Iron-based and MgB$_2$ classes of superconductors

Part II - IBS

Marina Putti

University of Genova and CNR-SPIN

3rd-14th September 2018 EASIschool in Vienna
The lecture will review:

1) the basic properties of IBS, including the interplay between superconductivity and AFM, unconventional pairing;

2) the superconducting properties, including the upper critical field $H_{c2}$, critical current density $J_c$ and critical parameters;

3) the development and fabrication of wires and tapes.
Iron based superconductors (IBS)

- Fe-oxypristide superconductors
  - LaFeAsO$_{1+y}$F$_{2}$ 26K
  - LaFePO 4K
  - LaNiP 2K

- SmFeAsO$_{1+y}$F$_{2}$ (HP synthesis) 55K
  - CeFeAsO$_{1+y}$F$_{2}$ 41.43K

- LaFe$_{1-x}$Co$_x$AsO 14K

- New doping approach

- Fe-fluoropristide superconductors
  - CaFe$_1-x$Co$_x$AsF 22K
  - FeSe 26K (under HP)

- Hole doped FeSe$_2$As$_2$

- Other structure with Fe-tetragonal lattice

- Epitaxial thin film
  - Sr$_2$Fe$_2$As$_2$ (water induced) 25K
  - Sr$_2$Fe$_2$As$_2$ (epitaxial thin film) 20K

- Single layer FeSe

- Date (Received)
IBS families

FeAs conducting layer

LaO(F) blocking layer
two dimensional tetragonal lattice of iron

112 type (CaFeAs₂)

1111 type (LaFeAsO)

11 type (FeSe)

111 type (LiFeAs)

122 type (BaFe₂As₂)

21113 type (Sr₂VFeAsO₃)

Intercalated FeSe-11
Superconductivity occurs upon
substituting O with F, H
Deficiency of O
heterovalent RE
Fe with Co
heterovalent AE metal
external pressure
internal pressure
substitution of Te with Se, S
external pressure

**REFeAsO**  
1111  
$T_{c,max} = 58$ K

**AEFe$_2$As$_2$**  
122  
$T_{c,max} = 40$ K

**Fe(Se,Te)**  
11  
$T_{c,max} = 21$ K
<table>
<thead>
<tr>
<th>Material</th>
<th>M-site dopant</th>
<th>$T_c$ (K) vs $x$, $y = z = 0$</th>
<th>Fe-site dopant</th>
<th>$T_c$ (K) vs $y$, $x = z = 0$</th>
<th>As-site dopant</th>
<th>$T_c$ (K) vs $z$, $x = y = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaFe$_2$As$_2$</td>
<td>K</td>
<td>38/0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rb</td>
<td>23/0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SrFe$_2$As$_2$</td>
<td>K</td>
<td>36.5/0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Na</td>
<td>35/0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cs</td>
<td>37/0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>La</td>
<td>22/0.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaFe$_2$As$_2$</td>
<td>Na</td>
<td>33/0.66</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RE=La, Ce, Pr</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

RE=La, Ce, Pr 40 -46

Co  22/0.2

Ni  20.5/0.1

Pd  19/0.11

Rh  24/0.11

Ru  21/0.9

Pt  25/0.1

Co  20/0.2

Ni  10/0.15

Pd  9/0.15

Rh  22/0.25

Ru  13.5/0.7

Ir  22/0.5

Pt  16/0.16

Co  17/0.06

Ni  15/0.06

Rb  18/0.1

P  30/0.7

P  27/0.7

P  13/0.3

P  26/0.6
$T_c$ is higher in the order $1111 > 122 > 11$.
Does interlayer spacing of FeAs layers enhance optimal $T_c$?

- Phenomenological correlation of $T_c$ with the tetrahedron angle and with the anion height
- Anion height is a structural parameter associated with strength of spin fluctuation

Phase diagrams:

\[ \text{LaFeAsO}_{1-x}F_x \]

S. Sanna et al., PRB 80, 052503 (2009).
A. Martinelli et al PRL 106, 227001 (2011)

\[ \text{SmFeAsO}_{1-x}F_x \]
Phase diagrams:

FeTe

FeSe
Parent compounds:
LaFeAsO

\[ \text{resistivity [m} \Omega \text{cm]} \]

Temperature [K]

- a SDW ordering of Fe (≈0.4\(\mu_B\)/Fe)
- associated to a tetragonal-orthorhombic transition

C. de la Cruz et al., 2008 Nature 453 899

1111

122
FeTe exhibits:
- bicollinear AFM ordering of Fe ($\approx 2.5 \mu_B/\text{Fe}$)
- spin direction 45° rotated in respect to 1111 and 122
- Tetragonal to monoclinic transition
Superconducting order parameter:
- MgB$_2$ : two-band $s$ wave with the same sign
- IBS : two-band $s\pm$ wave

Superconductivity promoted by AFM fluctuations which couple e- and h-bands

Igor I. Mazin, Nature 464 (2011) 183
In case of $s \pm$ wave pairing a rapid suppression of $T_c$ with impurities has been predicted.

Superconductivity in IBS is quite robust against disorder.
The lecture will review:

1) the basic properties of IBS, including the interplay between superconductivity and AFM, and unconventional pairing;

2) the superconducting properties, including the upper critical field $H_{c2}$, the critical current density $J_{c}$ and the critical parameters;

3) the development and fabrication of wires and tapes.
Upper critical fields

1111
NdFeAs(OF)

122
Ba(FeCo)₂As₂

11
Fe(SeTe)

Putti et al. SUST 23 034003 (2010)
Upper critical Fields

![Graph showing upper critical fields for various superconductors.](image)

C. Tarantini et al., PRB 84, 184522 (2011)
### Superconducting parameters

<table>
<thead>
<tr>
<th></th>
<th>1111</th>
<th>122</th>
<th>11</th>
<th>YBCO</th>
<th>MgB$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_c$ [K]</td>
<td>55</td>
<td>38</td>
<td>16</td>
<td>93</td>
<td>39</td>
</tr>
<tr>
<td>$B_{c2}(0)$ [T]</td>
<td>&gt;50</td>
<td>60</td>
<td>55</td>
<td>&gt;50</td>
<td>20-30</td>
</tr>
<tr>
<td>$\xi_{ab}$ [nm]</td>
<td>2.5</td>
<td>3</td>
<td>1.5</td>
<td>2.2</td>
<td>10</td>
</tr>
<tr>
<td>$\gamma_H$</td>
<td>5</td>
<td>2</td>
<td>2-3</td>
<td>4-14</td>
<td>3-5</td>
</tr>
<tr>
<td>$\lambda_{ab}$ (nm)</td>
<td>200</td>
<td>200</td>
<td>490</td>
<td>180</td>
<td>50-100</td>
</tr>
<tr>
<td>Ginzburg number</td>
<td>$4 \cdot 10^{-4}$</td>
<td>$2 \cdot 10^{-5}$</td>
<td>$1 \cdot 10^{-3}$</td>
<td>$&gt;10^{-3}$</td>
<td>$&lt;10^{-5}$</td>
</tr>
</tbody>
</table>

\[ G_i = \frac{\Delta T}{T_c} \]

Width of the critical regime around $T_c$

\[ G_i = \left[ \frac{\gamma \cdot kT_c}{H_c^2(0)\xi^2(0)} \right]^2 \propto \gamma^2 \cdot T_c^4 \]

Several similarities with HTS:
High $H_{c2}$, small coherence length, unconventional pairing
but, lower anisotropy
Critical current density of thin films

J_c @ low temperature is:

- Large (above $10^6$ A/cm$^2$ in self-field)
- Almost field independent
- Nearly isotropic

Critical current density:

- \( J_c \) is almost isotropic with increasing both the temperature and the magnetic field.
- \( J_c \) remains above \( 10^5 \text{ A/cm}^2 \) @0.8 \( T_c \)
- Pinning by point defects

\( T_c = 18 \text{ K} \)

P. Yuan et al., SUST 29 (2016) 035013
Also in IBS Jc is suppressed by misaglined grains.

- In HTS $\theta_C \approx 4^\circ$
- In IBS $\theta_C \approx 10^\circ$
- IBS has Advantageous GBs over HTS

Lee et al., Appl. Phys. Lett. 95, 212505 (2009).
Katase et al., Nat. Commun. 2, 409 (2011)

Kawale et al., ASC 2014
The lecture will review:

1) the **basic properties** of IBS, including the interplay between superconductivity and AFM, unconventional pairing;

2) the **superconducting properties**, including the upper critical field $H_{c2}$, the critical current density $J_c$ and the critical parameters;

3) the development and fabrication of wires and tapes.
Comparison of polycrystalline IBS & HTS

DyBa$_2$Cu$_3$O$_{7-y}$ polycrystal

Intragrain $J_c$

Transport $J_c$

$J_{cm}$ (sample size)

4.2 K

Seuntjens et al., JAP. 67, 2007 (1990)

SmFeAsO$_{0.85}$ polycrystal

Intragrain $J_c$

Transport $J_{ct}$ (Magneto Optical)

4.2 K

Yamamoto et al., SUST 21, 095008 (2008)
Best performances for the 122 family

$J_c$ rather flat and in the best samples close to $10^5$ A/cm$^2$ above 10 T
The goal: to achieve highly in-plane oriented practical metal-tape substrates.

Main technologies for ReBCO-CC manufacturing
Excellent results obtained on 11 thin films growth on IBAD and RABiTS

- $J_c > 10^5 \text{A/cm}^2$ at 35 T on RABiTS
- $J_c > 10^5 \text{A/cm}^2$ at 9 T on IBAD-LMO with in-plane misalignment $\Delta \phi \sim 7.7^\circ$
State of the art 122 IBS -CC


Development of IBS technical conductors over the years

Coated Conductors

PIT Wires & Tapes

T = 4.2K
self-field

I. Pallecchi, M. Eisterer, A. Malagoli, M. Putti, SUST (2015) 28

Practical application

@ B = 10 T
122 tapes

Jc anisotropy
Awaji EUCAS2015

Development of 122-PIT wires&tapes using scalable industrial processes at the Institute of Electrical Engineering, Chinese Academy of Sciences (IEECAS).

The first 100-m-class 122 wire

Cross-section of 114 multi filamentary 122 wires&tapes

SppC Design Scope (201701 version)

- **Baseline design**
  - Tunnel circumference: 100 km
  - Dipole magnet field: 12 T, iron-based HTS technology (IBS)
  - Center of Mass energy: >70 TeV
  - Injector chain: 2.1 TeV

- **Upgrading phase**
  - Dipole magnet field: 20-24T, IBS technology
  - Center of Mass energy: >125 TeV
  - Injector chain: 4.2 TeV (adding a high-energy booster ring in the main tunnel in the place of the electron ring and booster)

Top priority: reducing cost! Instead of increasing field

Qingjin Xu. Status of high field magnet technology for CEPC-SPPC. 2017 FCC Week 29 May-2 June 2017 Berlin, Germany.

**Engineering critical current**

- **Expected IBS 2025 (IEECASS)**
- **IBS 2016 Y.Ma (IEECASS)**
- **IBS - Iron Based Superconductor**
  - Much lower cost and better mechanical properties expected
Advantages

- High field superconductors
- Isotropic Jc
- Effective pinning mechanisms
- Suitable for fabrication with cheap method

Disadvantages

- Moderate Tc
- Hazardous material
- Technology too young