Flux pinning behaviour of a BaFe$_2$(As$_{1-x}$P$_x$)$_2$ thin film on IBAD-MgO technical substrate


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Ba-122: Grain Boundaries

Co or P-doped Ba-122 Fe(Se,Te)

- Large $\theta_c$ ($\sim 9^\circ$)
- Gentle slope
- Suitable for wire applications
- Wide experimental range for LAGB studies

IBAD Architecture and Texture Quality

- Two IBAD-MgO templates with different texture quality
- Both with $\Delta \phi < \theta_c \sim 9^\circ$

Possible Grain Boundary Pinning

Film with poorer texture quality:
- Lower $T_c$ (possible strain effect)
- Higher in-field $J_c$

Possible grain boundary pinning

Similar behaviour was seen for Co-Ba122/IBAD-MgO

Katase et al., APL 98, 242510 (2011)

Purpose of this Study

Clarifying pinning behaviour of grain boundary networks in Fe-based superconductors by investigating in-field $J_c$ properties of a $T_c$-enhanced P-doped Ba-122 CC
Sample Preparation

Pulsed laser deposition

Growth temp.: 1200 °C
Substrate: IBAD-MgO on Hastelloy

Nd:YAG laser $(\lambda = 532 \text{ nm})$

Sintered target

$P = 5 \times 10^{-7} \text{ Pa}$
$\varepsilon = 3 \text{ J/cm}^2$
$f = 10 \text{ Hz}$

BaFe$_2$(As$_{1-x}$P$_x$)$_2$
$(x = 0.35)$

Characterisation
Crystalline quality: XRD
Composition: EPMA
Transport: 4-probe
DC field facility@NHMFL (up to 35 T)
**$T_c$ Enhancement**

<table>
<thead>
<tr>
<th></th>
<th>$P/(P+As)$</th>
<th>$T_s$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current film</td>
<td>0.31 (PLD target 0.35)</td>
<td>1200</td>
</tr>
<tr>
<td>Previous film</td>
<td>0.26 (PLD target 0.35)</td>
<td>1050</td>
</tr>
</tbody>
</table>


**Current film** ($T_c=28$ K)

**Previous film** ($T_c=23$ K)

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**Thin films on MgO s.c. [1]**

- Single crystals [2]
- Our film 31%
  - 33% 31 K
  - 34% 23 K
  - 38% 17 K
- Previous film (PLD target 0.35)
  - 23% 31 K
  - 17% 29 K
  - 9% 10 K
  - 0% 0 K
Epitaxial Growth

\(\theta/2\theta\) scans

\[\text{Normalized intensity} \quad \text{D} \omega (\degree)\]

\[\text{Intensity (counts)} \quad 2q (\degree)\]

Epitaxial film

- No impurities
- 00l oriented
- Fourfold symmetry
- No rotated grains
- Sharply out-of-plane textured
- \(\Delta \phi\) less than \(\theta_c (\sim 9^\circ)\)

Magnetic Field Dependence of $J_c$

High performance P:Ba-122 CC
- Self-field $J_c$ @4.2 K over 4 MA/cm$^2$
- Slightly anisotropic ($\gamma_{Hirr}$ ~ 1.3 – 1.7)
- Superior to MgB$_2$ and NbTi
- Comparable to Nb$_3$Sn above 20 T
Pinning Potential and $B-T$ Phase Diagram

- Pinning potential in expected range for Ba122
- Small vortex liquid region
- $H_{\text{irr}}$ up to 50 / 60 T
- Slightly anisotropic ($\gamma_{\text{Hirr}} \sim 1.3 – 1.7$)

*Ghorbani et al., APL 100, 072603 (2012)  
In-field transport

- Non-Ohmic linear differential (NOLD) signature up to 10 T
  → $J_c$ limitation by grain boundaries
- Power-law behaviour above 12.5 T
  → $J_c$ limitation by intra-grain depinning of flux lines
Angular Dependence of $J_c$

Angular Dependence of $J_c$

$$H_{c2}(\theta) = H_{c2}^c / F(\theta)$$

$$F(\theta, \gamma_{Hc2}, \delta) = (|\cos \theta|^{\delta} + \gamma_{Hc2}^{-\delta}|\sin \theta|^{\delta})^{1/\delta}$$

Angular Dependence of $J_c$

- Two distinct peaks at $H||c$ and $ab$
- $ab$-peak: fully determined by $H_{c2}$ anisotropy
- $c$-axis peak: due to network of threading dislocations comprising the LAGBs

Pinning Force Density for $B \parallel c$

Planar defects
Line defect arrays

- $f_p$ data fall onto the master curve of GB pinning for $H \parallel c$

Summary

- P-doped BaFe$_2$As$_2$ coated conductor samples realized by PLD
- $T_c$ increased up to 28 K by optimising growth condition
- NOLD signature at low fields due to $J_c$ limitation by GBs → crossover field
- GBs act as flux pinning centers, justified by $J_c$ scaling and $F_p$ analyses
- $c$-axis peak: GB pinning, $ab$ peak: $H_{c2}$ anisotropy
Pinning Force Density for \( B \parallel ab \)

\[
\frac{f_p}{f_{p_{\text{max}}}} = \frac{25}{16} h^{0.5} \left( \frac{1}{5} h \right)^2
\]

Planar defects
Line defects array

\[
\frac{f_p}{f_{p_{\text{max}}}} = \frac{9}{4} h \left( \frac{1}{3} h \right)^2
\]

Point-like pinning

- \( f_p \) follows GB pinning @ 10 and 15 K
- \( f_p \) neither follows GB nor point-like pinning for \( h > 2 \) at 20 K
- 4 K: point like pinning
- Dominant pinning mechanism changes with \( T \) for \( H \parallel ab \)

Currently limited application fields
(Round) Wire technology improving

MBE-grown P:Ba122/MgO

Jens Hänisch - Grain boundaries and pinning in a $\text{BaFe}_2(\text{As}_{1-x}\text{P}_x)_2$ thin film on IBAD-MgO technical substrate