PCP4-1

Anomalous Metal Interface Effect of Iron-based Superconductors

*Ryoga tajima[1], Yukihiro Miyamoto[1], Takenori Fujii[2], Azusa Matsuda[1]

Department of Physics, School of Advanced Science and Engineering, Waseda University Japan[1]
Cryogenic Research Center, the University of Tokyo Japan[2]

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)

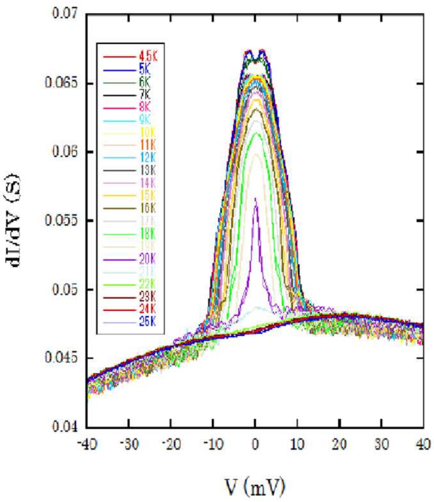

Fig. 1(a). The temperature dependence of the junction conductance using an Al electrode.

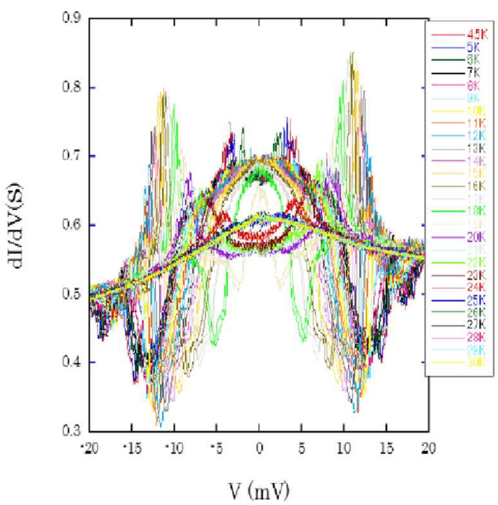

Fig. 1(b). The temperature dependence of the junction conductance using a Sn electrode.

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

PCP4-2

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

*Masataka Kawai[1], Fuyuki Nabeshima[1], Atsutaka Maeda[1]

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

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.

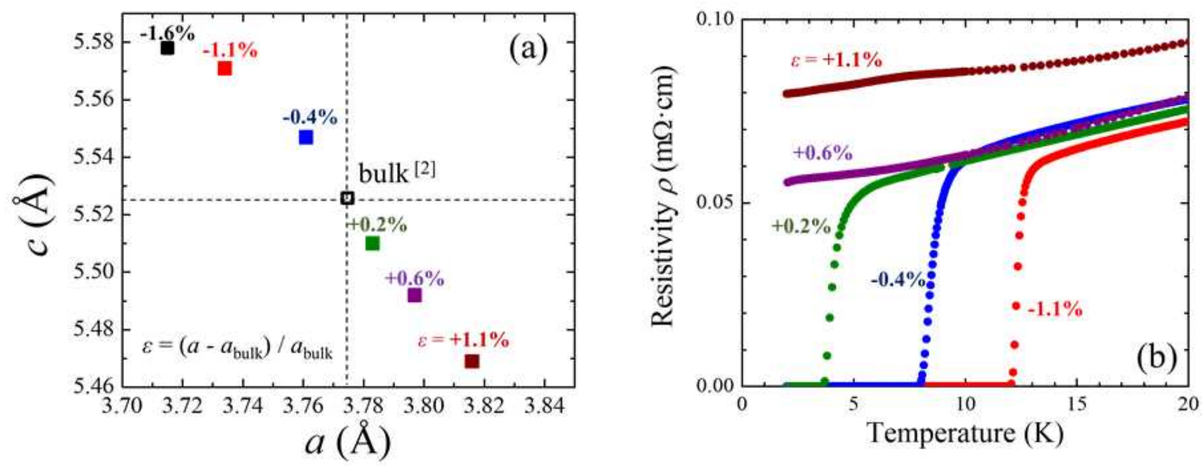

Fig. 1(a) Relation between the *a*- and *c*-axis lattice constants of the FeSe films in this study. (b)Temperature dependence of the electrical resistivity of the FeSe films with various magnitude of strain.

[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

*Takuya Matsumoto[1], Taito Omura[2], Takafumi Hatano[1,2], Kazumasa Iida[1,2], Hiroshi Ikuta[1,2]

Department of Materials Physics, Nagoya University, Japan[1]
Department of Crystalline Materials Science, Nagoya University, Japan[2]

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).

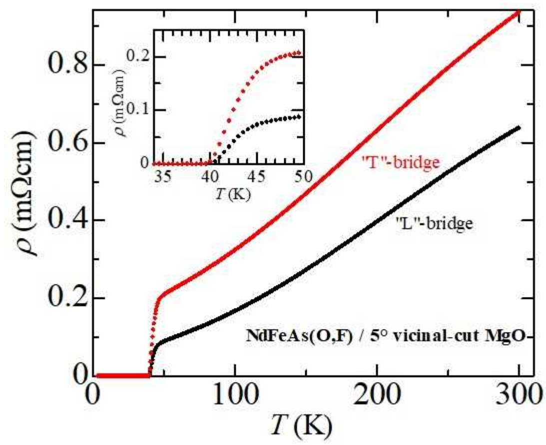

Fig.1 The temperature dependence of resistivity measured on the "L"- and "T"-bridges of a NdFeAs(O,F) thin film grown on a 5° vicinal-cut MgO substrate. The inset shows an enlarged view around the superconducting transition.

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

PCP4-4

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

*Omura Taito[1], Takuya Matsumoto[2], Takafumi Hatano[1,2], Kazumasa iida[1,2], Hiroshi ikuta[1,2]

Department of Crystalline Materials Science, Nagoya University, Japan[1]
Department of Materials Physics, Nagoya University, Japan[2]

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 f-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 (00l) 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).

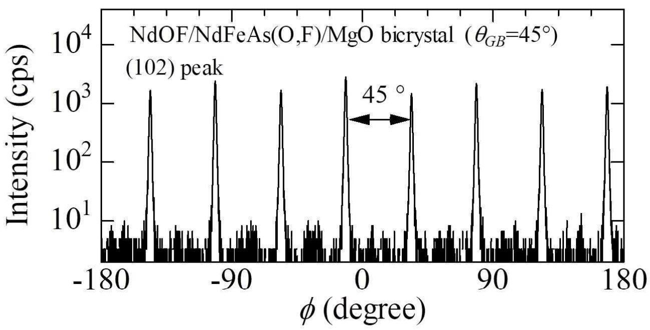

Fig.1. Azimuthal ϕ-scan profile of the off-axis (102) reflection of NdFeAs(O,F) thin film on [001]-tilt MgO bicrystal.

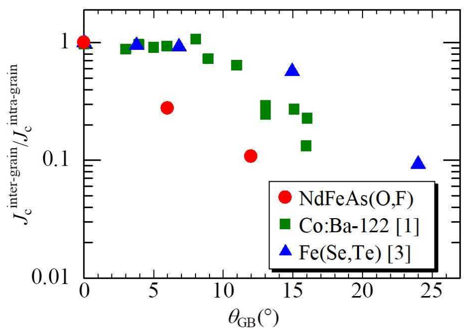

Fig.2. Mis-orientation angle θ_{GB} dependence of normalized inter-grain critical current density J_c .

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

PCP4-5

Search for superconductiveity in epitaxially deposited chromium thin films

*Hiroaki Nakanishi[1], Masashi Ohashi[1], Masaki Sawabu[1], Kae Maeta[1], Takahide Kubota[2,3], Koki Takanashi[2,3]

Graduate School of Natural Science and Technology, Kanazawa University[1]
IMR, Tohoku University[2]
CSRN, Tohoku University[3]

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

*Bunju Shinozaki[1], Shohei Ezaki[2], Tomotaka Odou[1], Kazumasa Makise[3], Takayuki asano[4]

Department of Physics, Kyushu University, Fukuoka 810-8560, Japan[1]
National Astronomical Observatory of Japan National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan[2]
National Institute of Advanced Industrial Science and Technology, Tsukuba 305-8560 Japan[3]
Department of Applied Physics, University of Fukui, Fukui 910-8507, Japan[4]

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 the δ 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

*Marie Mitsuishi[1], Nobuhito Kokubo[1], Satoru Okayasu[2], Tsutomu Nojima[3], Takahiko Sasaki[3]

Department of Engineering Science, University of Electro-Communications, Chofu, Tokyo, 182-8585, Japan[1]
Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan[2]
Institute for Material Research, Tohoku University, Sendai 980-8577, Japan[3]

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).
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[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

*Anjela Koblischka-Veneva[1,2], Michael R. Koblischka[1,2], Alex Wiederhold[1], Jörg Schmauch[1], Miryala Muralidhar[2], Masato Murakami[2]

Saarland University, Experimental Physics[1]
Shibaura Institute of Technology, Superconducting Materials Laboratory, Department of Materials Science and Engineering[2]

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

*Akira Sugimoto[1], Yuta Yanase[1], Takahiro Muranaka[2], Toshikazu Ekino[1]

IAS, Hiroshima Univ.[1]
Univ. of Electro-Communications[2]

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