

# Developement of long-length BMO doped REBCO coated conductors by hot-wall PLD process

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A part of this work is based on results obtained from  
a project subsidized by the New Energy and Industrial  
Technology Development Organization (NEDO).



# OUTLINE

## □ Introduction

- Production wire at Fujikura
- Hot-wall PLD concept for BMO doped-REBCO

## □ Results

- Selection of materials
- Optimization of deposition condition
- Thickness dependence of REBCO
- Fabrication of a 300 m long wire

## □ Summary

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# Fujikura's REBCO coated conductor

## ■ Typical Specifications

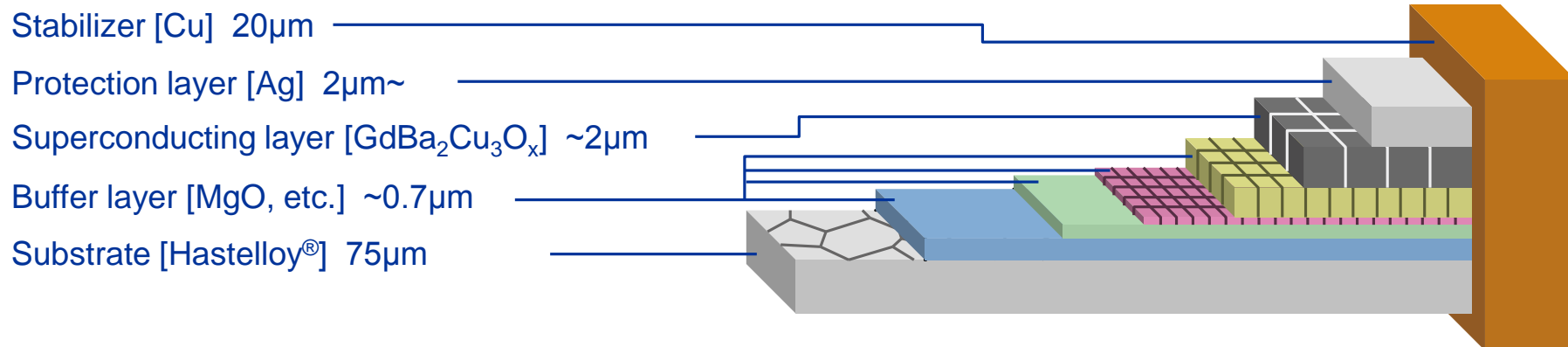
Sutabilizer:electroplated copper

Item	Width [mm]*	Thickness [mm]*	Substrate [μm]	Stabilizer [μm]	Critical Current ( $I_c$ ) [A] (@77K, S.F.)
FYSC-SCH04	4	0.13	75	20 x 2	$\geq 165$
FYSC-SCH12	12	0.13	75	20 x 2	$\geq 550$

- Specifications above are just references.
- If any questions or inquiries, please ask us detailed specifications.

\* Dimensions do not include thickness of insulating tapes.

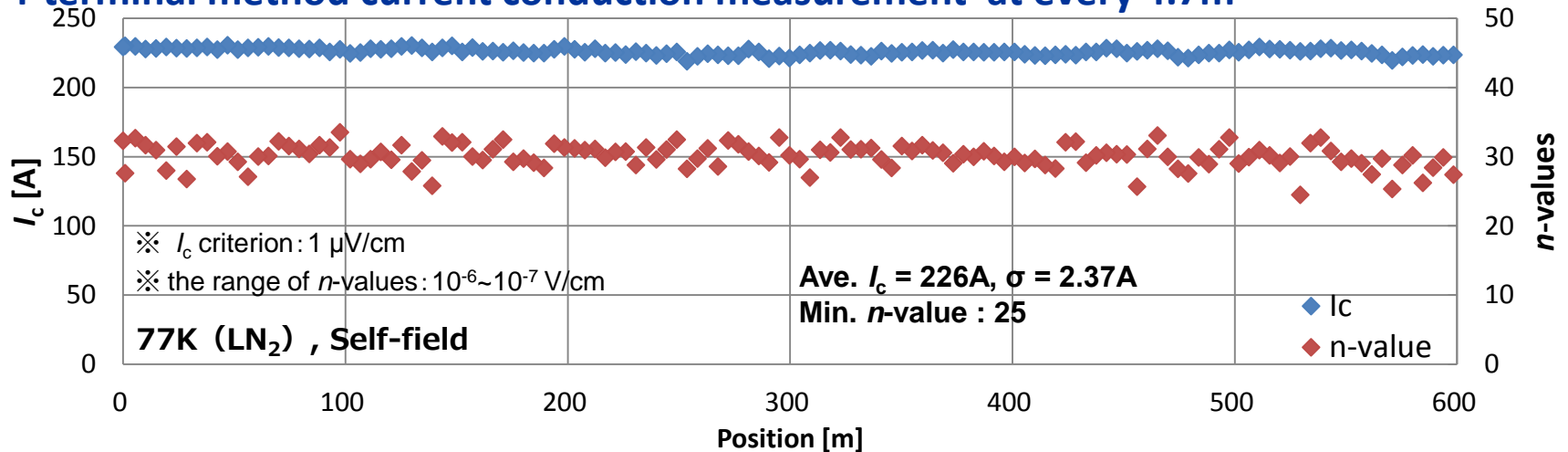
## <Schematic of 2G HTS wire (FYSC-SCH04)>



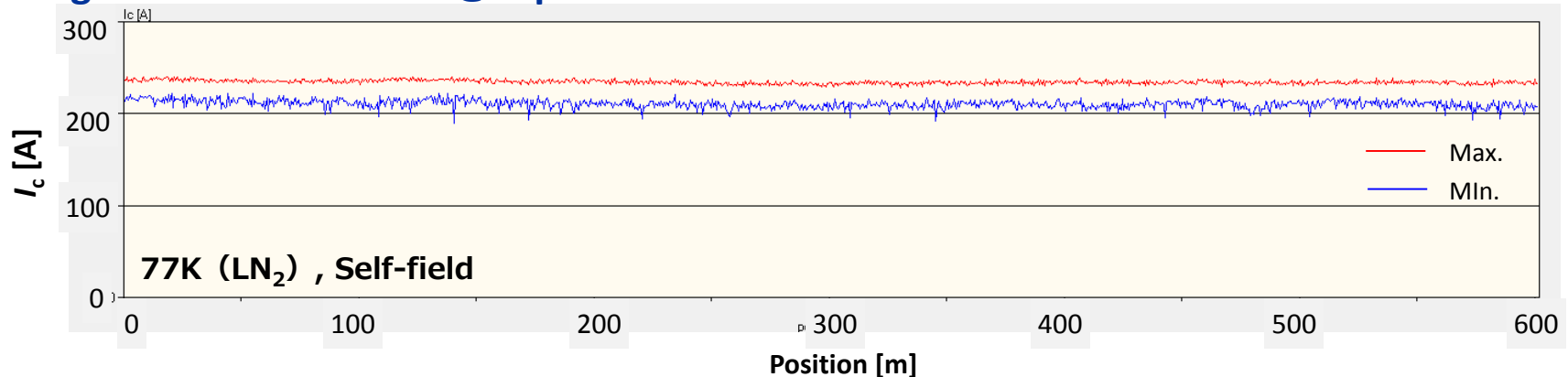
# Example data of longitudinal $I_c$ distribution

## Non-doped production wire with 4 mm-wide

### ■ 4-terminal method current conduction measurement at every 4.7m



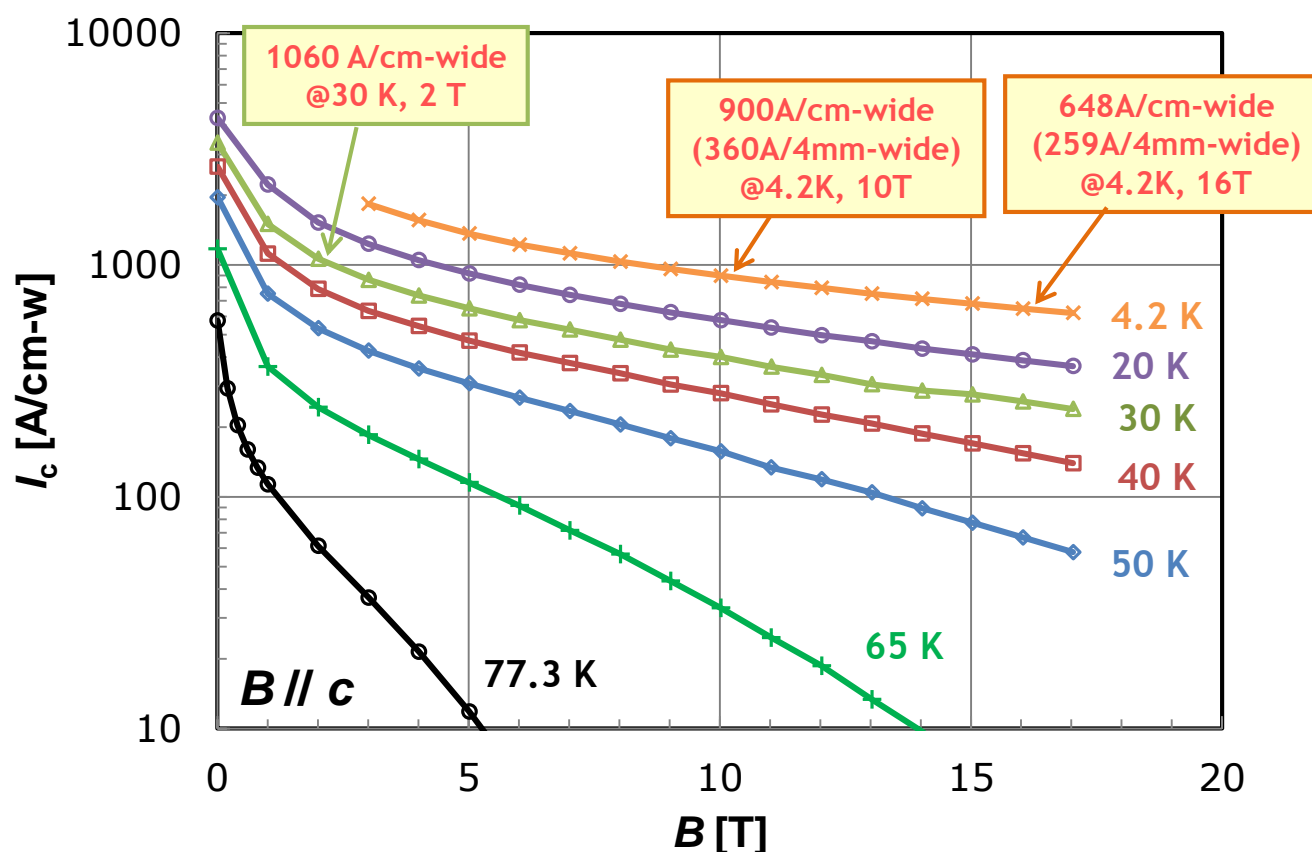
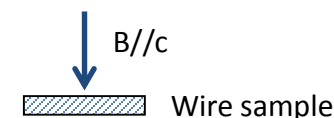
### ■ Magnetic measurement @Tapestar™



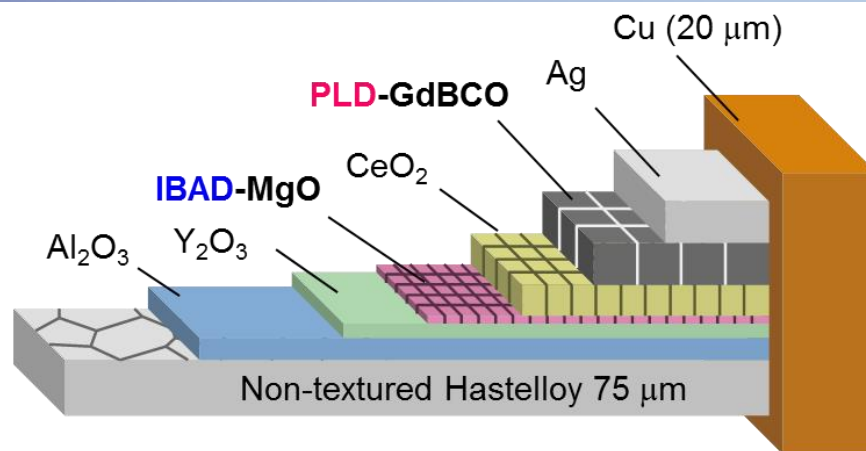
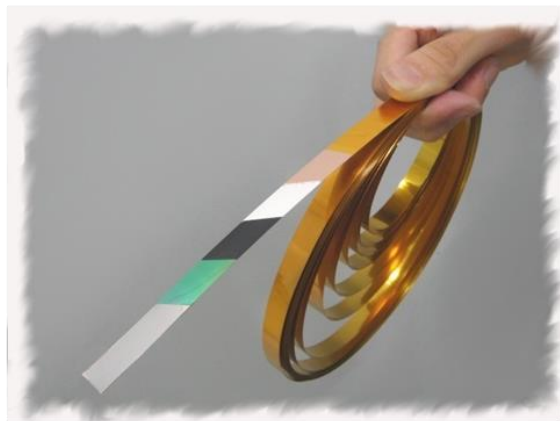
quite uniform  $I_c$  with 600m length are obtained

# Typical in-field $I_c$ of a production wire

- Example data of typical production wire
- Sample :  $I_c = 573 \text{ A@77K, s.f. (/cm-w)}$  ( $1.9\mu\text{mt}$ )



# Key techniques for REBCO wire fabrication

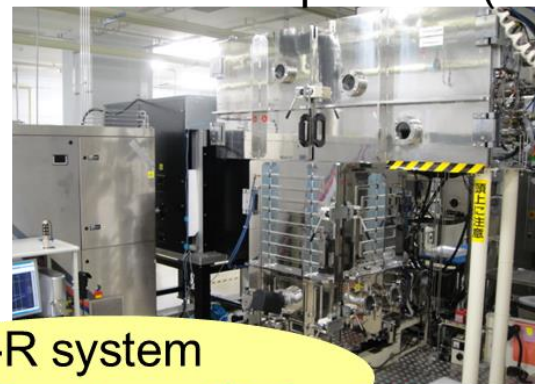


Ion Beam Assisted Deposition (IBAD)

Pulsed Laser Deposition (PLD)



R-to-R system  
with large ion source



R-to-R system  
with hot-wall heating

These techniques enable us to stably manufacture the high-performance and long-length REBCO wires.

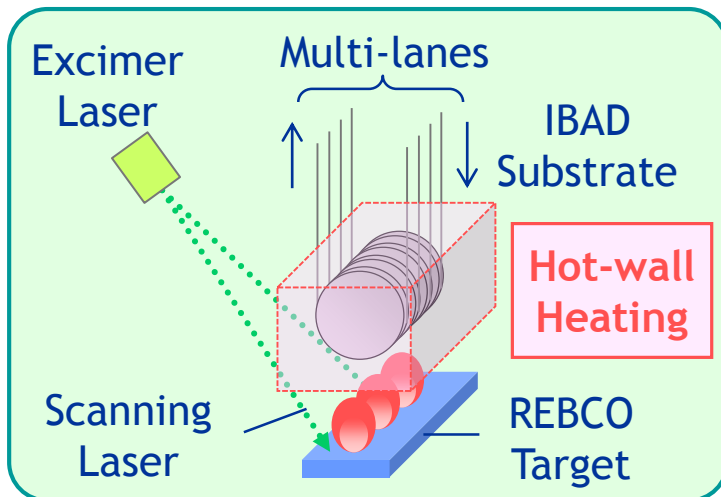
# BMO doping by Hot-wall PLD

Key issues for BMO doped REBCO wire are:

**"High in-field  $I_c$  & Reproducibility"**  
**"Long-length & Longitudinal  $I_c$  uniformity"**

Hot-wall PLD system realized:

- High  $I_c$  by thickening REBCO layer
- Excellent  $I_c$  uniformity  
by furnace-like stable substrate heating



Hot-wall PLD system is expected to overcome these issues.

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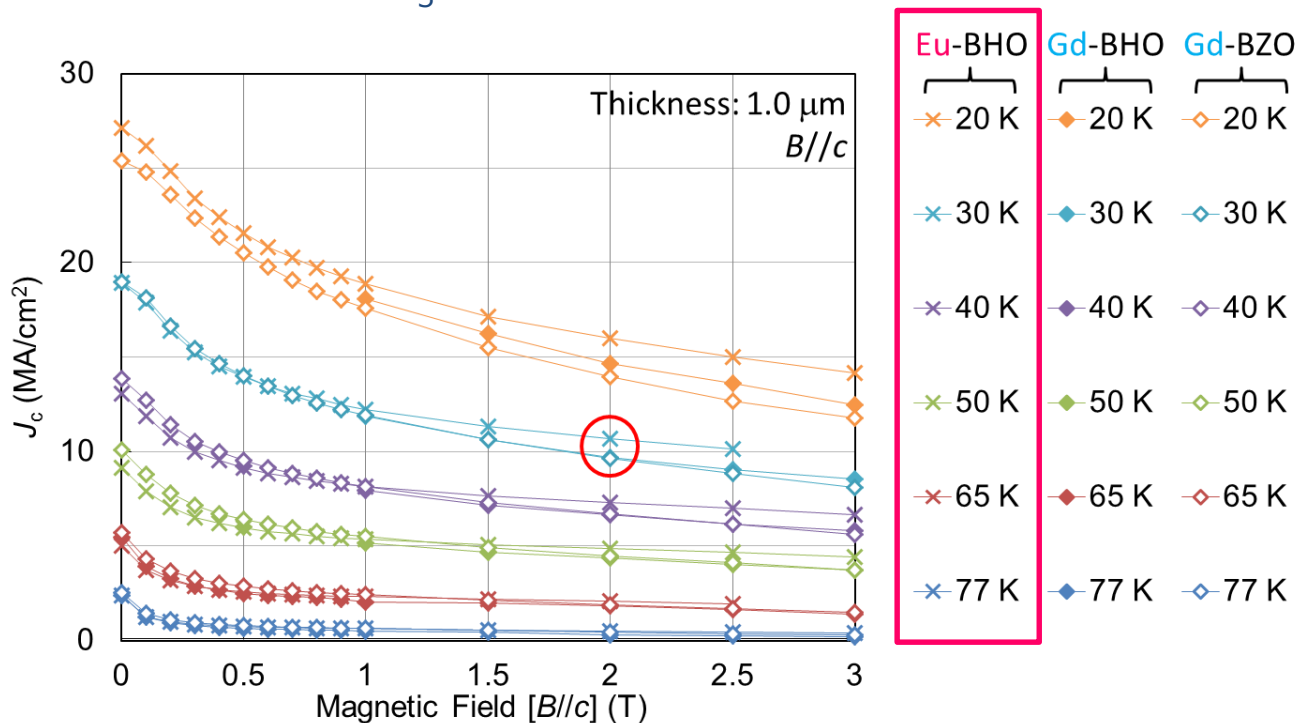
## □ Summary

# Selection of materials

## Investigations on RE element and BMO by preliminary deposition condition of Hot-wall PLD.

- GdBCO+5.0mol%BaZrO<sub>3</sub>
- GdBCO+3.5mol%BaHfO<sub>3</sub>
- EuBCO+3.5mol%BaHfO<sub>3</sub>

BHO doped EuBCO showed higher  $J_c$   
→ We chose this combination



Y. Iijima *et al.*, IEEE TAS vol. 27, no. 4, 6602804 (2017)

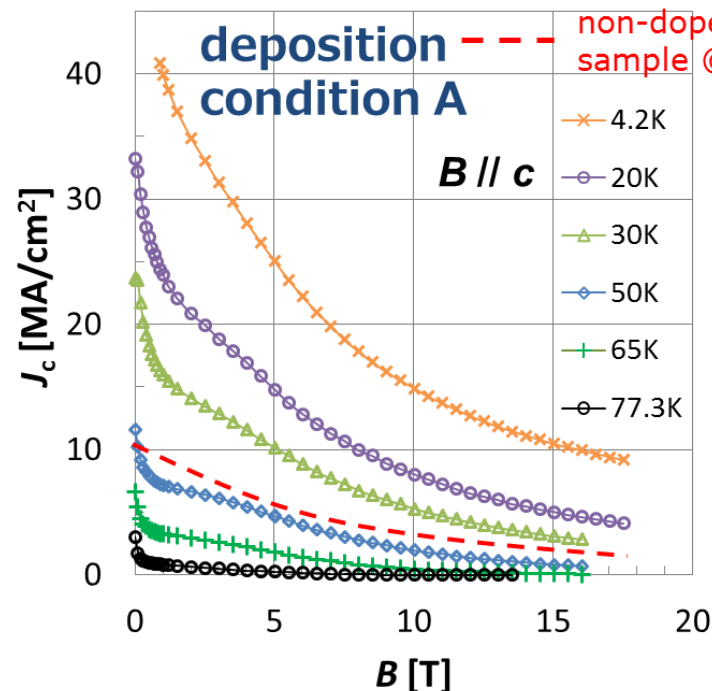
# Optimization of deposition condition

- Two types of optimized condition were found for BHO doped EuBCO.

**Condition A: High  $J_c$**

Growth rate ~ 5-7 nm/sec

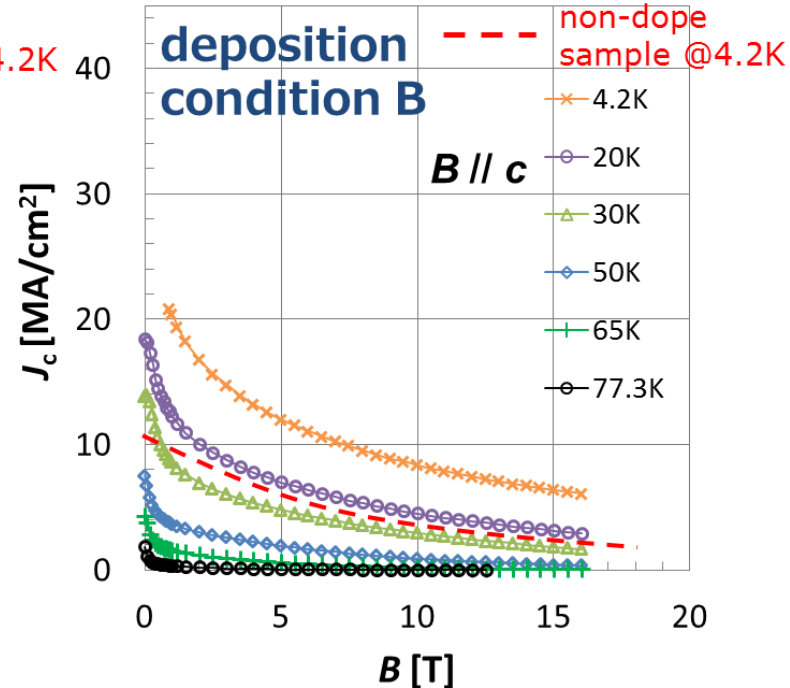
Thickness ~ 1  $\mu\text{m}$



**Condition B: High growth rate**

Growth rate ~ 20-30 nm/sec

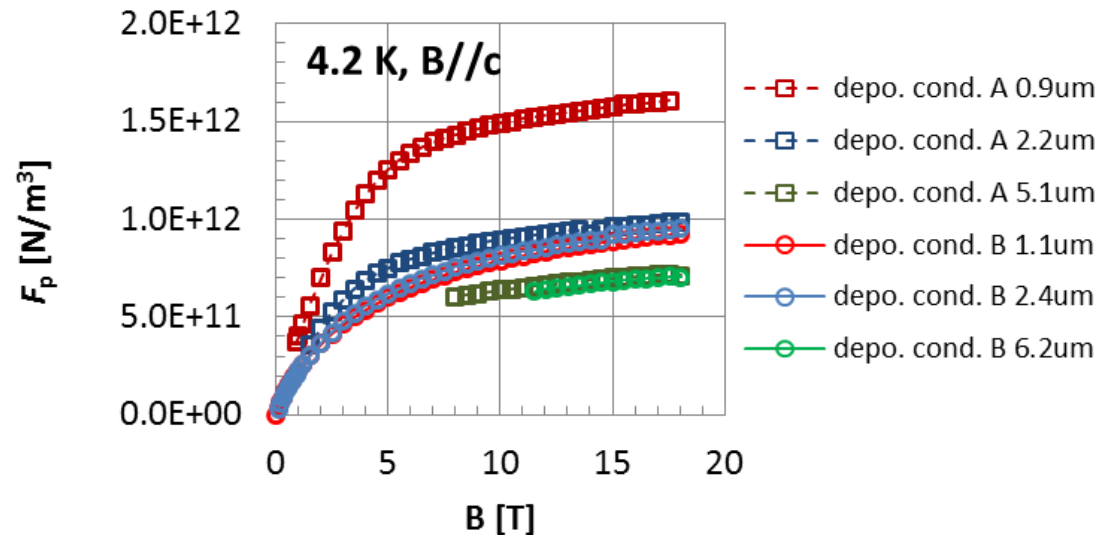
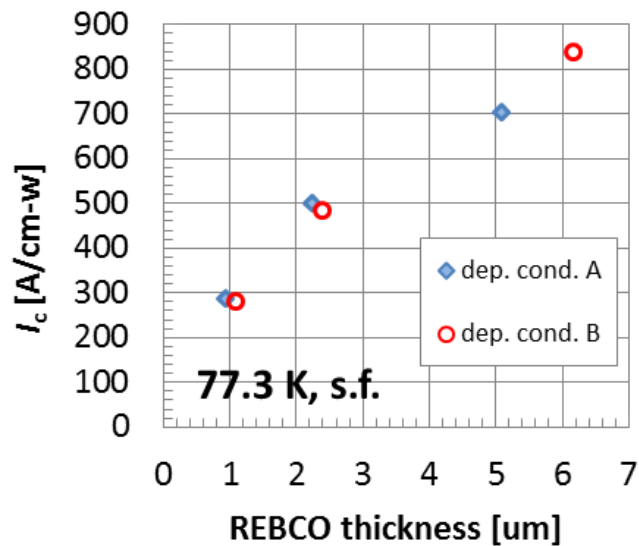
Thickness ~ 2-2.5  $\mu\text{m}$  → high " $I_c$ "



Y. Iijima *et al.*, IEEE TAS vol. 27, no. 4, 6602804 (2017)

# Thickness dependence of BHO doped EuBCO

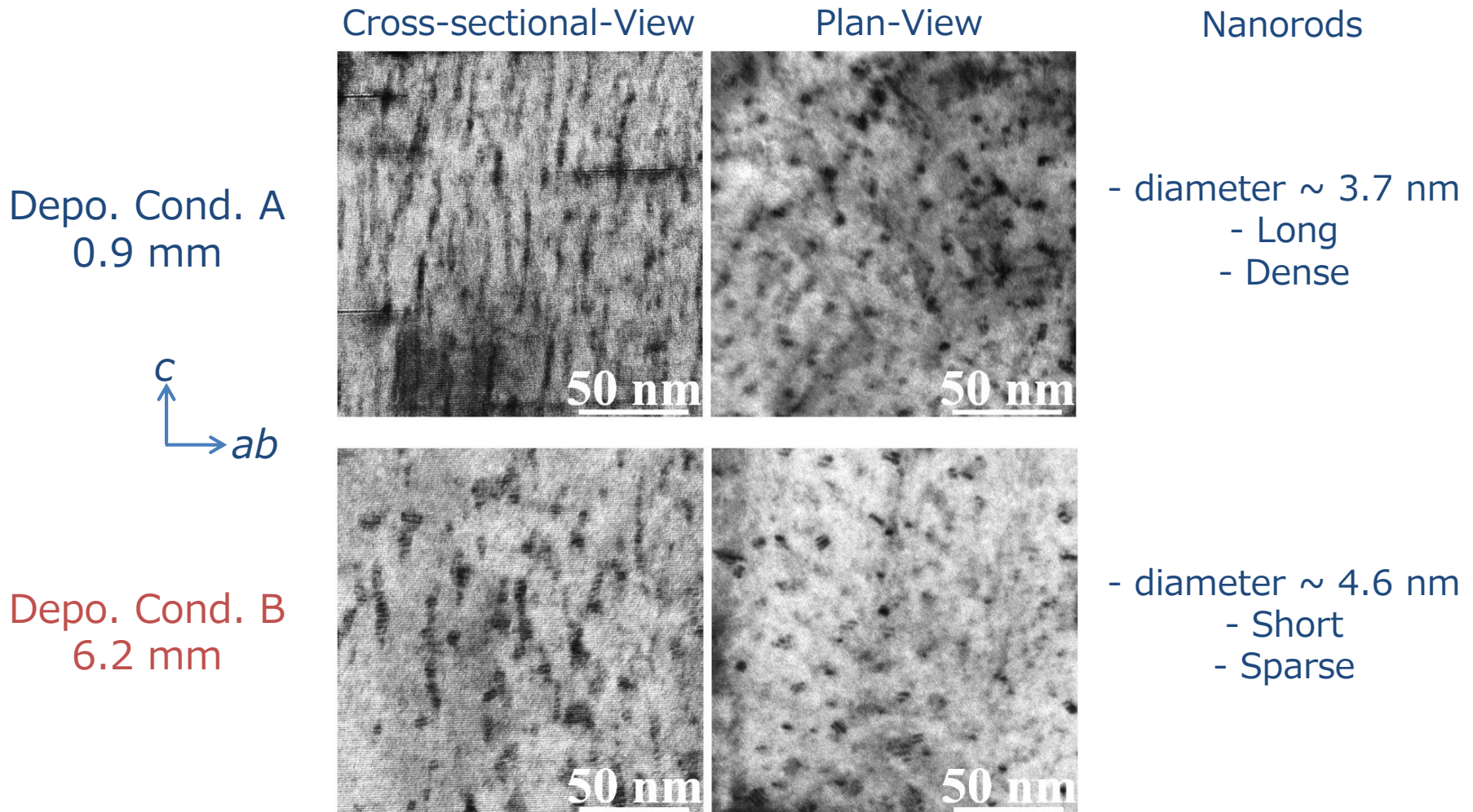
- Several thickness samples were fabricated using the two optimized deposition condition A and B.



- REBCO thickness dependence of  $I_c(77.3\text{K}, \text{s.f.})$  is similar in both conditions.
- 0.9  $\mu\text{m}$  thick sample of condition A shows quite large  $F_p(4.2\text{K})$ , but over 2  $\mu\text{m}$  thick samples have similar value to those of condition B samples.

\* This work includes some data measured at HFLSM, IMR, Tohoku University.

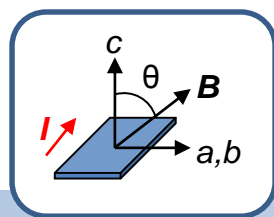
# TEM observation



\* Different thickness samples with same depo. cond. are similar to each other.

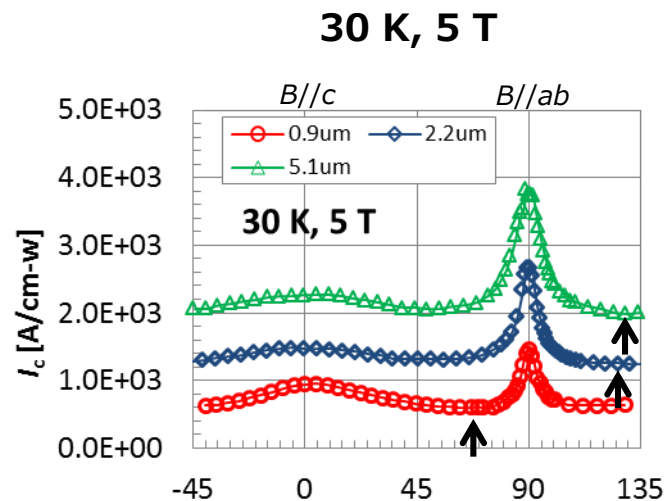
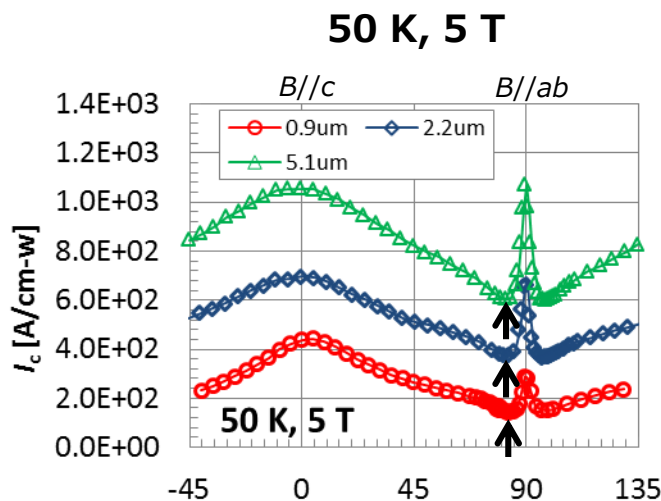
Why the microstructure differs depending on growth rate?

# Field angular dependence of $I_c$



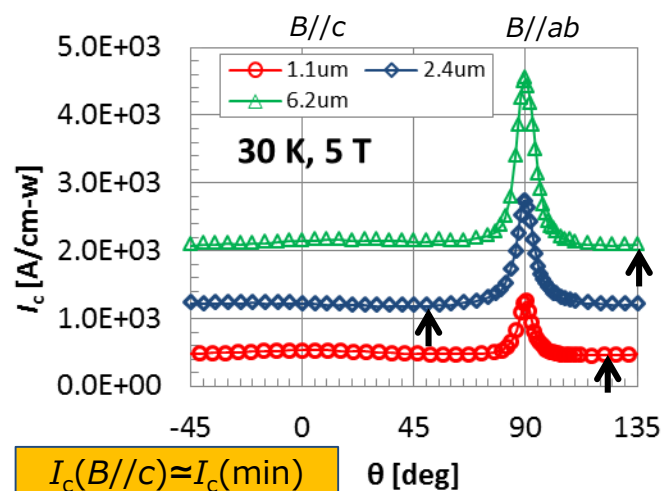
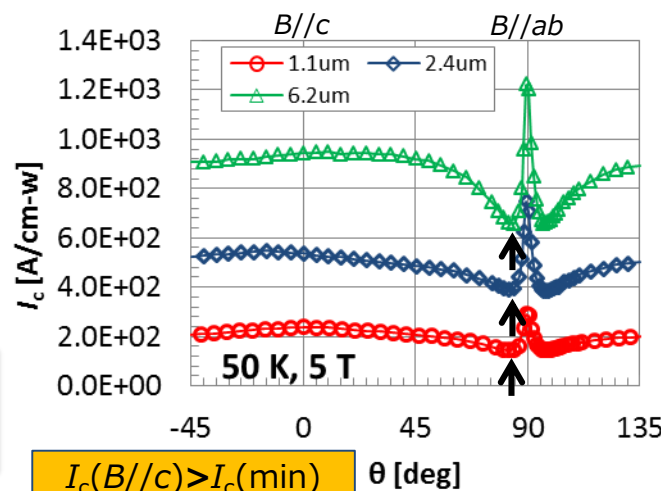
Depo. Cond.  
A

$\uparrow I_c(\min)$

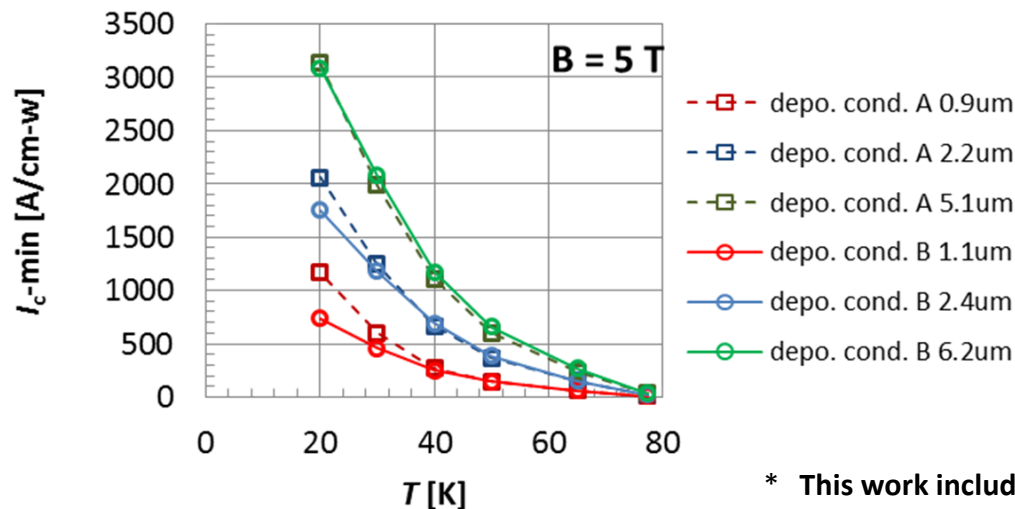
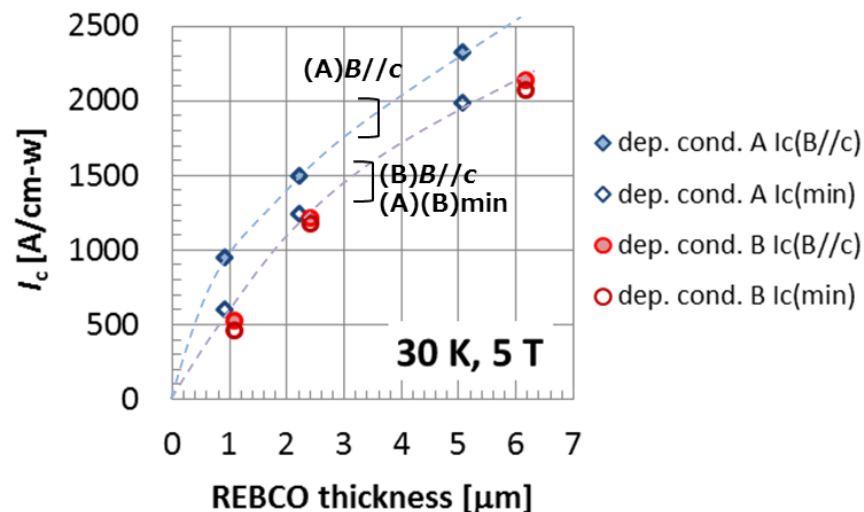
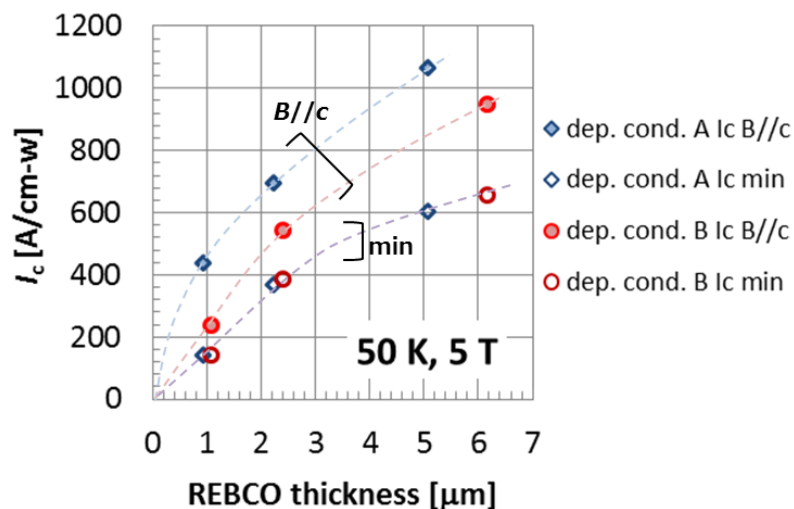


Depo. Cond.  
B

Focus on  
 $I_c(\min)$



# Thickness and Temperature dependence of $I_c(\text{min})$



$I_c(\text{min})$  lines are similar in both conditions.

In the case of

- REBCO thickness  $> 2 \mu\text{m}$
- Temperature  $> 30$  K

→  $I_c(\text{min})$  values are not so different by the depo. cond..

\* This work includes some data measured at HFLSM, IMR, Tohoku University.

# Conditions for fabricating long-length BHO doped EuBCO wires

## □ Materials

**3.5 mol% BaHfO<sub>3</sub> doped EuBCO** was adopted.

## □ Deposition Condition

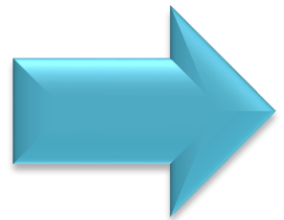
In order to ensure  
*sufficient throughput* considering mass production  
and  
*sufficient in-field  $I_c$  performance*,

**High growth rate condition : B** was adopted.

## □ REBCO Thickness

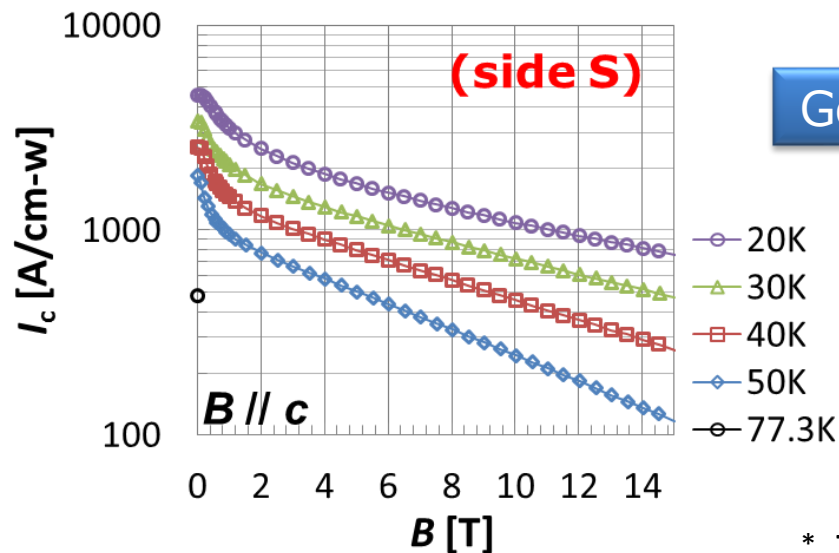
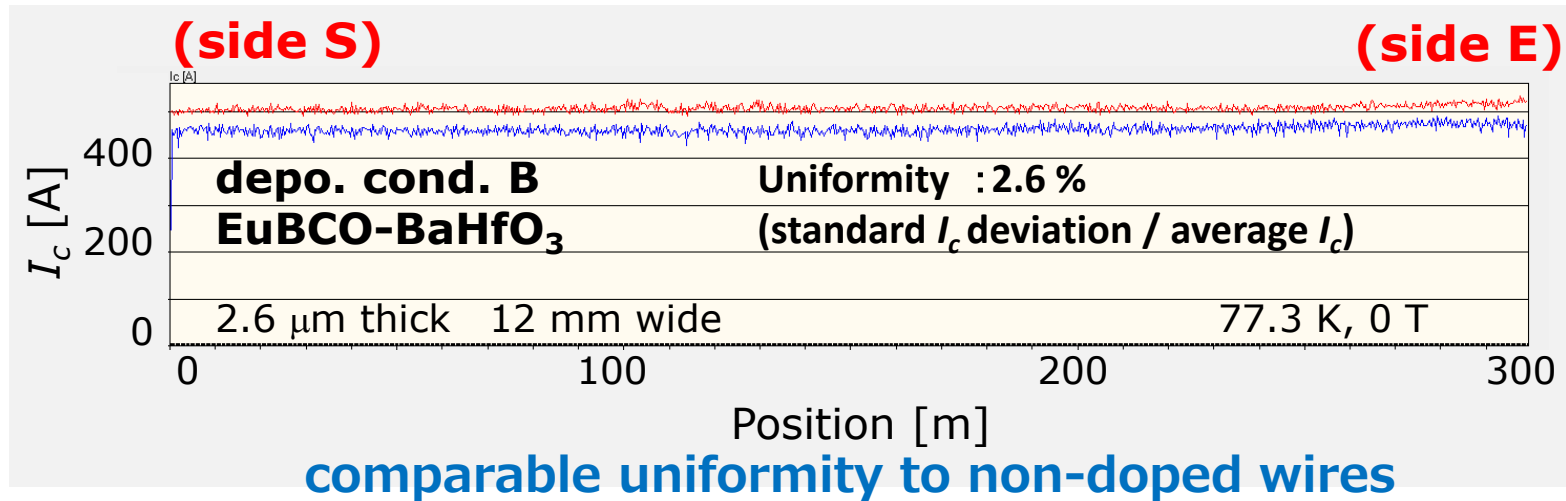
**2~3  $\mu\text{m}$  thick** was adopted.

**A 300 m long wire was fabricated.**



# 300m long BHO doped EuBCO wire

Tapestar® measurement

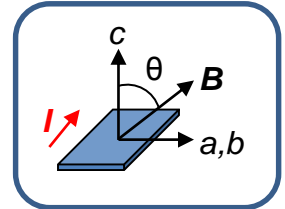
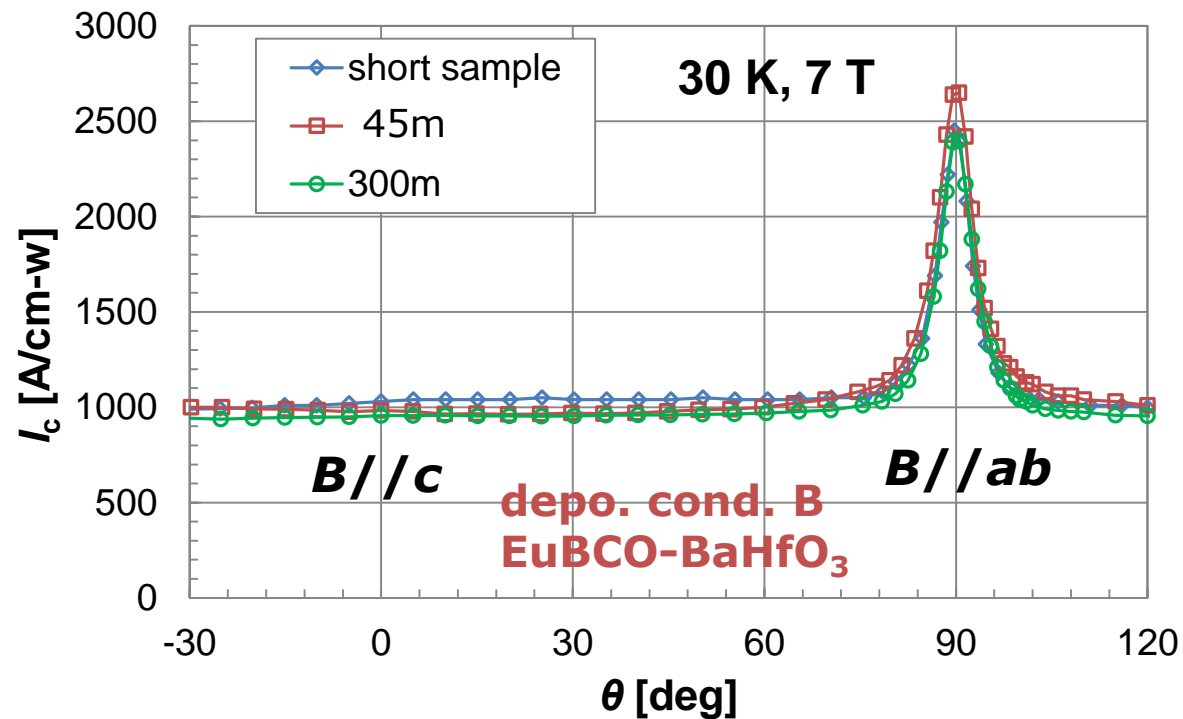


Good uniformity was obtained over 300 m.

In-field  $I_c$  measured at both end points  
are in good agreement,  
 **$I_c = 1755$  A/cm (side S)**  
 **$I_c = 1786$  A/cm (side E) @ 30 K, 2 T**

\* This work includes some data measured at HFLSM, IMR, Tohoku University.

# Reproducibility of $I_c$ - $B$ - $\theta$ characteristics



Good reproducibility of  $I_c$ - $B$ - $\theta$  characteristics was confirmed.

\* This work includes some data measured at HFLSM, IMR, Tohoku University.

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- BHO doped EuBCO wires were fabricated by Hot-wall PLD using the deposition conditions of
  - A: high- $J_c$  condition with growth rate  $\sim 5\text{-}7$  nm/sec
  - B: high throughput condition with growth rate  $\sim 20\text{-}30$  nm/sec.
- REBCO thickness dependence was investigated for BHO doped EuBCO CC fabricated under the two conditions of A,B.
  - Minimum  $I_c$  in angular dependence was almost equal under the two conditions, in the following cases.
    - REBCO thickness  $> 2\text{ }\mu\text{m}$
    - Temperature  $> 30\text{ K}$
- A 300 m long BHO doped EuBCO wire was successfully fabricated using condition B.
  - Longitudinal  $I_c$  uniformity  $\sim 2.6\%$
  - $I_{c@30K, 2T} = 1755\text{ A/cm-w}$  ,  $1786\text{ A/cm-w}$  @both end points
  - Reproducibility of  $I_c$ - $B$ - $\theta$  characteristics was confirmed

**Development for mass production of doped wire is under way.**

\*Please inquire individually for the commercial release time.

# Thank you for your attention !

Questions?

Fujikura booth is in exhibition floor  
or

E-mail : [ask-sc@jp.fujikura.com](mailto:ask-sc@jp.fujikura.com)

Web : <http://www.fujikura.com/>

# In-field $I_c$ measurement

## □ Evaluation sample

microbridge process of  
photolithography and wet etching

- Bridge length : 1 mm
- Bridge width : 30~40  $\mu\text{m}$

## □ Measurement @ HFLSM, IMR, Tohoku University

Four-probe transport, 1  $\mu\text{V}/\text{cm}$ -criteria

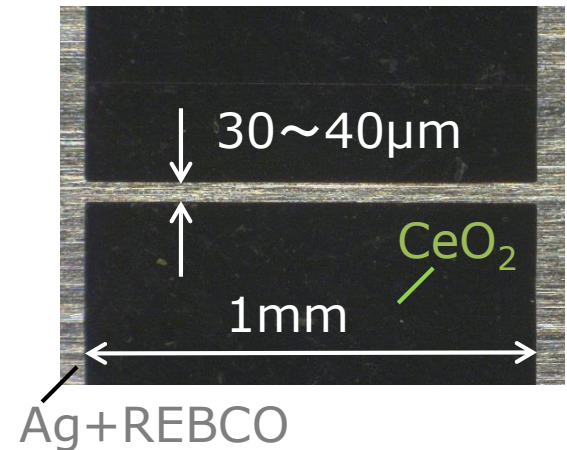
Equipments

- Applied field : 0~18 T, using SM
- Sample temp. : ~4.2 K, using GHe
- Field angle : -45°~135°, rotatable stage

## □ $I_c$ conversion (bridge $I_c \rightarrow 10\text{mmw } I_c$ )

$I_c(10\text{mmw}; B, T) =$

$$\frac{I_c(10\text{mmw}; 77.3 \text{ K, s.f.})}{I_c(\text{bridge}; 77.3 \text{ K, s.f.})} \times I_c(\text{bridge}; B, T)$$



20T-SM

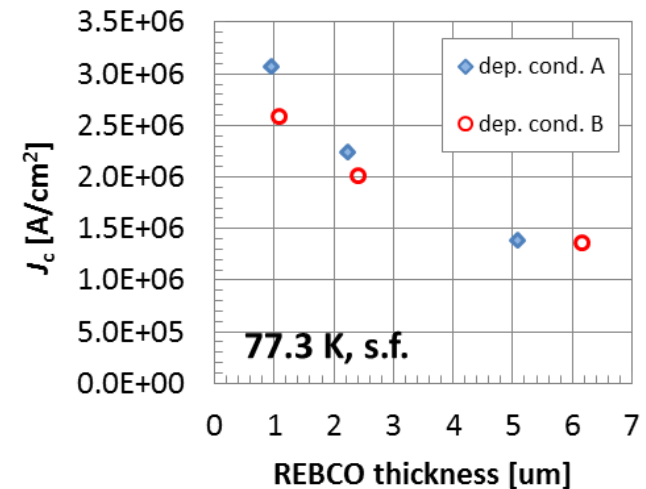
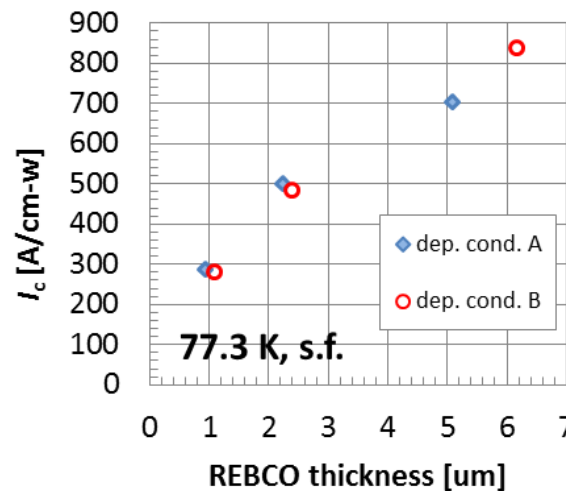


18T-SM

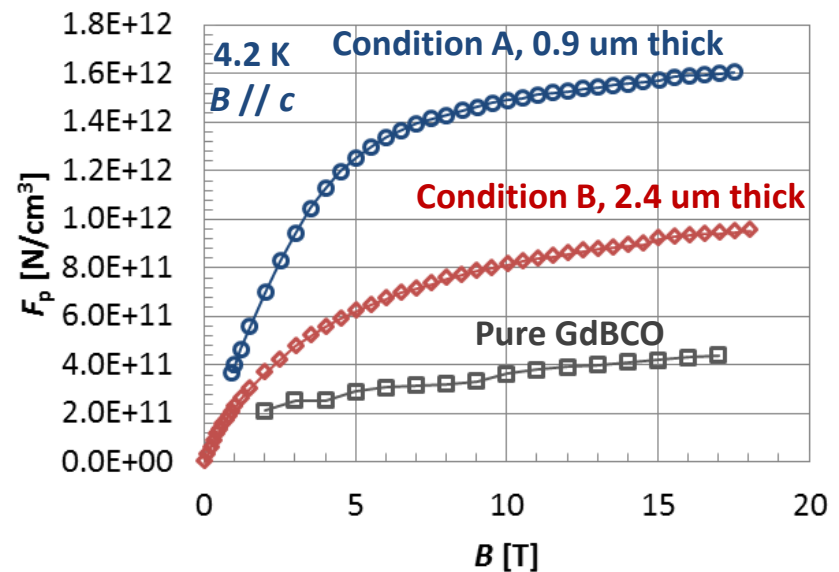
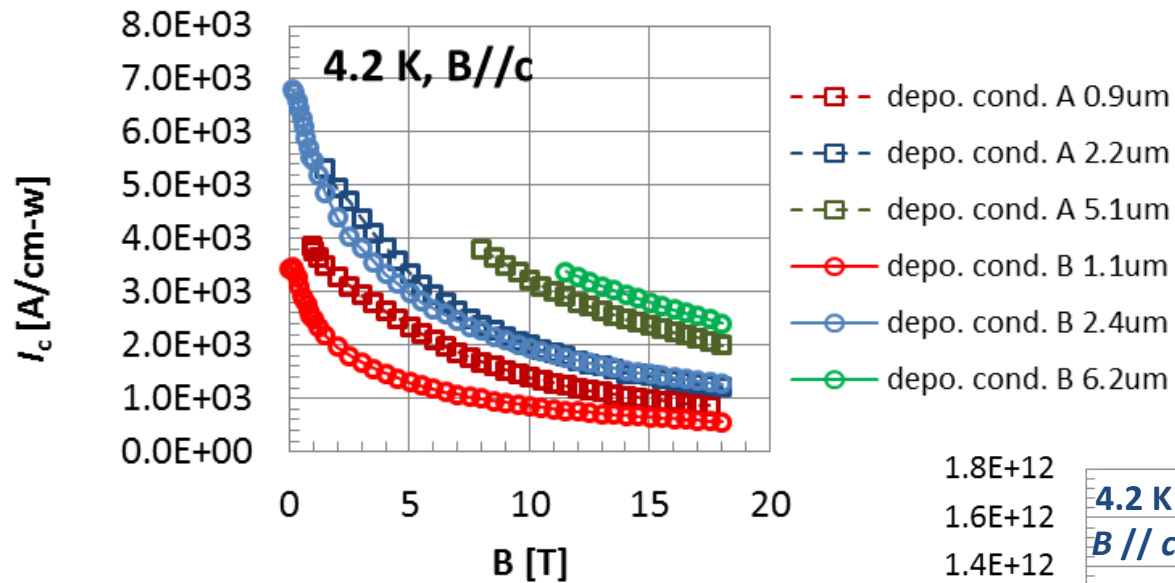
# Samples of thickness dependence investigation

Index	RE	BMO	Deposition Condition	Thickness [mm]	$I_c$ (77.3K, s.f.) [A/12mm]	$T_c$ [K]
A-1	RE	BaHfO3 3.5mol%	A	0.9	346	91.4
A-2			A	2.2	599	91.8
A-3			A	5.1	845	91.1
B-1			B	1.1	339	92.5
B-2			B	2.4	580	92.3
B-3			B	6.2	1006	92.2

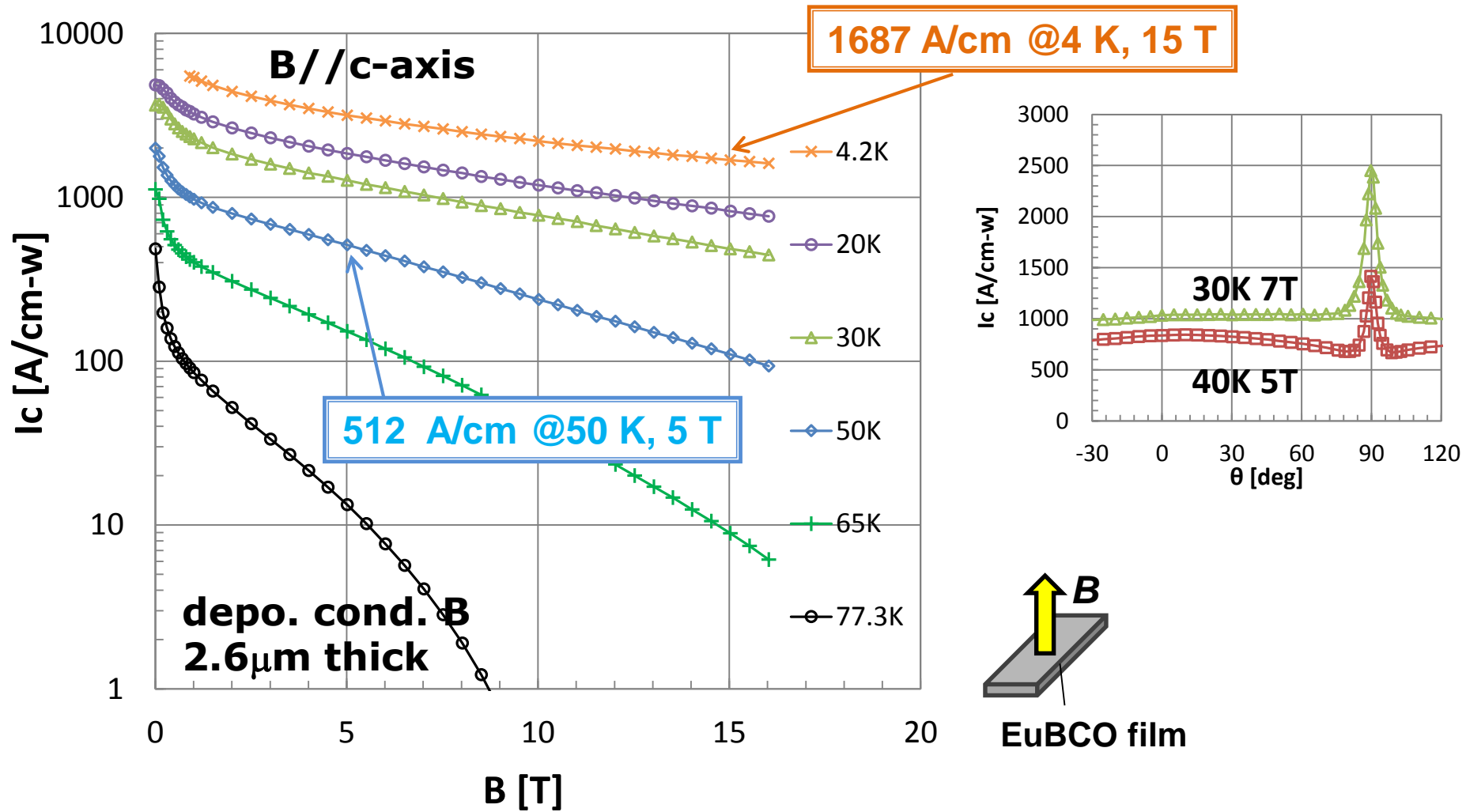
Depo. Cond.  
 A : growth rate  
 5~7 nm/sec  
 B : growth rate  
 20~30 nm/sec



# Ic - B at 4.2 K



# Ic properties in strong magnetic fields

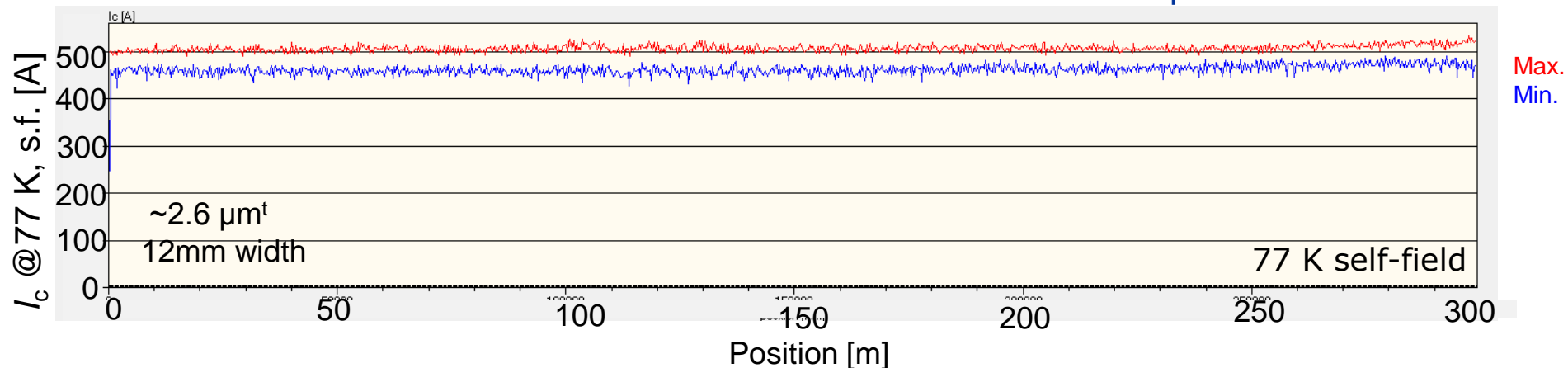


\* This work includes some data measured at High Field Laboratory for Superconducting Materials, Institute for Materials Research, Tohoku University.

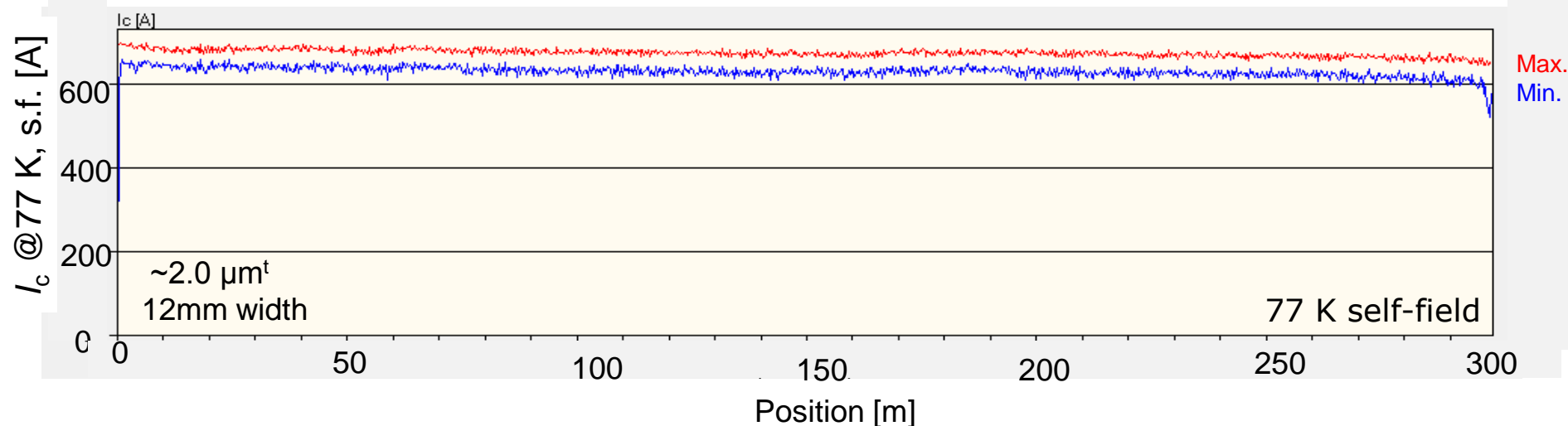
# Comparison of $I_c$ uniformity with non-doped wire

## ■ Artificial pinning wire (EuBCO + 3.5mol% BHO)

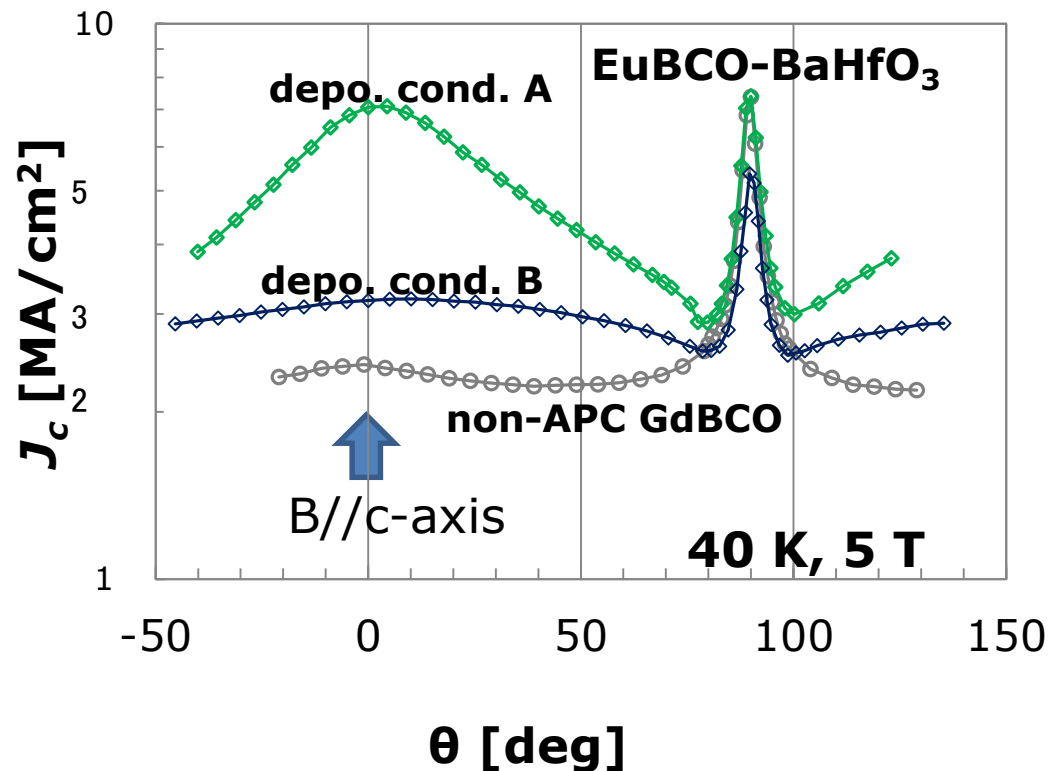
Tapestar® measurement



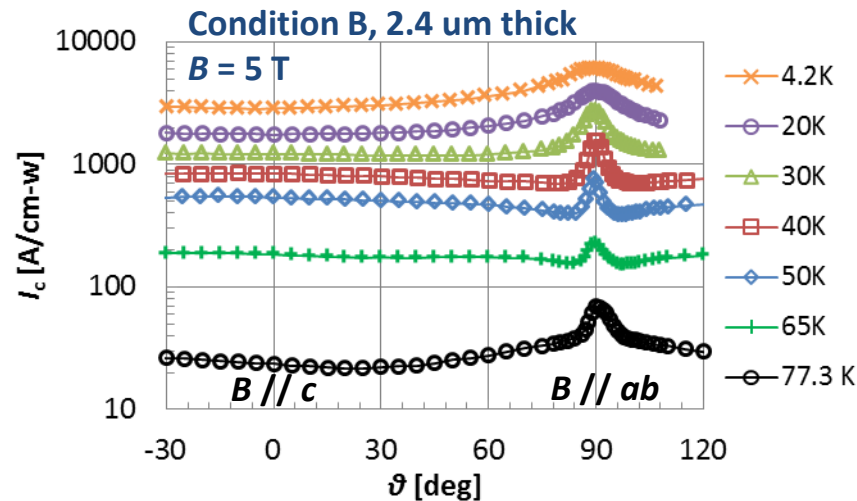
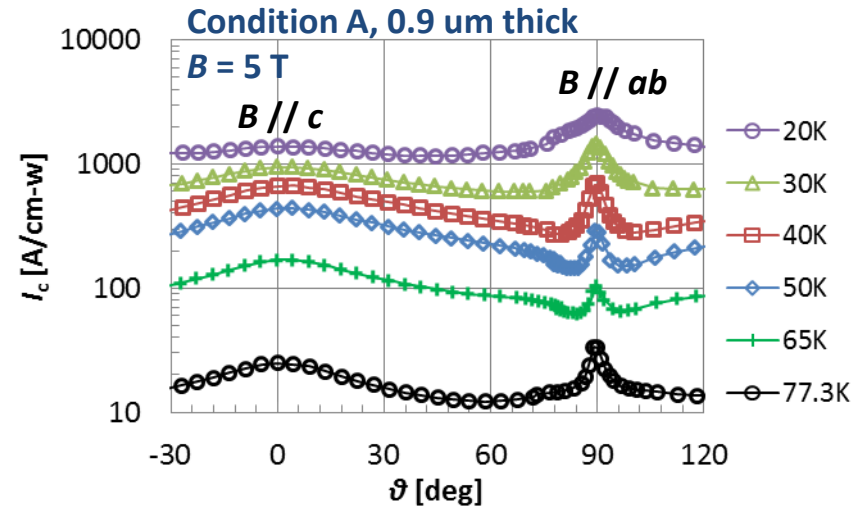
## ■ Production wire (GdBCO w/o artificial pinning)



# comparison of $J_c$ - $\theta$



# comparison of $I_c - \theta$



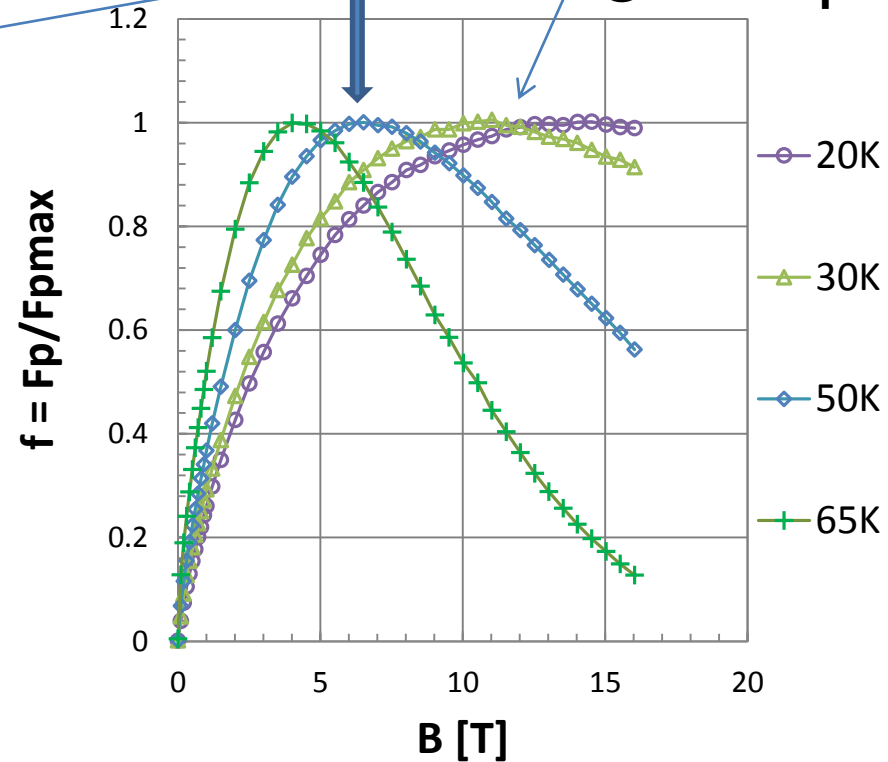
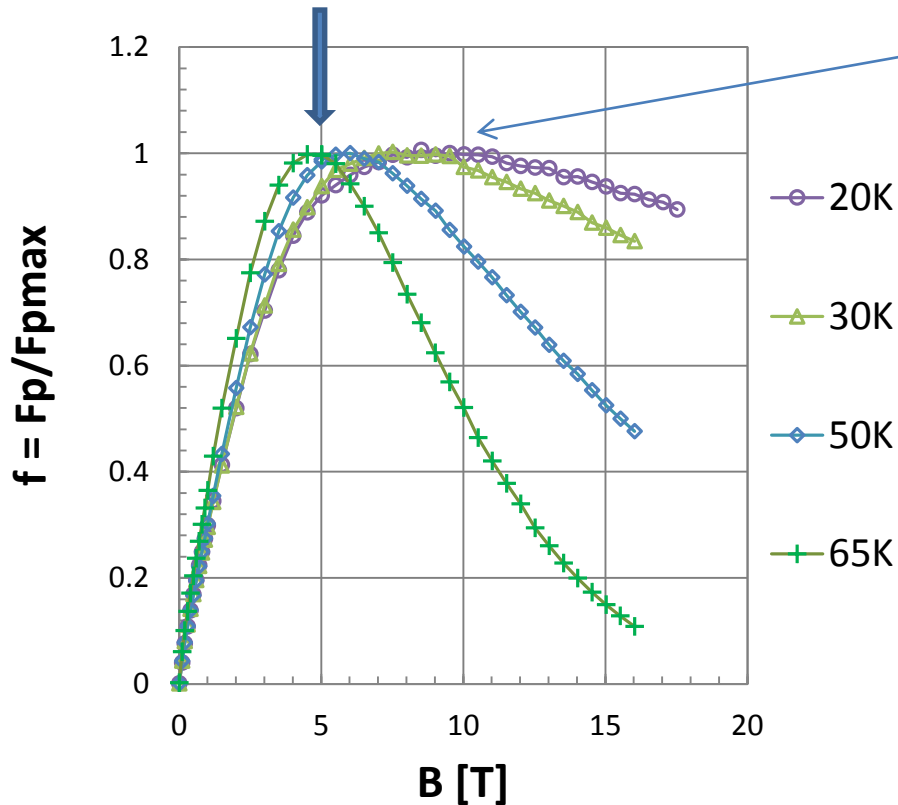
# Fp over 20 K

deposition condition A

deposition condition B

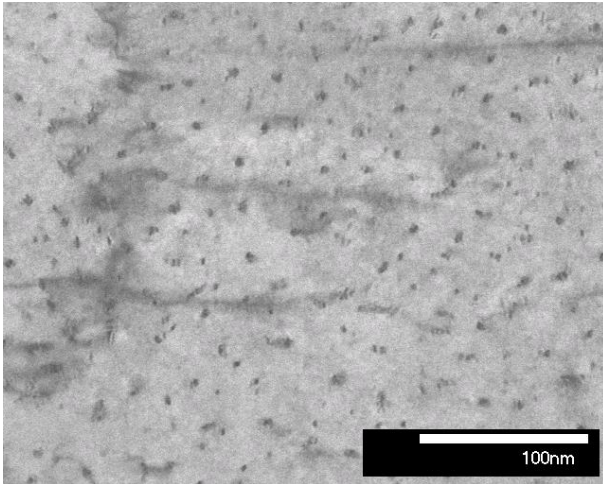
Matching field  $\sim 5\text{-}7\text{T}$  for c-axis correlated pinning

Peak shift  
higher field  
@low temp.

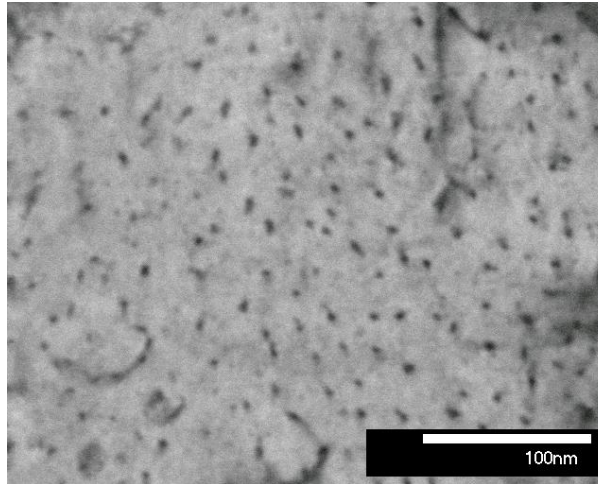


# Plan view STEM image

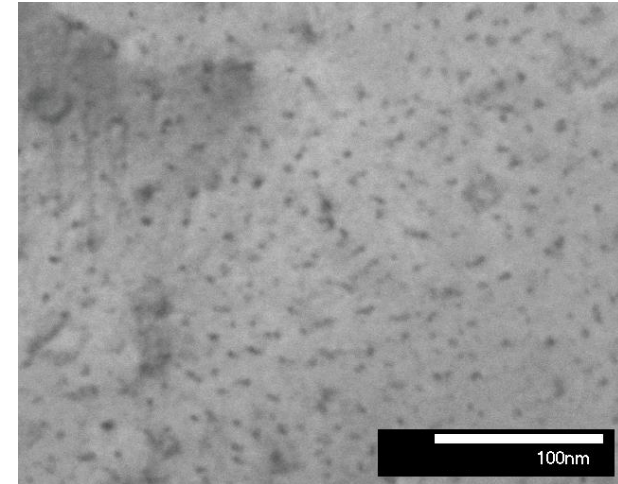
Depo. Cond. A  
0.9 $\mu\text{m}$



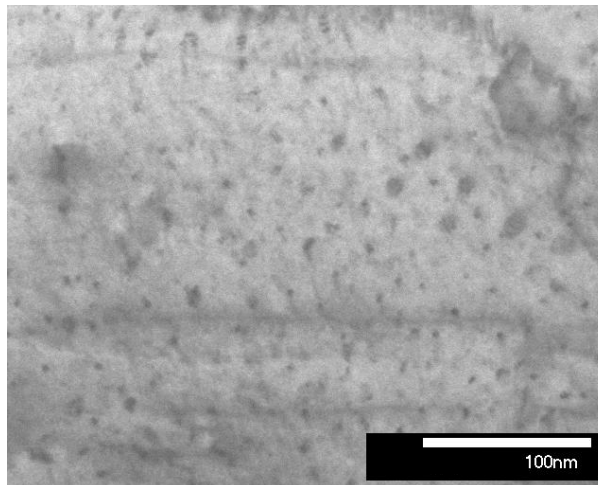
Depo. Cond. A  
2.2 $\mu\text{m}$



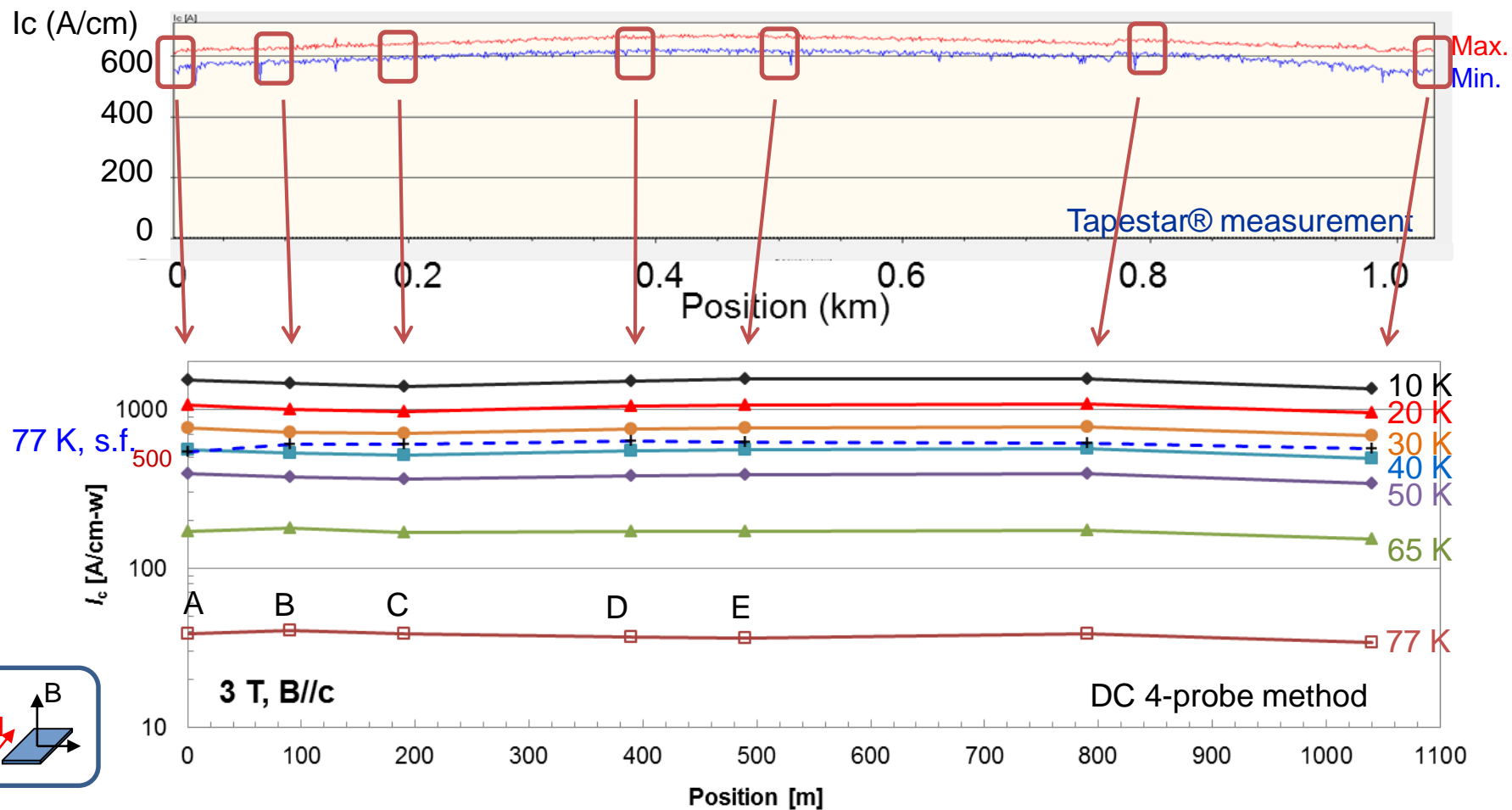
Depo. Cond. A  
5.1 $\mu\text{m}$



Depo. Cond. B  
2.4 $\mu\text{m}$



# In-field $I_c$ distribution in a 1 km long demo sample (10-77 K)



**Uniform in-field  $I_c$  in wide range of temperatures are observed**

STDEV / average < 5.8%

# BMO doping technique for REBCO C.C. by vapour phase deposition

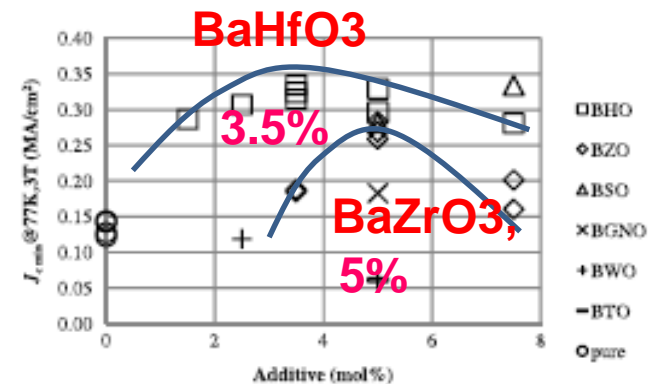
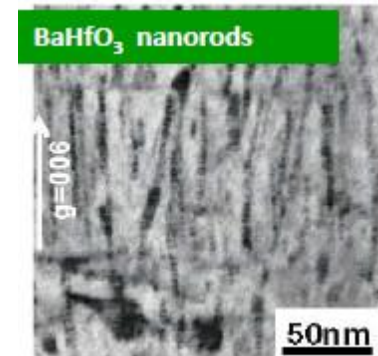
Big  $J_c$  enhancement in wide temperature range  
by **nanorod-like  $\text{BaMO}_3$**  structure

## ■ MOCVD (Houston Univ. )

- Biggest  $J_c/F_p$  obtained
  - 20MA/cm<sup>2</sup> at 30K 2.5T
  - 1.7TN/m<sup>3</sup> @ 4.2K

## ■ PLD (ISTEC, Nagoya Univ. etc.)

- BMO optimization (ISTEC)
  - **$\text{BaHfO}_3$**  doping vs  **$\text{BaZrO}_3$**  doping
- RE element optimization (ISTEC, Nagoya)
  - **Gd, Eu, Sm**
- LTG technique (Nagoya Univ.)
  - **thinner rod diameter**
  - 1.5TN/m<sup>3</sup> @ 4.2K



H. Tobita, *et al.* Supercond. Sci. Technol. 25 (2012) 062002

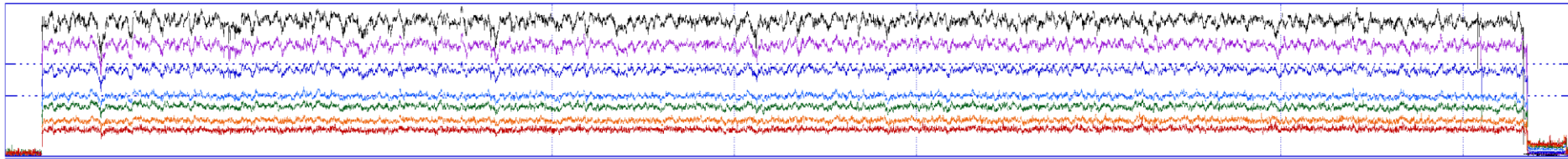
# End-to-end continuous measurement of in-field $I_c$

using in-field magnetization measurement by **Kyushu University**

Presented in **ASC2016** T. Fukuzaki, K. Higashikawa, T. Kiss, et al.

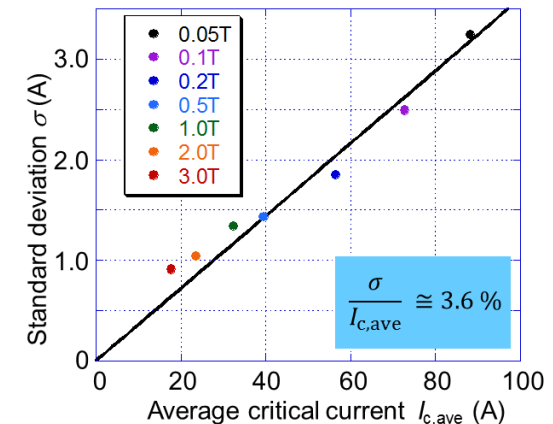
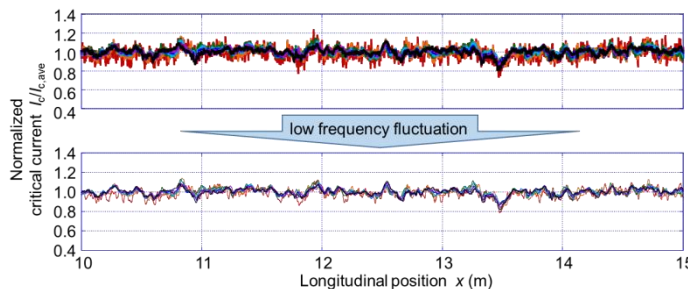
40m long BZrO-doped GdBCO sample  
depo. cond. B before optimization

77K 0.05T



77K 3.0T

- Shape of the  $I_c$  distribution is **similar among magnetic fields**
- Ratio of the standard deviation **does not depends on magnetic fields**



- $I_c$  distribution does not depend on magnetic fields
- $I_c(x)$  and  $I_c(B)$  can be estimated separately

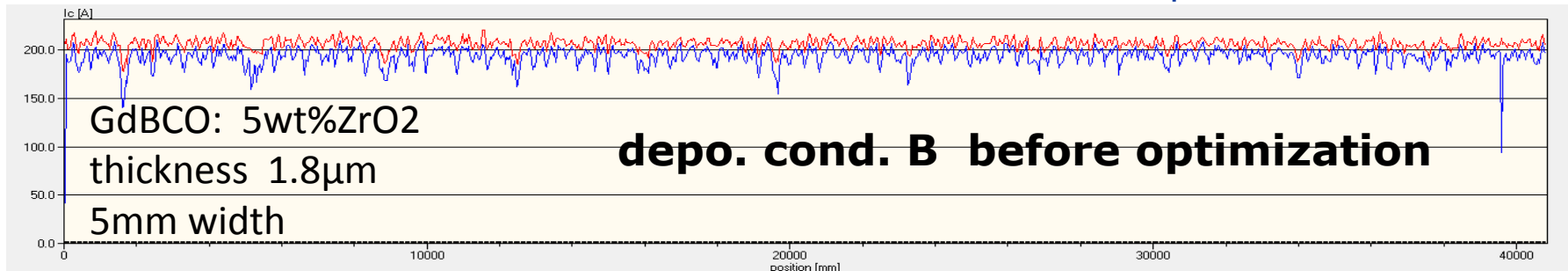
$\sigma$  is derived from the mean square



# 5mm<sup>w</sup> 40m long BaZrO<sub>3</sub> doped sample

longitudinal  $I_c$  distribution

Tapestar® measurement

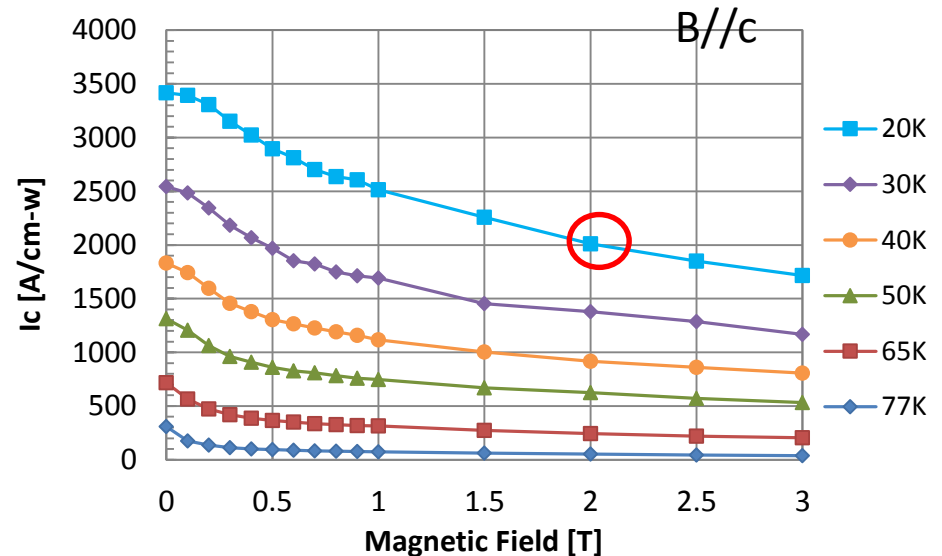


$I_c=309\text{A/cm}$  (77K,0T)

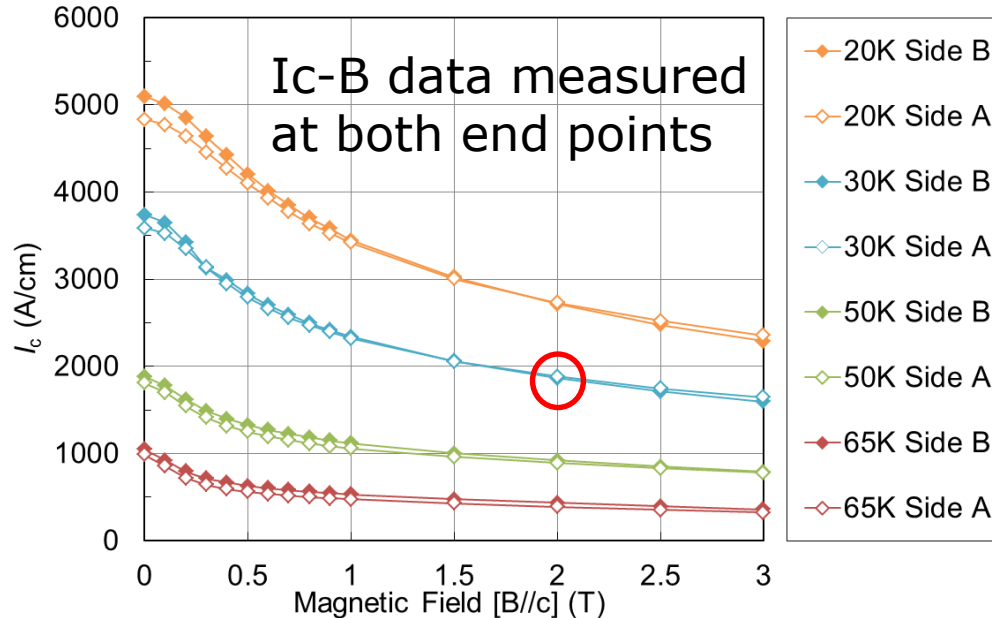
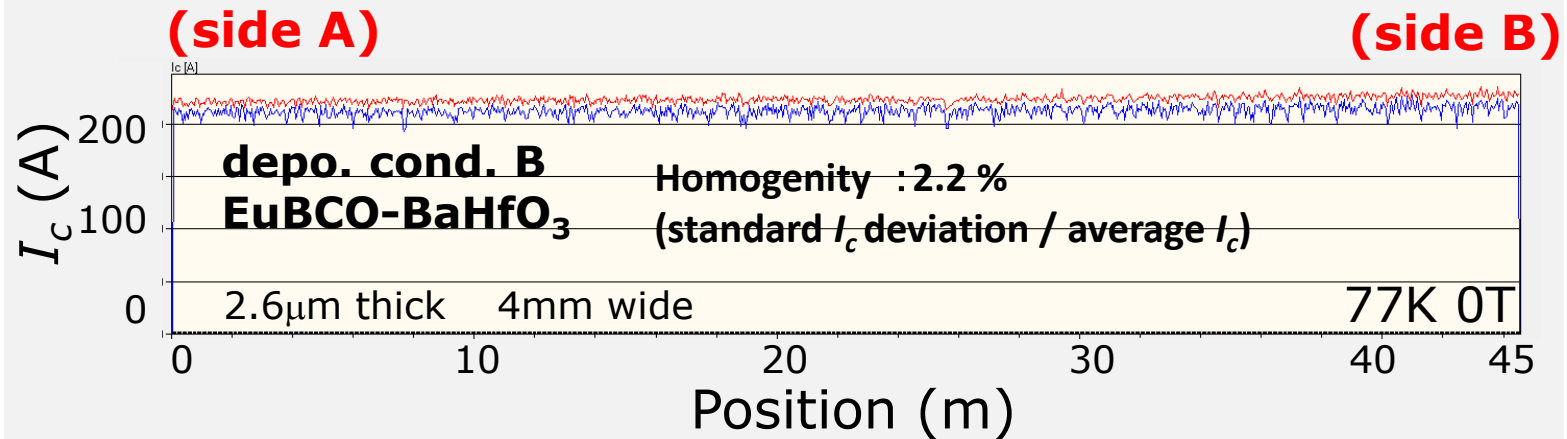
$J_c=1.7\text{MA/cm}^2$

Uniformity (STDV/ave. $I_c$ ) =3.9 (%)

**1380A/cm (30K 2T)**  
 **$J_c=7.7\text{MA/cm}^2$**



# 4mm<sup>w</sup> 45m long EuBCO -sample



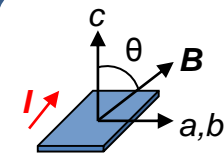
**$I_c = 1863 \text{ A/cm}$  (side A)**

**$I_c = 1883 \text{ A/cm}$  (side B)**

**$J_c = 7.2\text{--}7.4 \text{ MA/cm}^2$**

**@30K, 2T**

# 温度ごとと角度依存データ

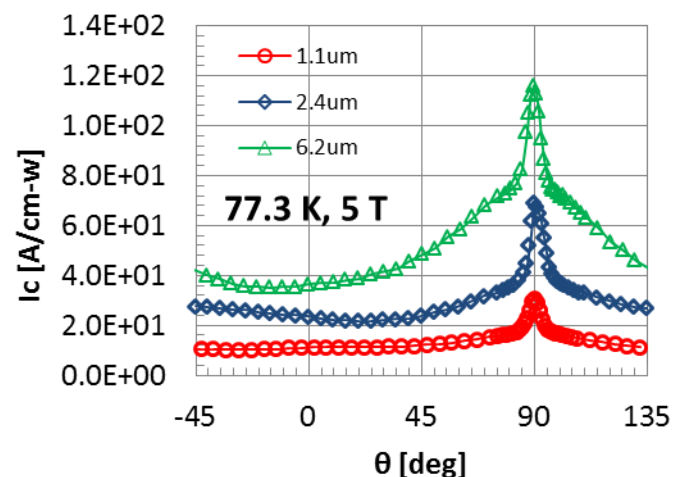
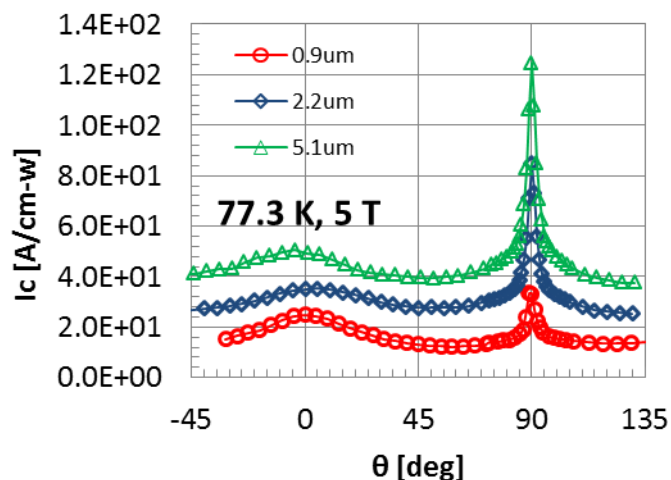


$I_c$

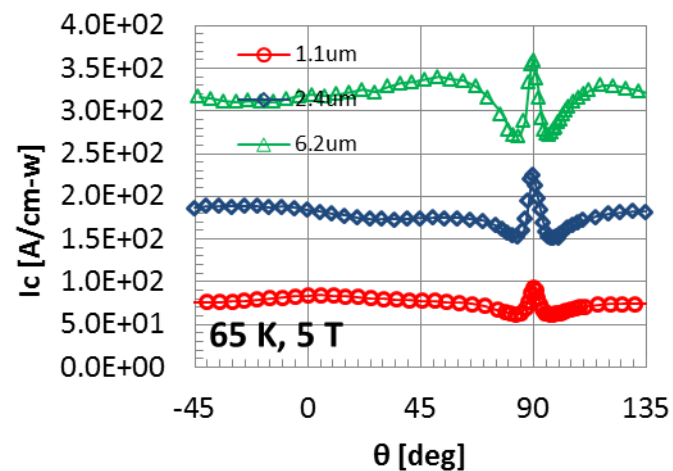
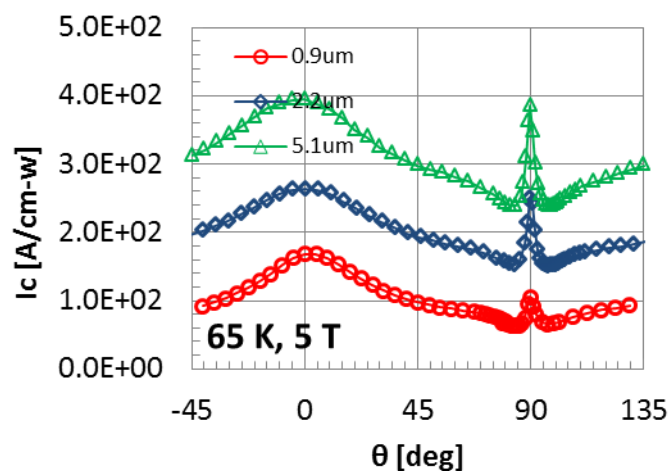
Depo. Cond. A

Depo. Cond. B

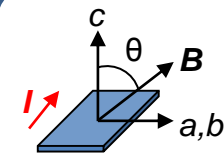
77.3 K, 5 T



65 K, 5 T



# 温度ごとと角度依存データ

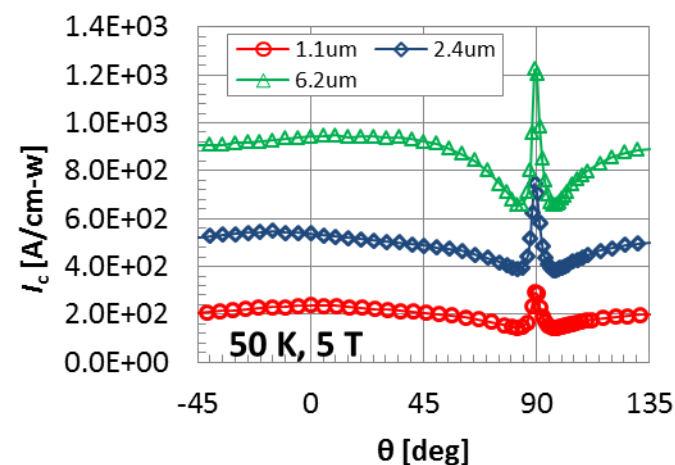
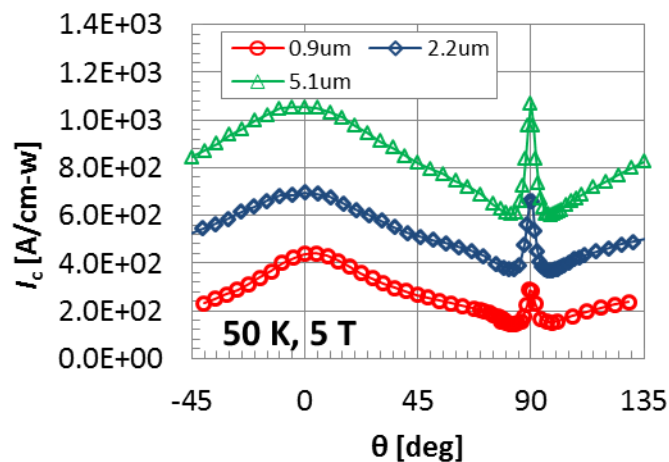


$I_c$

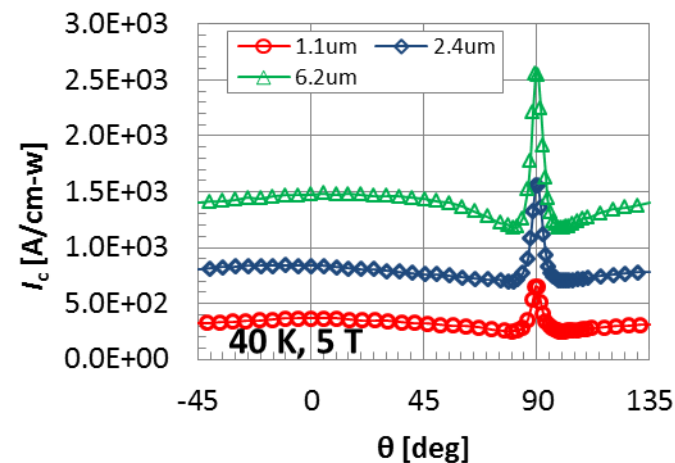
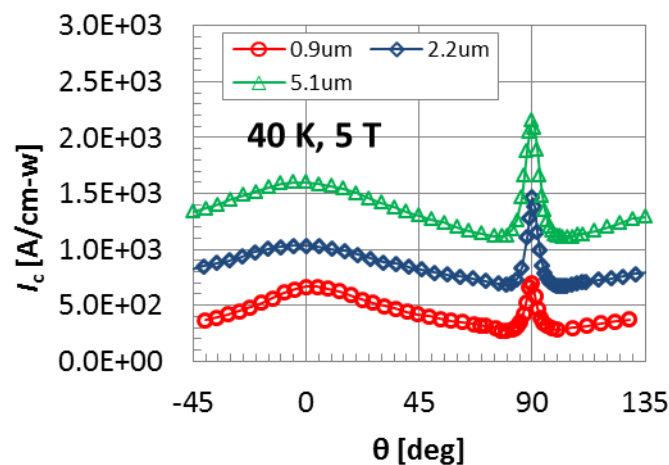
Depo. Cond. A

Depo. Cond. B

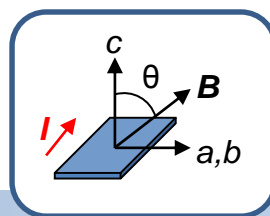
50 K, 5 T



40 K, 5 T



# 温度ごとと角度依存データ

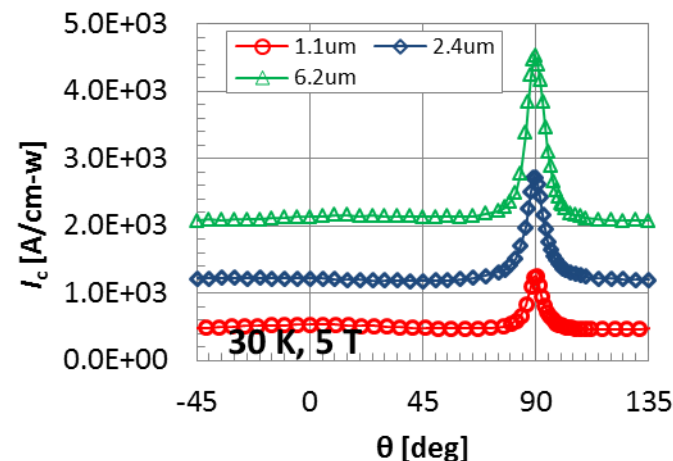
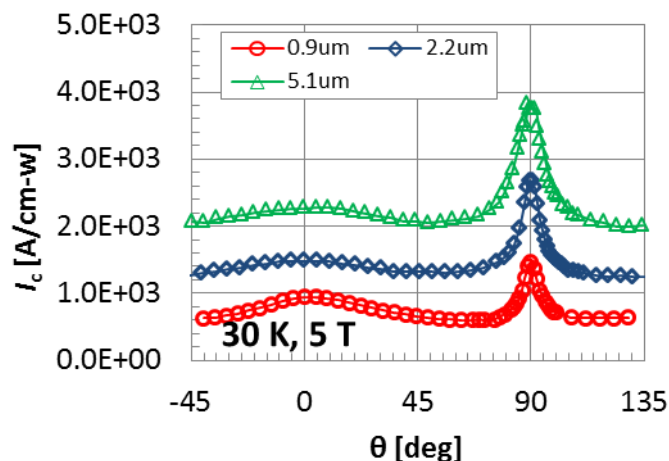


$I_c$

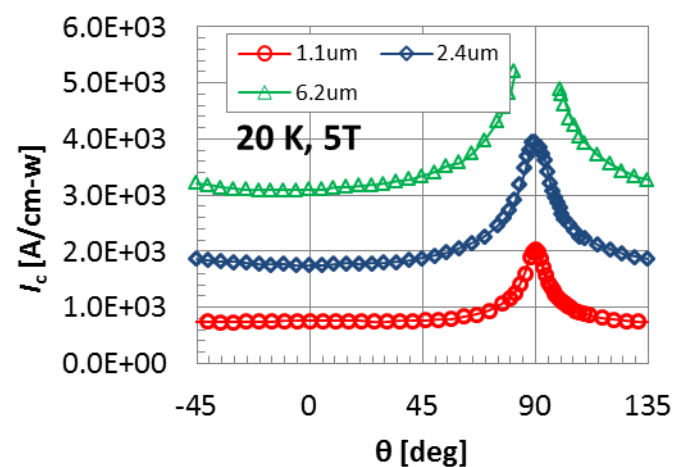
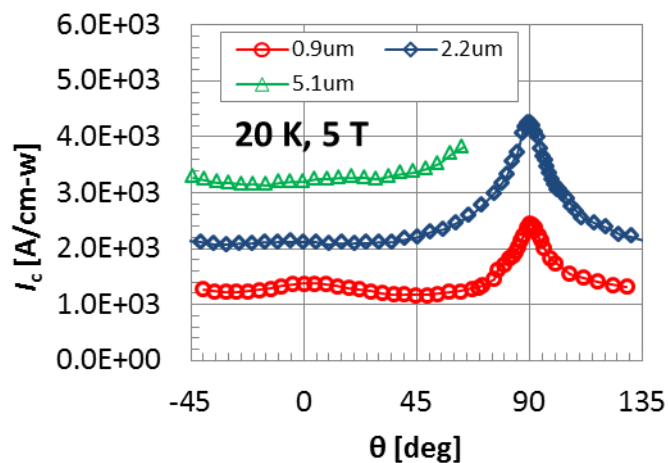
Depo. Cond. A

Depo. Cond. B

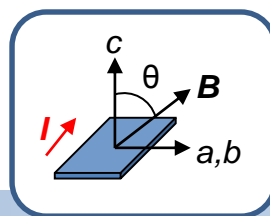
30 K, 5 T



20 K, 5 T



# 温度ごとと角度依存データ

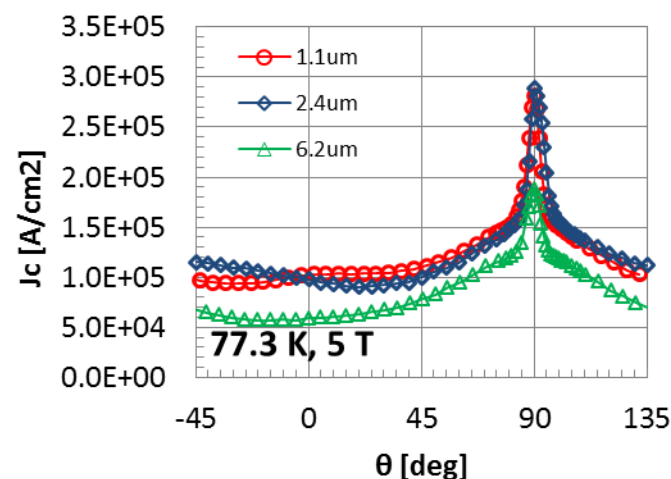
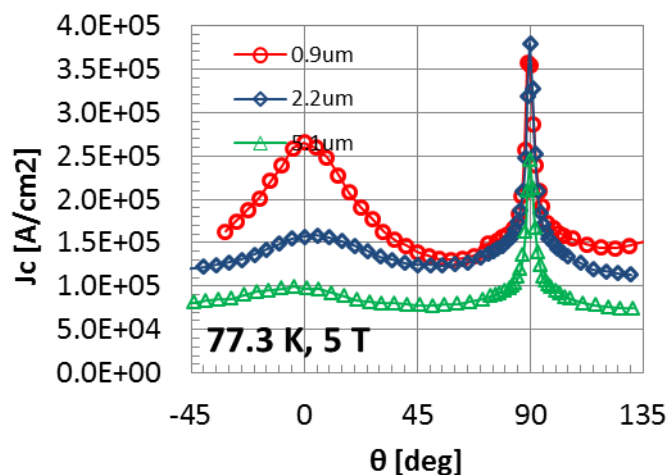


$J_c$

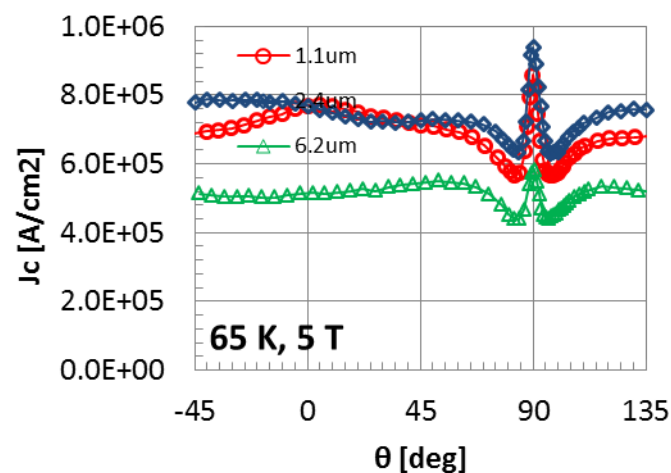
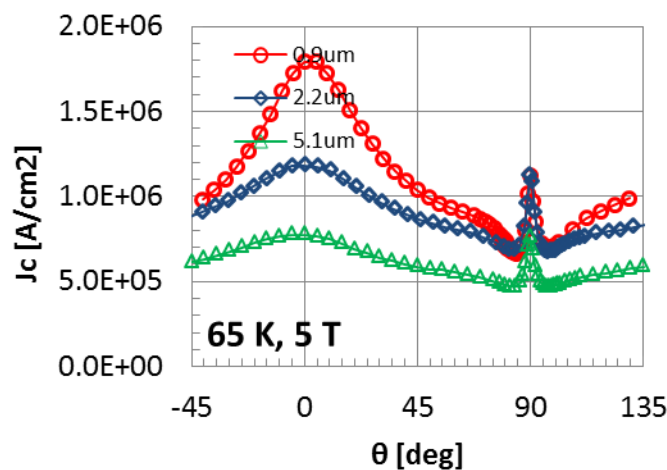
Depo. Cond. A

Depo. Cond. B

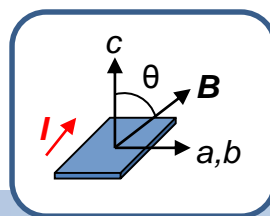
77.3 K, 5 T



65 K, 5 T



# 温度ごとと角度依存データ

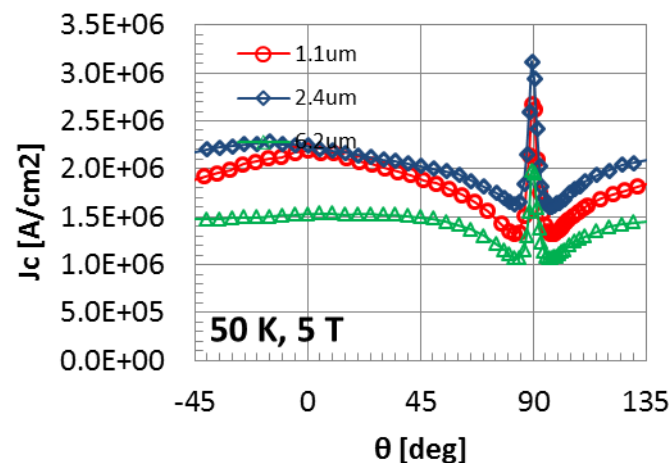
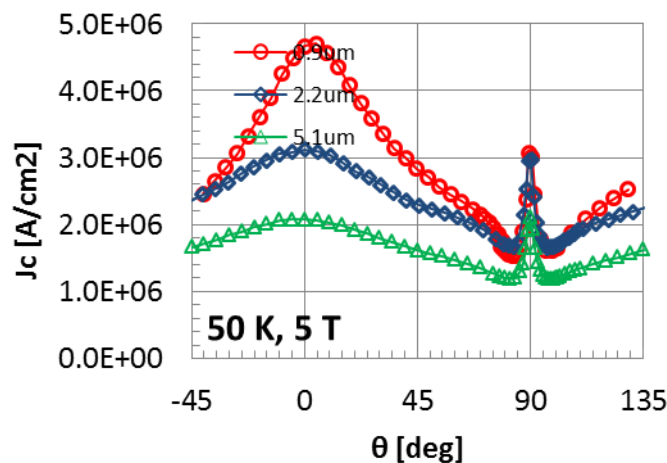


$J_c$

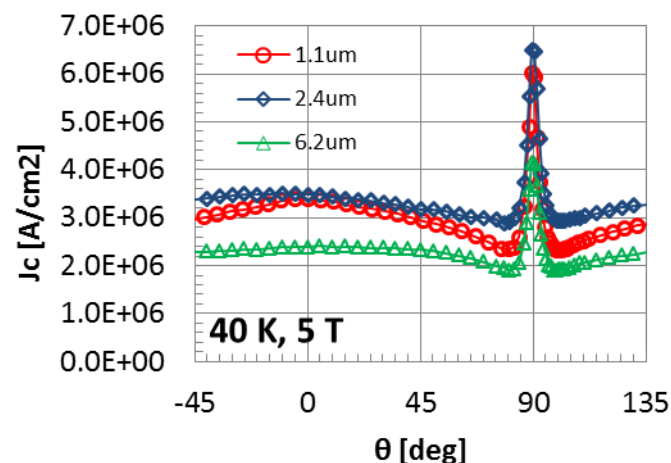
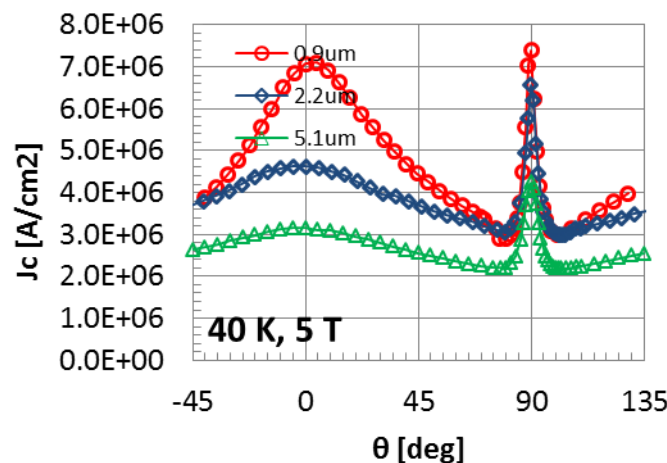
Depo. Cond. A

Depo. Cond. B

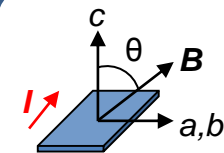
50 K, 5 T



40 K, 5 T



# 温度ごとと角度依存データ

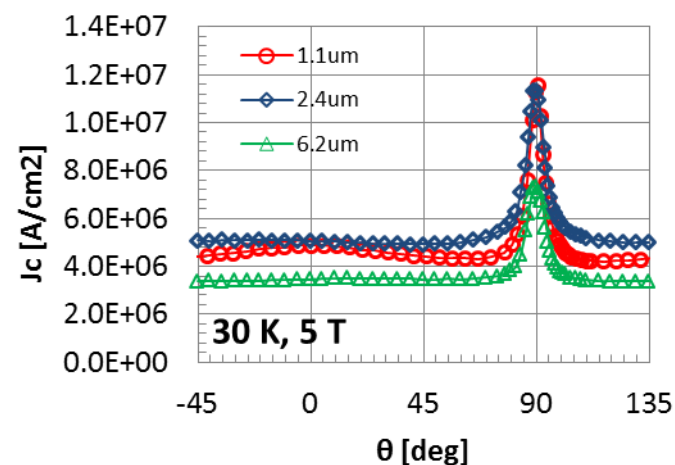
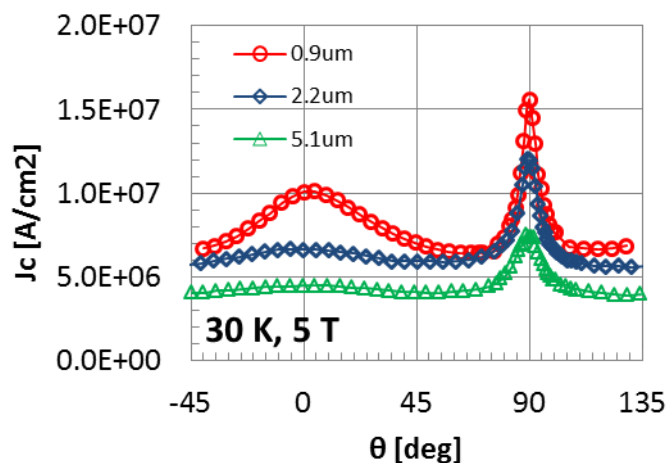


$J_c$

Depo. Cond. A

Depo. Cond. B

30 K, 5 T



20 K, 5 T

