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Iron-based Superconductors: advances towards applications

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Topics

- Materials
- Pinning and vortex matter
- Bulk magnets
- Thin films and devices
- Wires, tapes and Coated Conductors

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Status of high-field iron-based superconducting wires and tapes

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Iron-based superconductors (IBS), especially 122 type, are very promising candidates for high-field applications because of its ultrahigh H_{c2} > 70 T at 20 K, low anisotropy (<2 for 122) , and ease of fabrication. Recently, the highest transport J_c values have achieved 0.15 MA/cm^2 (I_c = 437 A) at 4.2 K and 10 T in densified and textured 122 tapes. Secondly, in order to reduce costs and improve the mechanical strength, high strength stainless steel/Ag and Cu/Ag 122 composite conductors have been fabricated, with transport J_c above 50 kA/cm^2 in 10 T. For round wires, the highest J_c value reached 31 kA/cm^2 in Cu/Ag composite sheathed wires at 4.2 K and 10 T. High-J_c multifilament 122 wires were successfully fabricated by the PIT method. More importantly, transport J_c of 100-m-class 122-type IBS wires has been tripled, compared to the first one, confirming the great potential for large-scale manufacture. Finally, as China is proposing the next generation high-energy particle accelerators for funadamental physics study, I will introduce the SPPC project and the role of IBS technology within it.

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Study of HTS coatings for beam impedance mitigation in the FCC

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The beam screen of the proposed FCC-hh collider at CERN presents several operating challenges. Its main function is to intercept the synchrotron radiation emitted by the beam, shielding the accelerator magnets, which are cooled at 1.9 K. It should operate at 50 K as a compromise between energetic efficiency and vacuum requirements; however at this temperature a copper coating facing the beam, like in the LHC at present, would have a relatively high electrical resistivity, thus a high beam coupling impedance, resulting in too little margins for beam stability.

Since 2016 a collaboration between CERN and several European institutes has been exploring the possibility of using HTS for the beam screen, in replacement of copper. We will discuss, based on a simple theoretical modelling, the selection criteria for the superconductor, which should guarantee a low surface impedance in a magnetic field up to 16 T. We will then discuss the two routes selected, namely a coating of Tl-based cuprates directly on the beam screen or soldering REBCO coated conductors on its surface. Several key milestones have been achieved during the collaborative work and a great deal of promising results have been demonstrated on test samples, including many different requirements related to the accelerator environment.

Finally, we will discuss the plans for the next phase of the collaboration, aimed at designing and fabricating proof-of-concept prototypes which could be measured in an ad-hoc impedance and field quality test set-up.

YBCO coated conductors and thin films for high frequency applications in dc magnetic fields

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High frequency applications for high-critical temperature (T_c) superconductors like $YBa_2Cu_3O_{7-\delta}$ (YBCO) have been for a long time essentially limited to the superconducting electronics field. As a consequence, no particular demands have been placed on their rf performances in intense magnetic fields. Recently this situation is changing, due to a revamped interest originating in some frontiers of the science. In the search for galactic axions [1], resonating cavities in medium-high static magnetic fields (1-2 T) are deemed as necessary to detect those elusive particles. Since high enough quality factors cannot be obtained through normal metals, superconductors are the unavoidable choice. Another application scenario is given by high energy hadron colliders presently under study: for example, the so-called future circular collider will require a beam shield with low enough dissipation in the GHz range at cryogenic temperatures within magnetic fields as high as 16 T [2].
The requirement for low losses conflicts with the short-range oscillatory vortex motion [3]. Vortex dynamics is governed by a main characteristics frequency, the (de)pinning frequency np, which separates low-frequency, small dissipation regimes from high frequency, large dissipation ones. A measure of νp represents an essential step for the evaluation of a superconductor performance in magnetic fields at high frequencies. In thin films the evaluation of νp is relatively straightforward when one measures both the real and imaginary part of the surface impedance Zs [3], but in coated conductors the complex, multilayered (YBCO film / buffer layers / metal substrate) structure [4] makes the task rather intricate [5].
In this work we report on surface impedance measurements performed on various YBCO coated conductors in the 60-T_c temperature with applied fields up to 1 T. We show how to reliably extract their main parameters and we report on values for νp that are promising towards high-frequency, high-fields applications. We finally present measurements in thin YBCO films on single crystal substrates up to 12 T, to set at least an order-of-magnitude evaluation of the losses to compare to the needs for very-high field applications.

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Superconductors for the Italian Divertor Tokamak Test facility project

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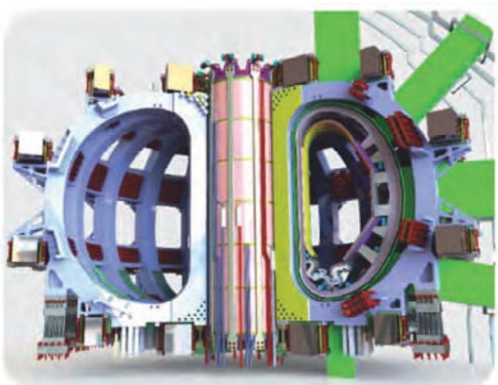
The "Divertor Tokamak Test" (DTT) facility is an experimental tokamak currently under construction in Italy, at the Frascati research center of ENEA. The main goal of this nuclear fusion project is to build a facility able to test various divertor solutions and magnetic configurations. The definition of the most appropriate approach to manage power and particles exhaust for the EU-DEMO machine is in fact still an open issue, and DTT should heavily contribute to the elaboration of a feasible solution. The DTT fully superconducting magnet system consists of 18 Toroidal Field (TF) coils, 6 Poloidal Field (PF) and 6 Central Solenoid (CS) stacked module coils, all independently fed. It is based on Cable-in-Conduit Conductors, and it employs about 25 tons of NbTi and about 75 tons of Nb_3Sn multi-filamentary wires. It has been designed to accommodate stringent requirements of performance and flexibility. In this paper, the main design drivers and up-to-date solutions for the magnet system are presented, from the superconducting strands up to the main structural components, and the outcome of their main analyses discussed in detail. An overview of the technical needs leading to the present design is provided, with a discussion on the aspects that mostly impact on the procurement and construction phases, which are already on-going.



Overview of the Divertor Tokamak Test facility (DTT) magnet system and structures.

Research status and direction of HTS Fault Current Limiters

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High temperature superconductors (HTS) own negligible electrical resistance and very high current density (ten to hundreds times the one of the copper). Not merely a scientific curiosity, their exceptional properties allows the development of power electrical devices with unachieved performance as well as new functionalities. Further advantages are the drastic increase of the efficiency, the compact size and the longer life. Several manufactures exist now around the world which are able to supply HTS materials for real scale application at decreasing costs. Furthermore, substantial progress, both in terms of performance and cost reduction, has also been achieved for cooling technology which is essential for the reliable operation of HTS.

The intrinsic non linearity of HTS material (transition to the normal state due to overcurrent) can be exploited for the development of superconducting fault current limiting (SFCL) devices, able to improve the performance (power quality and stability) of the grid in normal condition and to reduce the risk of disturbance, damage or black out due to fault. Long term field test of real scale HTS fault current limiter prototypes has been performed during the last years and first commercial installations of have also been introduced. In this presentation, the concepts of Superconducting Fault Current Limiters are presented and their state of development is investigated. The benefits that they can bring to the power grid are discussed with reference to practical application cases. Near future research directions, with particular reference to DC SFCL, are pointed out. The research activity on SFCL carried out at the University of Bologna is also resumed.

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Impact of non-local exchange on Iron Pnictides

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Ten years after their discovery, the physics of iron-based superconductors (IBSC) has yet to be clarified, and a unified understanding of their behaviour is far from being reached. Even though the major role played by local correlations has been widely assessed, low-energy models relying exclusively on them are not able to reproduce some fundamental properties, most notably the size of electron and hole pockets of the Fermi surface [1,2]. In this regard, we study the effect of non-local exchange in the presence of strong local correlations within the IBSC 122-family, by means of Slave-Spin@Density-Functional Theory simulations. Non-local exchange is treated at the Density-Functional Theory level via the screened hybrid functional HSE06, whereas local Hubbard- and Hund-type interactions are accounted for within the Slave-Spin method. Particular attention will be given to the impact of non-local interactions on the Fermi surface, via a thorough comparison with the available experimental data for different electron doping and degree of correlation.

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Elasto-transport: a probe for nematic fluctuations in iron-based superconductors

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The investigation of nematic orders in solid state systems has been strongly boosted in recent times by the suggestive hypothesis of their intimate link with the emerging unconventional superconductivity in copper-based and specially in iron-based superconductors (IBS) [1]. In the latter, the nematic order identifies a lowering of the rotational symmetry characterized by a tetragonal-to-orthorhombic structural transition, which typically anticipates the formation of a time-reversal-invariant magnetic order with additional signatures of orbital ordering [1]. Among the several ideas proposed to understand the role of the nematiciy in IBS, a groundbreaking intuition was to use the strain derivative of the resistivity anisotropy as a sensitive quantity mimic of the nematic order parameter [2]. This allowed to reveal an extended region of nematic fluctuations above the structural transition, where the crystalline symmetry is still tetragonal, and to distinguish the electronic origin of the nematic phase from a simple ferroelastic distortion [2].

In this work, we extended the experimental technique by introducing the strain-derivative of the thermoelectric coefficients, namely the Seebeck and the Nernst effects. This was realized by combining a standard thermoelectric measurement configuration, with the highly controlled uniaxial strain offered by a piezoelectric device (Figure 1a). By applying this new technique to the 1111 family of IBS, we discovered that a universal Curie-Weisslike behavior governs electric and thermoelectric elasto-transport above the structural transition, as a fingerprint of the original trigger of the nematicity (Figures 1b and 1c). Remarkably, our measurements reveal a band-selective character of the nematic phenomenology and show that different transport properties are not equivalently representative of the nematic susceptibility.

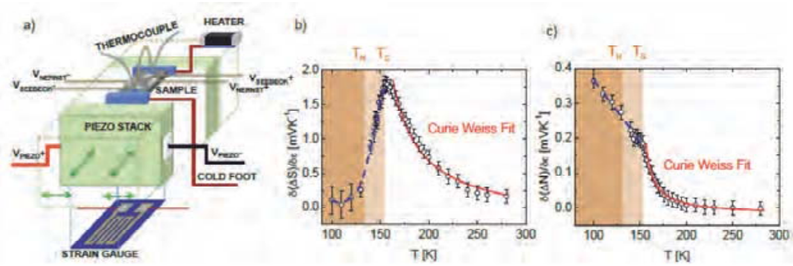

Figure 1: a) Schematic of our experimental setup for elasto-thermoelectric transport. b) Elasto-Seebeck and c) Elasto-Nernst effect of a LaFeAsO compound. Red curves are the Curie-Weiss fit for the nematic fluctuations.

Magnetic ordering and spin dynamics in $La_2O_3Fe_2Se_2$: a ^{139}La NQR study

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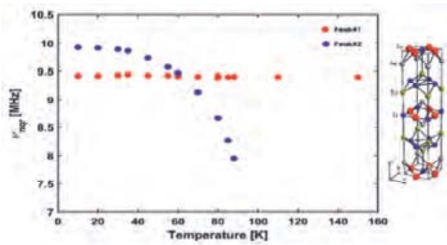
The unique spin and orbital properties of iron-based superconductors (IBSs), including orbitally-selective Mottness and charge ordering, have sparked remarkable interest in the last decade. The parent compounds of IBSs present a test-bed scenario for these properties. In particular, $La_2O_2Fe_2OSe_2$ has recently been a popular choice because of its peculiar antiferromagnetic (AFM) ordering. Its structure consists of alternating stacked layers of La_2O_2 and Fe_2OSe_2 along the c-axis (figure 1). Earlier reports proposed an in-plane FM and AFM magnetic ordering along a- and b-axis respectively [1], while later studies have argued for two perpendicularly-oriented AFM exchange interactions in the two different sub-lattices [2].

Nuclear Quadrupole Resonance (NQR) spectroscopy is a local probe that requires no external perturbations like magnetic field and/or strain; therefore it probes the equilibrium spin and charge ordering. We use both ^{139}La NQR spectra and relaxation measurements for $La_2O_2Fe_2OSe_2$, in order to understand and settle the questions on charge ordering and orbitally-selective behavior. We distinctly identify two magnetically non-equivalent La species (identified as peak#1 and peak#2), in spite of the presence of only one La site per unit cell and in agreement with previous reports [2]. Peak#2 (blue dots in figure 1) appears only below the transition temperature ($T_N \approx 90K$) and strongly shifts to higher frequencies down to about 30K where it saturates. On the other hand, interestingly the peak#1 (red dots), which is the main NQR line, does not broaden or shift, as expected due to the internal magnetic field attributed to an AFM ordering below TN with a magnetic hyperfine field perpendicular to the c-axis. These two non-equivalent sites can possibly be attributed to orbitally-selective behavior in the ordered phase which has been theoretically predicted for this system [3].



Left: ^{139}La NQR frequency positions vs. temperature. Right: Crystal structure of $La_2O_2Fe_2OSe_2$

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Evidence of the isoelectronic character of F doping in $SmFeAsO_{1-x}F_x$

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The $SmFeAsO_{1-x}F_x$ superconducting alloy has attracted much attention because of its high transition temperature (T_c = 58 K) at optimal doping [1]. Recent experiments [2] show that the Shubnikov de-Haas oscillations in the $SmFeAsO_{1-x}F_x$ do not change with F concentration. This behavior is somewhat surprising because it contradicts the common believe that F should behave as a donating impurity. In a semimetal, as the SmFeAsO, electron doping should widen the size of the Fermi surface for the electrons and shrink those related to the holes. Instead, experimental evidence suggests that the size of the Fermi surfaces is independent of F concentration. To shed light on this anomalous behavior, we study the electronic structure of the $SmFeAsO_{1-x}F_x$ alloy by means of firstprinciple calculations [3]. We find that, contrary to common believe, F-doping does not change the charge balance between electrons and holes free-carriers in $SmFeAsO_{1-x}F_x$. Indeed, within a narrow energy range across the Fermi energy, the effect of F-doping on the band structure dispersion is tiny in both the paramagnetic and stripe antiferromagnetic phase of $SmFeAsO_{1-x}F_x$. Using the concept of Baders charge, we discuss the charge balance between the conducting FeAs-layer and the $SmFeAsO_{1-x}F_x$ charge reservoir layer as a function of F concentration. The results of our calculations show that the charge state of the FeAs-layer is not influenced by the compositional change. Such a surprising behavior can be explained looking at the evolution of the band structure as a function of F concentration. We discover that the additional charge carried by fluorine, with respect to the oxygen, is compensated by a change in the oxidation state of the Sm ion from 3+ to 2+. A comparison with the $SmFe_{1-x}Co_xAsO$ system shows that such a charge compensation by the Sm ion is not shared by donors substituting at the Fe site.

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Planar defects and vortex pinning in $EuRbFe_4As_4$ iron-based superconductor

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We successfully synthesized $EuRbFe_4As_4$ single crystals by a "self-flux" technique. The systematic AC susceptibility and magnetic moment M(H,T) measurements were performed to investigate the vortex pinning in the $EuRbFe_4As_4$ superconducting single crystal. We show that Eu^{2+} magnetic ordering shifts to 5K in external magnetic fields of roughly 1T and find evidence of insignificant interaction between magnetic and superconducting layers. We found $U_0(H)$ follows an $H^{-0.47}$ dependence in magnetic fields above 0.1T and reaches 6700K at low fields along ab plane. Therefore, collective pinning with $U_0 \sim H^{-1}$ is not the case. According to the very recent TEM observations in Ca-1144 was found the presence of planar defects along the ab plane [1]. Given a similar synthesis method and the same structure of $EuRbFe_4As_4$, it can be assumed that $(Rb/Eu)Fe_2As_2$ layers may act as planar defects. Thus, the pinning mechanism here, considering $U_0 \sim H^{-0.47}$ at $H > 0.1T$, is maybe due to the planar defects [2]. However, additional investigation is needed to confirm our assumption.

The isothermal magnetization measurements M(H) were provided in Eu-1144 single crystal along ab plane. Our data shows that the $\Delta M(T) \sim J_c(T)$[3] width did not vastly change above or below Eu^{2+} magnetic ordering at 15 K. Thus, the influence of Eu2+ magnetic ordering on the ΔM values is insignificant compared to SC signal even at low temperatures. The $J_c(H)$ behaviour at different temperatures show that at low fields, typically about 100 – 350 Oe, J_c is independent of external field - single vortex regime is observed. At higher magnetic fields, from 0.01-0.1T up to 1.5 T, the critical current follows a power-law behaviour $J_c \propto H^{-a}$ with $0.55 < a < 0.68$. The a exponent values obtained in this work are in a good agreement with the theoretical prediction of $H^{-5/8}$, which indicates strong vortex pinning [4]. Considering the structural conformance with other compounds in this family, the Eu-1144 can be used as a source of strong pinning centres for the $CaKFe_4As_4$-based superconducting material to improve critical current density for practical applications.

Work was done using equipment of the LPI Shared Facility Center and supported by the Russian Foundation for Basic Research (RFBR project no. 17-29-10036).

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The Project PRIN HIBiSCUS: High performance-low cost Iron BaSed Coated condUctorS for high field magnets

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High superconducting transition temperature, upper critical field, and critical current density are the three major requirements for high magnetic field applications of superconductivity. Iron-based superconductors (IBS) could be a breakthrough of the intrinsic limits of low-T_c Nb_3Sn (20T at 4.2K) and of the extreme material complexity of copper oxide high-Tc superconductors (HTS), which leads to articulated and expensive processes for wire/tapes fabrication. The project HIBiSCUS aims at developing highly optimized IBS coated conductors (CCs), focusing on the trade-off between cost effectiveness and performances and taking advantage from an accurate material characterization.

HIBiSCUS is an Italian project funded by the Italian Ministry of University and Research (MIUR). It sees the collaboration of research groups that have always been active internationally in the field of applied superconductivity: The University of Genova with the role of project coordinator; CNR-Spin with the task of making the tapes, assisted by ENEA in the creation of the metal templates; Politecnico of Turin and the University of Roma3 with the advanced structural and electromagnetic characterizations in charge and the study of the effect of radiation on the performance of the CC (POLITO). The team has the final task of validating the new IBS-CC technology with respect to other technical superconductors.

Fe-based superconducting coated conductors – preparation, tuning of properties, and recent development

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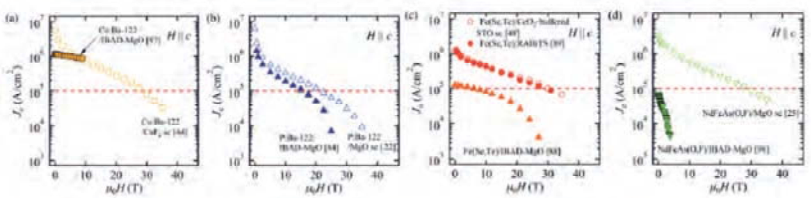
In the last 10 years, huge progress was made in thin film deposition of Fe-based superconducting (FBS) materials [1,2], not only for fundamental investigations of these new materials but also to evaluate their application potential. The critical current density J_c of FBS is, e.g., less sensitive to the presence of grain boundaries (GBs) than those of the high-T_c cuprates [3]. This is highly beneficial for the realization of cheaper conductors for high-field magnets at low temperatures. So, several groups have demonstrated FBS thin films on technical metallic substrates [4] and powder-in-tube processed FBS wires [5] as proof-of-principle studies for conductor applications. FBS on technical substrates also give many opportunities for studying the influence of GB networks on J_c and how uniaxial strain impacts the superconducting properties [6].

We review FBS thin film studies on technical metallic substrates, and focus on application-relevant properties like pinning improvement by natural and artificial defects as well as the transparency of grain boundaries and GB networks. The recent development of FBS thin films on technical substrates with their superconducting properties and application potential is discussed.



Comparison of J_c(H||c) properties of various FBS thin films on technical substrates and single crystalline substrates. Measurement temperature was 4.2 K except for NdFeAs(O,F) on IBAD-MgO. [4]

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Epitaxial $La_2Zr_2O_7$ and Zr-doped CeO_2 films by chemical solution deposition as buffer layers for Fe(Se,Te) film growth

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Iron based superconductors (IBS) are being intensively studied worldwide due to their interesting properties such as the low anisotropy and the very high upper critical field. As a consequence, IBS are candidate materials for very high magnetic field applications. Among the various families of IBS, Fe(Se,Te) system is attractive due to both low lattice anisotropy low toxicity. The best performances of Fe(Se,Te) were so far reached as epitaxial thin film grown on oriented substrate. Recently, high critical current density Fe(Se,Te) film has been obtained on single CeO_2 buffer layer deposited by pulsed laser deposition (PLD) on cube-textured Ni-W substrate. A fundamental step toward process simplification and cost reduction is the possibility of using inexpensive chemical solution deposition (CSD) methods to grow epitaxial buffer layers. In this contribution, the epitaxial growth of $La_2Zr_2O_7$ (LZO) and Zr-doped CeO_2 (CZO) films by CSD on commercially available (100) single crystal substrates such as $SrTiO_3$ and Y_2O_3-stabilized ZrO_2 (YSZ) and their use as buffer layers for Fe(Se,Te) film growth is shown. Preliminary results on Fe(Se,Te) film deposited on LZO or CZO grown on (001) $SrTiO_3$ and YSZ single crystal are reported. The influence of deposition conditions on LZO and CZO film microstructure was investigated and reported. It is revealed that sharp epitaxial growth can be achieved for both films in a large range of temperature. Conversely, the film surface roughness and grain coalescence are more complex and deserve a more careful control. Preliminary results on Fe(Se,Te) films deposited on CSD buffer layers show encouraging superconducting properties, although further optimization is necessary.

Fe(Se,Te) Coated conductors on simple RABiTS templates

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Among all the Iron-based Superconductor (IBS) families, the iron chalcogenide $FeSe_xTe_{1-x}$, also called 11 phase, is the simplest, and it is quite attractive because of its relatively ease of fabrication and the absence of toxic arsenic. 11 thin films have been successfully grown on single crystalline substrates and on technical metallic templates with complex architectures developed and already commercially available for the deposition of $YBa_2Cu_3O_{7-x}$. In particular, 11 thin films have been grown either on Ion Beam Assisted Deposition (IBAD) [1] and Rolling-Assisted Biaxially Textured Substrate (RABiTS) templates, showing values of critical current densities J_c as high as 10^5 A/cm^2 up to 30 T [2]. In IBS the exponential decay of J_c across misoriented grain boundaries seems to be less severe than for YBCO. Moreover, Fe(Se,Te) thin films are deposited without the presence of oxygen in a temperature range between 230°C and 550°C [3], much below the deposition temperature required for YBCO. These features have a strong impact on the development of a suitable CC technology relaxing significantly the film texture constraint and the role of the buffer layer architecture. Hence, it is possible to think about the development of much simpler metallic templates, reducing essentially the complexity and the manufacturing cost of IBS-CC, which may make them more attractive on the cost-performance basis.

In this work we show the development of 11 CCs with simpler and cost-effective RABiTS. The simplicity of the substrates could derive from both from the employment of commercial metallic alloys and also from the modification of the architecture of buffer layer. Buffer layers can be deposited with simple and scalable methods, can be reduced in number or even completely removed. These possibilities singularly or combined together contribute to the simplification and consequently to the cost reduction of 11 CCs. The different CC architecture studied will be presented, starting from the development of simpler metallic substrates made of a commercial alloy and without any buffer layer [4] to more complicated substrates which comprises NiW5% metallic tapes and different nitrides and oxides buffer layers [5], studying the properties of the Fe(Se,Te) thin films deposited on these substrates.

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Towards the study of uniaxial strain in epitaxial $FeSe_xTe_{1-x}$ films

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The discovery of high temperature superconductivity in layered iron-based material has ignited significant scientific interest in basic studies of their properties as well as for technological applications. Among them, iron selenide hasthe simplest crystal structuremaking it favorable for studying the underlying mechanism of superconductivity, which can be tuned either by strain or by doping [1]. In particular, it has been reported in literature that the transition temperature can be increased bycompressive substrate-induced biaxial strain in thin film. Our aim is to extend these investigations in order to study the correlation between uniaxial strain and critical temperature in thin films.

In order to study such thin film in a uniaxial strain cell, we will apply two different approaches. Firstly, we grew iron selenides on ultra-thin single crystalline substrates in order to reduce the necessary force for uniaxial straining of these samples. Therefore, a thin Fe(Se,Te) seed layer was deposited on these substrates at 400 °C using pulsed laser deposition, followed by a homo-epitaxially grown Fe(Se,Te) film at 300°C. All films are highly textured and show a maximum superconducting transition temperature of 21 K, 19 K and 17 K on CaF_2, $SrTiO_3$and MgO, respectively.

As second approach, the coated conductor technology will be used based either on textured ion beam assisted deposition (IBAD) layers or rolling assisted biaxially textured substrates (RABiTS). Therefore, we deposited pure as well as Te doped FeSe with a thickness of up to 200nm on these textured templates having a final cap layer of either CeO_2 or $LaMnO_3$. We found that $FeSe_{0.5}Te_{0.5}$ as well as FeSe grows epitaxially on these buffered metal tapes under optimized conditions with a superconducting transition temperature of up to 16 K for textured film on CeO_2 buffered metal tapes. These layers will be used to study the influence of uniaxial strain on the superconducting transition in these materials.

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Investigation of granularity in $FeSe_{1-x}Te_x$ thin films on various substrates

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High temperature superconductors are strongly impaired by grain boundaries, since the inter-granular current density strongly depends on the misorientation angle between adjacent grains. The granularity of pulsed laser deposited YBCO thin films on commercially available metallic templates has already been studied and the superconducting properties related to the local orientation of grains [1]. In recent years, Fe-based materials have been intensively studied for potential applications. Since they exhibit a reduced J_c dependence on grain boundary misorientation angles, they might be beneficial for high field applications. It was shown, that the commercially available coated conductor templates can also be used for the preparation of Fe-based superconducting layers carrying high J_c values. There are ongoing investigations, whether long length coated conductors based on Fe-materials can be realized. For this, it is essential to investigate the correlation between the local current transport and the microstructure on a grain level in order to understand and optimize the current transport capability of such conductors. As a first step, thin films of $FeSe_{1-x}Te_x$ are grown on various substrates. We present the superconducting properties of these thin films, which are investigated by means of magnetization measurements and Scanning Hall Probe Microscopy. With magnetic field mapping we can investigate the global critical current homogeneity and look at the current distribution in superconducting grains and across grain boundaries. The superconducting properties can then be related to the microstructure of these thin films.

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Developments of (Ba,Na)Fe_2As_2 and $CaKFe_4As_4$ HIP Round Wires

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Soon after the discovery of iron-based superconductors (IBSs), developments of superconducting wires and tapes carrying large critical current density, J_c, have started [1]. The practical level of J_c = $1x10^5$ A/cm^2 has been achieved even at high magnetic fields over 10 T [2]. However, among several IBS systems, only the 122-type materials have been exclusively studied. In particular, most of the work has been concentrated on K-doped 122-type materials, (Ba,K)Fe_2As_2 and (Sr,K)Fe_2As_2. On the other hand, good potential of Na-doped 122-type material, (Sr,Na)Fe_2As_2, as superconducting tape was demonstrated by AIST group [3] and confirmed by us [4]. To avoid the issue related to Na segregation in (Sr,Na)Fe_2As_2, we turned our attention to (Ba,Na)Fe_2As_2, and reasonably large J_c was achieved [5]. In this presentation, efforts to enhance J_c in (Ba,Na)Fe_2As_2 HIP round wires are presented. By optimizing the fabrication process, J_c even larger than that of (Ba,K)Fe_2As_2 HIP round wire [6], ~$4x10^4$ A/cm^2 (10 T), has been achieved. The HIP round wires were characterized by means of magneto-optical imaging as well as transport, magnetic, and X-ray measurements. J_c can be further enhanced in the tape form by improving texturing by either cold or hot pressing. On the other hand, a new type of IBS called 1144-type, which is a derivative of 122-type, has been discovered recently [7]. $CaKFe_4As_4$ is a typical superconductor among 1144-type materials, which are stoichiometric materials and reside in a slightly overdoped region. Studies on $CaKFe_4As_4$ single crystals have demonstrated modesty large J_c with peculiar anisotropy related to the presence of novel planar defects [8]. We will also present attempts to fabricate HIP round wires of $CaKFe_4As_4$ [9]. Studies on $CaKFe_4As_4$ single crystals have shown that the J_c drops fast as a function of magnetic field at temperatures below ~10 K, while J_c at high fields shows nonmonotonic temperature dependence at high temperatures. We find out that substitution of small amount of Co for Fe significantly improves J_c in $CaKFe_4As_4$ at low temperatures including its field dependence. With this in mind, we also attempted to fabricate $CaKFe_4As_4$ HIP wires with Co substitution.

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Characteristics and potential of application for 1144-type iron pnictide superconductors

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Since the discovery of superconductivity in LaFeAs(O,F) in 2008, a series of compounds with iron arsenide or chalcogenide layer have been developed such as REFeAs(O,F) (RE = rare earth) and $AEFe_2As_2$(AE = Ca, Sr, Ba, Eu, so-called 122). The $AEAFe_4As_4$ (A = K, Rb, Cs, 1144) superconductors are one of the recently developed iron-based superconductors with several unique features[1]. The structure of the compounds can be interepreted as a stacking of two kinds of 122-type compounds, AE122 and A122. The T_c, H_{c2} and γ of 1144-type compounds are comparable to those of (Ba,K)122, which is regarded as one of the best compound for high field applications. While the structure of 1144 is very close to that of 122, there are several important differences in the properties between 1144 and 122-type compounds. Compositional fluctuations in 1144 is in principle not possible, which is one of the prominent difference from 122. This is because there is large difference of ionic radii of AE and A in 1144, they do not make solid solutions in contrary to 122-type compounds. The feature is the origin of its unique defect structure as described below, and also it may contribute to the uniformity of physical properties in whole 1144 matrix. In addition, the critical current density(J_c) in CaK1144 are found to be different with those of 122-type compounds. Single crystals of 1144 can be grown by FeAs flux method, and we characterized their structural and physical properties. There is significant anisotropy in J_c along a- and c-axis, furthermore, J_c is enhanced with increasing temperature[2]. In TEM observation, intergrowth of nanoscale Ca122 phase is observed in CaK1144 single crystals because solid solution is not possible in 1144. Such unique defect structure in 1144 possibly act as vortex-pinning centres, and contribute to the unusual anisotropy and T dependence of J_c in this compound. These characteristics of 1144 makes it as promising material for practical applications. Recently we also tried to synthesize pure and high J_c polycrystalline samples of CaK1144. Optimization of synthesis conditions as well as effect of intentional additives are studied to enhance J_c. In this presentation, characteristic of superconducting properties of 1144-type superconductors, and recent studies to synthesize high J_c 1144 polycrystalline samples will be presented.

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Cold-press formed superconducting joint between $Ba_{0.6}K_{0.4}Fe_2As_2$ tapes

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Significant progresses toward high performance iron-based superconducting wires/tapes have been made over recent years [1]. Especially for (Ba,K)Fe_2As_2, the critical current density exceeded 1.5×10^5 A/cm^2 at 4.2 K under 10 T [2]. For the practical use, a superconducting joining technique is of critical importance. Recently, Zhu et al. reported that the superconducting joints fabricated via a hot press technique show a critical current ratio (CCR) of 63 % at 4.2 K under 10 T. They found cracks and a potassium loss around the joint area, which are considered to limit the performance of the joints [3]. For the improvement of the performance, it is required to reduce the number of the cracks and prevent the potassium loss. In this study, we fabricated superconducting joints between (Ba,K)Fe_2As_2 tapes by using cold press method and evaluated their performance. The Ag sheath of flat-rolled tapes was partially peeled off mechanically in a glove box filled with Ar gas. The joint width and the lap length are 2.5 mm and 4 mm, respectively. The superconducting cores were jointed face to face and the jointing part was wrapped with Ag foil. The joint part was uniaxial cold-pressed between stainless steel disks under pressure of 119 ~236 MPa for 30 seconds. The joint samples were sintered at 850 °C for 3 h under Ar atmosphere. The cross section of the joint was examined using SEM. Transport critical current measurements were performed by using a four-terminal method. Figure 1(a) shows critical currents of the tape and the joint together with CCR at 4.2 K under magnetic fields parallel to the tape surface. The CCR value of 29 % in 3.5 T at 4.2 K were achieved. Figure 1(b) shows a SEM image of the cross section of the joint. Cracks were not observed around the jointed part. On the other hand, as shown in Figure 1(c), inhomogeneous deformation and cracks were observed around the joint end part, which were possibly induced during the cold-press process. Such deformation and cracks are considered to limit CCR of the present joint.

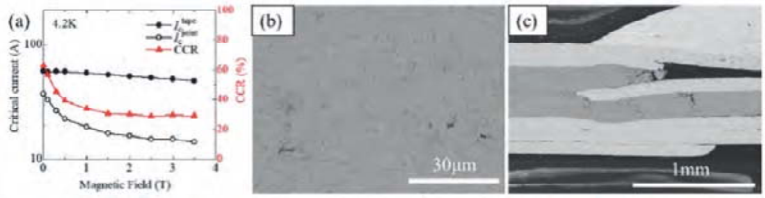

Figure 1. (a) Magnetic field dependence of I_c and CCR of (Ba,K)Fe_2As_2 tape and joint at 4.2 K under field parallel to the tape surface. SEM images of the cross section of (b) jointed area and (c) the end part of (Ba,K)Fe_2As_2 joints.

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Superconducting properties of the $BaFe_{2-x}Ni_xAs_2$ wire fabricated by hot gas extrusion method

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We successfully synthesized $BaFe_{2-x}Ni_xAs_2$ (BFNA) bulk samples by mechanical alloying (MA) [1-3]. Milling process occurred 7-10 times at 900-1000 rpm for 5 minutes. The superconducting phase occurred during short-term heat treatment about 850°C. We characterized the superconducting properties by magnetic susceptibility measurements, and X-ray diffraction analysis to estimate the amount of superconducting phase. All manipulations were done in a glove box with an argon atmosphere because of the high oxidation of metallic Ba on open air. The SEM investigations shows that annealing leads to the rapid growth of crystallites, which indicates the restoration of the long-range ordering in compounds. The average size of the crystallites is in a range of 3-5 μm.

The pre-synthesized superconducting material was used in fabrication of superconducting $BaFe_{2-x}As_2$ wire in brass and steel matrix using ex-situ hot gas extrusion powder in tube method. The wire manufacturing was as follows; the superconducting material was packed into steel and brass containers and welded in an argon atmosphere. Then containers with Ba-122 powder was extruded to a superconducting wire about 1m length with cross-sectional superconducting core area nearly $3x10^{-3}$ cm^2. Various experiments with extrusion temperature and pressure conditions make possible to obtain a superconducting wire core without «sausage» effect. We study superconducting properties of the best heat-treated and non-heat treated wire samples in magnetic fields up to 9T. We found that annealing significantly improving the transport critical current density (J_c) of the as-drawn wires. The transport measurements in best samples shows J_c about two order magnitude lower than in single crystal samples at 4.2 K in zero field, and rather high upper critical field about 45-50T. Thus, we can conclude that hot gas extrusion is suitable for fabrication iron based superconducting wires and their possible practical applications.

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Macroscopic and nanoscopic uniformity and its correlations to intergrain connectivity in K-doped Ba122 polycrystals

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Foreseeing the practical applications as a high field superconductor, Fe-based superconductor (FBS) must be produced in a long length wire form in which the materials are inevitably polycrystalline. In this case, the critical current density J_c across the grain boundary (GB) network, the so-called intergrain J_c, determines the overall J_c of any long-length conductor, whereas the intragrain J_c defines the ultimate J_c that has been proved its intrinsically great potential. In order to make $BaFe_2As_2$ (Ba122) FBS competitive as the high field conductor among the other high temperature superconductors, we must increase the critical current density J_c by improving the intergrain superconducting connectivity in the polycrystalline forms. But it is still largely unknown whether the grain boundary (GB) connectivity in the Ba122 is governed by extrinsic or intrinsic factors.

Indeed pervious works suggested that the intergrain connectivity of Ba122 can be easily degraded by extrinsic factors such as local or global impurity concentrations and grain boundary (GB) cracks. Such unpredictable GB connections caused by external factors often lead to poor reproducibility of intergranular J_c.

We recently upgraded the synthesis environment to reduce the oxygen and water level to <0.005 ppm and <0.01 ppm, respectively. This leads us to explore the actual impurity segregation and local stroichiometry at the grain boundaries in K-Ba122. In particular, our recent results indicate that the chemical instability and/or non-uniformity of K-Ba122 might significantly influence the intergrain connectivity.

The atomic resolution analytical scanning transmission electron microscope (S/TEM) revealed that, in K-Ba122 bulks made in the common glove box filled and flown with high purity Ar, Ba preferentially segregates with containing oxygen at the GBs, forming the network of insulated GBs. After significantly reducing the oxygen and water level to <0.005 ppm and <0.01 ppm, respectively, we successfully eliminated most of oxygen, but there was still the compositional variation present at the GBs. Interestingly the cleaner K-Ba122 has K preferentially segregated at the GBs. Both GB segregation caused a linear anomaly in the pinning force curve F_p that is the weak link signature. After careful evaluation of element purity, we could improve the intergrain connectivity judged by the Fp curve, but S/TEM still shows the contrasts of weakly coupled GBs.

In this presentation, we will discuss more details about such macroscopic intergrain connectivity, the GB nanostructures and how the stroichiometry instability can locally degrade the GBs in K-Ba122.

Recent progress in the development of Ba122 polycrystalline bulk materials

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The iron-based superconductors (IBSCs) with high T_c (~58 K) and H_{c2} (>100 T) are promising candidates for high field magnet applications [1]. 122-phase IBSCs demonstrate small electromagnetic anisotropy, high H_{irr} close to H_{c2} [2], and a critical grain boundary angle twice as large as that of YBCO [3]; therefore, applications in polycrystalline form are expected. In this study, $Ba(Fe,Co)_2As_2$ and $(Ba,K)Fe_2As_2$ polycrystalline bulk samples were prepared by sintering mechanically alloyed powder in expectation of enhancement of H_{c2} by introduction of lattice defects and improvement of J_c by control of microstructure. Elemental metals were ball-milled using a planetary ball-mill apparatus under high purity Ar. The milled powders were pressed into disk-shaped pellets, vacuum-sealed in quartz tubes and sintered at 600C for 48 h. The phases and microstructure were evaluated by XRD, SEM, STEM and EDS for before and after heating samples. The intra- and inter-granular superconducting properties (T_c, H_{c2}, and J_c) were evaluated by PPMS and SQUID VSM. With milling, FWHM of Co-doped Ba122 XRD main peak expanded, and the c-axis remarkably elongated without the change in Co doping level. Lattice defects (stacking faults) introduced by high energy milling are considered as one of the reasons for the FWHM broadening and increased c. Although the deterioration of crystallinity suppressed T_c by 5.5%, it was still higher than the typical T_c of single crystals. A slope of $H_{c2}(T)$ increased by 50% and exceeded that of single crystals and thin films [4], suggesting that the lattice defects enhanced electron scattering and changed T_c and H_{c2}. To the best of our knowledge, this is the first example of artificially improved H_{c2} in 122-phase IBSCs by defects engineering. On the other hand, with an increase in the E_{BM}, magnetization J_c increased, showed optimum, and then decreased by an order of magnitude. The change of J_c seems to correspond to the change in microstructure. The maximum J_c values obtained for Co-doped Ba122 and K-doped Ba122 are the highest among Ba122 samples fabricated under ambient pressure and comparable to that of HIP processed wires [5].

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Synthesis of the bulk sodium-doped $SrFe_2As_2$ and $BaFe_2As_2$ by mechanical alloying for applications

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Here we report successful synthesis of the hole-doped iron-based superconductors $Sr_{1-x}Na_xFe_2As_2$ (SNFA) and $Ba_{1-x}Na_xFe_2As_2$ (BNFA) by mechanical alloying in high-energy planetary ball mill. Synthesized samples exhibit bulk superconductivity with the sharp superconducting transition according to the magnetic susceptibility measurements.
The required phases were obtained from the metallic Sr (99.9%) or Ba (99.9%), Na (99.95%) and precursor FeAs (Fe, 99.98% + As, 6N) taken in a stoichiometric ratio of 0.4:0.6:2 for SNFA [1] and 0.6:0.4:2 for BNFA [2], accordingly. The reaction was done after 2 hours of mechanical treatment in tungsten carbide milling jar using Fritsch Pulverisette 7 Premium Line planetary ball mill. XRD measurements showed the phase formation began after two cycles of 5 minutes of treatment and complete formation is done after 2 hours of milling. Synthesized phases of optimally doped $Sr_{0.4}Na_{0.6}Fe_2As_2$ and $Ba_{0.6}K_{0.4}Fe_2As_2$ exhibit no superconductivity before the heat-treatment.
The formation of the primarily amorphous non-superconducting phase in the SNFA and BNFA compounds during the mechanical alloying was shown and optimum milling time found to be approximately 1-1.5h. The compounds obtained exhibit superconductivity with the sharp superconducting transition after the annealing for both samples. We carried out a number of short-term heat treatment experiments for potassium-doped Ba-122 previously and found out the optimal sintering temperature is 850°C [3,4]. Obtained samples of SNFA and BNFA were sintered correspondingly. During the heat-treatment, the long-ordering restores and crystallites began to grow. It results in densifying of the material and superconducting properties improving – superconducting critical temperature onsets of approximately 35K and 37K for optimally doped SNFA and BNFA, correspondingly, with sharp transitions. Mechanical alloying appears to be an up-and-coming technique for large scale producing high-quality ceramic material of SNFA and BNFA superconductors for bulk applications.
The work was performed with financial support of the Russian Foundation for Basic Research (project no. 17-29-10036) using equipment of the Lebedev Physical Institute's Shared Facility Center.

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Role of annealing treatments on microstructure and superconducting properties of polycrystalline Fe(Se,Te)

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Among Iron Based Superconductors (IBSCs), iron chalcogenides are characterized by lower toxicity with respect to iron pnictides, making them attractive for large scale applications. The Fe(Se,Te) system, in particular, is characterized by critical temperatures of approximately 15 K and magnetic critical fields above 50 T at low temperature. Superconducting properties of the Fe(Se,Te) system are directly related to its microstructure. However, in the framework of a not well assessed phase diagram, a large spread of chemico-physical and functional properties is commonly reported for compounds characterized by similar overall chemical compositions. This is in particular observed in materials obtained by melting routes, where the formation of chemical inhomogeneity and multiple phases is commonly described. To complicate the matter, composition and morphology of these inhomogeneities seem to play a role on the behaviour of the superconducting phases, pointing out the need to assess the effect of post-synthesis thermal treatments on phase stability and therefore on the material performance.

In this work, the effect of different post synthesis annealing treatments is studied. A melting route has been adopted to synthesize polycrystalline samples, subsequently subjected to thermal treatments at different temperatures. Morphology and microstructure have been characterized by means of diffraction and microscopy techniques. The superconducting properties have been evaluated by means of electrical and magnetic measurements.

It is observed how microstructure, chemical composition and morphology of the obtained products strictly depend on the annealing temperature. Moreover, a crucial role of the cooling step is evidenced: different cooling procedures can lead in fact to the formation of high temperature (T_c > 18 K) superconducting phases or to the optimization of the whole bulk superconducting behaviour.

Appearance of SmFeAsO as a mother phase of iron-based superconductor during a solid state reaction in the 580° to 980° C temperature range

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Low-temperature heat treatment is effective for fabrication of $SmFeAsO_{1-x}F_x$ superconducting tapes by ex-situ powder-in-tube (PIT) technique to achieve their high transport critical current density (J_c) [1]. The lowest temperature for the formation of a SmFeAsO crystallographic phase is a possible guide for the proper final heat-treatment temperature in the technique. We demonstrate evolution of the SmFeAsO phase during a solid-state reaction in a mixture of SmAs, Fe_2As, FeAs, and Sm_2O_3 at temperatures (T) from 580°C to 950°C. X-ray diffraction (XRD) measurements indicated a significant increasing of the SmFeAsO phase within 620°C ≤ T ≤ 670°C, as shown in Fig. 1 (a). Scanning electron microscopy (SEM) with Energy-dispersive X-ray spectroscopy (EDX) analysis of a polished 580°C sample showed a compound uniformly composed of Sm, Fe, As, and O (Sm-Fe-As-O) and a mottled structures composed of Fe_2As and FeAs, indicating high fluidity of Fe-As phase at 580°C, as shown in Fig. 1 (b) and (c). This work therefore shows the SmFeAsO phase grows at 620°C and suggested that the Fe-As phase can work as a self-flux around 580°C.

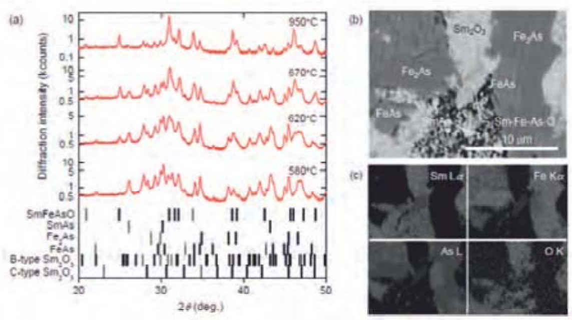

Fig. 1 (a) Heat-treatment temperature (T) dependence of X- ray diffraction (XRD) patterns at room temperature of the pulverized samples heated from SmAs, Fe_2As, FeAs, and Sm_2O_3. (b) Back-scattered electron (BSE) scanning electron microscope (SEM) image and (c) energy-dispersive X-ray spectroscopy (EDX) elemental mapping of a polished sample heated to 580°C. Reproduced from [2].

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A detailed investigation into the evolution of J_c vs pressure in Ba122: observation of an optimal pressure and significant increases in J_c

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Pressure has been consistently shown to have a significant effect on the superconducting properties of high-temperature superconductors (HTS), resulting in observed increases of critical current density (J_c) and/or critical temperature (T_c) [1]. Here, we present a study exploring the effect of hydrostatic pressure on the J_c and T_c of a series of $Ba(Fe_{1-x}Ni_x)_2As_2$ single crystals, performing measurements over a range of pressures to reveal a more detailed picture of the pressure dependencies in HTS materials. Preliminary results reveal a consistent local maxima around a critical pressure (P_c) of 0.4-0.6 GPa for plots of J_c vs pressure. Many interesting, and potentially useful, effects can be observed such as increases in J_c as high as 300% from 0 to 0.4 GPa as well as a pressure induced shifting of the second magnetization peak in some samples. The series of crystals studied will include doping levels corresponding to underdoped, optimally doped, and overdoped regimes, as well as doping levels associated with a proposed quantum critical point [2]. Interrogation of the how the P_c, percentage increases of J_c, and pinning behaviors evolve for different dopings will shed light on the nature of the mechanism by which pressure successfully augments superconducting properties.

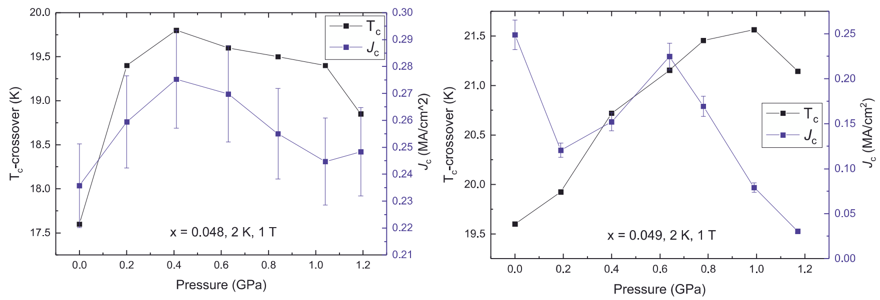

Figure 1: Plots of J_c and T_c vs pressure for two optimally doped $Ba(Fe_{1-x}Ni_x)_2As_2$ single crystals reveal a critical pressure at which we find a local maxima in J_c.

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Hydrogen doped NdFeAsO epitaxial thin films with high critical currents

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LnFeAs(O,F) (Ln=Sm or Nd) has the highest superconducting transition temperature T_c (~58 K) among the Fe-based superconductors. Hence a lot of efforts have been devoted to improving the critical current density J_c of this material for conductor applications. As a result, in-field properties of epitaxial NdFeAs(O,F) thin films have been improved. On the other hand, it is intriguing to investigate how heavily electron doping influences the critical current properties of LnFeAsO systems. However, the number of studies on the hydrogen doping to LnFeAsO is limited due to the difficulty of the crystal growth of this system. Here, we have successfully fabricated hydrogen doped epitaxial NdFeAsO thin films via topotactic reaction. A parent NdFeAsO thin film was grown by molecular beam epitaxy on a MgO(001) single crystalline substrate. The NdFeAsO filmand CaH_2 powder were sealed in an evacuated quartz tube and annealed at 500°C for 36 hours, which is the similar method reported in ref. [1] X-ray analyses revealed that the film grew phase-pure epitaxially on MgO(001) with a cube-on-cube configuration. The Hall measurements revealed the increase in the carrier concentration n for H-doped NdFeAsO compared with that of F-doped NdFeAsO: n at 50 K for H-doped NdFeAsO was ~5×10^{21} cm^{-3}, whereas the corresponding value for F-doped NdFeAsO was ~2×10^{21} cm^{-3}. Albeit our film was indeed in the over-doped regime, the film showed a high superconducting transition temperature T_c of 49 K, which is comparable to our ordinary NdFeAs(O,F) thin films on MgO(001) substrates [2]. Figure 1 shows the J_c(H) properties of a NdFeAs(O,H) film measured in fields up to 7 T at T=4 K. J_c was calculated by using an extended Bean model. Self-field J_c was around 8 MA/cm^2. In-field J_c was slightly lower than NdFeAs(O,F), which may be due to the over-doping. The detailed fabrication, structural as well as superconducting properties of NdFeAs(O,H) thin films will be presented in the talk.

This work was supported by JST CREST Grant Number JPMJCR18J4.

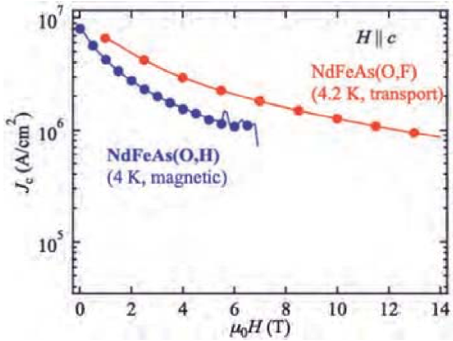

Figure 1: J_c-H properties of NdFeAs(O,H) and NdFeAs(O,F) epitaxial thin films grown on MgO.

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Structural properties of Co-doped $BaFe_2As_2$ thin films

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Fe-based superconducting thin films [1] are of interest for fundamental understanding of Fe-based superconductivity and applications such as superconducting tapes [2]. Co-doped $BaFe_2As_2$ (Ba-122) is a widely studied model system of Fe-based superconductors. However, the growth mechanisms of epitaxially grown Ba-122 films are not fully understood yet due to various fabrication parameters and possible interaction with the substrate material [3]. In this work we have investigated Ba-122 thin films with electron microscopy and correlate the results with their superconducting properties. $Ba(Fe_{1-x}Co_x)As_2$ thin films with nominal doping of x = 0.08 were deposited onto single-crystalline substrates (CaF_2, $LaAlO_3$, MgO) via pulsed laser deposition from stoichiometric sintered target materials. Cross-section samples were prepared using the focused-ion-beam in-situ lift-out technique. (Scanning) transmission electron microscopy ((S)TEM) in combination with electron energy loss and energy-dispersive X-ray spectroscopy (EELS/EDXS) was used to investigate the microstructure.

In general, epitaxial growth is observed on CaF_2 and $LaAlO_3$. Ba-122 directly deposited on MgO shows polycrystalline structure (Fig. 1a-c). Stacking faults (SFs) on the Ba-planes show dark contrast in STEM images and appear in varying densities depending on the substrate material and deposition parameters (Fig. 1a,b,d). EELS analysis reveals the presence of O at the SFs which causes the dark contrast in high-angle annular dark-field (HAADF) STEM Z-contrast images. EDXS analysis shows Fe-rich precipitates which are observed in all samples (Fig. 1b,e). The formation of BaF_2 at the Ba-122/CaF_2 interface and near precipitates is observed (Fig. 1e-g). A high critical temperature of $T_{c,90}$ = 26.5 K for a 36 nm thick Ba122 film on CaF_2 (Fig. 1a) was measured.

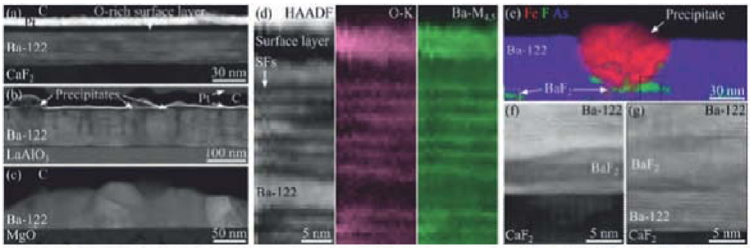

Figure 1: Cross-section HAADF-STEM images of Ba-122 films on (a) CaF_2, (b) $LaAlO_3$ and (c) MgO. (d) HAADFSTEM image and O and Ba maps obtained by EELS from a region containing many SFs. (e) Qualitative superimposed Fe, F and As elemental maps obtained by EDXS. The As map indicates the Ba-122 phase. Fe-rich precipitates and the formation of BaF_2 is visible. (f, g) Corresponding high-resolution HAADF-STEM images of the regions marked in (e).

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Optical properties of $BaFe_{1.91}Ni_{0.09}As_2$ film analyzed in the framework of multiband Eliashberg theory

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The temperature dependences of the plasma frequency, superfluid density and London penetration depth were determined from terahertz spectra of conductivity and dielectric permittivity of $BaFe_{1.91}Ni_{0.09}As_2$ film with critical temperature T_c = 19.6 K. Part of experimental data were analyzed within a simple three-band Eliashberg model where the mechanism of superconducting coupling is mediated by antiferromagnetic spin fluctuations, whose characteristic energy scales with T_c according to the empirical law $\Omega_0 = 4.65k_BT_c$, and with a total electron-boson coupling strength $\lambda_{tot} = 2.17$.

Electric Transport Properties of Iron-Based Superconducting Nanowires

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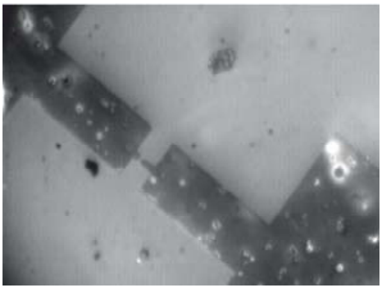
The recent discovery of iron-based superconductors has opened the way to the realization of new applications, mostly toward high magnetic fields, but also in electronics [1]. Among them, nanowire detectors seem to be the most interesting ones, due to their ability to detect a single photon in the visible and IR spectral region. Although not yet optimal for light detection, nanowire detectors realized with iron-based superconductors would bring clear advantages due to the higher material critical temperature, also possibly profiting of the peculiar material properties. However, there are several challenges to overcome regarding mainly: the fabrication of ultra-thin films with good superconducting properties [2], the development of appropriate passivation techniques [3], the optimization of nano-patterning processes, and the realization of high quality electrical contacts [4].
Test devices made by films of Co-doped $BaFe_2As_2$, with a thickness of 20 nm, have been fabricated, by pulsed laser deposition, on CaF_2 substrate and passivated in situ with a thin layer of $MgAl_2O_4$. Subsequently, several nanowire structures have been patterned with electron beam lithography (see Figure below), and electrically contacted to gold pads. The experimental transport characterizations of the realized nanostructures show good properties in terms of material resistivity and critical current, with a critical superconducting transition temperature T_c of 16 K for a 500 nm wide nanowire.
Details on the fabrication and low temperature characterization of the realized nanodevices are presented, together with a study of degradation phenomena induced by ageing effects.



Photograph of one of the investigated nanostructures.

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Structural and Electronic properties of FeSe films grown by PLD

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High-T_c superconducting materials are of technological importance due to their applications in single-photon detectors, quantum computers, Josephson junctions etc. One such exotic superconducting material is FeSe with a very simple crystal structure (Fe layer sandwiched between two adjacent Se layers) have attracted a lot of attention due to their intriguing superconductor properties such as T_c~8 K in bulk FeSe to as high as 70 K in single-layer FeSe film [1-3]. This dramatic enhancement in T_c has gained a lot of interest in understanding the origin of high-temperature superconductivity in such a two-dimensional (2D) FeSe system.
Here, we deposited 20 nm FeSe film on $SrTiO_3$ (001) and CaF_2 (001) substrates by means of Pulsed Laser Deposition technique using KrF excimer laser. We will present initial studies of structural, topography and electronic properties by means of XRD, LEED, STM and ARPES. From EDX, we found that the system is slightly off-stoichiometric due to volatile nature of 'Se' element and still need to be understood on how to control the exact stoichiometry. STM topography images show screw-like growth mode with unit-cell step heights. The ARPES measurements performed at 55 and 25 eV shows a hole-like band at the G point. This study would provide basic understanding and growth control of FeSe films by PLD technique.

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Magnon light scattering in iron based chalcogenide films

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The isotropic compressive lattice strain typically featured by high quality iron based chalcogenide films has been acknowledged for influencing superconductor properties and for the relatively high T_c critical temperatures in Fe(SeTe) films, of order of T_c=22 K [1,2]. Electronic and magnetic properties in Fe(SeTe) films are also affected by the lattice compression. We have characterized FeTe and superconductor $FeSe_{0.5}Te_{0.5}$ films by micro-Raman spectroscopy, in order to investigate the effects of the lattice compression on the light scattering response. We found that beyond the conventional phonon Raman scattering, the light interacts with spins through the excitation of magnon pairs in Anti Ferromagnetic (AF) FeTe films, as in the case of monocrystals. We do not observed this Raman mode in the $FeSe_{0.5}Te_{0.5}$ films that exhibited, instead, a broad Raman band at a relatively lower energy of about 1520 cm^{-1}. The assignment of this Raman mode to unconventional light scattering mechanisms, related to single-magnon excitation, is argued as consequence of compressive state of film lattice [3]. The Raman signal intensity changes with the temperature, featuring two relative maxima at T ≈ 50 K and T ≈ 190 K, which we attribute to the temperature dependence of the spin fluctuation levels.

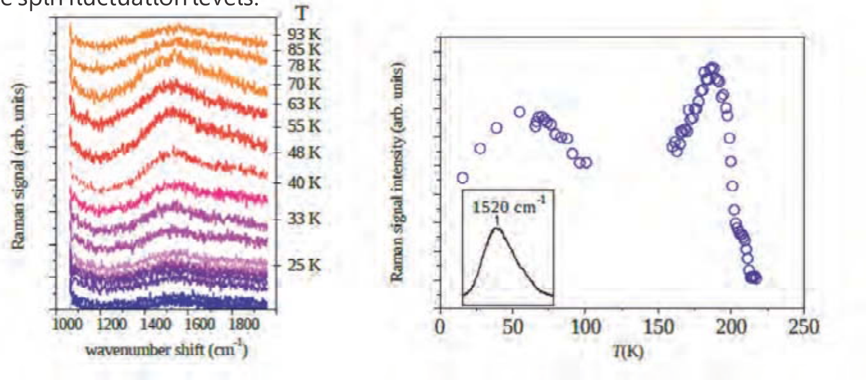

Figure 1. Raman spectra of $FeSe_{0.5}Te_{0.5}$ film on CaF_2 substrate. The Raman band at 1520 cm^{-1} occurs at temperatures lower than T ≈ 220 K and its maximum intensity depends strongly on the temperature, reaching two relative maxima at T ≈ 50 K and T ≈ 190 K.

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Physical properties optimization of the stoichiometric $CaKFe_4As_4$ superconductor

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Control of the actual doping level in iron-based superconductors is always a challenge. To overcome this issue, the stoichiometric $CaKFe_4As_4$ (1144) superconductor [1-2] with high transition temperature of 35 K has been placed as a strong contender for magnet application owing to its very high upper critical field (H_{c2}~100 T), low anisotropy and high critical current density (up to J_c~10^8 A/cm^2) [3]. In this talk, we describe the physical and magnetic properties of different polycrystalline 1144, optimized to achieve the highest superconducting properties and synthesized between 900 to 1100°C [4]. Our study confirms that the formation of phase pure 1144 occurs over a much narrower window and its highly prone to multi-phase formation as compared with the 122 family. As a result, the superconducting properties are enhanced for the pure 1144 phase, but they are likely to be affected by the inter and intra-granular behaviour originating from the microstructural nature of polycrystalline $CaKFe_4As_4$, similar to other iron-based superconductors. Based on our study, we construct the synthesis phase diagram for polycrystalline 1144 [4] which is in good agreement with that reported for single crystals [2]. Furthermore, we discuss the post annealing effect of the optimal 1144 samples at various sintering temperatures that would also be very helpful for the processing of 1144 wires and tapes. The current progress of the fabrication of superconducting 1144 wires and tapes will also be presented.

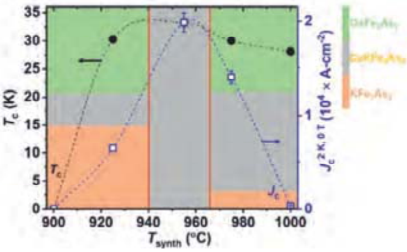

Figure: Synthesis phase diagram for $CaKFe_4As_4$. The red lines are guide for the eye to show the optimal synthesis region.

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Multiband anisotropic superconductivity in $CaKFe_4As_4$

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The temperature dependence of the in-plane (λ_{ab}) and the out-of-plane (λ_c) components of the magnetic penetration depth in an extensively characterized sample of superconducting $CaKFe_4As_4$ (T_c=35 K) were investigated using muon-spin rotation (μSR). A comparison of λ_{ab}^{-2}(T) measured by mSR with the one inferred from ARPES data confirms the presence of multiple gaps at the Fermi level. An agreement between these techniques requires the presence of additional bands, which are not resolved by ARPES experiments. These bands are characterized by small superconducting gaps with an average zero-temperature value of Δ_0=2.4(2) meV. The experiments on λ_{ab}^{-2}(T) suggest that in $CaKFe_4As_4$ the $s^\pm$ order parameter symmetry acquires a more sophisticated form by allowing a sign change not only between electron and hole pockets, but also within pockets of similar type [1].

The magnetic penetration depth anisotropy $\gamma_l = \lambda_c / \lambda_{ab}$ was further obtained by combining results of λ_{ab}^{-2}(T) and λ_c^{-2}(T) measurements. γ_λ is almost temperature independent for T<20K (γ_l ~ 1.9) and it reaches ~ 3.0 by approaching T_c. The change of γ_λ induces the corresponding rearrangement of the flux line lattice (FLL), which is clearly detected via enhanced distortions of the FLL μSR response. Comparison of γ_λ with the anisotropy of the upper critical field γ_{Hc2}) studied in Ref [2], reveals that γ_λ is systematically higher than $\gamma_{\lambda Hc2}$ at low-temperatures and approaches γ_{Hc2} for T approaching T_c. The anisotropic properties of λ are explained by the multi-gap nature of superconductivity in $CaKFe_4As_4$ and are caused by anisotropic contributions of various bands to the in-plane and the out-of-plane components of the superfluid density [3].

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London penetration depth anisotropy in $CaK(Fe,Ni)_4As_4$

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We report on the anisotropic behavior of the London penetration depth of $CaK(Fe_{1-x}Ni_x)_4As_4$ (CaK1144), discussing how it relates to its electronic structure, how it can be tuned by disorder to match specific requirements for applications. The CaK1144 family of iron-based superconductors (IBS) is particularly suitable for the study of fundamental superconducting properties due to the stoichiometric composition of the “optimal” compound $CaKFe_4As_4$, exhibiting clean-limit behavior and having a fairly high critical temperature $T_c \approx 35$ K [1].
The London penetration depth λ_L was measured with a microwave coplanar resonator technique [2] that allowed us to deconvolve the anisotropic contributions $\lambda_{L,ab}$ and $\lambda_{L,c}$ and obtain the anisotropy parameter $\gamma_\lambda=\lambda_{L,c}/\lambda_{L,ab}$ [3]. CaK1144 single crystals with Ni doping level x=0, 0.017, and 0.034 were analyzed both in the pristine state and after 3.5 MeV proton irradiation to introduce scattering centers. The $\lambda_{L,ab}(T)$ and $\gamma_\lambda(T)$ found for the undoped pristine sample are in good agreement with previous literature [4] and are here compared to ab-initio density functional theory and Eliashberg calculations [5], showing that gap anisotropy in CaK1144 is present and relevant also for application-related properties. The dependence of London penetration depth anisotropy on both chemical and irradiation-induced disorder is discussed to highlight which methods are more suitable to decrease the direction dependence of electromagnetic properties whilst keeping a high critical temperature. Lastly, the relevance of an intrinsic anisotropy such as γ_λ on application related anisotropic parameters (critical current [6], pinning [7,8]) is discussed in light of the recent employment of CaK1144 in the production of wires [9].
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Effects of ion irradiation on 122 and 1144 families of iron-based superconductors, analyzed by a microwave technique

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We report on the effects of particle irradiation on the properties of iron-based superconductors. We used different ion beams and energies (3.5-MeV H^+, 250-MeV Au, 1.2-GeV Pb) on the so-called 122 and 1144 families, in a large variety of compounds. In this work, we compare several irradiation experiments we recently performed, pointing out similarities and peculiarities.

The 122 family is based on the parent compound $BaFe_2As_2$, which becomes superconducting when substitutions are operated: we investigated 122 single crystals with partial substitution of K in the Ba site ($Ba_{1-x}K_xFe_2As_2$, x=0.42, hole doping), of Co or Rh in the Fe site ($Ba(Fe_{1-x}Co_x)_2As_2$, x=0.075, and $Ba(Fe_{1-x}Rh_x)_2As_2$, x=0.068, electron doping), and of P in the As site ($BaFe_2(As_{1-x}P_x)_2$, x=0.33, isovalent). All these cases represent optimal doping, with critical temperatures ranging from 24 to 38 K. Moreover, within this family, systems also containing magnetic rare-earth-metal elements are of interest, since at low temperatures they develop additional magnetic ordering of local moments. We analyzed $EuFe_2(As_{1-x}P_x)_2$ crystals, showing magnetic ordering of Eu^{2+} moments below a superconducting critical temperature of about 24 K.

Of the 1144 family, we studied the $CaKFe_4As_4$ stoichiometric composition, exhibiting clean-limit behavior and T_c of about 35 K, and $CaK(Fe_{1-x}Ni_x)_4As_4$ with x=0.017 and 0.034.

The microwave analysis of the crystals was done by means of a coplanar-waveguide-resonator technique, allowing us to obtain critical temperature, London penetration depth, quasiparticle conductivity, and complex surface inductance [1, 2]. These quantities and their modifications after irradiation can be used as a reference for the materials' quality degradation, useful for applications in harsh environments, and for validation of phenomenological or theoretical models, to address more fundamental questions about the mechanism of superconductivity [3-7] and the interplay of superconductivity and magnetism [8] in such compounds.

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Unique critical current properties in 1144-type $CaKFe_4As_4$ superconductor

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The enhancement of critical current density (J_c) is one of the key issues towards superconductivity applications. After the discovery of iron-based superconductors (IBSs), which are considered as candidate materials for high-field applications, high J_c values have been achieved by various techniques to introduce artificial pinning centers, while a further improvement of J_c is desired. Among various IBSs, $BaFe_2As_2$ (Ba122)-based materials have been considered as promising candidate for applications owing to the moderately high T_c up to 38 K, the large upper critical fields ~ 100 T, and the small anisotropy. Because superconductivity in Ba122-based IBSs emerges with chemical substitution (doping), superconducting (SC) properties depends on the doping level. On the other hand, $CaKFe_4As_4$ (CaK1144), which is discovered in 2016 [1], is superconducting without chemical substitution. We report unprecedented vortex pinning properties in the $CaKFe_4As_4$ (CaK1144) system arising from the inherent defect structure. Scanning transmission electron microscopy revealed the existence of nanoscale intergrowths of the $CaFe_2As_2$ phase, which is unique to CaK1144 formed as a line compound. The J_c properties in CaK1144 are found to be distinct from other IBSs characterized by a significant anisotropy with respect to the magnetic field orientation as well as a novel pinning mechanism significantly enhanced with increasing temperature. We propose a comprehensive explanation of the J_c properties based on the unique intergrowths acting as pinning centers [2].

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Novel $CaKFe_4As_4$ superconductor synthesis: Effect of annealing and Sn addition on the structure, microstructure and superconducting properties

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Bulk superconductors are highly in demand for various engineering and technological applications as they generate very high magnetic fields (Tesla scale), possibly utilized for MRI, NMR, motors, superconducting electromagnets, magnetically levitating trains, etc. Here the critical current density (J_c) is a primary parameter its enhancement is important for realizing stable trapped field performance and developing suitable practical applications. In real materials, J_c is not intrinsic parameter and can be improved by engineering the microstructure with various dopants and/or modifying the grain connectivity. Compared to the pre-existing and thoroughly studied high-temperature superconductors, such as $REBa_2Cu_3O_{7-\delta}$, Bi-Sr-Ca-Cu-O, and MgB_2, the newly developed Fe-based superconductors (FBSs) possess several advantageous such as high critical magnetic fields B_{c2}, larger critical angle, and low suppression of J_c under magnetic fields. Among FBSs, novel $AEAFe_4As_4$ (1144, where AE = alkaline earth elements and A = alkaline metals) superconductors with superconducting transition temperature (T_c) of 36 K [1], exhibit robustness of the temperature dependence of J_c possibly due to the inter-grown intrinsic pinning centers with 5-10 nm length scale [2], making this material most suitable candidate for bulk magnets.

In the present work we studied the optimization of synthesis conditions for producing high pure CaK-1144 polycrystalline powders via a conventional solid-state reaction method in detail. Two times sintering at 900°C for 3h followed by quenching is required to avoid the formation of impurity phases, mainly $(AE/A)Fe_2As_2$ (122). Post-annealing effect was studied on the polycrystalline CaK1144 samples at various temperatures (300°C-700°C). A systematic improvement in T_c was observed from 32 K -35 K by increasing annealing temperature, together with the change of the lattice constants. Aiming to improve the 1144 grain connectivity, Sn addition effects was also studied. The effect of sintering temperature was investigated for 10wt% Sn added CaK-1144 samples and 700°C is the optimal condition. Beyond 700°C, the 1144+Sn sample was decomposed to $CaFe_4As_3$, 122 and Fe-As phases. To further improve the conglutination of weak links (grain boundaries, GB) of the superconducting 1144 grains, up to 40wt% Sn was added. The sample with 30wt% Sn addition and sintering at 700°C showed improved J_c performance from 11.8 kA/cm^2 (Sn-free) to 21.7 kA/cm^2 at 4.2 K and self-field. Detailed microstructural investigations evidence that the enhancement in the J_c performance is ascribed to the improved grain boundary connectivity. Present results establish that the addition of Sn to the 1144 polycrystal samples is chemically stable and supporting promising J_c properties required for practical applications.

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Neutron irradiation experiments on iron-based superconductors

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Irradiation experiments offer the unique possibility to change the defect structure in superconductors and investigate the resulting changes in the superconducting properties on the very same sample.
I will review neutron irradiation experiments performed in the TRIGA reactor in Vienna. Results on iron-based and cuprate superconductors will be compared. The transition temperature decreases upon the introduction of disorder in both these material classes, although weaker in the iron-based materials. The change in critical current density is qualitatively very similar in all compounds and the maximally achievable currents at low fields and temperatures are around 2.5% of the depairing current density. A correlation between the transition temperature and the critical current density after irradiation was found. The application prospects of iron-based superconductors are discussed based on their intrinsic properties.

Opportunities in studying vortex pinning and dynamics in large pulsed magnetic fields: how to reach beyond DC magnets

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Expanding non-linear transport studies (I-V curves) to magnetic fields above those accessible by DC magnets can bring valuable information on the vortex matter phase diagram of superconductors. The recent progress in the fabrication of very-high field all-superconducting and hybrid magnets make it technologically relevant to study vortex pinning and dynamics in this regime. However, pulsed magnetic fields reaching 100T in milliseconds impose technical and fundamental challenges that have prevented the realization of these studies. We developed a fast I-V DC technique that enables determination of the superconducting critical current in pulsed magnetic fields, beyond the reach of DC magnets. We demonstrate this technique on iron- and copper-based superconductors on single crystal and metallic substrates with excellent agreement with DC field measurements. We find that the I-V characteristics change with the magnetic field rate, and capture this unexplored vortex physics through a model based on the broken symmetry of the vortex velocity profile produced by the applied current.

In the last part of my talk, I will briefly describe angular dependent studies of vortex pinning and dynamics in $RbEuFe_4As_4$ single crystals with columnar defects (Cds). This IBS has T_c ~ 37K and undergoes a magnetic ordering of the Eu moments at T_m ~ 15K, making it an excellent system to study the interplay of superconductivity and magnetic order. For large densities of CDs (matching fields B_Φ ~ 10T), the irradiated crystals exhibit high J_c and a lock-in phase (where vortices remain trapped into the CDs even if **H** is tilted away from them), that spans unusually large angular and field ranges. This leads to the unusual and technologically attractive condition of almost isotropic pinning by aligned CDs.

Anisotropy in iron-chalcogenide Fe(Se,Te) thin films: still a puzzling problem

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The influence of the electronic mass anisotropy on the thermodynamic superconducting and pinning properties is critical to understand its behavior. In particular, it determines whether a material is suitable for high field applications or not. Iron-chalcogenides are some of the most isotropic superconductors. With lowest anisotropy among them, the Fe(Se,Te) thin films are characterized by very low and robust values of both the anisotropy factors g_j in the critical currents [1,2], and g_H in the thermodynamic critical fields [3,4]. Nevertheless, puzzling questions arise considering the behavior of vortex dynamics in this material, in which the angular dependence of vortex instability shows trends much similar to that of Bi-2212 [1], a well-known highly anisotropic HTS belonging to the BSCCO family. In order to solve this part of the Fe(Se,Te) puzzle, a deeper analysis on fundamental superconducting properties is required. Here, we present measurement results of the angular dependence of the upper critical fields up to magnetic fields of several tens of tesla. Our measurements performed up to 16 T show behavior that in some regions is consistent with fully 2D high anisotropy and an anisotropic 3D material. We also measured $YBa_2Cu_3O_7$ thin films that is a well-known 3D HTS material to compare against the results on Fe(Se,Te) films.

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Vortex parameters in $FeSe_{0.5}Te_{0.5}$ thin films at microwaves

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Iron-Based Superconductors (IBS) are particularly interesting for applications thanks to their relatively high upper critical fields, low anisotropy, good grain connectivity [1]. Their physics is also very intriguing, thanks but not limited to the strict relationship between the superconducting pairing mechanism and the magnetic orderings appearing in their phase diagrams. Among the various iron-superconductors families, the FeSeTe system is subject of intense studies because of many peculiarities: simple crystal structure, absence of As, promising critical current density values [2]. It is therefore interesting to determine how it behaves in high frequency regimes, where thin films are a natural choice for applications.
Microwaves are a powerful tool to access fundamental parameters of vortex physics. In particular, they allow to derive the following vortex parameters: the flux-flow resistivity yields information on the dynamics of the quasiparticles, the Labusch parameter yields a measure of the steepness of the pinning potential wells, and the depinning frequency assesses the frequency rangewhere the material is suitable for high-frequency applications in a dc magnetic field. Hence, we present here a high frequency (16.5 GHz) study of the surface impedance in the mixed state of $FeSe_{0.5}Te_{0.5}$ thin films with statically applied magnetic fields up to 1 T, normal to the sample surfaces (i.e. parallel to their c-axis). Through standard high-frequency vortex motion models [3] we extract and discuss the relevant vortex parameters. We observe relatively high values for the pinning constant ~ 21.5 GHz, in line with similar results on single crystal and superior to other IBS. A comparison with traditional superconductors Nb and Nb_3Sn is favourable for $FeSe_{0.5}Te_{0.5}$, but its high dissipation on the vortex cores, testified by flux-flow resistivity values in excess of the Bardeen-Stephen limit, requires further understanding in view of high-frequency applications in moderate fields.

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Vortex dynamics and irreversibility line in nearly optimally doped $RFeAsO_{1-x}F_x$ superconductors (R = La, Ce, Sm)

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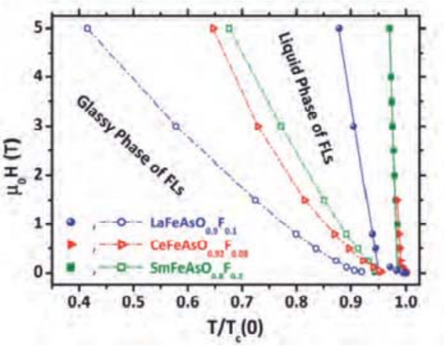
Ac susceptibility and static magnetization measurements were performed in the nearly optimally F-doped iron based oxypnictide $RFeAsO_{1-x}F_x$ superconductors with R=Sm, Ce, La. The magnetic field-temperature phase diagram of the mixed superconducting state is drawn for the three materials, displaying a sizable reduction of the liquid phase upon increasing T_c in the range of applied fields (0 < H < 5 T) [1,2]. This result indicates that $SmFeAsO_{0.8}F_{0.2}$ is the most interesting compound among the investigated ones in view of possible applications. The field-dependence of the intragrain depinning energy U_0 exhibits a common trend for all the samples with a typical crossover field value (2500 Oe < H_{cr} < 5000 Oe) separating regions where single and collective depinning processes are at work.



Phase diagrams for the flux lines (FLs) in the investigated samples (from ref.[2]).

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Study of vortex pinning anisotropy in irradiated Ba122 superconductors by quantitative magneto-optical imaging

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Iron based superconductors [1] are promising for applications and intensive studies are nowadays performed for investigating their pairing mechanism and gap symmetry. For applications, high critical temperatures and high upper critical fields are among their interesting properties. These superconductors are robust against high-energy particle irradiation, therefore the irradiation with protons and heavy-ions at high fluences can be effective for enhancing the critical current density without appreciable degradation of the critical temperature. In particular, it was already shown that high-energy heavy-ions form correlated defects along the irradiation direction [2], while proton irradiation produces isotropic damage in the crystal lattice [3]. Here, we present the study of the vortex pinning anisotropy in Ba122 single crystals (doped with Co, K and P), irradiated both with heavy ions (Au, Pb) and with protons, along the c-axis. On some of these crystals, we irradiated three zones: with Au ions, with protons, with both particles, along with a fourth zone that is left unirradiated for comparison with as-grown properties. The samples were characterized by means of the quantitative magneto-optical technique with an indicator film. The magnetic field distribution and the local current density values were measured at different temperatures and for several applied fields. In this way, we studied the anisotropy of vortex pinning by analyzing the critical current density dependence on the local magnetic field and we described the results with the help of an empirical model [4]. We found that effects of proton and heavy-ion irradiation are additive, for what concerns vortex pinning. Thus critical current density can be enhanced greatly in these materials by the combination of point and correlated defects induced by high-energy particle irradiation.

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Flux creep and second magnetization peak effect in type-II superconductors: correlation and universality

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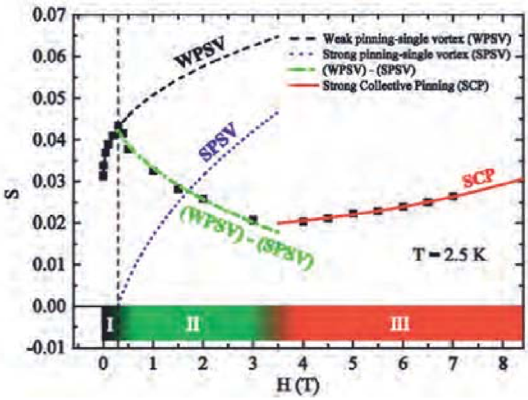
The correlation in type-II superconductors between the creep rate S and the peak effect in J_c, as a function of the field (H), has been investigated at different temperatures by starting from the minimum in S(H) and the onset of the peak effect detected on a $FeSe_{0.5}Te_{0.5}$ sample. In particular, by analysing the entire S(H) curves and comparing our results with other data from the published literature, we find evidence that the flux dynamic mechanisms behind the appearance of the peak effect in J_c (H) are activated at fields well below those where the critical current starts effectively to increase. Moreover, the discovered universal relation between the minimum in the S(H) and the peak effect in J_c (H) shows that both can be attributed to a sequential crossover between a less effective pinning (at low fields) to a more effective pinning (at high fields), regardless of the type-II superconductor taken into consideration.



S as a function of H at T = 2.5 K. The black dashed line is the fit of the first S(H) increase with equation (1). The blue dotted line is the strong pinning single vortex behavior speculated for the vortices that enter in the twin boundaries using equation (1). The green dashed-dotted line is the fit of the decreasing S(H) data with the equation described by the subtraction of the black and blue line. The red solid line is the fit of the second S(H) increase with equation (1). In the bottom of the figure, the field intervals relative to the three S(H) portions are identified with different colours.

Graphic design
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