## ASC2024 Salt Lake City

### **Status of Iron Based Superconductors: characteristics**

### **and relevant properties for applications**

Kazumasa Iida, Nihon University



### 2024.9.3, Salt Lake City



superconductivity

**IOP** Publishing



## Acknowledgement



K. Kondo, M. Chen, T. Hatano, H. Ikuta **D. A. D. Qin, M. Naito, A. Yamamoto** 





**KYUSHU** 

Z. Guo, H. Gao, H. Saito, S. Hata



J. Hänisch, B. Holzapfel



C. Tarantini, J. Jaroszynski



H. Hiramatsu, H. Hosono



T. Suzuki, M. Miura

Supported by



(16H04646, 20H02681)





B. Maiorov

S. Eley

## **Overview**

#### **1. Iron-based superconductors (IBSs)**

• Physical properties

### **2. Tuning of the superconducting properties**

- SC transition temperature (strain, monolayer, intercalation, EDLT)
- Grain boundary, GB
- Critical current density (natural defects, APC, thermodynamic approach)

#### **3. Progress Toward applications**

• Use of IBS wires and bulks in magnets, and perspective

## Discover of Iron based superconductors (IBSs)

#### **First Fe-based superconductor in 2006**



Published on Web 07/15/2006

#### **Iron-Based Layered Superconductor: LaOFeP**

Toshio Kamiya,<sup>†,§</sup> and Hideo Hosono\*,<sup>†,‡</sup>

*ERATO-SORST, JST, Frontier Collaborati*V*e Research Center, Tokyo Institute of Technology, Mail Box S2-13, ERATO-SORST, JST, Frontier Collaborative Research Center, Tokyo Institute of Technology, Mail Box S2-15,*<br>4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan, Frontier Collaborative Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan, and Materials and Structures **Fe** 





Iron-Based Layered Superconductor La[O<sub>1-x</sub>F<sub>x</sub>]FeAs (x = 0.05-0.12) compound, LaOFeAs, which undergoes superconducting transition

iron-based layered oxy-particle layered oxy-particle layered oxy-particle landscape with  $T_c = 26$  K  $\begin{array}{r}\n\text{subject to} \\
\text{with } T - 26 \text{ K}\n\end{array}$ 

Yoichi Kamihara,\*<sup>,†</sup> Takumi Watanabe,<sup>‡</sup> Masahiro Hirano,<sup>†,§</sup> and Hideo Hosono<sup>†,‡,§</sup>

ERATO-SORST, JST, Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, Materials and (La3<sup>+</sup>O2-) layer transfers the carriers generated in the (La3<sup>+</sup>O2-) shows the structure of a FeP4 tetrahedron with P-Fe-P bonding angles *Structures Laboratory, Tokyo Institute of Technology, Mail Box R3-1, and Frontier Research Center, Tokyo Institute* We have been studying several quaternary oxypnictides, LaOM*Pn* Design) in the same temperature range. Figure 1b shows typical of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan

Received January 9, 2008; E-mail: hosono@msl.titech.ac.jp synthesis and the crystal structure analysis of LaOFeP were 5 January 5, 2000, L<sup>2</sup>mail nosono⊛msitucontac.jp<br>P







#### Iron based superconductors (IBSs): FeAs or Fe*Ch* tetrahedron



#### Electronic structure: Multiband superconductors  $\mathbb{R}^3$  . The short enough for direct Fe-Fe hopping to be important, while the As-As distances are 3.677 A˚ , across the Fe layer, and *<sup>a</sup>* \$ <sup>4</sup>*:*<sup>036</sup> <sup>A</sup>! , in plane.

#### similar to that reports that reports  $\mathsf{F}_{\mathsf{Q}}$ Fe3*d* orbitals play an important role for superconductivity

The crystal structure is layered with apparently distinct LaO and transition metal pnictide layers (see, e.g., Ref. [4]). Importantly, it forms with a wide range of rare earths and pnictogens, with the transition elements Mn, Fe, and orbitals dominate the Fe 3*d* orbitals dominate the al DOS around F<sub>-</sub>  $\bf{total}$  DOS around  $\bf{\textit{E}}_{\textit{F}}$ 

104.4&). The Fe-As distance is 2.327 A˚ . The Fe-Fe distance

ship between magnetism and superconductivity, the origin of the remarkably high *Tc*, and the chemical and structural parameters that can be used to tune the properties. Here we show that LaOFeAs is in fact close to magnetism, with competing ferromagnetic and antiferromagnetic fluctua-

#### → Multiband superconductors Five Fe 3*d* bands across  $E_F$



D. J. Singh and H.-M. Du, *Phys. Rev. Lett.* **100** 237003 (2008).



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#### Mganetic phase diagrams of 122, 1111 and 11 and disappears at x∼ 0:6 (78) or x > 0.7 (79). The superconductivity is observed even at the holedoped end material material (x 1) Material (x 1) Material corresponds to 0.5 holes per Fe atom. In the electronas a *Fermion* Tc of 22 K appears at x 22 K appears at x 42 K appears at x 12 K appears at x 12 K appears to the h

**Fig. 3** Electronic phase diagram of SmO1−*x*F*x*FeAs using the nom-



T. Shibauchi et al., *Annu. Rev. Condens. Matter Phys.* **5** 113 (2014). I. Silibauchi e*t an., Annu. Rev. Condens. Matter Phys.* **5** 115 (2014).

doped case, superconductivity vanishes at only 0.15 electrons per Fe atom (although note that each

pound with the nominal composition GdO0*.*83F0*.*17FeAs, it turned out that a fine-grained powder has better potential for  $\mathsf{not\text{ }harmful\text{ }to}$ peaks were not resolvable for that sample. superconducting phase diagram of the FeSe1−*<sup>x</sup>*Te*<sup>x</sup>* system, as  $\frac{1}{2}$  function  $\frac{1}{2}$ ) SC (c.f. Cuprates) not harmful to SC (c.f. Cuprates)

## High upper critical field,  $H_{\rm c2}$ , and low anisotropy



 $H_{c2}$  measurements. The very short Ginzburg-Landau (GL)  $\gamma_{\text{Hc2}}$ 

 $H_{c2}$  c<sub>2</sub> of two-band behavior, which can reasonably be function, which in the dirty (**a**) and the clean reasonably (**a**) and

*b*<sub>c2</sub>  $\gamma$ *Hc2 γHc<sub>2</sub> γHc<sub>2</sub>* 

 $H_{c2}$  c

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Plenary presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

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## Comparison between cuprates and IBSs



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#### A significant jump of  $T_{\mathrm{c}}$  by pressure Resistivity,  $\overline{\phantom{0}}$ 1.5  $\overline{\phantom{a}}$  $\mathsf{L}$ <u>L</u> Temperature (K) Zero-point *T*<sup>c</sup> –4

 $T$  (7) GD

2.5

35

0.0 **FeSe:** 

130 K -> 153 K (15 GPa) 9 K -> 37 **HgBa<sub>2</sub>Ca<sub>2</sub>Cu<sub>3</sub>O<sub>8+8</sub>:** 

J. Phys. Soc. Jpn.



N. Takeshita et al., J. Phys. Soc. Jpn. 82 023711 (2013). S. Margadonna et al., PRB 80 064506 (2009).

dependence of T<sup>c</sup> is shown in the inset, in which the rate of increase of T<sup>c</sup> is for the resistivity measurements. The resistivity measurements of  $\frac{10}{2}$  Final observed pressures. (c), (d) Fina pressure. This behavior is in sharp contrast to previous  $\mathbf{r}$  $\blacktriangleright$  isotropic president temperatures (no zero resistivity has ever been realized at discussion can be made on the  $\tau$ ssure ennances, *i<sub>c</sub>* and  $\triangleright$  Isotropic pressure enhances  $T_c$ 

 $t$  $\triangleright$  Chemical pressure also enhances  $\tau_{\rm c}$  restraing the statice parameter a (angstro  $\overline{\phantom{a}}$   $\overline{\$ ccuro alco onhancos  $\triangleright$  Chemical pressure also enhances  $T_c$ 



Temperature (K)

H. Takahashi *et al., Nature* **453** 376 (2008).



z. Ren, Z. Zhao, *Adv. Mater.* **21** 4584 (2009). . 2001).

#### Pressure & strain induced superconductivity in Ba122 CaF2 is 1.9 × 10−<sup>5</sup> /K at 300 K, higher than that of Ba-122 with 1.0 × 10−<sup>6</sup> / III DAIZZ electron microscope, which was operated at 300 kV and has a resolution of 300 kV and has a resolution of  $\alpha$  ${\sf superconductivity}$  in  ${\tt Ba122}$



#### **Bilayer**

### tetrahedron. The reduction of the Ba-122 dimension elongates the tetragonal structure along the c

field perpendicular to sample surface. Insets are temperature-dependent re-



FIG. 1. !Color online" !a" !*xx*!*T*" curves of BaFe2!As1<sup>−</sup>*x*P*x*"<sup>2</sup> in S. Kasahara *et al*., *PRB* **81** 184519 (2010).

 $\epsilon$  Community structures, and results in an enhanced super-J. Engelmann, K.I. *et al.*, *Nat. Commun.* **4** 2877 (2013). J. Kang

nun. 4 2877 (2013). J. Kang et al., PNAS 117 21170 (2020).

compressive biaxial strain, rather than oxide substrates. Note that the CTE of

∼0.6 Å. A series of STEM HAADF images were obtained at a resolution of

axis, while higher compressive strain and strain and strain and strain and stronger clamping  $\mathcal{F}_{\mathcal{A}}$ 

## $T_c$  =65 K in a monolayer of FeSe





#### ≻ SC gap opened at between 55 K  $\leq T \leq 65$  K for 1 ML

- Ø Only electron-like pockets appeared at M-point for 1 ML
- Ø Hole-like pocket started to appear at Γ-point for over 2 ML
- Ø FeSe ML is very sensitive to air -> quickly degraded

Wang *et al*., *Chin. Phys. Lett*. **29** 037402 (2012). Tan *at al*., *Nat. Mater*. **12** 634 (2013).

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#### **Tuning superconducting properties,**  $T_c$ **, by intercalation**  $\overline{\text{r}}$  displays the magnetic susception of  $\overline{\text{r}}$ are Kreen, and Kreen and precent with the Kreen precent with  $\sigma$

after the hydrothermal ionic exchange.

#### $\overline{1}$  **Eq.** PHF<sub>8</sub>S<sub>8</sub> (11111) cingle crystal tals of K<sub>1</sub>.63 **pm** and the K<sub>1</sub>.6 pm and the second  $\frac{1}{2}$  is the second of  $\frac{1}{2}$  for  $\frac{1}{2}$  is the second of  $\frac{1}{2}$  for  $\$ **(Li,Fe)OHFeSe (11111) single crystal**

produced powder samples of FeSe11111 [8–11]. Our recipe for

crystals.



 $\begin{bmatrix} 1 & 0 \\ 0 & \end{bmatrix}$  on  $\begin{bmatrix} 0 & 0 \\ 0 & \end{bmatrix}$  of  $\begin{bmatrix} 0 & 0 \\ 0 & \end{bmatrix}$  ion-Dong *et al., Phys. Rev.* B, **92** 064515 (2015).

 $\triangleright$  (Li, Fe) OH FeSe single crystal  $\binom{n}{1}$ .  $\binom{n}{2}$  can be also collected at  $1$  and the 180  $\ldots$ structure refinement is performed in light of the reported by ion exchange areas are magnetic transition at  $538$ FIG. 2. (Color online) Magnetic properties of K0*.*8Fe1*.*6Se2 and  $\triangleright$  (Li,Fe)OHFeSe single crystals grown rected for demagnetization factor under zero-field cooling (ZFC) and

 $\overline{40}$ 

 $50$ 

 $\triangleright$  Flactronic structure is very s (Li0*.*84Fe0*.*16)OHFe0*.*98Se based on the structural refinement.  $tho$   $Eo$ So MI  $(T_{c1}$   $A2$  K) lame Fe5e ML (1<sub>0</sub> ~ 42 K) **Electronic structure is very similar**  $\triangleright$  Electronic structure is very similar to  $tho$   $E_0$ C MU  $(T_{c1}$   $A2$  K) the FeSe ML ( $T_\mathrm{c}$  ~ 42 K)  $^{14}$ 

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Plenary presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.<br>.

#### The dc magnetic measurements were conducted on a Quantum Design MPMS-XL1 system with a time DVnant field less than 4 more magnetization, which sets in around 42 K as shown in a shown in around 42 K as shown in a shown in a in Fig. 2(a), and by the zero resistivity at 42.4 K as in Fig. 2(b). Despite its high crystalline quality, the 0.5 MA/cm<sup>2</sup> at ⇠20 K for the FeSe-11111 thin film. All the XRD experiments were performed at room tonerhes I n  $\frac{9}{2}$  equipped with the Ge  $\frac{1}{2}$ tion and epitaxy, which is even superior to our FeSe-<u>Intercalation s</u> Tuning superconducting properties,  $T_c$ , by intercalation

9 kW), equipped with two Ge (220) monochromators.

ity of the FeSe-1111 film is confirmed by the dia-

in the aspects of structure, morphology, crystalliza-



detectable. The *c*-axis parameter for the FeSe-11111

perconductors. The '-scan of (101) plane in Fig. 1(c)

**behavior of FeSe.** (a) Schematic intervalstrations of the crystal structures of the cryst

## Tuning superconducting properties, T<sub>c</sub>, by protonation

# Protonation-induced SC in FeSe



### Electric double layer transistor (EDLT)



### Tuning superconducting properties by EDLT

#### **SC induced** by EDLT

first demonstration

#### in IBS [**FeSe~0.6nm]**

J. Shiogai *et al*., *Nat. Phys.* **12** 42 (2016).



#### *T***<sup>c</sup> enhancement** by EDLT

### $FeSe_{0.8}Te_{0.2}$  ( $>10$  nm)

S. Kouno *et al*., *Sci. Rep.* **8** 14731 (2018).



 $V_{\text{G}}=0$  V **12 K -> 38 K** 



#### So far, enhancement of  $T_c$  by EDLT only for FeSe & Fe(Se,Te) 25 ir

TlFe<sub>1.6</sub>Se<sub>2</sub> (~20 nm) NdFeAsO (~7 nm)

250 200

T. Katase *et al*., *PNAS* **111** 3979 (2014).

## **Ambipolar suppression of** *T***<sup>c</sup>** K. Iida *et al., unpublished* **BaFe<sub>2</sub>(As,P)<sub>2</sub> (~10 nm)**



 $(V) =$  10<sup>0</sup> 1.  $\left| -1.50 \right|$ 2.0 4.0 1.64 1.68 1.69 1.76 1.78 2−*y* =  $\overline{0}$ a gate electrode. The transfer curves  $\begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix}$  curves  $\begin{bmatrix} -1.68 \\ -1.68 \end{bmatrix}$ (ID)] at a drain voltage (VD) of +0.3 V and output curves (I<sup>D</sup> vs. V<sup>D</sup>  $\widehat{\mathcal{C}}$  of  $\mathbb{N}$   $\mathbb{L}$  of the EDLT were then  $\mathbb{N}$   $\mathbb{L}$  were then  $\mathbb{N}$  $\begin{array}{cc} \text{S} & \text{I} & \text{I} & \text{I} \end{array}$  $\mathbb{R}^2$  if  $\mathbb{R}^2$  $\blacksquare$  and the Pt coil gate electrodes applied to the Pt coil gate electrodes and  $\blacksquare$ 100 200 300  $\frac{1}{I(K)}$  in the maximum ID in the transfer curve cu  $r_{\rm abs}$   $\sim$   $r_{\rm obs}$   $\$  $10.5.$  The gate leakage current ( $10.5.$  A,  $\Delta$  Lower) also increased at V<sup>G</sup> up to +4.0 V but was clearly smaller than I<sup>D</sup> in the whole VG region. After a set of the VG region vertex  $\mathcal{A}(\mathcal{A})$ initial values of  $100$  when  $200$  was  $300$  $\sigma$   $\tau$  (K)

placement in the ion liquid. Probably due to the same reason,  $\mathcal{L}$ 

 $3400$   $10$   $20$ 

 $V_{\odot} = 0$ 

 $V_{\rm c} = +2$  V  $V_{c} = +4$  V

*T* (K)

3600

3800

*R*sheet (

ପି

4000





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## Large critical angle  $\theta_c$  & constant  $J_{\text{c,inter}}(\theta_{\text{GB}} > -15^{\circ})$



T. Hatano, K.I. *et al*., *NPG Asia Mater.* **16** 41 (2024). K. Iida *et al*., *Supercond. Sci. Technol*. **32** 074003 (2019). T. Katase *et al*., *Nat. Commun*. **2** 409 (2011). W Si *et al*., *Appl. Phys. Lett*. **106** 032602 (2015). E. Sarnelli *et al*., *IEEE Trans. Appl. Supercond*. **27** 7400104 (2017).



 $\triangleright$  A critical angle  $\theta_c$  of 9°, which is larger than cuprate

▶ The 
$$
J_{\text{c,inter}}
$$
 is constant at  $\theta_{\text{GB}} > \sim 15^{\circ}$ 

## Excellent GB properties in (Ba,K)122

#### Unchanged  $\theta_c$  for (Ba,K)122 even in field



### GB transparency is increased by over-doping (Ba,K)122



- $\triangleright$  Over-doped grains enhanced the proximity effect
- $\triangleright$  SNS 11 model described the data

Z. Cheng *et al*., *Mater. Today Phys*. **28** 100848 (2022).

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#### Detailed analyses on polycrystalline (Ba,K)122 amne cika Koll*o*  $\sum_{i=1}^{n}$

#### Hot-pressed (Ba,K)122 tape



- $\triangleright$  Grain alignment is important (GB connectivity)
- > Clean GB is important (the number of GB connections)  $\triangleright$  Clean GB is importar The EDS elemental mapping in Fig. 2 revealed that such sample. The grains are approximately 0.5–1.0 μm in size. number of GB connections) some large grains appear very slightly uniaxially textured,

F. Kametani *et al*., *Appl. Phys*. Express **17** 013004 (2024). −. Kametani *et al., Appl. Phys*. Express **17** 013004 (2024). the center of the GBs. The EDS maps identify the former as core in Ag-SS than in Ag-HP; however, such porosities do not

#### Despite the minor difference in Difference in Difference in Julie in Julie in Julie in Julie in Julie in Julie reas wetting phase an (Blocking the supercurrent flow)  $\mathbf{B} \cdot \mathbf{A}$ Hot-pressed (Ba,K)122 tape **FeAs** wetting phase and BaO



contrasts between the Ba122 grains and the bright bands at

continuous bright contrast is FeAs, whereas the discontinuous dark contrast is Ba–O. Detailed in 4MOr2A-01 by F. Kametani (4/9)

∼0.2–0.5 μm in size, indicating the lower density of the Ba122 core in Ag-SS than in Ag-HP; however, such porosities do not extend along the GBs. As seen in Fig. 3(b), there are continuous clean GB networks in Ag-SS in contrast to Ag-HP. The HAADF-STEM imaging in Fig. 3(b) showed

The Japan Society of Applied Physics by IOP Publishing Ltd

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**a**,  $\frac{1}{2}$  from room temperature to be the from the from  $\frac{1}{2}$ 

### Natural defects in IBS thin films



## APC in IBS thin films



 $\checkmark$  Unlike cuprates, IBSs are robust against irradiation (disorder)

 $\checkmark$  For Ba-122,  $T_c$  decreases with -1 K/mol% (cf. -0.2~-0.1 K/mol% for REBCO)

[1] S. Lee *et al*., *Nat. Mater*. **12** 392 (2013). [2] C. Tarantini *et al*., *Sci. Rep.* **4** 7305 (2014). [6] S. Meyer *et al*., *J. Phys.: Conf. Ser*. **1559** 012052 (2020).

[3] S. Seo *et al*., *NPG Asia Materials* **12** 7 (2020). [7] T. Horide *et al*., *Thi. Sol. Films* **733** 138802 (2021).

[8] T. Ozaki *et al*., *Nat. Commun*. **7** 13036 (2016).

[9] C. Tarantini *et al*., *SuST* **31** 034002 (2018). [10] D. Li et al., *Sust* **32** 12LT01 (2019).

[4] J. Lee *et al*., *SuST* **30** 085006 (2017). [5] M. Miura *et al*., *Nat. Commun*. **4** 2499 (2013).





**Target modifications Tangle 19 Trotor (BZO nano cylinders)** expanded image of the contrast region due to a BZO nanorod. expanded image of the contrast region due to a BZO nanorod.

Magnetic Field (T)

8

6

,  $H_{\text{Weyl}}$  and  $H_{\text{Weyl}}$ 

,  $H_{\text{H}}$  and  $H_{\text{H}}$ 

4.2K<br>(H ⊥ film)

 $+4444$ 

 $\overline{a}$  in the strain peaks of the strain peaks of the strain peaks of the strain peaks of the structure difference between FST (PbO-

 $\text{FeSe}_{0.5}\text{Te}_{0.6}$ Figure 6. Plan-view micrographs of 2 mol.% BZO-Co-Ba122 thin film. (a) TEM diffraction contrast image shows the uniform distribution of  $S_{\rm eff}$  (2017)  $S_{\rm eff}$  (2017)  $S_{\rm eff}$  (2017)  $S_{\rm eff}$  and 2017)  $S_{\rm eff}$  (2017)  $S_{\rm eff}$  (  $B_1$  are normal to the image. (c) High angle annular dark field scanning TEM (HAADF-STEM) taken along TE To investigate the origin of the strong pinning effect, the

**(splayed cascade defects)**

**Proton irradiation**



T. Ozaki et al., Nat. Commun. **7** 13036 (2016).

 $-$  - 0 mol.% BZO  $-$  2 mol.% BZO

 $-4$  mol % BZO

 $4.2K$ 

 $(H \perp film)$ 

160

140

S. Seo *et al*., NPG *Asia Materials* **12** 7 (2020). are no other phase peaks present despite the periodically S. Seo et al., NPG Asia Materials 12 7 (2020).  $F = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ S. Seo et al., NPG Asia Materials 12 7 (2020).  $\mathcal{L}$  is the dashed circles represent lattice distortion points. The strain scale bar is the strain contrast at the strain con

2 mol.% BZO

 $-4$  nm

To investigate the origin of the strong pinning pinning  $\mathbb{E}[\mathbf{r}]$ 

previously reported study [29]. In addition, there was contrast  $\frac{1}{100}$   $\frac{1}{100}$   $\frac{1}{100}$   $\frac{1}{100}$ 

 $700 \%$   $4444.1$   $1400 \%$ 

In analogy with BZO:YBCO system [39], during the growth of this film films, the BZO may form nano-size second the BZO may form nano-size second the B phase in both P- or Co-Ba122 matrix to reduce an interfacial energy from large mismatch between BZO and Ba122.  $H_{\text{H}\text{H}\text{m}}$ 

fuu %

12

14

5

10

These nanoscale defects can cause  $\mathcal{L}$ 

## Mn-doped (Li,Fe)OHFeSe (11111) thin films



### Thermodynamic approach + APC



## Solubility limit in SmFeAsO



S. Iimura *et al*., *J. Asia Ceramic Societies* **5**, 357 (2017).

- Substitution level is limited up to  $\sim$  0.2 (For SmFeAsO1-*x*F*x*)
- For H, the substitution level is increased **up to ~0.8**
- Heavily electron doping can be achieved

32

### Thermodynamic approach + APC for SmFeAs(O,H)



M. Miura, K. I. *et al*., *Nature Materials* (2024).

## Current status of the best-performing  $J_c$ -*H* (single xtal. sub.)



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- $=$  20-60 Hz > multi turn PLD system, operating at *f*=20-60 Hz  $P<sub>2</sub>$
- 32  $\triangleright$  FeSe<sub>0.4</sub>Te<sub>0.6</sub> target,  $\phi = 60$  mm,  $t = 8$  mm  $\overline{a}$
- $\overline{1}$  $\triangleright$  Self-field  $I_c{\sim}$ 108 A @ 4.2 K (1 m tape,  $T_c{=}17.5$  K)  $\overline{K}$  $\ddot{\phantom{1}}$
- $\sim$  175 A corresponding to  $J_c$   $\sim$  2.3 MA/cm<sup>2</sup> Detailed in 2MOr2A-06,-07  $\triangleright$  Short sample: Self field *I*<sub>c</sub>~175 A corresponding to *J*<sub>c</sub>~2.3 MA/cm<sup>2</sup>  $I \sim 175$  A corresponding to  $I \sim 2.3$  MA/cm<sup>2</sup> entries a Detailed in 2MOr2A-06-07  $\sim$ 52  $\overline{\phantom{a}}$

.<br>รวค*์* L. Liu *et al., Adv. Eng. Mater*. **25** 2201536 (2023).

S. Wei et al., Sust 36 04LT01 (2023). pancake coil, (c)The insert hybrid magnet, and (d)Part of the testing device.

The four-probe measurements by the four-probe method in a physical probe measurement system  $\mathcal{F}_{\mathcal{F}}$ Detailed in 2MOr2A-06,-07  $\sigma$  by H. Liu & Y. Liu and the four-probe method in a physical probe method in a physical probe measurement system in a physical probe measurement system in a physical probe measurement system in a physical property meas

## Fe(Se,Te) tapes

#### **Realising a cheap, Fe(Se,Te) Coated Conductor**



• **Thick films** of Fe(Se,Te) by e-depo

Reported by L. Piperno (1MOrB-02, 2/9)

• **Irradiation effects** on Fe(Se,Te) films

Reported by M. Iebole & F. Rizzo (1MOr1B-03, -04, 2/9)

#### • **Pinning mechanism**

Microwave vortex motion in FeSe

Reported by N. Pompeo

 $(1$ MOr1B-05, 2/9)  $37$ 



## (Ba,K)122 bulks fabricated by data- & researcher driven process design



### $CaKE<sub>4</sub>As<sub>4</sub>$  (1144) bulk samples

Hybrid phase between  $AeFe<sub>2</sub>As<sub>2</sub>$  ( $Ae = Ca$ , Sr) and *A***Fe2As2 (A=K, Rb, Cs)**

- Ø The *c*-axis textured 1144 was realized
- $\triangleright$  A self-field  $J_c$  of reached 12 kA/cm<sup>2</sup>, which is comparable to that of K:Ba122 bulks



*T***c~36 K w/o doping**

 $3.0$ 

### Current status of *J<sub>c</sub>-H* plots for IBSs tapes (short samples)



- Ø Fe(Se,Te)/IBAD-MgO showed the highest  $J_c$  in low field regime although  $T_c$  is the lowest
- $\triangleright$  In-field  $J_c$  of K-doped Ba122 tape was superior to that of the P-doped Ba122/IBAD-MgO

#### Perspective (still mature … but ) conductors: National  $\mathcal{S}^{(1)}$  and  $\mathcal{S}^{(2)}$  and  $\mathcal{S}^{(3)}$  and  $\mathcal{S}^{(4)}$



Supercond. Sci. Technol. 32 (2019) 070501 (3pp) https://doi.org/10.1088/1361-6668/ab1fc

Superconductor Science and Technology compounds are used in dustrially, with intensive work on NB3Sn optimization still under the NSS n optimization<br>Still under the NSS n optimization still under the NSS n optimization still under the NSS n optimization still **OP** Publishing<br>The other materials are still considered in the research and development phase. The research and development phase of the research and development phase of the research and development phase. The research a

Thus,  $\frac{1}{10}$  is the discovery of  $\frac{1}{10}$  is the discovery of intervals of intervals of iron based superconductors (IBS) in  $\frac{1}{10}$  is the class of a new class of intervals of intervals of intervals of intervals

Viewpoint 2008 [10] opened the doors to a new perspective for microscopic models. J. Jaroszynski Interpretation studies show that IBS phenomenology and superconductions of the CrossMark

#### Constructing high field magnets is a real tour de force applications. In the motions of them have a high critical current and the motions. In the motion helpful in explaining the latter. From a practical point of view, IBS are ideal  $\frac{1000 \text{ V}}{1000 \text{ V}}$

temperature superconductivity still lacks a widely accepted microscopic model.

Jan Jaroszynski  $maxing$  it more  $ex$ than Nb<sub>3</sub>Sn. Attempts to make a superconducting wire started immediately, using  $\frac{323}{100}$  $\frac{1}{2}$  and the generation of superconducting who stated immediately,  $\frac{1}{2}$  and  $\frac{1}{2}$  either the powder-in-tube (PIT) [11–13] or coated conductor [14, 15] methods.  $T_{\text{tot}}$  viewpoint on the letter by Donglian and  $T_{\text{tot}}$  superconduction  $T_{\text{tot}}$ making it more expensive than NbTi, but with much higher critical parameters either the powder-in-tube (PIT)  $[11-13]$  or coated conductor  $[14, 15]$  methods. Moreover, the cost of IBS wire can be four to five times lower than that of  $Nb<sub>3</sub>Sn$ , The paper by Wang et al  $\mathcal{I}_1$  reports on the first test on the first test of a coil made of a coil made of

#### The cost of IBS wire can be four to The cost of IBS wire can be four to Jc. For all known superconductors of the time, these critical values were low,

five times lower than that of Nb<sub>3</sub>Sn, conduction metals, compounds, and allows the useful superconductors and allows the useful superconductors and a  $N_{\rm 3}$  and  $N_{\rm 4}$  and  $N_{\rm 4}$  and  $\gamma_{\rm 4}$  and  $\gamma_{\rm 4}$  are found. Within a short time, with time, with  $\mathbf{f}$ <sub>114)</sub>  $\qquad \qquad \mathbf{f}$   $\qquad \qquad$   $\qquad \mathbf{f}$   $\qquad \qquad$   $\qquad$   $\qquad \mathbf{f}$   $\qquad \qquad$   $\qquad$   $\qquad$   $\qquad$   $\qquad$   $\qquad$ 

>20 T at 4.2 K or >10 T at 20-30 K **making it more expensive than NbTi,**  kilometer lengths of Nb3Sn wire were fabricated and the first 6 T 'supermagnet' more expensive than NDTL.  $\mathbf{S}$  is the superconductor industrial phase. Note that  $\mathbf{S}$ 

> but with much higher critical 19JI

> parameters than Nb<sub>3</sub>Sn.  $\mathsf s$  than ND $\mathsf s$ Sn. Theory impact on the search for  $\mathsf s$ conducting materials.

## Summary

- 1. A review of the current status of IBSs has been conducted.
- 2. A review of various techniques for tuning  $T_c$  has been conducted.
- 3. High-angle grain boundaries (GBs) do block supercurrent flow, but not as severely as in the cuprates. This is a driving force for magnet applications using polycrystalline wires and bulk materials.
- 4. A strategy for improving the polycrystalline tapes and bulks of K-doped Ba122 has been proposed.
- *5. J<sub>c</sub>-B* performances have been improved significantly by APC and thermodynamic approach combined with APC (films).
- 6. Long length wires and tapes have been developed significantly.

# Thank you for your attention!



**Iron-based Superconductors: Advances towards applications**

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