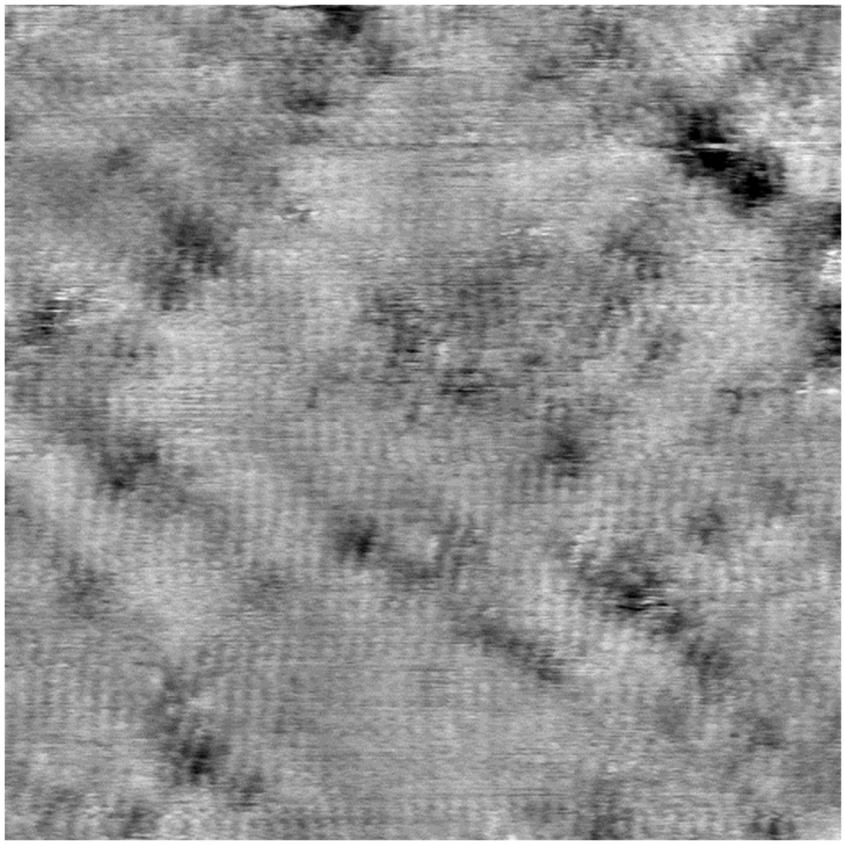
In BiS_2 based superconductors such as $LaO_{1-x}F_xBiCh_2$ (Ch = S, Se), the electronic properties are controlled by the carrier density, which is determined by the amount of substituted F. Above x=0.5, this material is predicted theoretically to exhibit charge density wave instability which shows supermodulation on BiS_2 plane due to the phonon instability and the fermi surface nesting [1].
Recently, in $LaO_{0.5}F_{0.5}BiSe_2$ single crystals, scanning tunnelling microscopy and spectroscopy (STM/STS) measurements revealed the appearance of supermodulation on $BiSe_2$ plane [2], whose period is different from that predicted from the Fermi surface nesting. To certify whether this observed modulation is one due to the Fermi surface nesting or not, we performed STM/STS experiments on samples with different F concentrations. STM/STS measurements were performed on x = 0.1 and x = 0.5 samples at 4.2 K. The observed surface was prepared by cleavage at 4.2 K *in situ*.
STM/STS observations revealed that the supermodulation existed in both x = 0.1 and x = 0.5 samples. Furthermore, the period of the modulation was five times of the lattice constant regardless of the carrier concentration. This indicates that the observed modulation is not caused by the electronic origin such as the Fermi surface nesting.

[1] T. Yildirim, *Phys. Rev. B* **87**, 020506(R) (2013)
[2] S. Demura, (in preparation)

Keywords: BiS2, BiSe2



PCP1-4

Scanning tunneling microscopic observation in $LaO_{1-x}F_xBi_{1-y}Pb_yS2$

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BiS_2-based superconductors *Ln*(O,F)Bi*Ch*$_2$ (*Ln*=La,Ce,Nd... , *Ch*=S,Se) have a layered crystal structure which resembles that of copper oxide superconductors. In addition, their properties are changed by career doping or elemental substitution. In $LaO_{0.5}F_{0.5}BiS_2$, we discovered that the superconducting properties are enhanced by partial substitution of Pb for Bi. In addition, it was found that the temperature dependence of resistivity in $LaO_{1-x}F_xBi_{1-y}Pb_yS_2$ shows anomalous behavior. To investigate the effect of Pb substitution microscopically, we performed STM/STS measurements in $LaO_{0.5}F_{0.5}BiS_2$ and $LaO_{0.5}F_{0.5}Bi_{0.92}Pb_{0.08}S_2$. The single crystals used in this study were synthesized by the CsCl/KCl flux method.
A square lattice of Bi atoms was observed on the cleaved surface of $LaO_{0.5}F_{0.5}Bi_{0.92}Pb_{0.08}S_2$. However, the observed surface was rather rough in contrast to the flat surface observed in other BiS_2-based superconductors. In addition, tunneling spectra changed locally. These features are considered as the characteristics of Pb substituted system. In parent material ($LaO_{0.5}F_{0.5}BiS_2$), we have not obtained a clear STM image so far. This seems to indicate low density of states at E_F in $LaO_{0.5}F_{0.5}BiS_2$.

Keywords: p-electron system, tunneling microscopy, substitution effect

PCP1-5

Observation of Superconducting gap and Vortex lattice in the transition metal tri-calchogenide $ZrTe_{3-x}Se_x$ by Scanning Tunneling Spectroscopy

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Tokyo institute of Technology[2]

Transition metal tri-calchogenide $ZrTe_3$ has the quasi one dimensional layered system: a layer formed by trigonal prismatic $ZrTe_6$ chains elongated along the *b* axis is stacked along the *c* axis. Because of the crystal structure, this material shows an anisotropic resistivity in the in-plane and along the *c* axis direction. Furthermore, this material shows a charge density wave at around 63 K along the *a* axis and filamentary superconductivity below 2 K. Recently, it is reported that the bulk superconductivity appears at around 4 K by the Se substitution of 4 % for Te [1]. Therefore, the anisotropic superconducting properties due to the anisotropic crystal structure are expected. In this study, an observation of superconducting gap and vortex lattice was performed in $ZrTe_{1-x}Se_x$ using a scanning tunnelling microscopy and spectroscopy (STS) measurement at 2 K to investigate the anisotropic superconducting properties. From the STS measurement, the superconducting gap and the anisotropic vortex lattice were successfully observed on the surface of $ZrTe_{1-x}Se_x$. We will report these results in detail in the presentation.

[1] X. Zhu *et al.*, Sci. Rep. **6**, 29674 (2016).

Keywords: Superconductivity, vortex, STM/STS

PCP1-6

Crystal structure and physical properties of layered compound $LaOSbSe_2$

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Okayama University, Japan[1]

We report on the crystal structure and physical properties of a novel layered compound $LaOSbSe_2$. The compound crystallizes in a tetragonal structure with space group $P4/nmm$. The structure consists of alternately stacked layers of LaO and bilayers of $SbSe_2$, and is isostructural with BiS_2-based superconductors such as $LaO_{1-x}F_xBiS_2$. Electric resistivity measurements revealed that $LaOSbSe_2$ is a semiconductor. We will also report on the effects of chemical doping, as well as first-principles calculations.

Keywords: BiS2 superconductors, chemical substitution, new materials, SbSe2 layers

PCP1-7

Crystal Growth and Superconducting Properties of Topological Superconductor Candidates $A_xBi_2Se_3$ (A = Sr, Nb)

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Bi_2Se_3 is well known as a typical topological insulator. After the discovery of superconductivity in Cu-intercalated Bi_2Se_3 ($Cu_xBi_2Se_3$) [1], it became a promising topological superconductor candidate. The topological superconductor is theoretically predicted to have topologically nontrivial surface/edge states, which can host Majorana fermions. These fermions follow non-Abelian statistics and are expected to be applied to quantum computers. However, $Cu_xBi_2Se_3$ has several problems such as inhomogeneity, unstable in the air, low superconducting volume fractions. Recently, it was reported that Sr and Nb intercalated Bi_2Se_3 ($Sr_xBi_2Se_3$, $Nb_xBi_2Se_3$) also showed superconductivity [2, 3].

In this study, we have grown single crystals of $Sr_xBi_2Se_3$ by the melt growth method. Large single crystals have been successfully obtained. In contrast to $Cu_xBi_2Se_3$, the shiny metallic surface of $Sr_xBi_2Se_3$ remains even after exposure to the air for a long time. From transport measurements, superconductivity was confirmed in $Sr_xBi_2Se_3$ single crystals. The transition temperature monotonically increased with nominal compositions, up to ~ 3.2 K for $x = 0.25$. The resistivity under various magnetic fields was also measured and the superconducting parameters ware determined using the WHH and GL models. We will also discuss crystal growth and transport properties in single crystals of $Nb_xBi_2Se_3$, including a comparison of $A_xBi_2Se_3$ (A = Cu, Sr, Nb).

[1] Y. S. Hor *et al.*, Phys. Rev. Lett. **104**, 057001 (2010).

[2] Z. Liu *et al.*, J. Am. Chem. Soc. **137**, 10512 (2015).

[3] Y. Qiu *et al.*, arXiv:1512.03519 (2016).

Keywords: Topological superconductor, Crystal growth, Superconducting parameters

PCP1-8

Crystal Growth and Superconducting Properties of Pb-doped $NiBi_3$ having Strong Spin-Orbit Coupling

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Topological electric phases are expected to appear in materials composed of heavy elements due to the band inversion by strong spin-orbit coupling. In case of a topological superconductor, while a superconducting gap exists in the bulk, unique gapless states hosting Majorana fermions are predicted to emerge in the surface or at the edge and inside the magnetic flux core. In this study, as a candidate of a topological superconductor, we have investigated $NiBi_3$ (T_c = 4.06 K [1]), which is expected to have strong spin-orbit coupling due to bismuth. $NiBi_3$ has a crystal structure composed of one-dimensional atomic chains, which are bonded in two perpendicular directions by van der Waals force. We have considered $NiBi_3$ is an excellent material for the exploration of topological superconducting materials because it has relatively high T_c, the stoichiometric composition, and is stable in the atmosphere.

From the results of the first principles calculations, it was confirmed that electronic structures in $NiBi_3$ were significantly influenced by spin-orbit coupling. Furthermore, theoretical calculations suggested that hole-carrier doping could increase T_c. Therefore, we have tried to substitute Pb for Bi to dope hole carries. We succeeded in growing single crystals of $NiBi_{3-x}Pb_x$ with x = 0.0 to 0.3 by using the self-flux method. The temperature and the magnetic-field dependences of the resistivity in $NiBi_{3-x}Pb_x$ crystals were measured, respectively. In accord with the theoretical prediction, T_c slightly increases with the amount of Pb doping (x). As compared with the slight enhancement of T_c, it was found that the critical field remarkably increased: about three times higher in $NiBi_{2.7}Pb_{0.3}$ than that of pure $NiBi_3$.

[1] X. Zhu *et al.*, Phys. Rev. B **86**, 024527 (2012).

Keywords: NiBi3, Superconducting Properties, Single Crystal, Electronic Structures

PCP1-9

Effect of Sulfur and Selenium Substitution on $ZrTe_3$

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Department of Physics, Tokyo University of Science, Japan[1]

$ZrTe_3$ is one of transition metal trichalcogenide compounds, having the structure composed of triangular prismatic chains. This material undergoes a charge density wave (CDW) transition at 63 K and shows filamentary superconductivity below 2 K.
Recent paper reported that partial Se substitution with Te of 4% suppressed the CDW order and induced bulk superconductivity at around 4 K [1]. Since the ionic radius of Se is smaller than that of Te, superconductivity is possibly induced through lattice strain caused by the element substitution. Therefore, substitution of S ion, which has the smaller ionic radius than that of Se ion, is promising way to increase superconducting transition temperature (T_c).
In this study, we synthesized $ZrTe_{3-x}Ch_x$ (Ch = S, Se) single crystals and measured their superconducting properties. The sample substituted for S ion of 10% shows superconductivity at 3 K in a magnetic susceptibility measurement. At the conference, we will discuss the difference in superconducting properties between S and Se substituted samples.

[1] Zhu X *et al* 2016 *Sci. Rep.* **6** 26974

Keywords: charge density wave, trichalcogenide

PCP2-1

Observation of surface 1*T* phase on 2*H*-$NbSe_2$ by STM/STS

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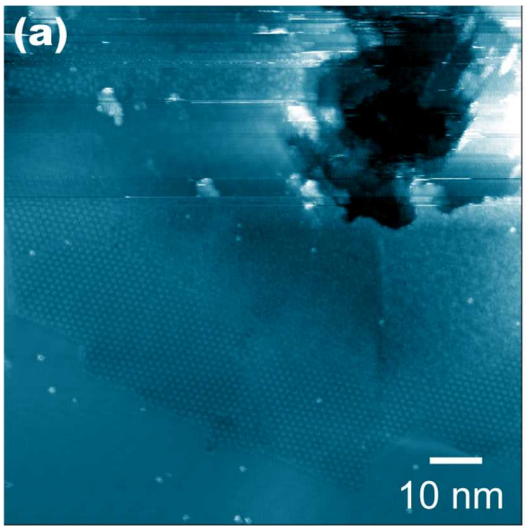
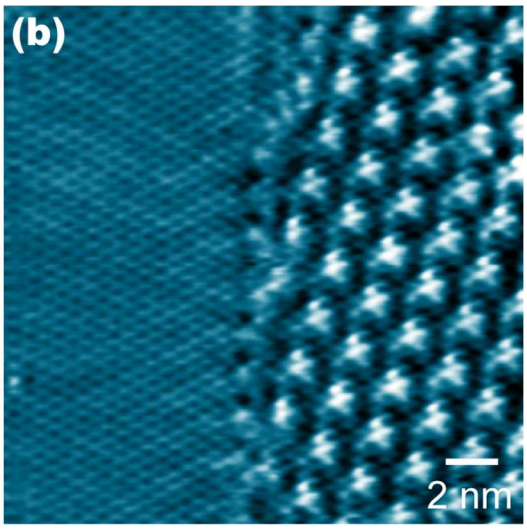
Tokyo University of Science[1]

One of the transition metal dichalcogenides, 2*H*-$NbSe_2$ has been studied for a long time because of the existence of charge density wave (CDW) below 33 K and emergence of superconductivity below 7 K. On the other hand, other polytypes, such as 1*T* and 4*H*-$NbSe_2$, have been less studied because of difficulty in single crystal growth. Recently, H. Wang *et al.* reported that a short pulse bias voltage from an STM tip creates 1*T*-$NbSe_2$ on 2*H*-$NbSe_2$ surface. They also revealed that the 1*T*-$NbSe_2$ shows a CDW with $\sqrt{13}\times\sqrt{13}$ periodicity, which is also observed in 1*T*-TaS_2. However, the electronic state is not clarified yet in the study. According to another report by Y. Nakata *et al.*, monolayer 1*T*-$NbSe_2$ also shows the same CDW as that observed by STM and seems to be a Mott insulator with similar gap size to that of 1*T*-TaS_2. Motivated by these studies, we have tried to clarify the electronic states of 1*T*-$NbSe_2$ on the surface of 2*H*-$NbSe_2$ created by application of the pulse bias voltage from the STM tip.
Figure 1(a) shows an STM image that is taken after the application of a pulse voltage on 2*H*-$NbSe_2$ at 4.2 K. This image shows depression of the surface structure. The magnified image near the depression is shown in Fig. 1(b). This image clearly shows the coexistence of the original 3×3 CDW in 2*H*-$NbSe_2$ and the $\sqrt{13}\times\sqrt{13}$ CDW in 1*T*-$NbSe_2$ successfully. We report on not only the structural change but also the change in the electronic states at the conference.





Keywords: 1T-NbSe2, STM, STS

PCP2-2

Effects of the Co-Intercalation of Lithium and Ethylenediamine into 1T-TaS_2 and 2H-TaS_2

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Layered compounds 1T-TaS_2 and 2H-TaS_2 have been studied for more than four decades owing to the discovery of charge density wave (CDW) and superconductivity. A variety of metal atoms and organic molecules have been intercalated into the compounds to elucidate the relationship between CDW and superconductivity [1]. So far, however, there is almost no report on the co-intercalation of metal atoms and organic molecules into 1T-TaS_2 nor 2H-TaS_2.

We have succeeded in synthesizing new co-intercalation compounds of 1T-$Li_x(C_2H_8N_2)_yTaS_2$ with the superconducting transition temperature T_c = 3.2 – 4.0 K via the co-intercalation of Li and ethylenediamine (EDA) $C_2H_8N_2$ into 1T-TaS_2. On the other hand, no superconductivity was observed in the only EDA-intercalated sample of x = 0, while superconductivity with T_c = 3.7 K was observed in 1T-$Li_{0.5}TaS_2$ where EDA was de-intercalated from 1T-$Li_{0.5}(C_2H_8N_2)_yTaS_2$ with T_c = 3.5 K. Moreover, it has been found that the commensurate CDW (CCDW) transition observed in 1T-TaS_2 is suppressed in all the intercalated samples.

We have also succeeded in synthesizing new co-intercalation compounds of 2H-$Li_x(C_2H_8N_2)_yTaS_2$ with T_c = 3.2 – 4.5 K. T_c has been found to be the highest, namely, 4.5 K in the only EDA-intercalated sample of x = 0 and decrease with increasing x. That is, the co-intercalation of Li suppresses the superconductivity in 2H-$(C_2H_8N_2)_yTaS_2$, indicating that the electron doping due to intercalated Li is harmful to the superconductivity. Moreover, it has been found that the incommensurate CDW (ICCDW) transition is suppressed in all the intercalated samples.

The band calculation using WIEN2k has revealed that the density of states at the Fermi level decreases and increases with increasing x in 1T-$Li_x(C_2H_8N_2)_yTaS_2$ and 2H-$Li_x(C_2H_8N_2)_yTaS_2$, respectively.

It has been concluded that both the electron doping due to intercalated Li and the structural disorder due to intercalated EDA suppresses the CCDW and ICCDW transitions, leading to the appearance of superconductivity. Moreover, it has been concluded that T_c roughly increases in correspondence to the increase of the density of states at the Fermi level.

[1] R. A. Klemm, Physica C **514**, 86 (2015).

Keywords: superconductivity, intercalation, transition metal dichalcogenides, lithium

PCP2-3

Effect of non-magnetic rare earth substitution for Zr on mixed anion $Zr(P,Se)_2$ superconductors

*Kosuke Iwakiri[1,2], Taichiro Nishio[1], Kenji Kawashima[2,3], Shigeyuki Ishida[2], Kunihiko Oka[2], Hiroshi Fujihisa[2], Yoshito Gotoh[2], Akira Iyo[2], Hiraku Ogino[2], Hiroshi Eisaki[2], Yoshiyuki Yoshida[2], Hijiri Kito[2]

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AIST[2]
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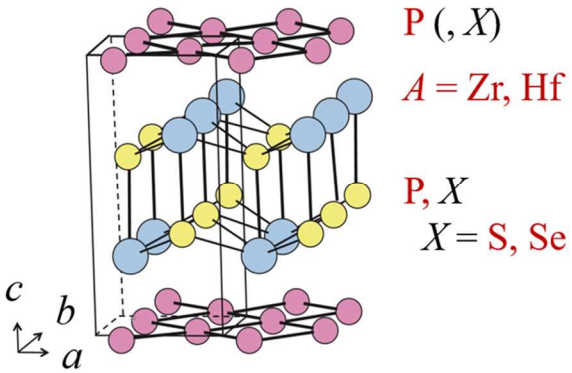
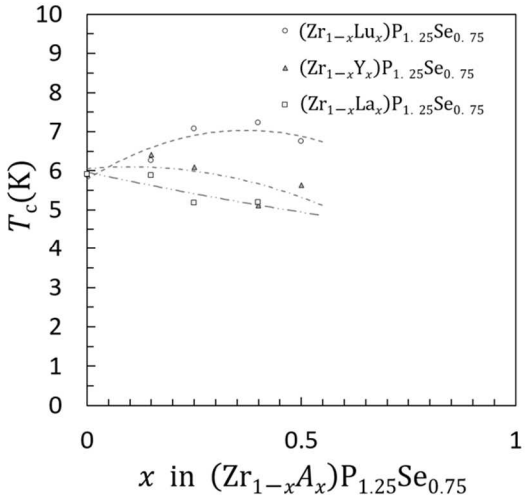
We have reported various physical properties [1] and single crystal growth [2] concerning the group of APX (A = Zr, Hf; X = S, Se) superconductors (Fig. 1) with PbFCl type crystal structure (space group $p4/nmm$) including Zr - P - Se superconductors (the superconducting transition temperature (T_c) ~ 6.3 K). These compounds are layered structures as seen in cuprates and iron-based superconductors. Furthermore, T_c depends on an elemental substitution quantity. Thus T_c is likely to rise even further.
For increasing T_c, we investigated the substitution effect of Zr atoms of $ZrP_{1.25}Se_{0.75}$ by nonmagnetic rare earth atoms. Figure 2 shows T_c as a function of an amount of substitution x by several rare earth atoms. Clearly, the substitution by Lu atoms gives rise to an enhancement of T_c (T_c reaches to 7.22 K when $x \sim 0.4$ and decreases with further substitution). In addition, the lattice constants are proportional to an amount of the substitution as Vegard's law. In the presentation, we report the details and implications of these results [3].

[1] H.Kitô *et al.* : J.Phys.Soc.Jpn. 83 (2014) 074713.
[2] H.Kitô *et al.* : The Physical Society of Japan(Fall 2014 meeting) 9aPS-13.
[3] K. Iwakiri : Tokyo Univ. of Science Graduation thesis(2016)





Keywords: Mixed anion superconductor, APX (A = Zr, Hf; X = S, Se), substitution effect

PCP2-4

Single Crystal growth of mixed anion Zr(P, Se)$_2$ superconductor and related materials

*Hijiri Kito[1], Kousuke Iwakiri[1,2], Taichiro Nishio[2], Kenji Kawashima[1,3], Shigeyuki Ishida[1], Kunihiko Oka[1], Hiroshi Fujihisa[1], Yoshito Gotoh[1], Akira Iyo[1], Hiraku Ogino[1], Hiroshi Eisaki[1], Yoshiyuki Yoshida[1]

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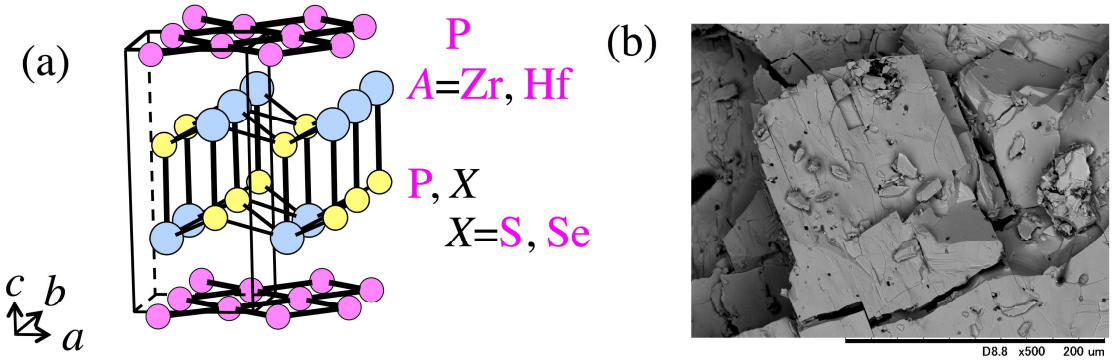
IMRA Material R&D Co., Ltd[3]

A new method to grow single crystals of PbFCl-type mixed anion $AP_{2-x}X_x$ (A=Zr, Hf, X=S, Se) superconductor [1] are examined. Using a wedge-type, cubic-anvil, high- pressure apparatus, single crystals of $ZrP_{1.25}Se_{0.75}$ (A=Zr, X=Se) were grain grown from nominal composition melts under a pressure of 2.0 GPa. Plate-like obtained single crystal with approximate edge sizes of 200×200×10 micron^3 was measured on electron probe microanalysis and X-ray diffraction indicate that the as-grown boules are a single phase $ZrP_{1.25}Se_{0.75}$. Superconducting transition temperature (T_c) is 6.31 K for $ZrP_{1.25}Se_{0.75}$ single crystal. Single crystal growth of the substitution of non-magnetic rare earth ions for A (A=Zr) site were from the nominal composition $(Zr_{0.60}Lu_{0.40})PSe$ also successful and T_c is reached at 7.50 K for these single crystals [2]. In the presentation, we will also discuss the crystal growth of these compounds.

[1] H. Kitô *et al.* J. Phys. Soc. Jpn. 83 (2014) 074713.
[2] H. Kitô *et al.*, private communication.



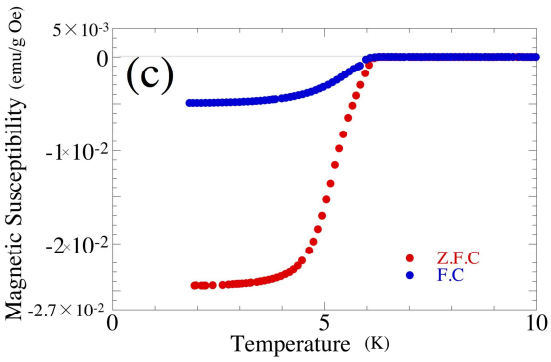


Fig.(a) The crystal structure for PbFCl-type $AP_{2-x}X_x$ (A=Zr, Hf; X=S, Se).
Fig.(b) SEM image of the obtained typical $AP_{2-x}X_x$ (A=Zr, X=Se) crystal
Fig.(c) The temperature dependence of the magnetic susceptibility under H=20 Oe for the obtained typical $AP_{2-x}X_x$ (A=Zr, X=Se) crystal.

Keywords: Single crystal Growth, Mixed anion superconductor, AP2-xXx (A=Zr, Hf; X=S, Se)

PCP2-5

Synthesis and Superconductivity of a Strontium Digermanide $SrGe_{2-\delta}$ with $ThSi_2$ Structure

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

We have succeeded in crystallizing a new strontium digermanide (SrGe2-δ) with the ThSi2-type structure (tetragonal $SrGe_2$) [1], which is theoretically predicted to compete with the EuGe2-type one (trigonal SrGe2) under pressure [2]. The tetragonal SrGe2 appeared as a metastable phase in samples at approximately 900°C under a pressure of 2 GPa. X-ray diffraction studies show that the tetragonal SrGe2 is formed by the reaction between trigonal SrGe2 and excess Sr. The composition of the tetragonal SrGe2 was analyzed to be $SrGe_{1.66(4)}$. Lattice parameters for the tetragonal SrGe2 are determined to be a = 4.559(4) Å and c = 14.42(1) Å. The tetragonal SrGe2 shows metallic resistivity behavior and exhibits superconductivity with a critical temperature (T_c) of 7.3 K, which is the highest among compounds with the ThSi2-type structure. Superconducting properties of the tetragonal SrGe2, such as the upper critical field, and the effect of pressure on T_c, are presented and superconductivity is discussed on the basis of electronic band structure calculations.

[1] A. Iyo, I. Hase, K. Kawashima, S. Ishida, H. Kito, N. Takeshita, K. Oka, H. Fujihisa, Y. Gotoh, Y. Yoshida and H. Eisaki, Inorg. Chem. **56** (2017) 8590.
[2] J. T. Wang, C. Chen and Y. Kawazoe, Phys. Rev. B **91** (2015) 054107.

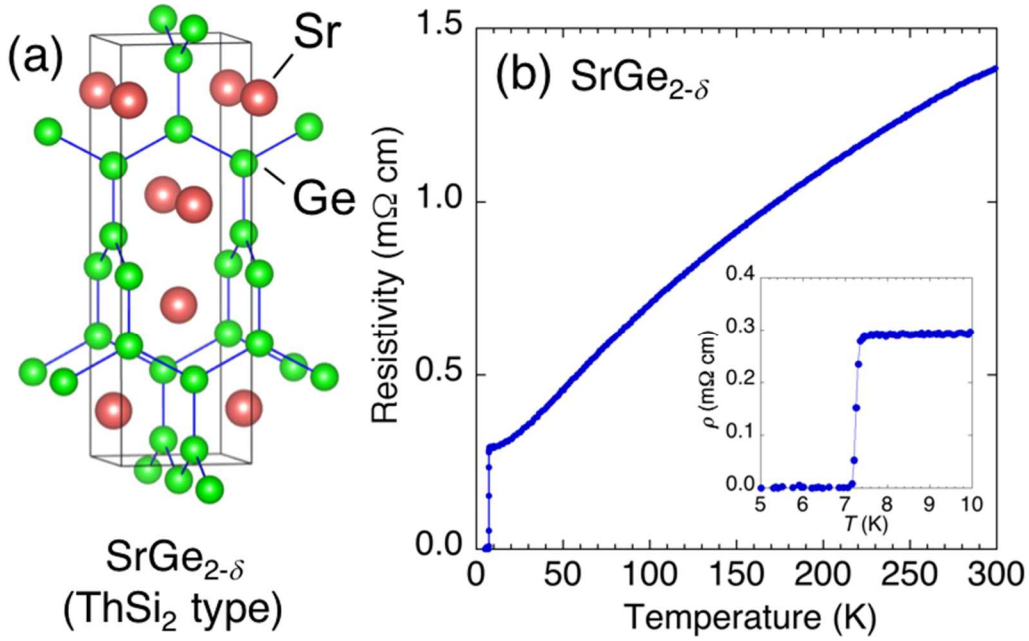

Fig. (a) Crystal structure and (b) temperature dependence of resistivity for a new strontium digermanide (SrGe2-δ)

Keywords: New superconductor, ThSi2-type structure, High-pressure synthesis, Band structure calculations

PCP2-6

Electronic Structure of Novel Binary Superconductor $SrGe_2$: A First-principle study

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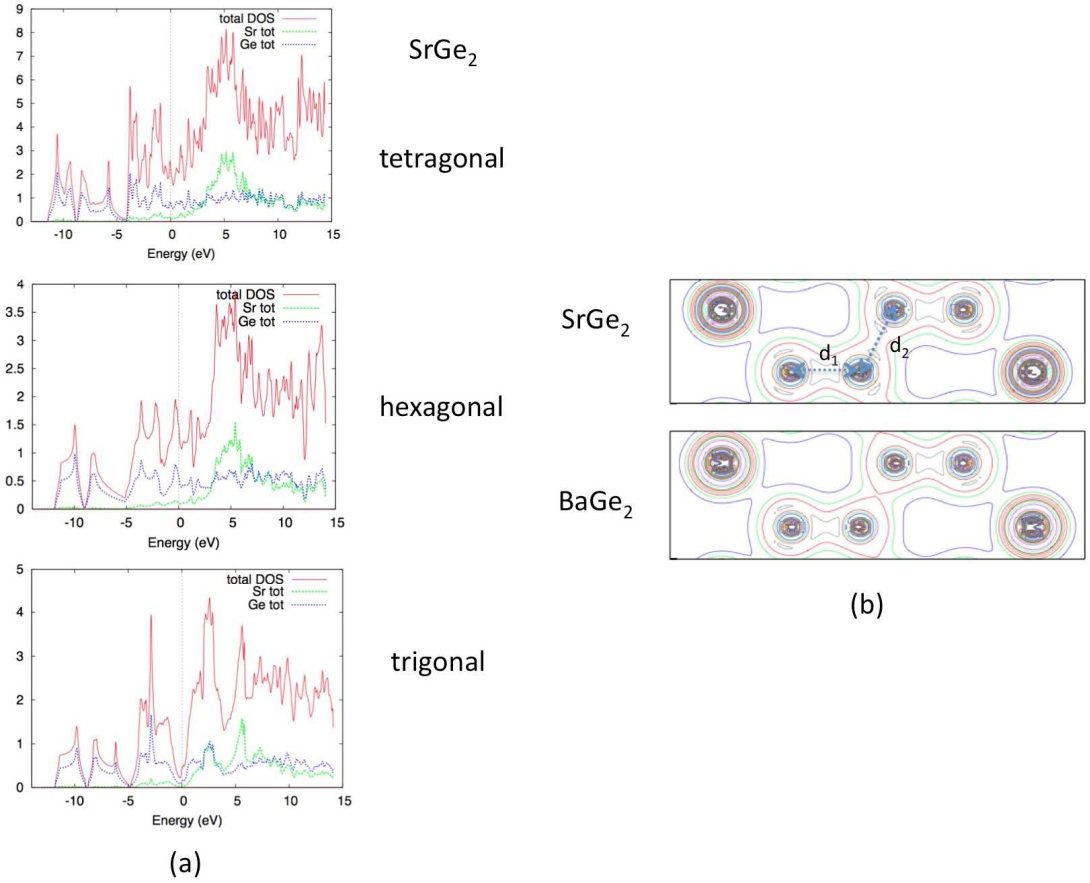
Due to the simplicity of its composition, many binary superconductors have been developed so far. Some are practically used like Nb_3Ge, and others have high T_c like MgB_2 or single layer FeSe. Recently we discovered that tetragonal $SrGe_{2-x}$ shows superconductivity by high pressure synthesis[1]. This compound attracts our attention because it has the highest T_c among AGe_2 series (A: alkaline-earth or rare-earth element).

In this paper we investigated the electronic structure of $SrGe_2$ from first principles. There are several polymorphs of $SrGe_2$, and the obtained density of states at the Fermi level (=$D(E_F)$) per $SrGe_2$ is 5.5, 20.3, 16.3 Ry^{-1} for trigonal, hexagonal and tetragonal structure, respectively. $D(E_F)$ of tetragonal $SrGe_2$ is not more than the isostructural and isovalent compound $BaGe_2$, which has lower T_c than $SrGe_2$. Electron density map suggests that the valence electrons in $SrGe_2$ form a three-dimensional network, while in $BaGe_2$ they form a dimer.

[1] A. Iyo *et al.* Inorg. Chem. **56** (2017) 8590.



Keywords: binary superconductor, electronic structure, SrGe2, ThSi2-type structure

PCP2-7

The electrical resistance of gold-capped chromium thin films

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From the point of view not only of pure research but also of applied and practical one, there are many examples of superconducting thin films. But almost all of them were those in which superconductivity disappears when the film thickness is made thin. It is likely to make a superconducting electron pair when it becomes thinner than the mean free path of electrons. On the other hand, Schmidt et al. reported that thin films of chromium (Cr) metal suppress the antiferromagnetic ordering and become superconductive at T_C ~1.5 K (P. H. Schmidt et al., Physics Letters, **41A**, 367 (1972)). Taking account that the bulk Cr is an antiferromagnet below T_N = 311 K and does not show superconductivity, the relationship between film thickness and existence of superconductivity of Cr is opposite to the other examples of superconducting thin films. Recently, we have studied the electrical resistance of Cr thin films (M.Ohashi et al., Physics Letters, A, **380**, 3133 (2016)), and found a sudden decrease in resistance at T_C = 1.5K. However, the electric resistivity did not drop to zero below T_C and the resistivity drop ratio was very small in all film. Talking account that aluminum wires were bonded as electrodes on the film plane because chromium oxide layer is uncongenial to the gold wires, such behavior may come from superconductivity of aluminum wires. In the present work, we prepared polycrystalline Cr thin films capped by gold layer in order to prevent the oxidation. Several thickness polycrystalline Cr thin films were deposited on silicon substrate using ion beam sputtering. The gold layer were deposited 5nm on Cr film surface. Gold wires were bonded as electrodes on the film plane. The electrical resistance was measured using the Quantum-Design PPMS between 0.5 and 350K. The X-ray measurement was performed using Rigaku SmartLab. The details of the results will be reported in the presentation.

Keywords: Cr film, Electric resistivity, Superconductivity

PCP2-8

Diamond Anvil Cell with Boron-doped Diamond Electrodes and Undoped Diamond Insulating Layer

*Ryo Matsumoto[1,2], Aichi Yamashita[1,2], Hiroshi Hara[1,2], Tetsuo Irifune[3], Hiromi Tanaka[4], Hiroyuki Takeya[1], Yoshihiko Takano[1,2]

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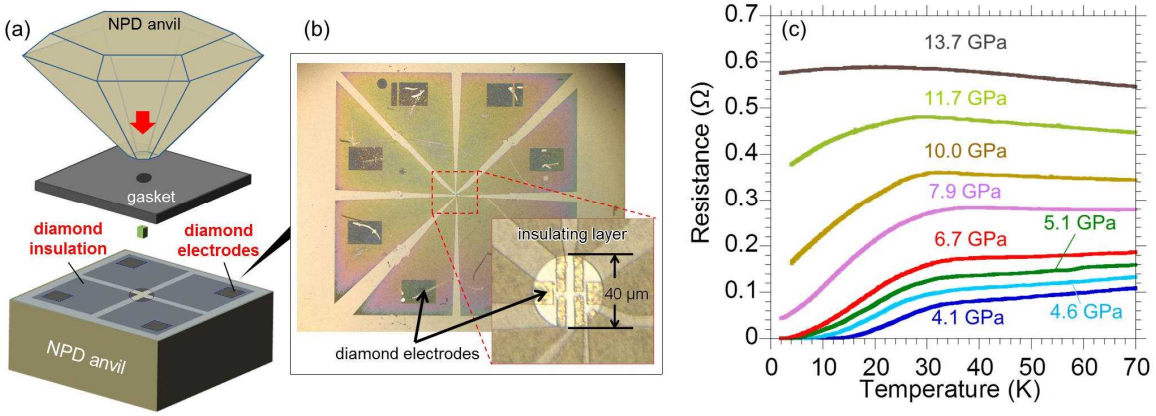
NIT, Yonago College[4]

The great discovery of 200 K superconductivity in H_3S under 150 GPa has recently reported by resistivity measurements using a diamond anvil cell (DAC) [1]. It is interesting that if we can measure the resistivity under extremely higher pressure above 300 GPa, superconductivity at room temperature in hydrogen could be observed [2]. However, resistivity measurement using DAC is difficult because it requires the small sample sizes (< 100 μm) and the hard electrodes. Moreover, an insulating layer should be inserted between the electrodes and a metal gasket which is also broken by applying pressure. In this study, we focused on the boron-doped metallic diamond [3,4] and undoped diamond as a very hard electrode and an insulating layer, respectively. The diamond electrodes and insulating layer have been designed on the bottom diamond anvil as presented in Fig (a). As shown in Fig (b), the resistivity measurements of single crystal FeSe have been demonstrated using the developed device under various pressures, and then the pressure effect for T_c was clearly observed.

[1] A. P. Drozdov et al., *Nature* **525**, 73(2015).
[2] N. W. Ashcroft, *Phys. Rev. Lett.* **21**, 1748 (1968).
[3] R. Matsumoto et al., *Rev. Sci. Instrum.* **87**, 076103 (2016).
[4] R. Matsumoto et al., *Jpn. J. Appl. Phys.* **56**, 05FC01 (2017).



Keywords: Diamond anvil cell, High pressure

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

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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).

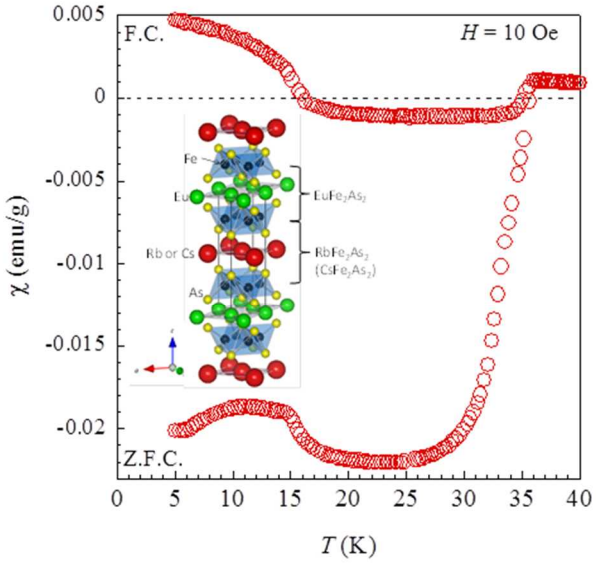

Fig. 1

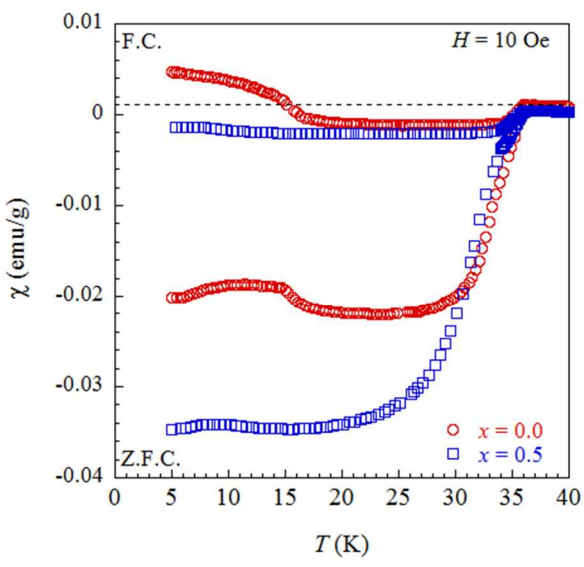

Fig. 2

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

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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 $LaFeAs_{1-x}P_xO_{1-y}(F/H)_y$ 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

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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).

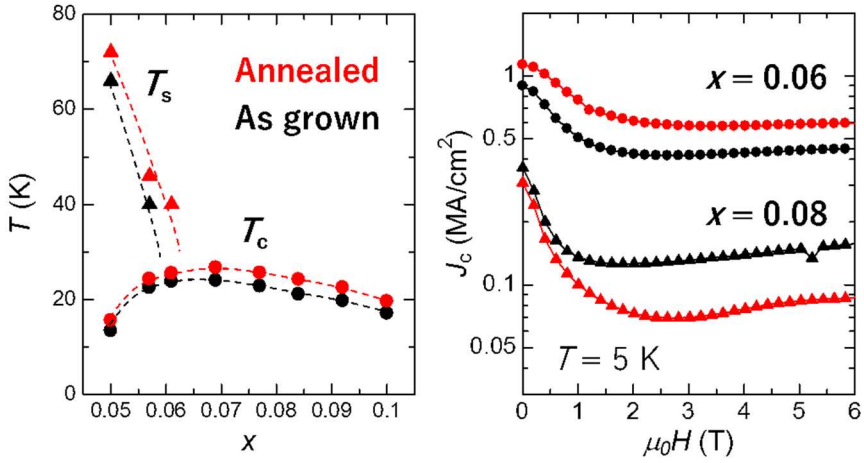

Fig. 1 (left) Doping dependence of T_c and $T_{N/s}$ for as-grown and annealed $Ba(Fe_{1-x}Co_x)_2As_2$. (right) Magnetic field dependence of J_c for as-grown and annealed $Ba(Fe_{1-x}Co_x)_2As_2$ (x = 0.06 and 0.08).

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

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Nishina Center, RIKEN, Wako, Saitama, Japan[2]
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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 $YBa_2Cu_3O_{7-\delta}$ [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.

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[2] Y. Nakajima *et al.*, Phys. Rev. B **80**, 012510 (2009).
[3] T. Tamegai *et al.*, Supercond. Sci. Technol. **25**, 084008 (2012).
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[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

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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.

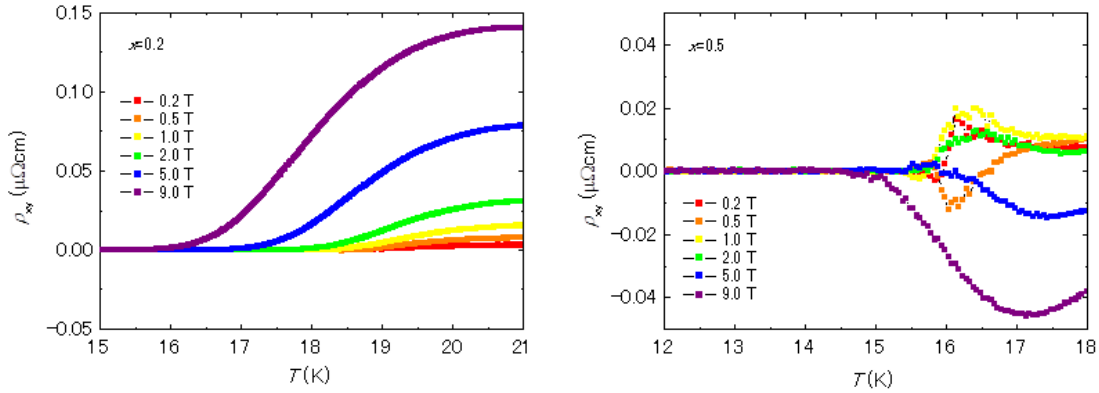

Fig. The Hall resistivity for x=0.2 (left) and x=0.5 (right).

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PCP3-8

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

PCP3-9

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 (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.

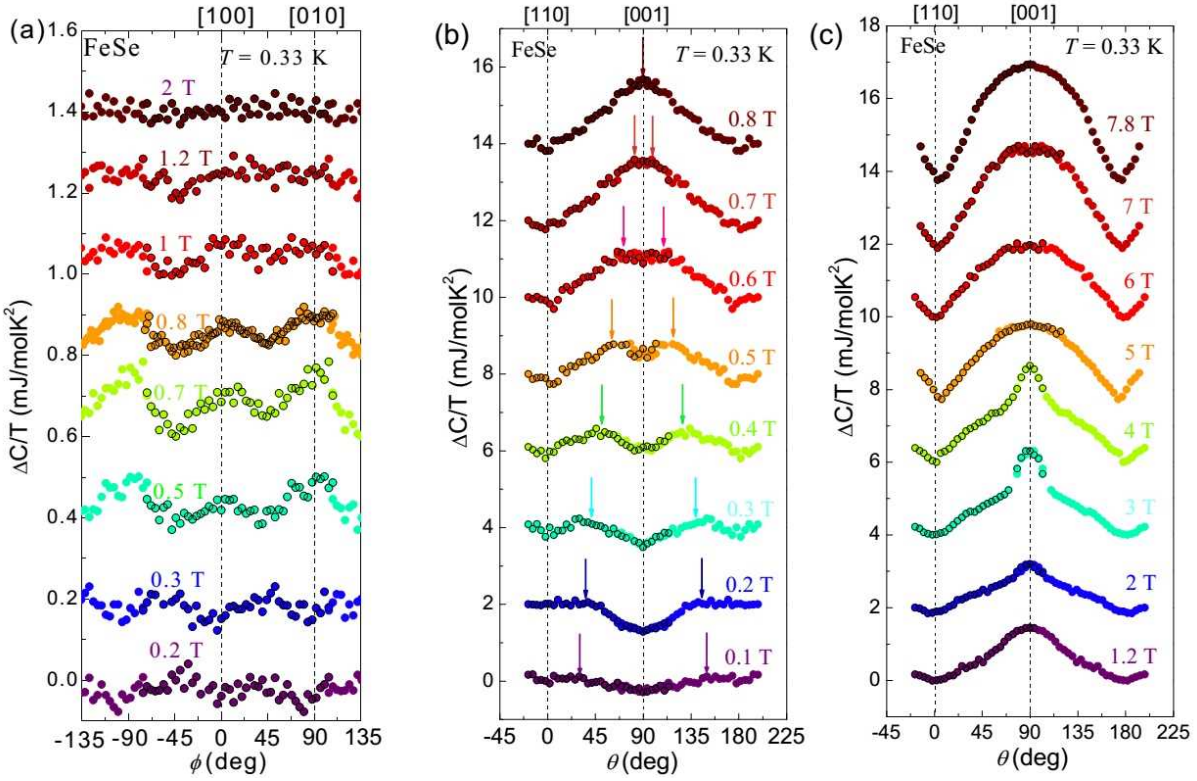

Fig. (a) Azimuthal angle dependence of the specific heat $\Delta C(\phi)/T$ measured under various fields at 0.33 K. $\Delta C(\phi)=T$ is defined as $C(\phi)/T - C(-45^\circ)/T$, and each subsequent curve is shifted vertically by 0.2 mJ/molK². Polar angle dependence of the specific heat $\Delta C(\theta)/T$ 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/molK².

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

PCP4-1

Anomalous Metal Interface Effect of Iron-based Superconductors

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We have studied the proximity effect of iron-based superconductors (IBS) by using an Andreev spectroscopy. The proximity effect between IBS and a conventional metal is expected to be sensitive to the pairing symmetry of IBS. Previously, we have studied the junctions, in which one electrode was a Fe[Te,Se] single crystal and the counter electrode was metal/(metal oxide)/Pb triple layers. The metal layer was expected to show the proximity effect. There, we observed an abnormally large gap in some combination of the electrodes [1]. In some reason, the junctions were interpreted as an IBS/N type. Then, the large gap structure could be induced by the interface effect of IBS and a specific metal (in this case, Pb).

Here, we report the results of the Andreev spectroscopy of the Co-doped Ba-122 single crystals (T_c~22 K), using a same junction structure as previously used. In the present experiment, Al, Pb, Sn, and Ag of ~2 nm thickness were used as a metal layer. Here, we did not intentionally oxidize the metal surface, so that no oxide layer was expected. Figure 1 shows the temperature dependences of junction conductance, for (a) an Al and (b) a Sn electrode, respectively. In the case of Al, we have observed conventional Andreev spectra, with a gap value of ~2mV and ~11 mV, consistent with the previous reports [2]. Similar spectra were obtained for Ag and Pb electrodes. On the other hand, in the case of Sn, the spectra were very anomalous both in the structure and in the temperature dependence. Although we could not interpret them well, they resemble to our Fe[Te,Se] results [1], in terms of the tunnel-like dip structure and an associated large-gap value. The present observation indicates that the specific combination of an IBS and a layering metal strongly alters spectra, irrespective to the type of IBS. It supports our hypothesis that the large gap formation is due to an interface effect of adjacent metal.The interface could dope a carrier into IBS and/or modify the characteristics of IBS due to inter-diffusion. Note that in our junctions, none of the combination of proximity metal-IBS accommodates with a Josephson current.

[1] N. Fujioka *et al.* , *Physica C* **518** , 28 (2015)
[2] K. Terashima *et al.* , *Proc Natl Acad Sci U S A* **106**,7330 (2009)

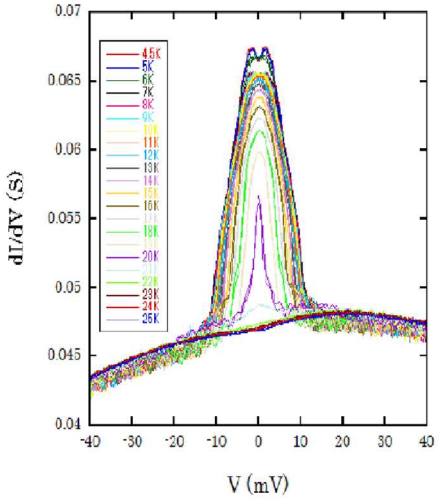

Fig. 1(a). The temperature dependence of the junction conductance using an Al electrode.

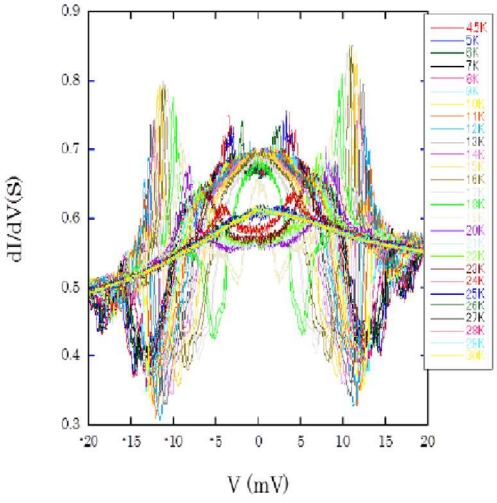

Fig. 1(b). The temperature dependence of the junction conductance using a Sn electrode.

Keywords: superconductor, Fe[Te,Se], Co-doped Ba-122, Andreev spectroscopy

PCP4-2

Transport properties of FeSe epitaxial thin films under in-plane strain

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The iron-chalcogenide superconductor, FeSe, is the most suitable material for understanding the superconductivity of the iron-based superconductors (FeSCs) because it has the simplest crystal structure among the FeSCs, composed of conducting planes alone. Although the superconducting transition temperature (T_c) of bulk FeSe is 8 K, those of epitaxial thin films on CaF_2 substrates reach 12 K[1]. Because the films are compressed along the *a*-axis, it suggests that the T_c depends on the in-plane strain. Thus, to confirm this, and to clarify the mechanism of this T_c enhancement, we prepared FeSe films with various magnitude of strain, including tensile strain, and measured the transport properties of those films.
All of the in-plane strained films in this study were grown by pulsed laser deposition (PLD) with a KrF laser. The single-crystal substrates we used were $LaAlO_3$ (LAO), $(LaAl)_{0.7}$-$(SrAl_{0.5}Ta_{0.5})_{0.3}O_3$ (LSAT) and CaF_2. The magnitude of strain was evaluated by X-ray diffraction measurements and the result are shown in Fig. 1(a).
The temperature dependence of the electrical resistivity is shown in Fig. 1(b). We confirmed the systematic change of T_c along with the change of the in-plane strain parameter, ε. In addition, we measured the Hall effect and the magneto-resistance. In this presentation, we will also report the change of the transport properties of the films along with the change of ε and discuss the effects of the strain on superconductivity.

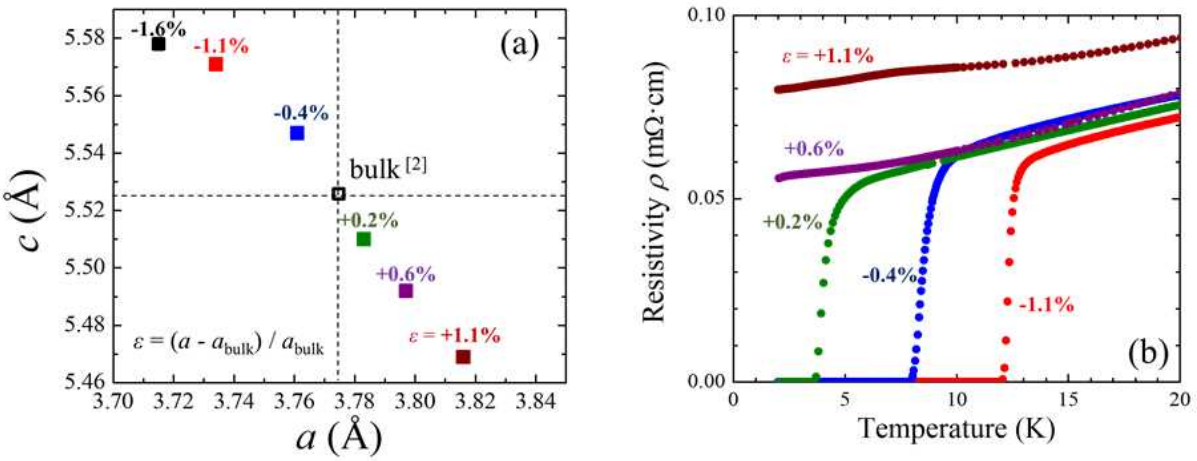

Fig. 1(a) Relation between the *a*- and *c*-axis lattice constants of the FeSe films in this study. (b)Temperature dependence of the electrical resistivity of the FeSe films with various magnitude of strain.

[1] F. Nabeshima et al., Appl. Phys. Lett. 103, 172602 (2013). A. Maeda et al., Appl. Sur. Sci. 312, 43 (2014). [2] T. M. McQueen et al., Phys. Rev. B 79, 014522 (2009).

Keywords: iron-chalcogenide, thin films, strain, transport properties

PCP4-3

Transport Properties of NdFeAs(O,F) Epitaxial Thin Films Grown on Vicinal-Cut MgO Substrates

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For FeSe, *AE*Fe_2As_2 (*AE*=Ca, Sr, Ba) and *A*FeAs (*A*=Li, Na), measurement of transport properties along the crystallographic *c*-axis is possible because large single crystals can be grown. However, the size of available *Ln*FeAsO (*Ln*: lanthanide elements) single crystals is still limited, which makes transport measurements difficult. Measurements of transport properties of *Ln*FeAsO using a micro-bridge fabricated by a focus-ion-beam technique have been reported[1], but this method is rather complicated. Here, we report a simple way to measure both r_{ab} and r_c of NdFeAs(O,F) epitaxial thin films on vicinal-cut MgO substrates, where r_{ab} and r_c are the resistivity along the *ab*-plane and *c*-axis, respectively. NdFeAs(O,F) epitaxial films having a thickness of 40 nm were grown on vicinal-cut MgO (001) single crystalline substrates. The vicinal angle was 5° or 10° measured from the [001] direction towards [100]. During the growth, the surface was monitored by reflection high energy electron diffraction (RHEED). RHEED pattern of the thin films showed oriented and tilted growth with a smooth surface, and X-ray diffraction pattern showed a *c*-axis textured growth. These results indicate an epitaxial growth of NdFeAs(O,F) on both the 5° and 10° vicinal-cut MgO substrates. After structural characterizations, two bridges, "L"- and "T"-bridges, were fabricated by photolithography and Ar-ion beam etching methods. The bias current flows parallel to the *ab*-plane in the "L"-bridge, whereas the bias current crosses the *ab*-plane in the "T"-bridge. Fig. 1 shows the temperature dependence of resistivity measured on the "L"- and "T"-bridges on the 5° vicinal-cut MgO substrate. The normal state resistivity of the "T"-bridge is higher than that of the "L"-bridge. This reflects the anisotropy of r_{ab} and r_c, since both components (i.e. r_{ab} and r_c) contribute to the total resistivity in the "T"-bridge. The anisotropy $g=r_c/r_{ab}$ increased with decreasing temperature, and the value of g was about 170 at the superconducting transition temperature. This work was partially supported by the JSPS Grant-in-Aid for Scientific Research (B) Grant Number 16H04646.

[1] P. J. W. Moll *et al.*, *Nat. Mater.* **9**, 628 (2010); H. Kashiwaya *et al.*, *Appl. Phys. Lett.* **96**, 202504 (2010).

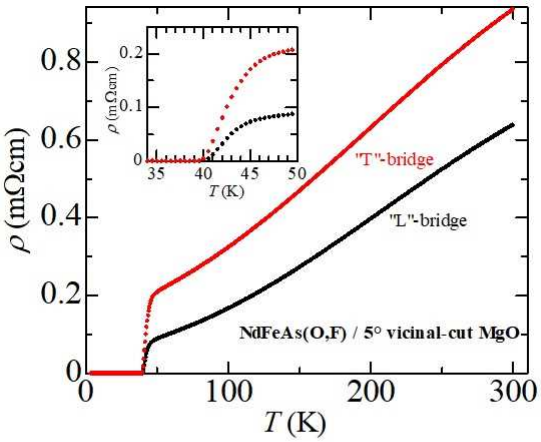

Fig.1 The temperature dependence of resistivity measured on the "L"- and "T"-bridges of a NdFeAs(O,F) thin film grown on a 5° vicinal-cut MgO substrate. The inset shows an enlarged view around the superconducting transition.

Keywords: Iron-based superconductor, Oxypnictide, Vicinal growth, Anisotropy

PCP4-4

FABRICATION OF GRAIN BOUNDARY JUNCTIONS USING NdFeAs(O,F) SUPERCONDUCTING THIN FILMS

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Systematic studies on the mis-orientation angle (θ_{GB}) dependence of transport properties of Co- and P-doped $BaFe_2As_2$ (Ba-122) as well as Fe(Se,Te) have been reported [1-3], but not for *Ln*FeAs(O,F) (*Ln*: lanthanide elements) to date. Here we report on the fabrication of epitaxial NdFeAs(O,F) thin films on [100]-tilt MgO bicrystal substrates with θ_{GB}=6°, 12°, 24° and 45°, and their inter- and intra-grain transport properties. The thin films were grown by molecular beam epitaxy using solid sources, Fe, As, NdF_3, Fe_2O_3, and Ga [4]. After structural characterization by X-ray diffraction, the thin films were photolithographically patterned and etched by Ar-ion milling to form micro-bridges for transport measurements. Figure 1 shows the azimuthal ϕ-scan profile of the off-axis (102) reflection of NdFeAs(O,F) thin film on 45° [001]-tilt MgO bicrystal. Eight peaks from two adjacent grains with a θ_{GB} of 45° are clearly observed that are sharp and strong. In addition, only (00*l*) peaks were observed by θ-2θ scan, indicative of an epitaxial growth of NdFeAs(O,F). In figure 2, the θ_{GB} dependence of inter-grain critical current density J_c is shown. Unlike Co-doped Ba-122 and Fe(Se,Te), the decay of inter-grain J_c with θ_{GB} is rather significant. As a possible reason of this result, we think that fluorine may have diffused preferentially to the grain boundary region and eroded the crystal structure. This work was partially supported by the JSPS Grant-in-Aid for Scientific Research (B) Grant Number 16H04646.

[1] S. Lee *et al.*, *Appl. Phys. Lett.* **95**, 212505 (2009); T. Katase *et al.*, *Nat. Commun.* **2**, 409 (2011).
[2] A. Sakagami *et al.*, *Physica C* **494**, 181 (2013).
[3] E. Sarnelli *et al.*, *Appl. Phys. Lett.* **104**, 162601 (2014); W. Si *et al.*, *ibid.* **106**, 032602 (2015).
[4] Kawaguchi *et al.*, *Appl. Phys. Lett.* **97**, 042509 (2010); T. Kawaguchi *et al.*, *Appl. Phys. Express* **4**, 083102 (2011).

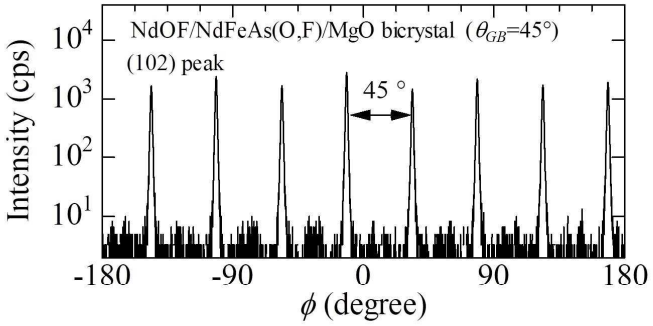

Fig.1. Azimuthal ϕ-scan profile of the off-axis (102) reflection of NdFeAs(O,F) thin film on [001]-tilt MgO bicrystal.

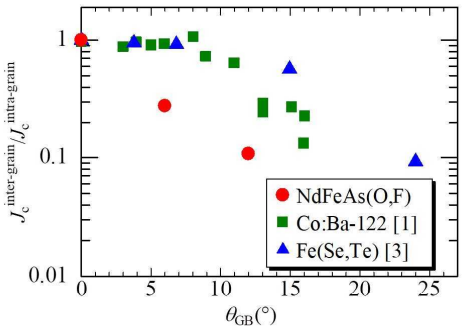

Fig.2. Mis-orientation angle θ_{GB} dependence of normalized inter-grain critical current density J_c .

Keywords: Iron-based superconductor, Oxypnictide, Grain boundary junction

PCP4-5

Search for superconductiveity in epitaxially deposited chromium thin films

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It is well-known that chromium (Cr) is an antiferromagnet below the Neel temperature T_N=311K. On the other hand, Schmidt et al. have reported that chromium thin films suppress the antiferromagnetic ordering and become show superconductive at T_C=1.5K (P. H. Schmidt et al., Physics Letters, 41A, 367 (1972)), while there was no experimental data such as resistivity drop and the Meissner effect. Recently we prepared epitaxially deposited Cr thin films and measured the electrical resistance at low temperature. It was found that the electrical resistance dropped to zero at 3.2K for the one film of 50nm thick, while there was no reproducibility. In the present study, we investigate the relation between the crystal structure and the electrical resistivity for single crystal Cr films to clarify the condition which shows superconducting. Single crystal chromium films were deposited on MgO 001 substrate using a conventional magnetron sputtering device. X-ray measurements were performed using a Rigaku SmartLab diffractometer in a high-resolution setup with Ge 400×2 crystal collimator, Ge 220×2 crystal analyzer, and $CuK_{\alpha 1}$ radiation (λ=1.54059Å). The thickness of the chromium oxide layer is obtained to be about 1 nm by X-ray reflectivity measurements. The electrical resistance was measured by a four-point collinear four-probe dc method with the current direction on the film plane. Aluminum wires were bonded on the film plane by wire bonding. The temperature dependence of the electrical resistivity was measured using the Quantum-Design PPMS between 0.5 and 350K. The details of results will be reported in the presentation.

Keywords: Cr film, Single crystal, Electrical resistivity, X-ray diffraction

PCP4-6

Inelastic Scattering Rate of Electron near Superconducting Transition Temperature of NbN Thin Films

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We have investigated the transport properties of the superconducting NbN thin films with $32\Omega<R_{sq}^{N}<1180\Omega$ epitaxially deposited on the (100) MgO substrates, where the R_{sq}^{N} is the normal state sheet resistance. We analyzed i) the excess conductance $\sigma'(T)=\sigma(T)-\sigma^{N}$ in the absence of the magnetic field H above the superconducting transition temperature T_c by the sum of Aslamazov-Larkin(AL) and Maki-Thompson(MT) terms given by$\sigma_{theo}'(T,\delta)=\sigma_{AL}'(T)+\sigma_{MT}'(T,\delta)$ for thermal fluctuations, where $\sigma^{N}=1/R_{sq}^{N}$ and δ is the pair breaking parameter, and analyzed ii) the magneto conductance $\Delta\sigma(T,H)=\sigma(T,H)-\sigma(T,0)$ at various temperatures above T_c. We found 1) the $\sigma_{theo}'(T,\delta)$ can be well fit to $\sigma_{exp}'(T)$ with use of a suitable value of theδ relating to the inverse of the inelastic scattering time $\tau_{in}(T)$ as $\delta=h/16k_BT\tau_{in}(T)$, and 2) the H dependence of$\Delta\sigma_{exp}(T,H)$ can be well explained by the theoretical expression$\Delta\sigma_{theo}(T,H,\tau_{in})$ with a suitable value of$\tau_{in}(T)$ at a wide range of temperature, where the$\Delta\sigma_{theo}(T,H,\tau_{in})$ is given by the sum of weak localization term $\Delta_L(T,H,\tau_{in})$, AL term $\Delta_{AL}(T,H)$ and MT term $\Delta_{MT}(T,H,\tau_{in})$. We compared the inelastic scattering times$\tau_{in,F}(T)$ and$\tau_{in,M}(T)$ estimated from the analyses of$\sigma_{exp}'(T,0)$ with use of the above relation$\tau_{in}(T)=h/16k_BT\delta$ and$\Delta\sigma_{exp}(T,H)$, respectively. Although values of the rate $1/\tau_{in,F}(T)$ and $1/\tau_{in,M}(T)$ are essentially the same magnitudes, both quantities show the anomalous decrement form the theoretical expression for $1/\tau_{in}(T)$ given by the sum of three dominant terms $1/\tau_{fluc.}(T)$, $1/\tau_{e\text{-}e}(T)$ and $1/\tau_{e\text{-}ph}(T)$, where the first, second and third terms correspond to superconducting fluctuation, electron-electron scattering and electron phonon scattering mechanisms. This discrepancy between experiment and theory suggests the existence of the additional contribution from density of state to quantum correction to the conductance.

Keywords: superconducting thin film, fluctuation conductivity, inelastic scattering time

PCP4-7

Observation of fluxoid states and interstitial vortices in perforated mesoscopic triangle of amorphous superconducting thin films

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In mesoscopic superconductors, arrangements of quantized magnetic flux(vortices) are determined by the interplay between the confinement geometry and mutual repulsive interaction. While many of unique mesoscopic flux states have been proposed theoretically [1] and observed experimentally [2-5], direct observation of some of unique flux states, including the multiply quantized flux(giant vortex) and anti flux(anti-vortex), remains an experimental challenge [6]. In this study, we report magnetic visualizations of fluxoid states in perforated mesoscopic triangles of amorphous superconducting thin films with the scanning SQUID microscope. We observed the fluxoid quantization with multiple flux quanta at the hole and the penetration of interstitial vortices between the hole and the sample edge. The penetration field H_p of the interstitial vortex depends on the sample size and varies as H_p with the spacing between the hole and the sample edge.

[1] B. J. Baelus, et al., Phys. Rev. B 69, 064506 (2004).
[2] N. Kokubo, et al., Phys. Rev. B 82, 014501 (2010).
[3] N. Kokubo, et al,. J. Phys. Soc. Jpn 83, 083704 (2014).
[4] N. Kokubo, et al,. J. Phys. Soc. Jpn 84, 043704 (2015).
[5] N. Kokubo, et al., in Multi-Vortex States in Mesoscopic Superconductors (Chapter 3), The Oxford Handbook of small Superconductors, edited by A. V. Narlikar, (Oxford University Press, United Kingdam), 81-107 (2017).
[6] L. F. Chibotaru, et al., Nature 408, 833 (2000).

Keywords: Mesoscopic superconductors, Fluxoid States, Scanning SQUID microscope

PCP4-8

Analysis of the microstructure of bulk MgB_2 using EBSD and t-EBSD

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The grain orientation, the texture and the grain boundary misorientations are important parameters for the understanding of the magnetic properties of the bulk MgB_2 samples intended for super-magnet applications. Such data can be provided by electron backscatter diffraction (EBSD) analysis. However, as the grain size of the MgB_2 bulks is preferably in the 100-200 nm range, the common EBSD technique working in reflection works only properly on highly dense samples. In order to achieve a reasonably good Kikuchi pattern quality on all samples, we apply here the newly developed transmission EBSD (t-EBSD) technique [1] to MgB_2. This method requires the preparation of TEM slices by means of focused ion-beam milling, which are then analyzed within the SEM, operating with a specific sample holder. Furthermore, we identified the Kikuchi pattern of the MgB_4 phase which appears at higher reaction temperatures and may act as additional flux pinning sites. We present several EBSD mappings of samples including two-phase scans with MgB_4 as a secondary phase.

[1] P. W. Trimby, Ultramicroscopy 120, 16 (2012).

Keywords: EBSD, Grain orientation, MgB2, pinning

PCP4-9

Nanoscale Investigations of the MgB_2 Superconductor by STM/STS

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Since the discovery of the superconductivity with T_c = 39 K, the MgB_2 compound has been one of the most fascinating superconductors both from the physical sciences and applications points of view. It is widely recognized that the superconductivity possesses an s-wave pairing symmetry with the existence of the multiple gaps consisting of the 2 dimensional σ band and 3 dimensional π band [1]. However, in spite of the numerous studies about this compound, the details of the nanoscale features of the electronic states and the gap distributions were not yet completely understood.

Here, we present the results of the nano-scale measurements using the low-temperature scanning tunneling microscopy/spectroscopy (STM/STS) apparatus to clarify the nano-scale electronic structures. The measurements were carried out at 4.9 K to 40 K using a Pt-Ir tip in ultra-high vacuum condition. From the STS measurements, the two kinds of gaps, 2Δ ~20 and ~ 10 meV were observed, which were considered to be corresponding to the σ-band and π-band, respectively. The scanned maps of the conductance (dI/dV) and the gap values obtained in the area of 4 nm x 4 nm show the relatively homogenous gap distributions consisting of the σ band type (average of peak-to-peak voltage $V_{\mathrm{pp\ ave}}$ (~2Δ) ~ 14 meV with the standard deviation σ~3 meV) with local conductance peaks at zero-bias voltage. The details of measured results including such intriguing features will be discussed and summarized.

[1] P.C. Canfield, G.W. Crabtree, Physics Today 56 (2003) 34.

Keywords: MgB2, STM/STS, tunneling spectroscopy

PCP5-1

Cu hyperfine coupling constants of $HgBa_2CaCu_2O_{6+\delta}$

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The ratios of ^{63}Cu hyperfine coupling constants in the double-layer high-T_c superconductor $HgBa_2CaCu_2O_{6+\delta}$ are estimated from the anisotropies in Cu nuclear spin-lattice relaxation rates and spin Knight shifts to study the nature of the ultraslow fluctuations causing the T_2 anomaly in the Cu nuclear spin-echo decay [1]. The ultraslow fluctuations may come from magnetic fluctuations spread over a region around the wave-vector $q = 0$, otherwise charge/phononic fluctuations.
[1] Y. Itoh, T. Machi, and A. Yamamoto: Phys. Rev. B **95**, 094501 (2017).

Keywords: Hg1212, NMR

PCP5-2

Rare-earth dependence of in-plane anisotropy of resistivity in Bi2201 series high temperature superconductors

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The presence of a pseudogap phase in the phase diagram of copper oxide high temperature superconductors is well established, where the density of states at the Fermi energy is partially depleted above the superconducting transition temperature. The origin of the pseudogap and its relation to superconductivity have been actively discussed. It was reported that the in-plane four-fold rotational (C_4) symmetry is spontaneously broken in the pseudogap phase. Measuring the resistivity anisotropy is one of the simplest ways to verify the electronic anisotropy raising from the broken C_4 symmetry. Indeed, it was reported that the in-plane resistivity is highly anisotropic for underdoped $La_{2-x}Sr_xCuO_4$ and $YBa_2Cu_3O_{7+\delta}$[1].

In $Bi_2Sr_2CuO_{6+\delta}$ (Bi2201), the superconducting transition temperature and pseudogap formation temperature (T^*) depend on the rare-earth element substituted for Sr even when the same amount is doped [2]. Hence, we can prepare samples that have the same hole concentration but different T^*, and it would be interesting to study the in-plane anisotropy and compare it with T^*. For this purpose, we measured the in-plane anisotropy of resistivity following the method reported in Ref. [3] on single crystals of Bi2201 doped with different rare earth elements. In a sample doped with 30% of La, we observed that the in-plane anisotropy increased with lowering the temperature, suggesting the breaking of C_4 symmetry. This is in a sharp contrast with a sample doped with 10% of La which showed no enhancement of the resistivity anisotropy. Based on our experimental results, we will discuss the relationship between T^* and the breaking of C_4 symmetry.

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[2] Y. Okada *et al.* J. Phys. Soc. Jpn. **77**, 074714 (2008).
[3] P. Walmsley and I. R. Fisher, *Rev. Sci. Instrum.* **88**, 043901 (2017).

Keywords: Cuprate, Pseudogap, Nematicity, Transport

PCP5-3

Effect of Ba-substitution for Sr in the Bi-2201 Phase of $BiPb(Sr,La)_2CuO_{6+\delta}$

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The highest value of the superconducting transition temperature T_c in the Bi-2201 phase is ~ 40 K for $(Bi,Pb)_2(Sr,La)_2CuO_{6+\delta}$, *which is much lower than ~ 90 K in the Tl-2201 phase of* $Tl_2Ba_2CuO_{6+\delta}$ *[1,2]. Considering* the empirical rule that T_c increases with an increase of the distance between Cu and O, the reason for the lower T_c of the Bi-2201 phase is because larger Ba^{2+} ions in the Tl-2201 phase are replaced by smaller Sr^{2+} ions in the Bi-2201 phase. In this research, we have attempted *to* increase T_c of the Bi-2201 phase by extending the Cu-O distance through the substitution of Ba for Sr in $(Bi,Pb)_2(Sr,La)_2CuO_{6+\delta}$.
Polycrystalline samples of $BiPbSr_{1.15-x}Ba_xLa_{0.85}CuO_{6+\delta}$ were prepared by the solid-state reaction method. The iodometric titration was carried out to estimate the oxygen content. Magnetic susceptibility measurements were performed to determine T_c using a SQUID magnetometer. Measurements of the thermoelectric power at room temperature were carried out to estimate the hole-concentration in the CuO_2 plane [3].
The hole-concentration in the CuO_2 plane is almost constant despite the increase in the oxygen content $6+\delta$ with increasing x(Ba), as shown in Fig. 1. These results indicate that holes are supplied to Bi(Pb)-O layers rather than to the CuO_2 plane with increasing x(Ba). With increasing x(Ba), T_c does not increase but tends to decrease slightly. The decrease in T_c with increasing x(Ba) may be due to the local distortion caused by excess oxygen.

[1] S. Kambe *et al.*, Solid State Commun. **75** (1990) 435.
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Keywords: Bi-2201, Ba-substitution, Superconducting transition temperature

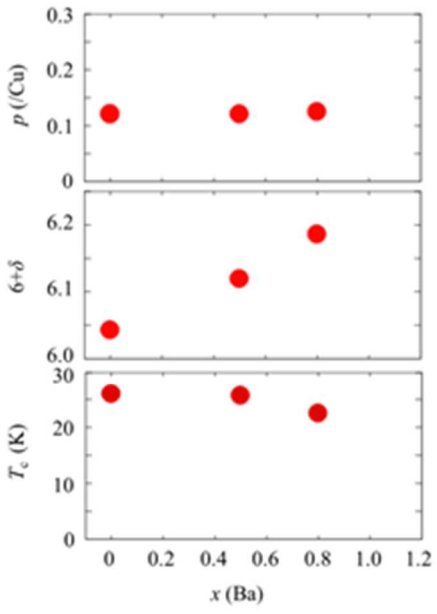

Fig. 1: Dependence of T_c, the oxygen content $6+\delta$ and the hole concentration in the CuO_2 plane p on the Ba content x in $BiPbSr_{1.15-x}Ba_xLa_{0.85}CuO_{6+\delta}$.

PCP5-4

Superconductivity above 100 K in the Bi-2212 Phase of $(Bi,Pb)_2Sr_2CaCu_2O_8$

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The high-T_c cuprate superconductor of the Bi-2212 phase, $Bi_2Sr_2CaCu_2O_{8+\delta}$, with T_c ~ 80 K prepared in air is situated in the overdoped region, because excess oxygen atoms are easily introduced in the BiO plane. Therefore, its T_c increases up to about 95 K by the decrease of hole concentration through the reduction annealing or the substitution of Y^{3+} for Ca^{2+} [1,2]. In addition, the highest T_c of 98.5 K is observed in $Bi_{1.6}Pb_{0.4}Sr_2CaCu_2O_8$ annealed in flowing gas of N_2 [3]. This increase in T_c is because the excess oxygen atoms causing local distortion are removed through the Pb-substitution and N_2-annealing. In this research, we have attempted to increase T_c further in Pb-substituted $Bi_{2-x}Pb_xSr_2CaCu_2O_8$ without excess oxygen by optimizing the Pb content, namely, the hole concentration.

Polycrystalline samples of $Bi_{2-x}Pb_xSr_2CaCu_2O_8$ *(0.32 ≤ x(Pb) ≤ 0.42)* were prepared by the conventional solid-state reaction method. The structural analysis was performed by the powder x-ray diffraction. Magnetic susceptibility measurements were carried out to determine T_c using a SQUID magnetometer.

Figure 1 shows the temperature dependence of the magnetic susceptibility for $Bi_{2-x}Pb_xSr_2CaCu_2O_8$,ormagnetic susceptibility rease in , in whic rconductors. or Sr has not succeeded yet, but their Tc'. It has been found that the maximum value of T_c, defined as the onset temperature of the shielding effect, is 102 K for x(Pb)=0.36. The present compound,ormagnetic susceptibility rease in , in whic rconductors. or Sr has not succeeded yet, but their Tc' is the first Bi-2212 phase with T_c above 100 K.

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[2] H. Eisaki *et al.*, Phys. Rev. B **69** (2004) 064512.

[3] S. Kambe *et al.*, Phys. Rev. B **42** (1990) 2669.

Keywords: Bi-2212, Pb-substitution, Superconducting transition temperature

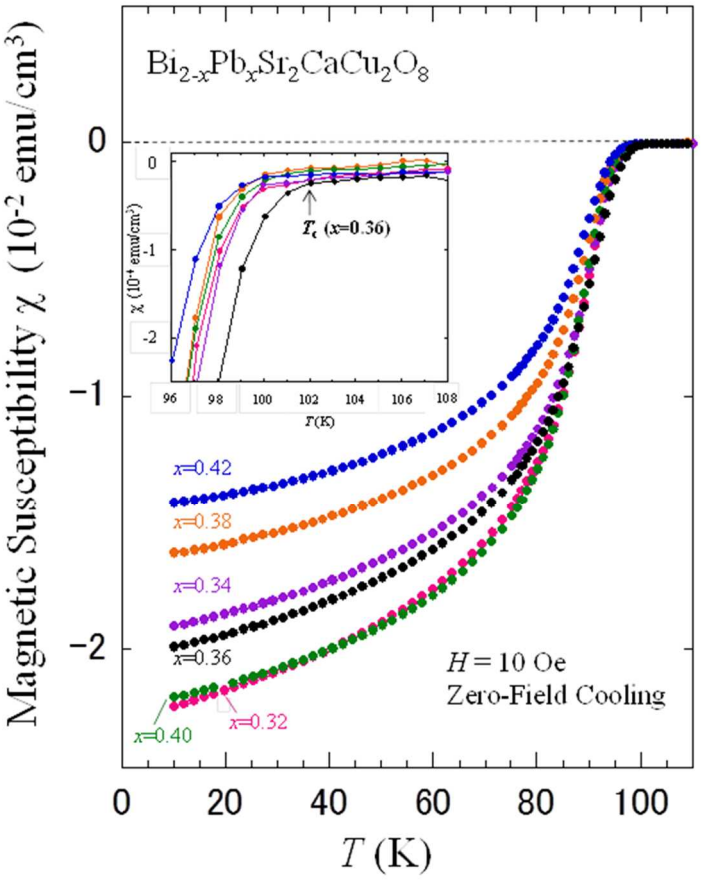

Fig. 1. Temperature dependence of the magnetic susceptibility for $Bi_{2-x}Pb_xSr_2CaCu_2O_8$.

PCP5-5

Preparation of (11*n*) Oriented $Bi_2Sr_2CaCu_2O_{8+x}$ Thin Films by Solution Methods using $NdGaO_3$ (100) Substrates

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$Bi_2Sr_2CaCu_2O_{8+x}$ (Bi2212) has a layered perovskite structure and forms an intrinsic Josephson junction (IJJ). This is considered to be a promising device that fills a frequency domain called the "terahertz gap". It has already been proved that a μW class continuous coherent terahertz wave can be oscillated [1]. The major preparation methods thus far have been reported on *c*-axis oriented Bi2212 which requires complicated procedures and dry etching, such as a precisely controlled etching process in depth direction in order to form the *c*-axis current paths. If a non-*c*-axis oriented thin film of which the *c*-axis parallel or incline to the substrate can be prepared, a planar type IJJ device can be fabricate simply by forming current paths parallel to the substrate [2]. The reason is that the *c*-axis current component is included in the current paths. In preparing such non-*c*-axis oriented thin films, it is important that selection of substrates focusing on lattice matching. If it is possible to prepare a non-*c*-axis oriented thin film by a solution method, planar type IJJ device can be fabricated by a simple process such as heat treatment after applying a solution by a printing method. According to our previous reports [3], (117) oriented Bi2212 thin films were formed by using $SrTiO_3$ (110) substrates metal-organic decomposition (MOD) method. In this study, we will report fabrication of (11*n*) oriented Bi2212 thin film using $NdGaO_3$ (100) substrate by the MOD method and flux method. Evaluation of the thin film was carried out through X-ray diffraction pattern and pole figure, observation of surface morphology by scanning electron microscope image, measurement of resistivity temperature dependency.

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[3] Y. Yamada, N. Mori, T. Atsumi, T. Kato, and T. Ishibashi, Physics Procedia 65, 165 (2015).

Keywords: BSCCO, Solution Method, Non-c-axis Oriented

PCP5-6

Intermediate Phase Evolution of YBCO Superconducting Film Fabricated by Fluorine Free MOD Method

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The second generation of high temperature superconducting tape, which use ReBCO film as superconducting carrier layer, has high superconducting current carrying capacity under strong field and good mechanical properties relative to other practical superconducting wire / tape, is considered to have Good application prospects. In its preparation process, Fluorine Free-Metal Organic Deposition has been studied in recent years because of its no need of vacuum environment, pyrolysis and crystallization growth rate, and environmental friendliness. In this paper, YBCO films were prepared on the single crystal and CeO_2 / IBAD-MgO / Y_2O_3 / Al_2O_3 / Hastelloy C276 technical substrate by FF-MOD technique. The samples were quenched and characterized in to systematically study the process of its phase evolution, it is presumed that $BaCO_3$ does not react directly with the oxides of Y and Cu elements at the time of phase formation, but undergoes a more complicated intermediate process. The YBCO phase crystals are randomly oriented, and then gradually converted into a biaxially textured YBCO crystal.

Keywords: 2G-HTS, YBCO, FF-MOD, phase evolution

PCP5-7

Superconductivity and magnetism in lanthanoid-substituted $FeSr_2YCu_2O_{6+\delta}$

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$FeSr_2YCu_2O_{6+\delta}$ has tetragonal $Ba_2YCu_3O_{6+\delta}$-type structure and exhibits superconductivity on the CuO_2 layer at 60 K and antiferromagnetic order of Fe at 20 K [1]. The lanthanoid atoms from Nd to Yb can be substituted for Y in $FeSr_2YCu_2O_{6+\delta}$ similarly to $Ba_2YCu_3O_{6+\delta}$, and additionally Tb can be substituted for Y in $FeSr_2YCu_2O_{6+\delta}$ while $Ba_2TbCu_3O_{6+\delta}$ is not formed. T_c decreases with increasing the ionic size of the lanthanoid atoms, and $FeSr_2NdCu_2O_{6+\delta}$ does not exhibit superconductivity although the oxygen content, 6+δ, is not mostly changed by the substitution of the lanthanoide atoms. The magnetic order of Fe is independent of the substitution of the lanthanoid atoms except for Gd, Tb and Dy. $FeSr_2TbCu_2O_{6+\delta}$ exhibit the magnetic order of Tb at 7 K.

[1] T. Mochiku *et al.*, J. Phys. Soc. Jpn. 71 (2002) 790.

Keywords: FeSr2YCu2O6+δ, lanthanoid substitution, magnetic order

PCP5-8

Dependence of T_c on the *RE*-ion Size in (*RE*,Ca)$Ba_2Cu_3O_6$

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According to the empirical rule of high-T_c for cuprate superconductors, the superconducting transition temperature T_c increases with an increase of the distance between Cu in the CuO_2 plane and the so-called apical-oxygen O_{ap}. The Cu(2)-O_{ap} distance in *RE*$Ba_2Cu_3O_6$ (*RE*: rare-earth elements) without the oxygen O_{chain} in the Cu(1)O chain is longer than that in *RE*$Ba_2Cu_3O_7$ with T_c ~90 K [1], so that its T_c is expected to increase up to more than 90 K. However, *RE*$Ba_2Cu_3O_6$ is an insulator because of the lack of O_{chain} which supplies holes to the Cu(2)O_2 plane. Therefore, we have carried out the hole-doping through the partial substitution of Ca^{2+} for RE^{3+} in insulating *RE*$Ba_2Cu_3O_6$.

Polycrystalline samples of $Gd_{0.6}Ca_{0.4}Ba_2Cu_3O_{6+\delta}$, $Yb_{0.6}Ca_{0.4}Ba_{1.6}Sr_{0.4}Cu_3O_{6+\delta}$ and $Lu_{0.6}Ca_{0.4}Ba_{1.6}Sr_{0.4}Cu_3O_{6+\delta}$ were prepared by the solid-state reaction method. The partial substitution of Sr^{2+} for Ba^{2+} was done in order to extend the solid solubility limit of Ca^{2+} for *RE* = Yb^{3+} and Lu^{3+}. The iodometric titration was carried out to estimate the oxygen content. Magnetic susceptibility measurements were performed to determine T_c using a SQUID magnetometer.

The dependence of T_c on the oxygen content 6+δ is shown in Fig. 1. At 6+δ ~ 6.0, it is found that T_c tends to increase as the ionic radius of *RE* decreases. T_c is 55 K in $Lu_{0.6}Ca_{0.4}Ba_{1.6}Sr_{0.4}Cu_3O_{6+\delta}$ with 6+δ ~ 6.0, while no superconductivity appears in $Gd_{0.6}Ca_{0.4}Ba_2Cu_3O_{6+\delta}$ with 6+δ ≤ 6.3. This is presumably because holes are more supplied to Cu(1) than to the Cu(2)O_2 plane with increasing ionic radius of *RE*. In the present work, the maximum T_c of (*RE*,Ca)$Ba_2Cu_3O_6$ is considerably lower than 90 K. The hopeful way to increase T_c further is discussed.

[1] M. Guillaume *et al.*, Z. Phys. B **6** (1994) 7963.

Keywords: REBa2Cu3O6, Ca-Substitution, hole doping

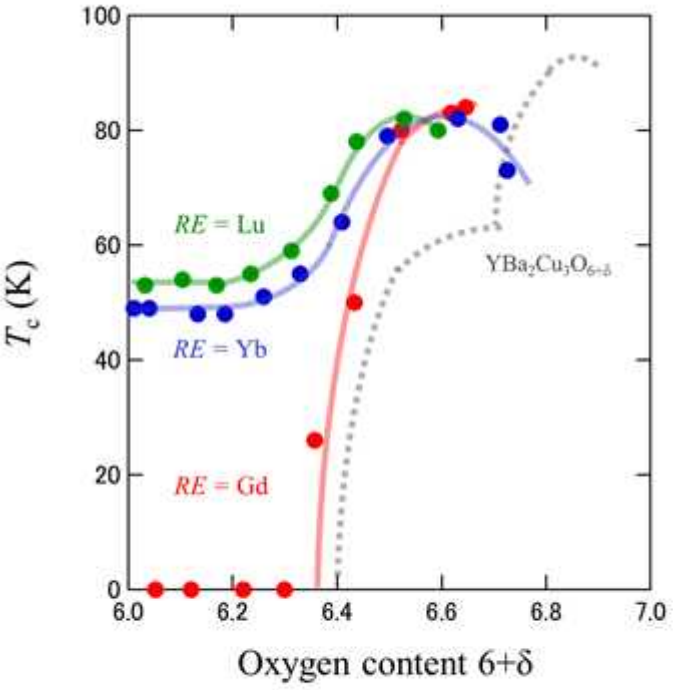

Fig. 1. Dependence of T_c on the oxygen content 6+δ in $RE_{0.6}Ca_{0.4}(Ba,Sr)_2Cu_3O_{6+\delta}$.

PCP5-9

Dependence of critical temperature on chemical composition in $Y(Sr,Ba)_2(Cu,Mo)_3O_z$ (z~7)

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Sr-substitution for Ba in $YBa_2Cu_3O_z$ (z~7; Y-"1-2-3") has been widely investigated and its superconductivity transition temperature (T_c) has proved to lower as Sr-content increases. Solubility of Sr is about 60 at.% [1] and fully substituted compounds, $YSr_2Cu_3O_z$ has been synthesized only under high-pressure [2]. Den and Kobayashi [3] have reported that partial substitution of Mo fou Cu stabilizes the Sr-based Y-"1-2-3", *i.e.*, $YSr_2(Cu_{2.7}Mo_{0.3})O_z$ is obtained as a single "1-2-3" phase. It is interesting that, on the other hand, effort of Mo substitution for Cu in the Ba-based one has been unsuccessful regardless of the chemical similarity between Ba and Sr. In this study, we report the effect of Sr/Ba ratio on the "1-2-3" formation in $Y(Sr,Ba)_2(Cu,Mo)_3O_z$ and composition dependence on T_c. Results are discussed mainly based on a high valency of Mo and effective ionic radius of Sr/Ba site.

Samples were prepared by a solid-state reaction of oxides and carbonates of each metallic element. Nominal compositions of $Y(Sr_{1-y}Ba_y)_2(Cu_{1-x}Mo_x)_3O_z$ (x=0~0.5, y=0~1) was used. Samples were evaluated by means of powder X-ray diffractometry (XRD) and four-probe method down to ~20 K respectively for phase identification and for a measurement of temperature dependence of electrical resistivity.

For Mo-free compositions (x=0), single "1-2-3" were not obtained for x<0.5 as described in [1], but it was found that Mo-substitution for Cu (x<0.4) moved the single-phase compositional range to Sr-rich region, *i.e.*, y values giving single-"1-2-3" samples were decreased as x increased up to ~0.3. This suggested that an effective ionic radius of Sr/Ba site and high valence-state of Mo (6+; confirmed by X-ray photoemission spectroscopy) played a crucial role for the stability of the Sr-based "1-2-3". Dependence of T_c on Ba content y was clearly different for a range of Mo content x of x≤0.1 (T_c>~60 K) and x≥0.2 (T_c<~50 K). This will be discussed on the stand point of oxgen configuration in the "charge reservoir" layer.

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[2] B. Okai, Jpn. J. Appl. Phys. **29**, L2180 (1990).
[3] T. Den and T. Kobayashi, Physica **C196**, 141 (1992).

Keywords: Sr-based "1-2-3", Mo substitutin for Cu, oxgen configuration

PCP6-1

Phase Diagram of High-Temperature Superconducting Cuprates and Iron Pnictides

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Phase diagram of high-temperature superconducting cuprates and iron pnictides is considered based on the theory emphasizing that the electronic state of superconductors can be described by the composed fermions. The theory is constructed with the Hamiltonian which is so modified by the unitary transformation using these fermion operators as to apply the mean field approximation [1]. The ground and excited states of the Hamiltonian are calculated using two representations in real and momentum space. The doping dependency of the gap energy, critical temperature and band structure *etc* are evaluated in various states such as pseudogap and superconductive states. It is indicated that the phase diagram about superconducting and non-superconducting states of cuprates and pnictides can be explained from the viewpoint of unifying two types of these superconductors.

[1] K. Nishi, J. Phys. Conf. Ser. 871 (2017) 012033.

Keywords: High-temperature superconductivity

PCP6-2

An Analysis of high-T_c cuprates in the superconducting state incorporating strong correlation effects based on a self-consistent perturbation expantion

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Many theoretical studies have been performed to describe basic properties of high-T_c superconductors. Noteworthy among them is the fluctuation exchange (FLEX) approximation [1]. This formulation incorporates higher-order terms in the perturbation expansion self-consistently satisfying conservation laws simultaneously. The FLEX approximation have been successful in reproducing various in normal-state properties of high-T_c superconductors, especially transport phenomena. However, the standard FLEX approximation cannot describe superconducting properties. Moreover, some approaches for the superconducting state don't satisfy the conservation laws, so we can't describe the transport phenomena appropriately. Recently, a consise extension of the FLEX approximation to the superconducting state was developed, called FLEX-S approximation [2]. This extention was performed by incorporating all the pair process by symmetrizing the vertex of each Feynman diagram considered in the original FLEX approximation. Using this formulation, we can perform a self-consistent perturbation expansion. This approach is expected to describe the properties of the superconducting state in such a way as to extend the FLEX approximation for the normal state. Note in this context that these two formulations satisfy various conservation laws naturally. In this presentation, we report calculations of the spectral function and the density of state in superconducting state based on the FLEX-S approximation. In this calculation, we apply this formulation to the Hubbard model on a 2D square lattice assuming a spin-singlet pairing. We set the parameters in the Hubbard model so as to reproduce the observed band structure of cuprate superconductors [3]. We show the band structure, the Fermi surface, the ralaxation time of the quasiparticle estimated by the spectral function, and the pair potential.

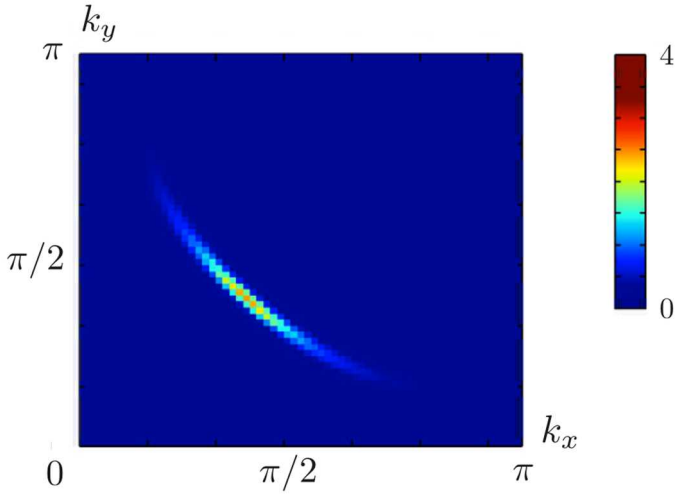

Fig.1 The Fermi surface of the YBCO model. We can see Fermi arc near k_x~k_y

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[3] H. Kontani, K.Kanki and K.Ueda, Phys. Rev. B. **59** (1999) 14273.

Keywords: high-Tc superconductor, self-consistent perturbation expansion, FLEX-S approximation

PCP6-3

Impurity-induced Mott transition in Doped Hubbard model

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Recent numerical studies [1] on the two-dimensional Hubbard (t-t'-U) model argued that antiferromagnetic (AF) (or phase-separated) states, instead of superconducting states, prevail up to $\delta \sim 0.2$ of doping rate for any t'/t. This result obviously contradicts the experiments of cuprate superconductors. For reconciling this contradiction, we have been studying the effects of point-type impurity potentials inherent in cuprates on paramagnetic (PM) and the AF states by means of a variational Monte Carlo (VMC) method. In a preceding publication [2], we argued that an impurity potential V of $U \lesssim V < V_M$ with $V_M/t \sim 2$ (U/t=12), namely in attractive and weakly repulsive cases, is almost screened out for strong correlations ($U/t \gtrsim 8$). As a result, the properties of the PM and AF states for the uniform case (V=0) are preserved in this range of V; for example, the AF states are metallic with pocket Fermi surfaces, whose positions depend on whether $t' > t_L$ [~(π,0), type I] or $t' < t_L$ [~(π/2,π/2), type II] with $t_L/t \sim 0.05$ (U/t=12).

In this presentation, we focus on the regime of repulsive potentials (V>0), which are realistic to cuprates. For $V > V_M$, the optimization in our VMC calculations does not converge in the PM state and has large fluctuations in the AF state. In this regime of V, staggered magnetization becomes large, especially, for the impurity density of $\delta_{imp} \geq \delta$. We find that the AF state with $\delta_{imp} \geq \delta$ is gapped by analyzing the momentum distribution function $n(\mathbf{k})$---the pocket Fermi surfaces vanish. Furthermore, the electron density in ordinary (non-impurity) sites is found to be preserved at 1 (half filling) for any δ_{imp} ($\geq \delta$), by adjusting the electron density in impurity sites. It indicates that an impurity-induced Mott transition takes place at $V = V_M$ in the AF state.

[1] R. Sato, H. Yokoyama, J. Phys. Soc. Jpn. **85**, 124707 (2016), and references therein.
[2] H. Yokoyama, R. Sato, K. Kobayashi, J. Phys. Conf. Ser. **871, 012032** (2017).

Keywords: cuprate, antiferromagnetic state, impurity potential, Mott transition

PCP6-4

Interhole correlation and Phase Separation in t-J model

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In connection with cuprate superconductors, it is important in the t-J model on the square lattice to clarify at what values of J/t the correlation between holes is switched from repulsive to attractive (J_I/t) and phase separation takes place (J_{PS}/t) [1] for a specific values δ (doping rate). In the limit of $\delta \to 1$, it is exactly known that $J_I/t=2$ [2] and $J_{PS}/t=3.4367$ [3], whereas for small values of δ of our interest, the problems---for instance, how J_I/t and J_{PS}/t evolves as δ decreases---are still unestablished. Some researchers seem to consider that the correlation is attractive even for $J/t \sim 0.3$, a plausible value for cuprates.

In this study, we reconsider these problems using a many-body variation theory with recently developed wave functions and procedures. In the limit of $J/t \to 0$, total energy (E/t) is lowered only by the hopping (t) term, so that the correlation should be repulsive in order to keep other holes away and the state should be uniform (not phase separated). On the other hand for $J/t \to \infty$, E/t is reduced only by the superexchange (J) term. Thus, the correlation should be attractive and the state phase separates. Because the values of J_I/t and J_{PS}/t depend on δ, first we fix J/t at 0.3 and study properties of the states with d-wave superconducting (d-SC) and antiferromagnetic (AF) orders for some values of δ. Then, we consider J/t dependence.

In estimating expectation values, a variational Monte Carlo method is employed for Jastrow-type wave functions. As a many-body factor, we use a long-range Jastrow factor, because hole pairs of long distance come to play an appreciable role as δ increases. In the one-body part, we use mixed wave functions of AF and d-SC orders, in which band renor- malization effects are introduced [4]. We also make a comparison with related studies [5].

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Keywords: t-J model, interhole correlation, phase separation, variational Monte Carlo

PCP6-5

Interplay between Staggered Flux and *d*-Wave Superconducting Orders in t-t'-J Model

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To understand the superconductivity (SC) in high-T_c cuprates, it is important to find out the origin of pseudogap phenomena, which behave like a shadow of SC [1]. Some experiments reported coexistence of the pseudogap and a SC gap [2]. Among various candidates for the pseudogap state, a staggered flux (SF) state, characterized by local circular currents in plaquettes that flow clockwise and counterclockwise alternately, was confirmed to be moderately stable and have properties mostly consistent with the pseudogap behavior [3]. In a previous publication [4], we studied whether the *d*-wave superconducting (*d*-SC) order coexists with or excludes the SF order, by applying a variational Monte Carlo (VMC) method to the square-lattice Hubbard (t-t'-U) model with diagonal transfer t'. It is found that the SF order competes with the *d*-SC order and is never stabilized for U/t =12 regardless of t'/t.

In this presentation, we consider the same issue for the t-t'-J model obtained from the strong coupling expansion of the Hubbard model. We check again whether the SF order coexists with or is excluded by the *d*-SC order, to compare with the previous result for the Hubbard model. In the trial wave function, we introduce the following features:
(1) We allow for the coexistence of SF and *d*-SC orders, by which we can treat a continuous description of their interplay from mutual exclusivity to coexistence.
(2) Inter-site S_z-S_z spin correlation factor is introduced in addition to the ordinary Jastrow correlations.
(3) Band renormalization effects are considered by adjusting the parameters of hopping integrals up to the fifth-neighbor sites; these effects are important near half filling.
In addition to clarifying the difference between the two models, it is interesting to discuss differences between the results of variationally accurate VMC methods and of Gutzwiller (mean-field-type) approximations [5].

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Keywords: Cuprate, Pseudogap, Staggered flux, t-J model

PCP6-6

Effects of Diagonal Hopping on Loop Currents in Fermionic Hubbard Model

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States with loop-current orders have been theoretically discussed as the origin of the pseudogap in cuprate superconductors, because the loop currents break time reversal and other symmetries [1,2] as some experiments observed below T^*. In addition, bosonic-Hubbard models with magnetic fluxes along a certain direction were virtually realized in ultracold-atom systems [3]. Thus, it is urgent to clarify the properties of loop-current states in a fermionic-Hubbard model with a magnetic flux. In such a background, we began to study a staggered-flux (ST) order which is a kind of loop-current orders [4], by means of a variational Monte Carlo method.

In the preceding study, to study the influence of a magnetic order on loop currents, we introduced a mixed state of ST and antiferromagnetic (AF) orders on the square lattice without diagonal hopping (t'=0). We found in non-doped (half-filled) cases that the two orders coexist for a finite magnetic flux, and the AF order increase the loop currents in a Mott insulator phase, whereas a state with a pure AF order is stabilized without a magnetic flux. In another recent study regarding a coexistent state of d-wave superconducting (d-SC) and AF orders [5] reported for doped systems that as t' is increased, the locus of Fermi surface in a pure AF state switches from around (π/2, π/2) to around (π, 0) at $t'=t_L\sim-0.05t$, and that this change is crucial for the appearance of a coexistent state.

Here, we study how diagonal hopping t' influences a mixed state of AF and ST orders in the Hubbard (t-t'-U) model. Recall that the pure ST state becomes metallic in doped cases with a Fermi-arc-like Fermi surface centered at (π/2, π/2) regardless of t', and this pocket Fermi surface is topologically the same as (in discord with) that of the pure AF state for $t'<t_L$ ($t'>t_L$), as above. It is indispensable for treating t' dependence to introduce band renormalization effects [5] in the AF part of a trial wave function. In the presentation, we would like to also consider band renormalization effects in the ST part.

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Keywords: staggered flux, antiferromagnetism, coexistent state, cuprate

PCP6-7

Optimized wave function by kinetic renormalization effect in strongly correlated region of the three-band d-p model for cuprate superconductors

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The mechanism of high-temperature superconductivity has been studied intensively since the discovery of cuprate high-temperature superconductors. It is certain that the electron correlation plays an important role in cuprate superconductors because parent compounds without doped carriers are insulators. It is important to clarify the phase diagram of electronic states in the CuO_2 plane. We investigate the ground state of the strongly correlated electronic models by employing the variational Monte Carlo method. We consider the three-band d-p model as well as the two-dimensional Hubbard model. We use the improved wave function that takes into account inter-site electron correlation beyond the Gutzwiller wave function. The ground-state energy is lowered considerably, which gives the best estimate of the ground-state energy for the two-dimensional Hubbard model in the world. We argue that there is a crossover from weakly to strongly correlated regions as the on-site Coulomb repulsion U increases when holes are doped. The antiferromagnetic (AF) correlation function increases as U increases in weakly correlated region, and has a peak at the intermediate value of U which is of the order of the bandwidth. The large U, greater than the bandwidth, suppresses the AF correlation to lower the ground-state energy by obtaining the kinetic energy gain. The large spin and charge fluctuations are induced in the strongly correlated region. This results in electron pairing and would lead to high-temperature superconductivity. The conventional spin fluctuation in weakly correlated region should be distinguished from that in strongly correlated region. It is just the spin fluctuation in strongly correlated region that would induce high-temperature superconductivity.

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Keywords: electron correlation, high-temperature superconductivity, optimized wave function, mechanism of superconductivity

PCP7-1

AC Resistivity of Driven Vortices of a Superconductor Measured by Mirowave technique

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Driven vortices of a superconductor have been investigated both extensively and intensively because of the importance in their industrial application and the interests in their fundamental properties. Vortex movements are described by the force balance equation consisted of driving force, viscous drag force, pinning force and thermal fluctuation. Dissipation of moving vortices arises from both viscous force and dynamic pinning force. However, microscopic nature of this dynamic pinning force is still poorly understood because of its nonlinearity and randomness. While some theories attribute dynamic pinning force to the elastic deformation of a vortex lattice[1][2], experimental verification is open to further studies.

So far, measurements of I-V characteristics are widely used to investigate the driven vortices. In addition, other measurement techniques, such as velocity noise[3], interference effect[3] and small angle neutron scattering[4] were employed to study the driven vortex lattice. Among those, we believe that the ac response of moving vortices is one of the most essential quantity to understand them, because moving vortices always feel time-dependent force due to the pinning. However, there have been almost no experiments focusing on this subject. Thus, we started to measure the ac response of vortex lattice under dc driving force.

We fabricated transmission line resonators made of Nb to observe the ac response of vortices under dc bias current. With these devices, we can measure complex resistivity as a function of dc driving force. As a result, a peak in Q-1 was observed around 30 mA (Fig. 1). This change was observed only under magnetic field, suggesting the vortex dynamics origin. We will discuss this phenomenon in more detail, including the frequency dependence, and also discuss these in terms of the complex resistivity.

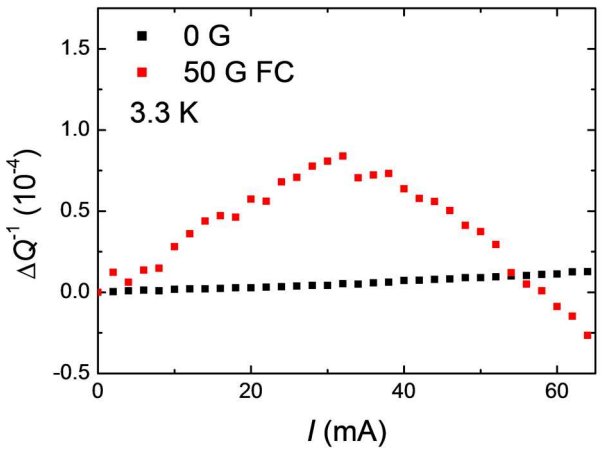

Fig.1 Current dependence of Q-1 with and without magnetic field.

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Keywords: Driven vortices, Pinning, Microwave response, Superconducting resonators

PCP7-2

Estimation of the size of the pinning potential from ac current-voltage characteristics

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An experimental determination of the pinning potential is of great importance from the practical as well as fundamental point of view. While much effort has been devoted to controlling and improving the pinning properties of superconductors, to the best of our knowledge, there has been no suitable experimental method to estimate the size of the pinning-potential well in actual materials. Here, we present a convenient method to estimate the mean diameter of the pinning potential d_p in amorphous superconducting films with weak random pinning from ac current-voltage (I_{ac}-V_{ac}) characteristics [1].
The $I_{ac,e}$-$V_{ac,e}$ curves at various frequencies f are measured in the vortex solid phase of amorphous Mo_xGe_{1-x} films, where $I_{ac,e}$ and $V_{ac,e}$ are the effective ac current and voltage, respectively. We clearly identify the frequency(f)-dependent effective current $I_{ac,es}$ and voltage $V_{ac,es}$ separating the linear regime where the vortices oscillate inside the pinning-potential well from the nonlinear regime where the vortices are depinned from the pinning potential. These features are qualitatively the same as those found numerically [2]. From the $V_{ac,es}$-f relation, d_p is estimated to be about 28 nm, which is comparable to the size of the vortex core. The result is consistent with the intuitive belief based on structural studies of amorphous films and other indirect experimental evidence that the amorphous films contain point-like pinning centers. The critical behavior associated with the transient dynamics of vortices near the depinning transition is also observed for the ac drive [1], which is similar to that for the dc drive [3]. The results further demonstrate the universality of the nonequilibrium depinning transition.

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Keywords: Vortex pinning, AC transport properties, Non-linear phenomena, Amorphous films

PCP7-3

Partial reordering of dc plastic flow by superimposing ac drive

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When a small ac force is applied to many particle systems with a random distribution and the number of cycles is increased, the particles gradually transform into an organized configuration called random organization. To obtain the information on how random organization evolves with the cycle number, we have recently conducted two-step measurements of time-dependent voltage $V(t)$ in response to the ac drive for vortices in amorphous Mo_xGe_{1-x} films with weak random pinning. In the first input experiment, we observed random organization, while in the second readout experiment, we found that the transient vortex configuration formed during random organization is not microscopically homogeneous but consists of disordered and organized regions [1]. It is well known, on the other hand, that when the vortices with organized configuration are driven by a small dc force slightly above the depinning threshold, they are gradually pinned by random pinning centers, indicative of dynamic disordering. Thus, it is interesting to examine how dynamic ordering emerges in plastic flow when an ac drive is superimposed with the dc drive, and what configuration such a vortex system takes.

To answer the question, here we again conduct two-step measurements of $V(t)$. In the first experiment, we find that random organization by ac drive is suppressed with an increase in the superimposed dc drive, and finally vanishes as the dc voltage is equal to the amplitude of the ac voltage in the steady state, where the vortices move in the forward direction only without retracing the path they just traveled. From the second readout experiment, we find that even in the steady state, the vortex configuration created with dc and ac drives is not microscopically homogenous but consists of two regions: a disordered region characterized by plastic flow by dc drive and an organized region characterized by ac drive without dc drive. The ratio of the ordered region to the total area decreases monotonically from 1 to 0 with superimposed dc drive, and finally falls to zero, where random organization in the first experiment disappears.

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Keywords: Plastic flow, Vortex structures, Nonequilibrium phenomena, Amorphous film

PCP7-4

Blocking phenomenon in a vortex system

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When a vortex lattice is driven by a dc current in a random pinning potential, fluctuating plastic flow (PF) occurs at small drives. PF changes to coherently moving flux flow (FF) at larger drives. While much effort has been devoted to understand the moving lattice states or dynamic transitions, PF is poorly understood at least experimentally. The study of PF would lead to interesting general problems: e.g., the system that exhibits PF displays liquidlike and solidlike properties at the same time [1].

We investigate the vortex configuration in PF using an amorphous Mo_xGe_{1-x} film with weak random pinning. First, we prepared steady-state PF by applying a small dc current I_{inp}, and then froze its vortex configuration by switching off I_{inp}. Subsequently, we applied a dc current I of the same amplitude as I_{inp} at time zero ($t = 0$), but the direction of I is either the same or opposite to the direction of I_{inp}, and measured the time evolution of voltage $V(t)$. When I is applied in the opposite direction to that of I_{inp}, $V(t)$ shows a sharp rise at $t = 0$ and a subsequent decay toward a steady-state voltage. By contrast, when I is applied in the same direction as that of I_{inp}, no relaxation of $V(t)$ was observed. These results indicate that in the former case, a greater number of vortices are mobile at $t = 0$ than in the latter case. We attribute its origin to the blocking effect for free vortices by pinned vortex bundles. That is, since there are regions in the sample where the distribution of pinning centers is slightly denser, vortices are pinned to them and form vortex bundles. When I is applied in one direction, some free vortices are blocked by the pinned vortex bundles. However, once the direction of I is reversed, the blocked vortices move abruptly, giving rise to a sharp additional voltage. In the FF regime, by contrast, $V(t)$ is found to be independent of the direction of I. This is reasonable, because in the FF state the pinning effects are so small that the blocking is no longer effective. The blocking effect observed here may be analogous to the clogging effect reported in the simulation for a two-dimensional bidisperse disk system with random pinning [2].

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Keywords: Vortex pinning, Nonequilibrium phenomenon, Plastic flow, Amorphous film

PCP7-5

Random organization and reversible-irreversible transition of vortices in tilted field

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When a periodic shearing force is applied to a many particle system with random configuration, particles self-organizes to avoid the next collision. This is called random organization. A relaxation time to reach the steady state exhibits a power-law divergence at the critical displacement of the reversible-irreversible transition (RIT). Random organization and RIT were first observed in colloidal suspensions [1] and later in a vortex system [2]. However, the nature of random organization remains still unclear, and there are interesting problems, which include how the configuration evolves associated with random organization and how anisotropy in the system affects random organization. Regarding the latter, we have recently studied random organization in the vortex system under the tilted field, where an anisotropic vortex-vortex interaction as well as an anisotropic vortex configuration is introduced [3]. The relaxation time of random organization for the vortices driven in the tilt direction was found to be much smaller than that in the untilted field [4]. The results indicate that the anisotropy introduced by the tilt field significantly limits possible configurations of vortices and expedites random organization.
Here, we extend this experiment to include random organization for the vortices driven *perpendicular* to the tilt direction. As a result, the relaxation time is found to be further decreased, approximately, an order of magnitude smaller than that for the vortices driven in the tilt direction. The vortex-vortex interaction along the flow direction is stronger when the vortices are driven in the direction perpendicular to the tilt direction than in the tilt direction. Therefore, the decreased relaxation time observed here is explained in terms of the enhanced vortex-vortex interaction for the vortices moving in the direction perpendicular to the tilt direction. The critical behavior of RIT is observed irrespective of the flow direction.

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Keywords: Nonequilibrium phenomenon, Vortex dynamics, Dynamic transition, Amorphous film

PCP7-6

Configuration of vortices in dc flow interacting with random pinning

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It is interesting how elastic objects interacting with a random substrate escape from a pinning potential and exhibit dynamical flow phases with an increase in a driving force. The phenomena appear in a wide variety of systems and have attracted broad attention. A vortex system with pinning is a suitable system to study such phenomena. It is well known that vortices driven by a small dc current, *I*, exhibit pinning-dominated plastic flow, while at large *I*, dynamic ordering of driven vortex lattices occurs. The dynamic transitions among different dynamical phases have been predicted numerically [1], and evidence of dynamic ordering has been obtained experimentally [2,3]. However, it has not been fully clarified how plastic flow at low *I* becomes ordered with an increase in *I*. Recently, we have proposed a novel method for detecting the configuration of vortices subjected to an ac drive in the transient as well as steady state for amorphous Mo_xGe_{1-x} films with weak random pinning [4]. In this method, after freezing the vortex configuration by cutting off the ac current, we conducted readout measurements of the time-dependent voltage $V(t)$ in response to the ac drive with various amplitudes, thus obtaining the information on the frozen vortex configuration.

In this work, we employ this method to study the change in the configuration of dc driven vortices in the steady state as a function of *I*. First, we freeze the configuration of the moving vortices in the steady state driven by *I*. Then, we perform the readout measurements of $V(t)$ for the frozen vortex configuration in response to the ac drive. As a result, we find that in the intermediate *I* regime between the plastic-flow and moving-lattice states, the vortex configuration is not microscopically homogeneous but consists of two regions: a highly disordered region characterized by plastic flow at small *I* and an ordered region characterized by flux flow or moving lattices at large *I*. With increasing *I*, the ratio of the ordered region to the total sample area increases monotonically from zero to unity.

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Keywords: Moving vortex phase, Dynamic transition, Non-equilibrium phenomena, Amorphous films

PCP7-7

Observation of Vortex Motion Using Scanning Tunneling Spectroscopy

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Investigation of vortex dynamics is important for the practical applications of superconductivity. It is also of fundamental importance, because a vortex system is a suitable system to study novel nonequilibrium phenomena and phase transitions. We have studied the dynamics of vortices driven by applied currents using various transport measurements, where we probe the mean velocity of vortices moving over the whole sample. However, it is also important to trace individual vortex motion and determine the time evolution of the vortex configuration. For the purpose, we have constructed a measurement system that enables to perform scanning tunneling microscopy and spectroscopy (STM/STS) measurements simultaneously with the transport measurements.
High-quality films of amorphous Mo_xGe_{1-x} with weak pinning have been prepared using an RF sputtering system installed in an ultra-high vacuum chamber. To prevent slight surface oxidation that might hinder the visualization of vortices, a thin film of gold was evaporated in situ onto the surface of the Mo_xGe_{1-x} film. In our STM/STS system, we drive the vortices by applying a current, and a voltage generated by vortex motion is measured. After freezing the configuration of moving vortices at a desired time by abruptly switching off the current, we acquire its image by STS. Thus acquired snapshot images of vortex configuration provide useful information, complementary to the transport data, in elucidating the vortex dynamics. This will help complete a dynamic phase diagram for dc-driven vortices in random potential, and to explore the nature of random organization [1] and novel nonequilibrium transitions [2,3].

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Keywords: STM/STS, Vortex structure, Vortex flow, Amorphous film

PCP7-8

Microscopic theory of the vortex-core charging in superconductors

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A number of studies on vortex-charging have been carried out based on the mean field theory of supercon- ductivity such as the Bogoliubov–de Gennes (BdG) equations [1,2]. However, the BdG equations cannot clarify mechanisms of charging explicitly. In addition, it is difficult to incorporate Fermi-surface and gap anisotropies in this approach.
Recently, studies on the flux-flow Hall effect have been carried out by using the augmented quasiclassical equations in the Keldysh formalism, incorporating the Lorentz and pair-potential gradient forces which are first order in quasiclassical parameter [3]. In addition, we have transformed the augmented quasiclassical equations into the Matsubara formalism, so that charging in superconductors can be calculated microscopically and quantitatively [4,5]. However, little study has been done on the valid parameter region of the quasiclassical equations.
We study the validity of the augmented quasiclassical equations by calculating the vortex-core charging of a two-dimensional s-wave superconductor in comparison with the result based on the BdG equations.

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Keywords: vortex charge, quasiclassical equations, BdG equations

PCP7-9

Paramagnetic and Glass States in YBCO Film Containing Nanorods at Low Magnetic Fields

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Recently, multilayered films comprised of $YBa_2Cu_3O_{7-x}$ (YBCO) layers containing nanorods have been extensively studied for flux pining properties in the strong magnetic field. Flux pinning properties of YBCO are strongly enhanced by columnar pins, which are produced by introduction of compound defects such as $BaHfO_3$ (BHO) nanorods.[1]
However, few experimental studies on magnetic glass properties have been investigated at low fields below the lower critical field H_{c1}. Magnetic flux disorder due to the random locations of nanorods in the YBCO film corresponds to that in the ceramic YBCO composed of sub-micron size grains, which showed the chiral-glass transition with the novel glass behavior at low fields.[2]
We have investigated magnetic-glass properties of YBCO multilayered film containing BHO nanorods at zero and small fields. The multilayered film comprising of BHO containing YBCO layers and pure YBCO layers was prepared on $SrTiO_3$ substrate by alternating ablation of YBCO-BHO mixed target and stoichionmetric YBCO target. The dc magnetization and the ac susceptibility were measured with a SQUID magnetometer. In the zero-field-cooling, the diamagnetism due to the Meissner effect is observed. On the other hand, the paramagnetic magnetization is shown in the field-cooling lower than H = 2.5 Oe below T_c= 87 K. The nonlinear susceptibility has the large peak at T_c, which reflects a glass-transition. The aging effect observed in spin glasses and chiral glasses occurs in the relaxation of zero field-magnetization below T_c.
In conclusion, paramagnetic Meissner behavior and magnetic-glass properties are observed in YBCO multilayered film containing BHO nanorods. The results suggest that the YBCO multilayered film is the novel magnetic-glass system at low fields.

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Keywords: YBCO film, flux pinning nanorod, ageing effect, paramagnetic magnetization

PCP7-10

Effects of chirality of a helical magnetic field on a superconductor

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A chiral helimagnet has a helical magnetic structure along one direction. This helical rotation in the chiral helimagnet comes from chirality of its crystal structure. Under a magnetic field, this helical structure changes into a periodic soliton structure, which called a chiral soliton lattice. The chiral helimagnet has many interesting physical features such as a giant magnetoresistance.

We focus on effects of the chiral helimagnet on a superconductor. It is known that a vortex state in the superconductor is affected by a ferromagnet in a ferromagnet / superconductor bilayer system. We expect novel influences of the chiral helimagnet on the superconductor. Therefore, we investigate effects of the chirality of the helical magnetic field on the superconductor.

We consider a chiral helimagnet / superconductor bilayer system. The effect of the chiral helimagnet on the superconductor is taken as an external magnetic field. On the other hand, we neglect the effect of the superconductor on the magnet. In our previous study, we focused on the effect of the magnetic field normal to an interface of the bilayer. Then, we investigated vortex states in a two-dimensional superconductor under the oscillating magnetic field. However, this two-dimensional system cannot treat effects of the chirality of the helical magnetic field. Therefore, we consider a three-dimensional system and investigate vortex states in the superconductor under the helical magnetic field. In order to obtain vortex states, we calculate the Ginzburg-Landau equations with the finite element method and obtain the order parameter in the superconductor.

In this presentation, we show vortex states in the superconductor under the helical magnetic field and discuss effects of the chirality of the helical magnetic field on the superconductor by comparing vortex states in the three-dimensional and the two-dimensional systems.

Keywords: Superconductor, Chiral helimagnet, Vortex states, Finite element method

PCP7-11

Theoretical Study of Spontaneous Half-quantized Vortices in 3D d-dot model

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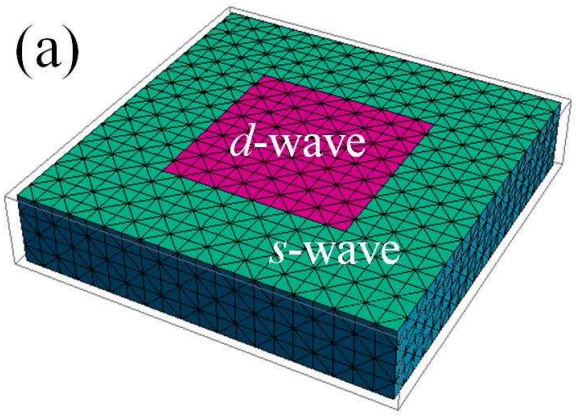
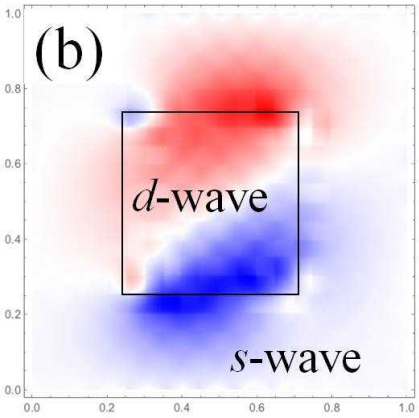
A d-dot is a nano-scaled composite structure that consists of a *d*-wave superconductor (SC) embedded in an *s*-wave matrix. Since the phase of the superconducting order parameter in the *d*-wave SC depends on direction, phase difference appears at the corner junctions between *d*-wave and *s*-wave SCs in d-dot's. Due to quantization of fluxoids including this phase difference, half-quantized vortices spontaneously appear at the each corner. This is a feature of d-dot's [1]. We can use Pb or Nb as *s*-wave SCs and $YBa_2Cu_3O_{7-\delta}$ (YBCO) as *d*-wave SCs.

The appearance of SHQVs in d-dots are proved in theoretically and experimentally [2]. But, since the previous simulation models of d-dots [3] are 2-dimensional, using these models we can't investigate effects of 3-dimensional structure of defects in d-dots. So we extend the d-dot models to 3D system using the finite element method (FEM) with volume coordinates. And numerical results using this 3D d-dot models suggest that c-axis anisotropy in *d*-wave SCs are important for appearance of SHQVs.



(a) a 3-dimensinal d-dot model



(b) Magnetic field distribution (top view)

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Keywords: GL equation, d-wave superconductor, Half-quantized vortex, Finite element method

PCP7-12

Impurity effects on critical temperatures for nano-structured superconductors

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The critical temperatures, Tc, of superconductors depend on the superconducting materials. However Tc depends on the size and shapes of superconductors for nano-structured superconductors, theoretically [1]. Parmenter showed that Tc increases with decreasing size of a cubic superconductor [2]. In experimental study, Nishizaki showed that high pressure torsion (HPT) makes many fine grains in a bulk of Nb and HPT makes Tc higher [3]. However Nishizaki also showed that HPT makes Tc lower for a bulk of V. Nishizaki discussed that the bulk of V include impurity, and the impurity in the bulk affects on Tc [4]. However Anderson showed that non-magnetic impurity doesn't affect Tc for bulk [5]. So we should make sure whether impurity effects on Tc or not for nano-structured superconductors.

We are calculating Tc of nano-structured superconductors, using finite element method (FEM) [6]. And in previous study, we showed that smaller and narrower superconductors shows higher Tc [7]. In this conference, we will talk about the impurity effects on nano-structured superconductor, by solving Gor'kov equations and Bogoliubov-de Gennes's (BdG) equations with the FEM. For the calculation of Bogoliubov-de Gennes equations, we introduce the impurity effects as random potentials. We will discus about the impurity effects on Tc, and size and shape effects on impurity effects.

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Keywords: Nano-structured, critical temperature, impurity, theoretical study

PCP7-13

Critical states in superconducting complex structures

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Magnetic flux penetrates into a superconducting strip from its edge when external magnetic field is applied perpendicular to the strip. Under the external magnetic field, there are two types of the flux penetration, which are critical state and a vortex avalanche. If ramping rate of the applied magnetic field is small, a critical state appears. On the other hand, the ramping rate is large, a vortex avalanche occurs.

The critical state is a metastable equilibrium state in which Lorentz force from a local current, and pinning force are balanced. The vortex avalanche is a thermo-magnetic instability phenomenon, in which heat generation due to vortex motion, heat transfer and vortex jump between pinning centers play important roles. In order to clarify conditions for the instabilities, we should first investigate critical states.

For a superconducting strip in the critical state, when critical current density is constant and an external field is applied, a shielding current flows parallel to an edge of superconductor, and magnetic flux density shows a linear distribution approximately.

In this presentation, we show numerical results for the critical states in a thin superconducting plate. Using two and three-dimensional finite element methods, we have solved the Maxwell equations, the heat equation and I-V characteristics for superconductors, and investigated flux density and current in a rectangular superconducting plate. Comparing results from two and three-dimensional calculation, we report detailed structures of the critical states.

Keywords: Vortex avalanche, Critical state, Finite element method

PCP7-14

Review of Quantum Electrical Standards and the Implementation of the 'Revised SI'

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The Josephson effect and quantum Hall effect have been utilized for voltage and resistance primary standards since 1990. And the other electrical standards are derived from the primary standards basically. In 2018, it is planned that the SI will be revised based on the latest measurements results of the Planck constant,
elementary charge, Avogadro constant, and Boltzmann constant. Review of the present quantum electrical standards and the detailed information of adoption of the 'Revised SI' will be presented.

Keywords: Revised SI, Quantum electrical standards, Josephson voltage standard, Quantized resistance standard

PCP8-1

Control of a single vortex in a stack of intrinsic Josephson junctions

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Penetrations of single vortices into a micron-sized single crystalline of $Bi_2Sr_2CaCu_2O_{8+y}$ (Bi2212) can be resolved in the c-axis resistance measurements using a stack of intrinsic Josephson junctions (IJJs) which are naturally contained in the crystal structure of Bi2212 [1-3]. We found that depending on field-sweep direction, an entry and exit of the first vortex into a stack of IJJs become irreversible below a certain temperature, normally ranging in 60 - 70 K. Probably, this behavior is related to the depinning transition that is confirmed in bulk crystals of Bi2212 as second order phase transition, since the boundary, where the irreversibility appears, in field-temperature (*H-T*) phase diagram locates at the position similar to the depinning-transition line. Employing this hysteretic vortex entry and exit, we have successfully demonstrated a vortex memory, in which both a vortex memory cell (a IJJs stack) and a control line are built in a flake of Bi2212.

Keywords: vortex memory, Bi2Sr2CaCu2O8+y, intrinsic Josephson junction, depinning

PCP8-2

Fabrications of Small and High-quality Intrinsic Josephson Junctions by Combinatorial Method of Ar-ion and Focused Ga-ion Etchings

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The fabrication of the small and high-quality intrinsic Josephson junctions (IJJs) is crucially important to study the macroscopic quantum tunneling and pseudogap phenomena occurring in high-T_c cuprate superconductors. The previous study on the fabrication of submicron $La_{2-x}Sr_xCuO_4$ (La214) IJJ stacks reported that argon ion etching after focused ion beam (FIB) etching was useful to control the thickness of IJJs [1]. In addition, the recent report of the transmission electron microscope (TEM) study on $Bi_2Sr_2CaCu_2O_y$ (Bi2212) IJJs suggested that the amorphous damage produced by the gallium ion etching was excellently removed by the argon ion etching [2]. Thus, the combination of both etching techniques is required to enhance the performance of small stacked IJJs.

Here, we present a study on the fabrication of Bi2212 IJJs by using the FIB etching and Ar-ion etching. First of all, we confirmed that the current-voltage (***I-V***) characteristics of small IJJs, which were sandwiched by two slits fabricated on the side wall of a microbridge, was never influenced by the direction of a Ga-ion beam in the FIB etchings processes. This shows a good agreement with our recent observation that the thickness of FIB damage is independent of the direction of the Ga ion beam [2]. We also found that Ar-ion etching after the FIB process is quite useful to enhance the performance of the ***I-V*** curves of IJJs. Furthermore, we succeeded in employing the double-side etching by the irradiation of Ar ions after the FIB microfabrication, by using the silicon substrate with a small square hole (50×50 μm^2). These results strongly support the importance of the combinatorial method of FIB and Ar-ion etchings for the fabrication of small and high-quality IJJs.

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Keywords: intrinsic Josephson junction, focused ion beam, Ar-ion etching

PCP8-3

Dynamics of Phase Switch in the Intrinsic Josephson Junctions Made of Bi2212 with Perfectly-stoichiometric Cation Compositions

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The intrinsic Josephson junctions (IJJs) of $Bi_2Sr_2CaCu_2O_y$ (Bi2212) cuprate superconductors have great advantage such as a perfectly smooth tunnel junction on an atomic scale and a high critical current density J_c. However, it is not necessarily enough to extract the underlying excellent properties of IJJs, because of a nonstoichiometry of cation compositions as well as oxygen nonstoichiometry in Bi2212 crystals. It is empirically known that the nonstoichimetry in cuprate superconductors induces inhomogeneity and constricts the superconducting transition temperature T_c and J_c. Here, we present a study on the phase switch in a small stack of IJJs with the cation compositions approaching to be perfectly stoichiometric, Bi:Sr:Ca:Cu=2:2:1:2. The previous magnetization measurements for the stoichiometric Bi2212 crystals suggested that the value of J_c in the vortex state was unexpectedly enhanced, implying the importance of the stoichiometric cation compositions [1].

We found that the switching current densities (~1.5×10^4A/cm^2) for the third phase switch (3rd SW), corresponding to the switch from the second branch to the third branch in the multiple-branched I-V curve, in the stoichiometric IJJs were 4 times larger than those for the conventional IJJs with the nominal compositions, Bi:Sr:Ca:Cu=2.1:1.9:1:2. In addition, it is found that an effective temperature T_{esc} for the phase escape is about 1.5 times larger than a bath temperature T_{bath} from 17 K to 35 K. This suggests that the cation stoichiometry enhances J_c so largely that the Josephson penetration depth becomes smaller than the lateral junction size [2]. Below 17 K, T_{esc} shows no temperature dependence, implying the occurrence of a classical-to-quantum crossover. This temperature is also about two times larger than that for the higher-order phase switches in the conventional IJJs [3]. These results clearly show that the cation stoichiometry in Bi2212 is quite important for the implementation of Josephson qubits utilizing IJJs at higher temperatures.

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Keywords: Bi-cuprate, intrinsic Josephson junctions, switching current distribution, macroscopic quantum tunneling

PCP8-4

Uncertainty analysis of the Boltzmann constant measured by Johnson noise thermometry using superconducting integrated circuit

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We report on our measurement of the Boltzmann constant by Johnson noise thermometry (JNT) using an integrated quantum voltage noise source (IQVNS) that is fully implemented with superconducting integrated circuit technology. The IQVNS generates calculable pseudo white noise voltages to calibrate the JNT system. The thermal noise of a sensing resistor placed at the temperature of the triple point of water was measured precisely by the IQVNS-based JNT. We accumulated data more than 429200 seconds in total (over 6 days) and used the Akaike information criterion to estimate the fitting frequency range for the quadratic model to calculate the Boltzmann constant. Upon the detailed evaluation of the uncertainty components, the experimentally obtained Boltzmann constant was $k = 1.3806436 \times 10^{-23}$ J/K with a relative combined uncertainty of 10.22×10^{-6}. The value of k is relatively -3.56×10^{-6} lower than the CODATA 2014 value.

Keywords: Boltzmann constant, Johnson noise, Superconducting electronics, pseudo random noise

PCP8-5

Spatiotemporal Dynamics and Collective Phenomena in a Driven Josephson Junction Network

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Spatiotemporal dynamics of phases of a current-driven Josephson junction network (JJN) in an external magnetic field is studied using a numerical simulation based on the resistively shunted junction model. We consider here a JJN which consists of a two-dimensional array of superconducting grains where each pair of the nearest-neighbor sites is connected by a Josephson junction. The array has some type of network structure with structural disorder. We focus on the spatiotemporal dynamics of the JJN with disorder in the presence of external currents with spatiotemporal modulation. The dynamics of the JJN shows complicated behaviors, and the dynamical properties depend on some controllable parameters of junctions and structure of the JJN. There exist synchronization phenomena and collective behaviors under certain conditions. Due to the effect of structural disorder, there also appear inhomogeneous behaviors in the current-driven dynamics. The complicated dynamics of the disordered JJN under spatiotemporal modulation effects are clarified in detail. The physical mechanisms that govern the synchronization dynamics and related spatiotemporal behavior of the JJN are discussed in comparison with another dynamical system.