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Critical current and nano-structural properties of K-doped $BaFe_2As_2$ epitaxial thin films by molecular beam epitaxy

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Introduction

- **Iron-based superconductor $Ba_{1-x}K_xFe_2As_2$ (K-doped Ba122)**
  - High superconducting parameter of T_c=38 K, H_{c2}~100 T, and J_c>1 MA/cm^2
  - Small electromagnetic anisotropy γ~1−2
  - → **Favorable material for high-field application**
- **Epitaxial thin film**
  - Essential for fundamental study and device application (*e.g.*, grain-boundary transport property)
  - Mostly studied in Co-doped Ba122
  - K-doped Ba122 epitaxial thin films have not been realized
  - → **Control of highly volatile potassium is necessary to realize K-doped Ba122 epitaxial thin films**

Background

Growth of epitaxial K-doped Ba122 was performed by several groups

	Substrate	Growth temperature	Crystallinity
N. H. Lee *et al.*[1]	Oxide*1	High-temperature growth & post-annealing	*c*-axis oriented
M. Naito *et al.*[2]	Oxide*2	Low-temperature growth	*c*-axis oriented
H. Hiramatsu *et al.*[3]	Oxide*3	High-temperature growth & post-annealing	*c*-axis oriented & weakly in-plane aligned
Previous work[4]	Fluoride*4	Low-temperature growth	**Truly epitaxial**

*1 *c*-cut Al_2O_3 and $LaAlO_3$(001) *2 $LaAlO_3$(001), MgO(001), *r*-cut Al_2O_3, and $SrTiO_3$(001)
*3 (La,Sr)(Al,Ta)O_3(001) *4 *AE*F_2(001) (*AE* = Ca, Sr, and Ba)

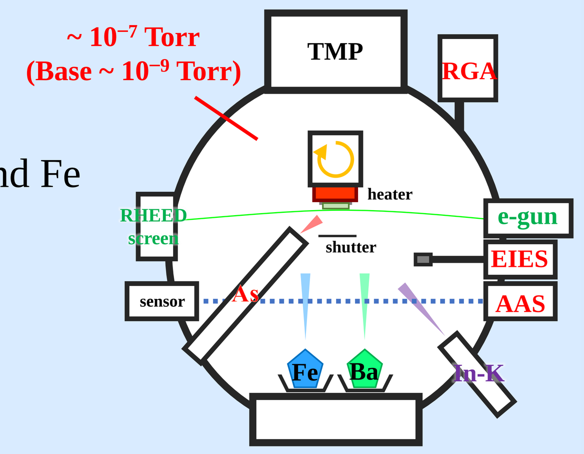
Epitaxial growth of K-doped Ba122 was realized by the combination of low-temperature growth and the usage of fluoride substrate

Purpose

Investigation of critical current characteristics and nanostructure of the high-J_c K-doped Ba122 epitaxial thin films

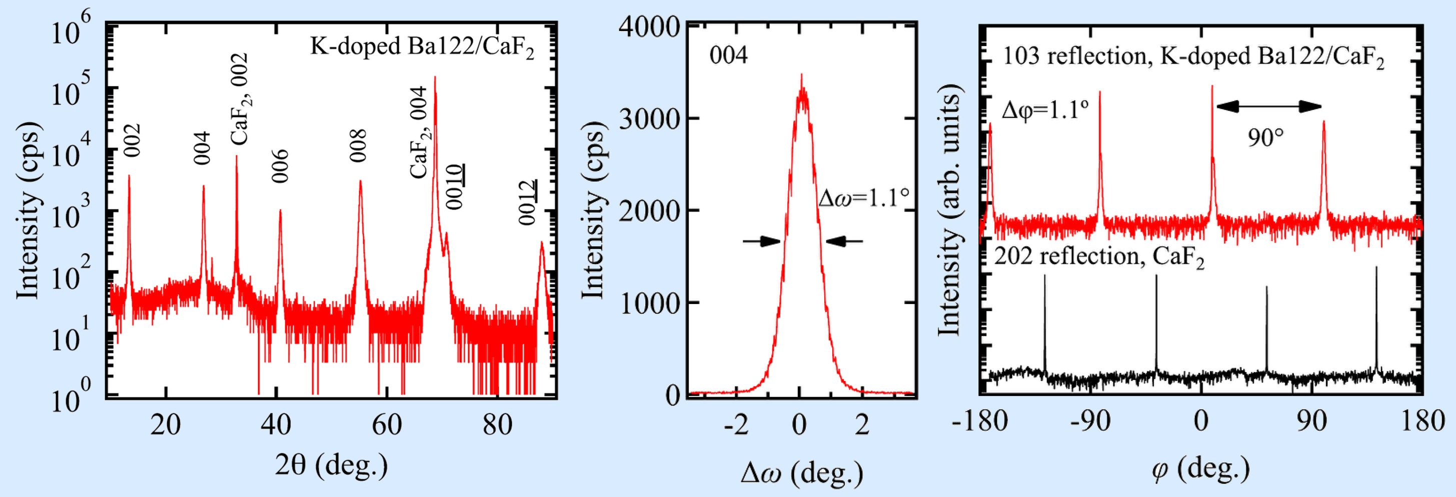
Experimental Procedure

- **Film preparation**
  - Growth using custom-designed molecular-beam epitaxy
  - Real-time monitoring of evaporation rate
    - i. Electron impact emission spectrometry (EIES) for Ba and Fe
    - ii. Atomic absorption spectrometry (AAS) for K
    - iii. Residual gas analyzer (RGA) for As
  - Low temperature growth (~395ºC) on CaF_2(001) substrate
- **Measurement**
  - X-ray diffraction
  - Transmission electron microscopy (TEM)
  - TEM-based scanning precession electron diffraction
  - Magnetization measurement



Simple sketch of MBE system

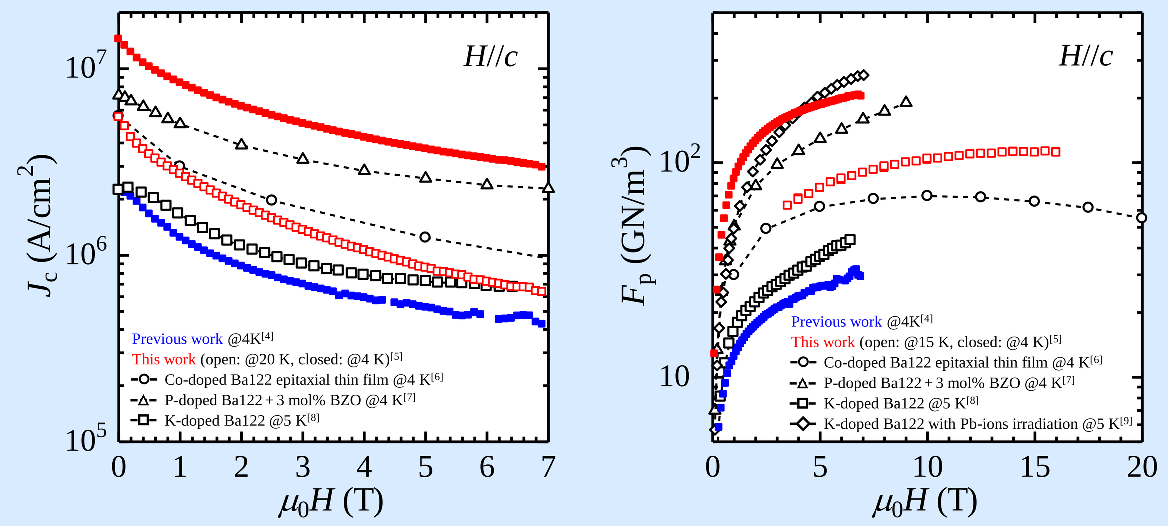
Crystallinity



- Sharp *c*-axis orientation
- Out-of-plane FWHM of $\Delta\omega$=1.1º for (004) reflection (equivalent to our previous report[4])
- Clear four-folded symmetry
- In-plane FWHM of $\Delta\phi$=1.1º for (103) reflection (improved by careful optimization of growth condition[4])

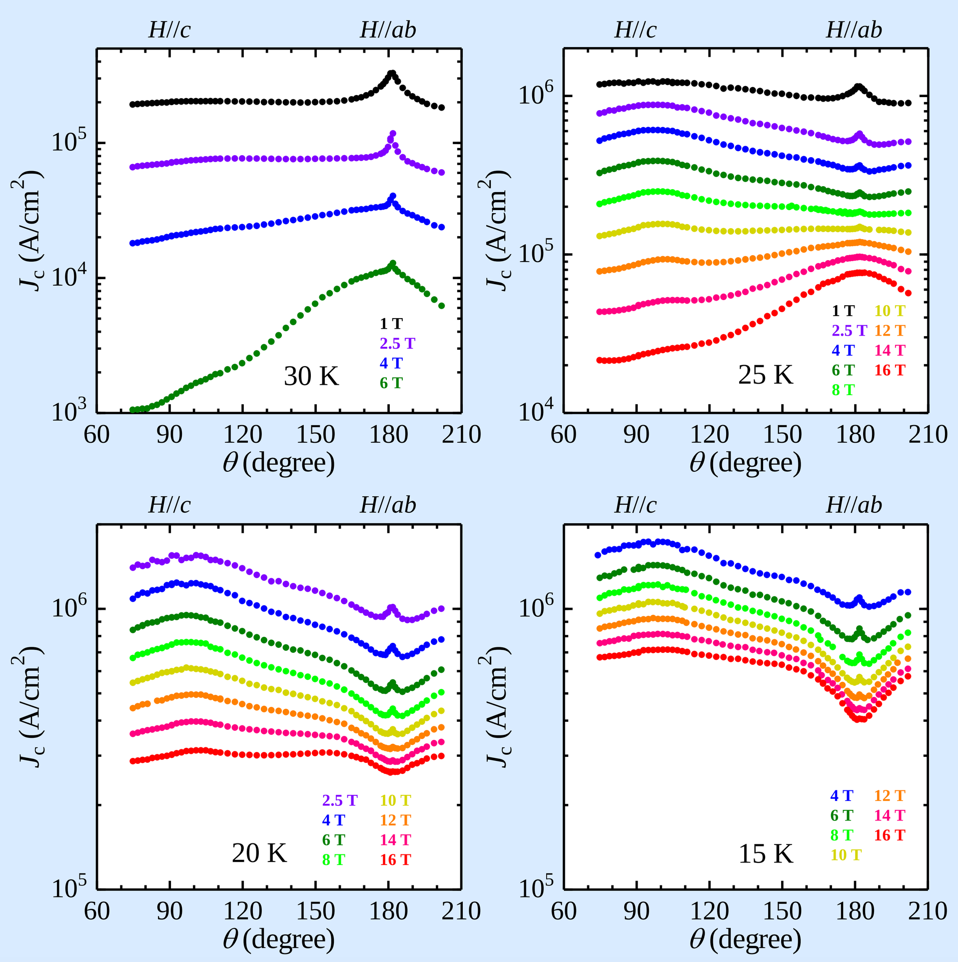
Successfully grown high crystallinity K-doped Ba122 epitaxial thin films on CaF_2

Critical current characteristics



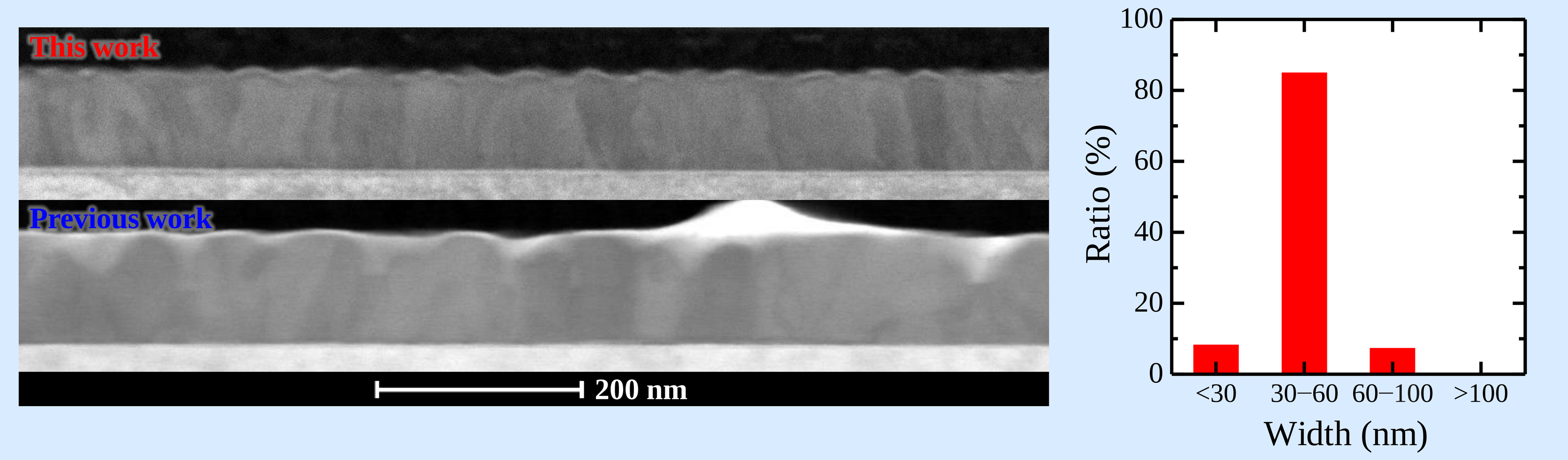
- Very high self-field J_c of **14.4 MA/cm^2** (one order higher than our previous report[4])
  → Higher than other 122-type epitaxial thin films
- Retain 3 MA/cm^2 under 7 T which corresponds to pinning force density of **200 GN/m^3**
- Up to 4 T, our K-doped Ba122 epitaxial thin film possesses the highest F_p among 122-type superconductors

Thin film with very high J_c was obtained without artificial pinning centers



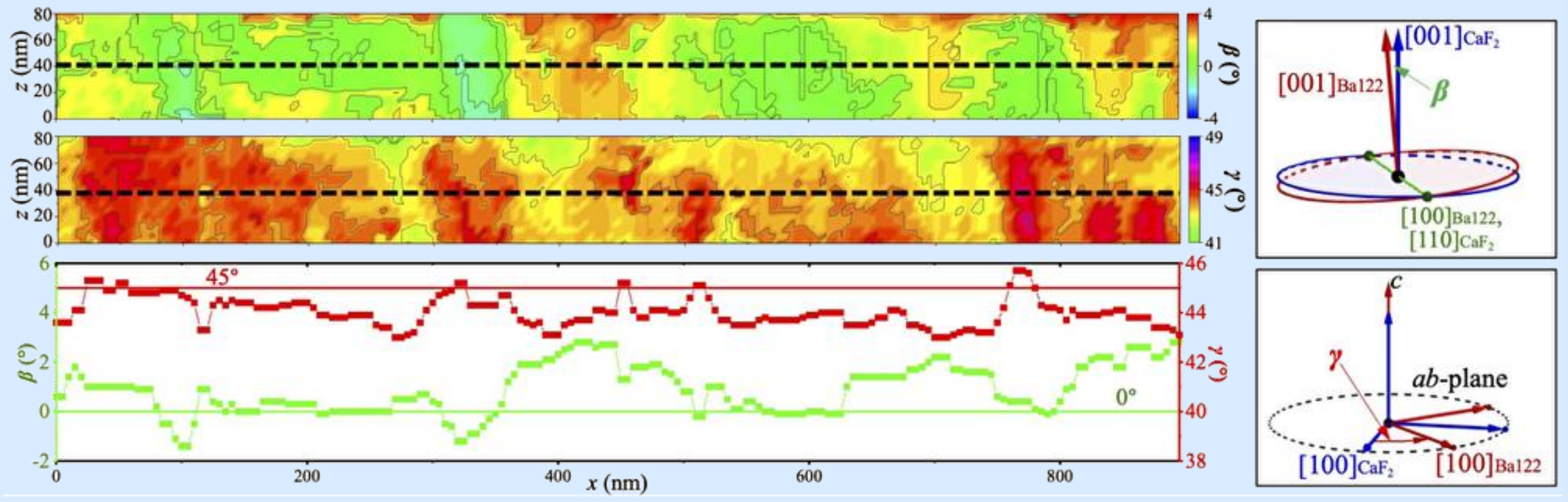
- J_c behavior is anisotropic at 30 K
  → Intrinsic pinning at *H*//*c*
- At 25 K, $J_c(H//c)/J_c(H//ab)$ is field dependent
  → $J_c(H//c) < J_c(H//ab)$ above 10 T
  → $J_c(H//c) \sim J_c(H//ab)$ at 10 T
  → $J_c(H//c) > J_c(H//ab)$ below 10 T
- $J_c(H//c) > J_c(H//ab)$ below 20 K, 16 T
  Strong flux pinning due to *c*-axis correlated pin is suggested
- $J_c(\theta)$ is not symmetric in the direction of the applied magnetic field relative to the *c*-axis
  → *c*-axis correlated pin is expected to be slightly tilted

Nanostructure



- No defects parallel to the *ab* plane (*e.g.*, stacking faults)
- Numerous grain boundaries along *c*-axis direction (slightly tilted)
  → Grain boundaries are low angle
  → Low-angle grain boundaries act as pinning centers
- Most of (~85%) the width of grains were 30−60 nm (high density low-angle grain boundary)

Uniformity of the grain size and high-density low-angle grain boundary enhanced pinning characteristics



- The world's first nanoscale crystal orientation analysis on iron-based superconductors
- The average grain rotation around *a*- (or *b*-) axis is $\Delta\beta_{average}$ =±1.5º, and around *c*-axis is $\Delta\gamma_{average}$ =45º±1º
- Consistent with the results obtained on angular dependence of J_c

Grain rotation resulting in the formation of low-angle grain boundary networks

Conclusion

- ✓ A very high J_c of 14.4 MA/cm^2 was obtained without artificial pinning centers
- ✓ Strong flux pinning due to *c*-axis correlated pin is suggested from angular dependence of J_c
- ✓ The small grain size of 30−60 nm resulted in high-density low-angle grain boundaries acting as pinning centers
- ✓ Phase purity, in-plane crystallinity, and introduction of pinning centers through optimization of microstructure are important for improving J_c

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