

Temperature dependence of flux pinning in REBCO films with artificial pinning centers

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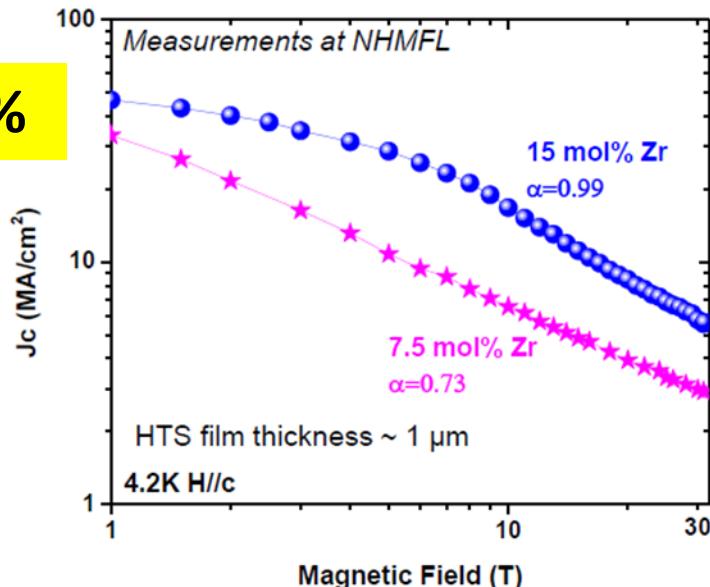


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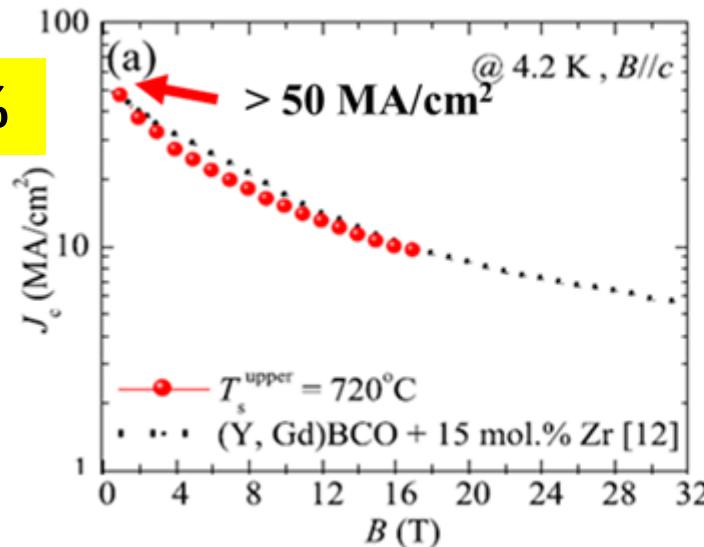
Very large global pinning force by nanorod APCs

$J_c/J_d > 20\%$

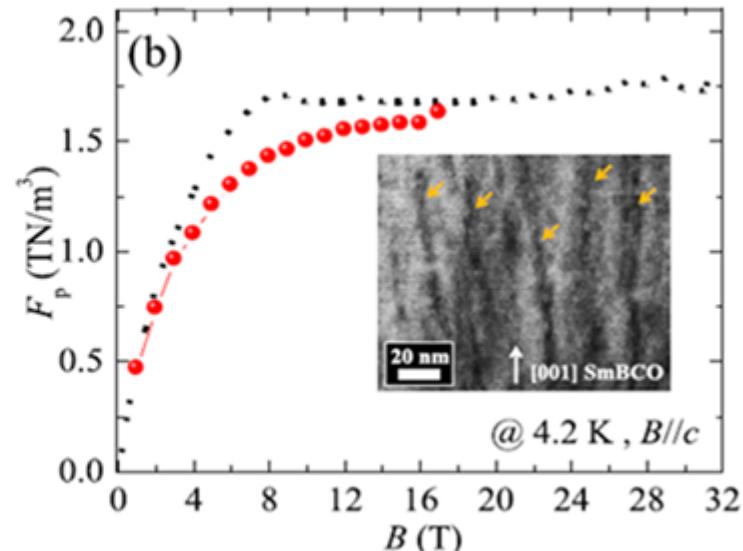
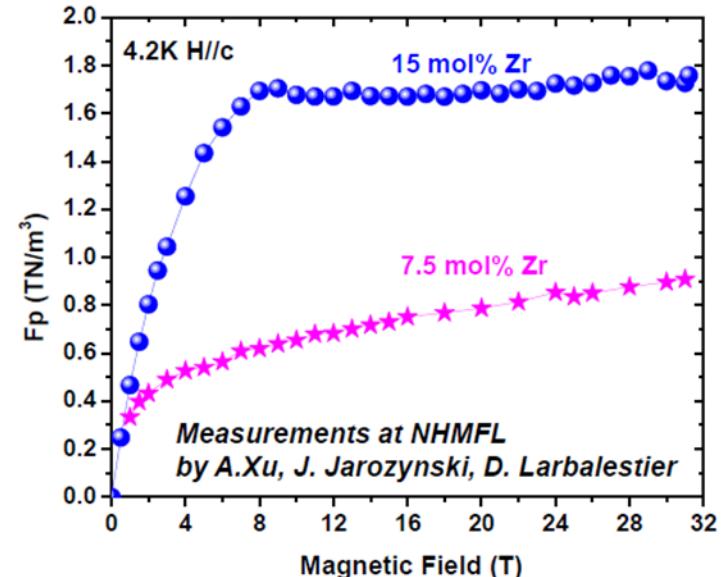


A. Xu *et al.*, APL mater 2, 046111 (2014)

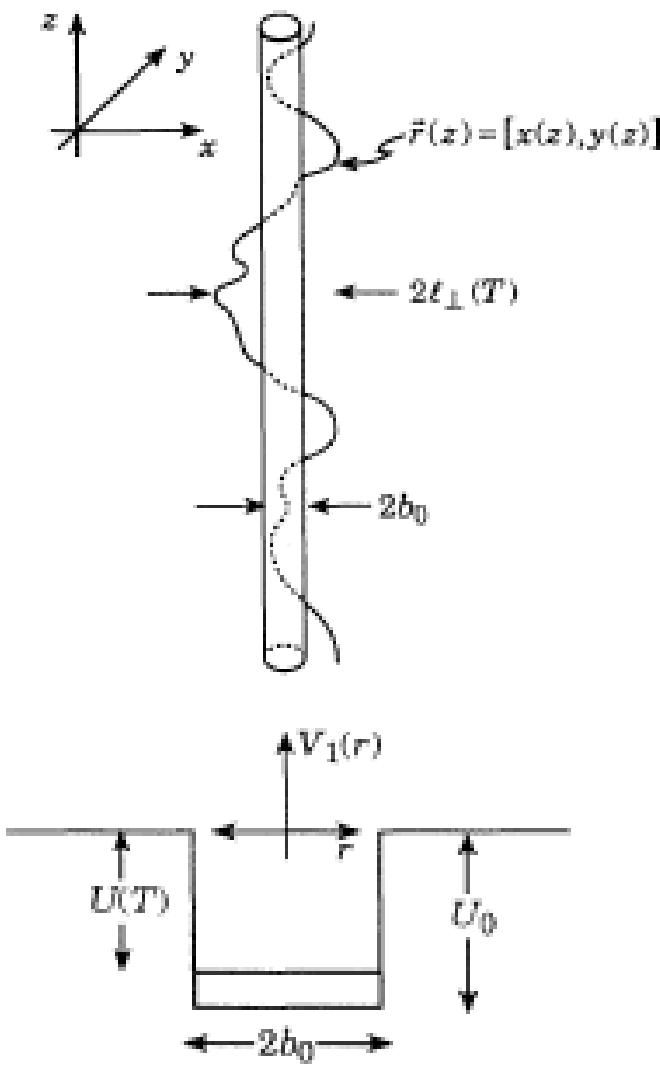
$J_c/J_d > 20\%$



S. Mira *et al.*, APL Mater. 4, 016102 (2016)



Estimate of J_c based on Bose Glass model



$$U_0 \approx \frac{1}{2} \varepsilon_0 \ln \left[1 + \left(\frac{c_0}{\sqrt{2} \xi_{ab}} \right)^2 \right]$$

$$J_c(0) \approx \frac{U_0}{\phi_0 \xi_{ab}}$$

$$J_c(T) \approx \frac{U(T)}{\phi_0 l_\perp}$$

Is quantitative estimate of J_c by TDGL equation possible?

✓ Time dependent Ginzburg- Landau equations

$$\frac{\hbar^2}{2m_s} \left(\frac{\partial}{\partial t} + i \frac{e_s}{\hbar} \Phi \right) \psi = \frac{\hbar^2}{2m_s} \left(\nabla - i \frac{e_s}{\hbar} \right)^2 \psi + \alpha |\psi| - \beta |\psi|^2 \psi$$

$$\frac{1}{\mu_0} \nabla \times (\nabla \times A - \mu_0 H) = j_s + j_n$$

$$j_s = \frac{\hbar e_s}{2m_s D} (\psi^* \nabla \psi - \psi \nabla \psi^*) - \frac{e_s^2}{m_s} |\psi|^2 A$$

$$j_n = \sigma \left(-\nabla \Phi - \frac{\partial A}{\partial t} \right)$$

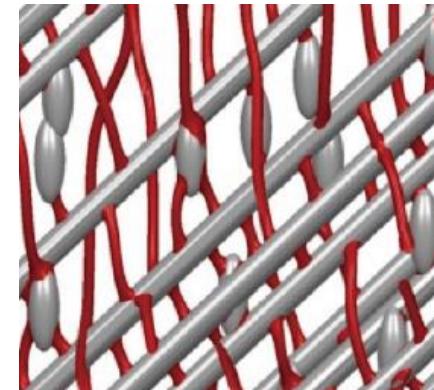
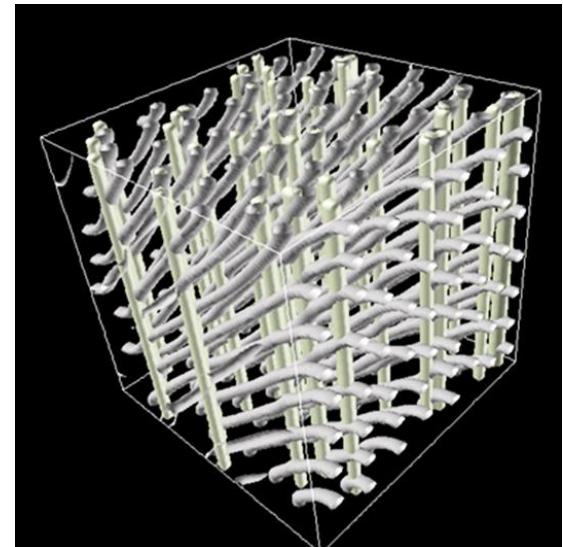
R. Kato et al., PRB (1993)

M. Machida et al., PRL (1993)

Q. Du et al., PRB (1995)

G. Crabtree et al., PRB (2000)

T. Winiecki et al., PRB (2002)



✓ High Kappa limit

$$(\partial_t + i\mu)\psi = \varepsilon(r)\psi - |\psi|^2 \psi + (\nabla - iA)^2 \psi$$

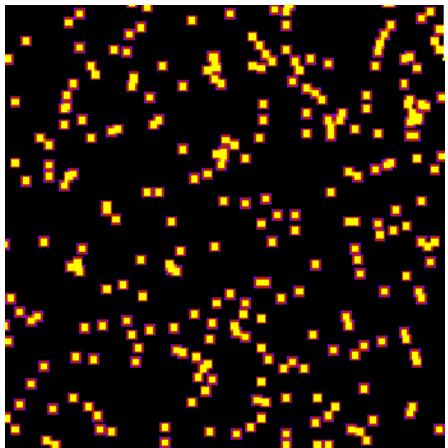
$$j = \text{Im}[\psi^* (\nabla - iA)\psi] - (\nabla \mu + \partial_t A)$$

I. A. Sadovskyy et al., Adv. Mater. (2016)

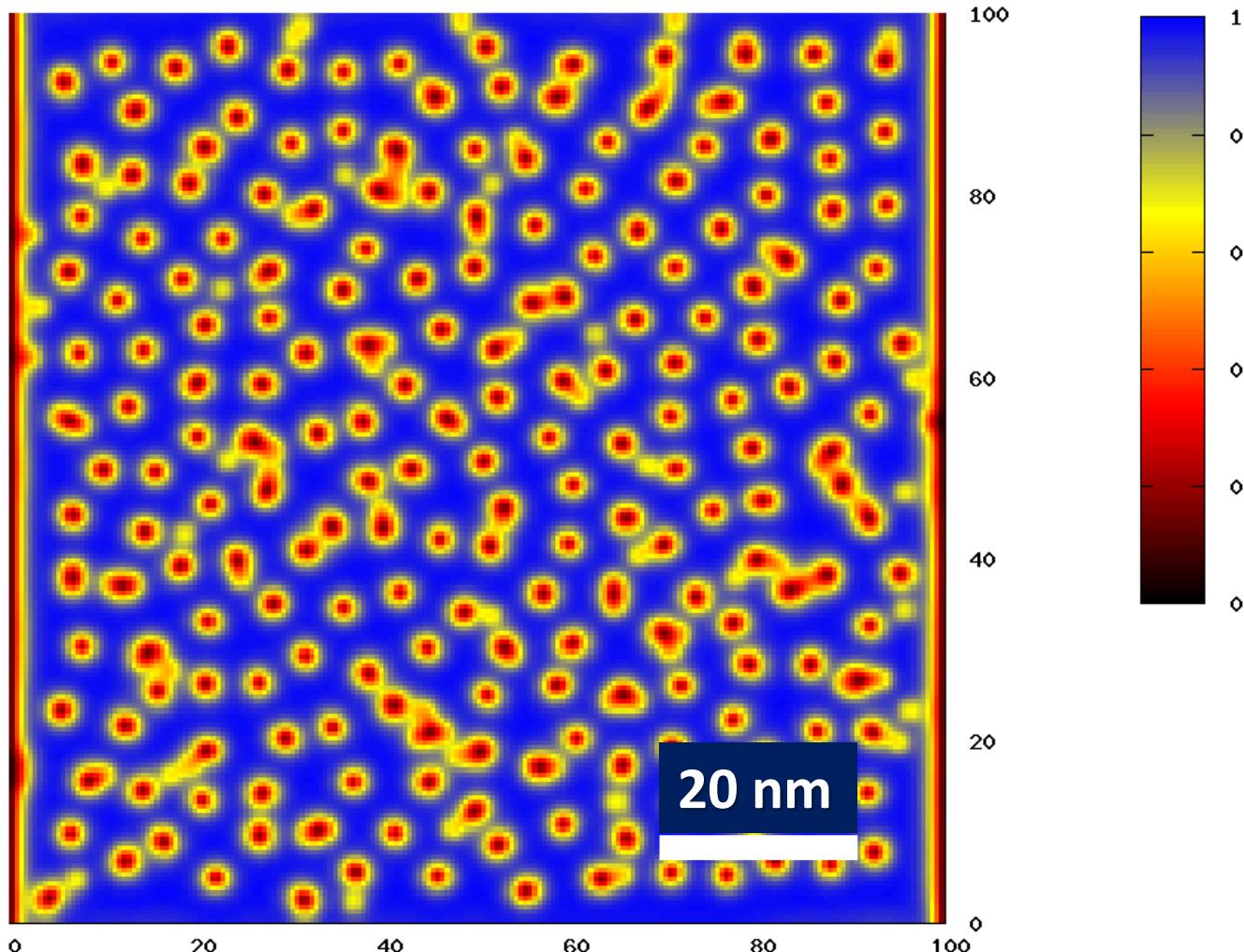


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TDGL simulation of ideal nanorod artificial pinning centers



$B = 14.6 \text{ T}$

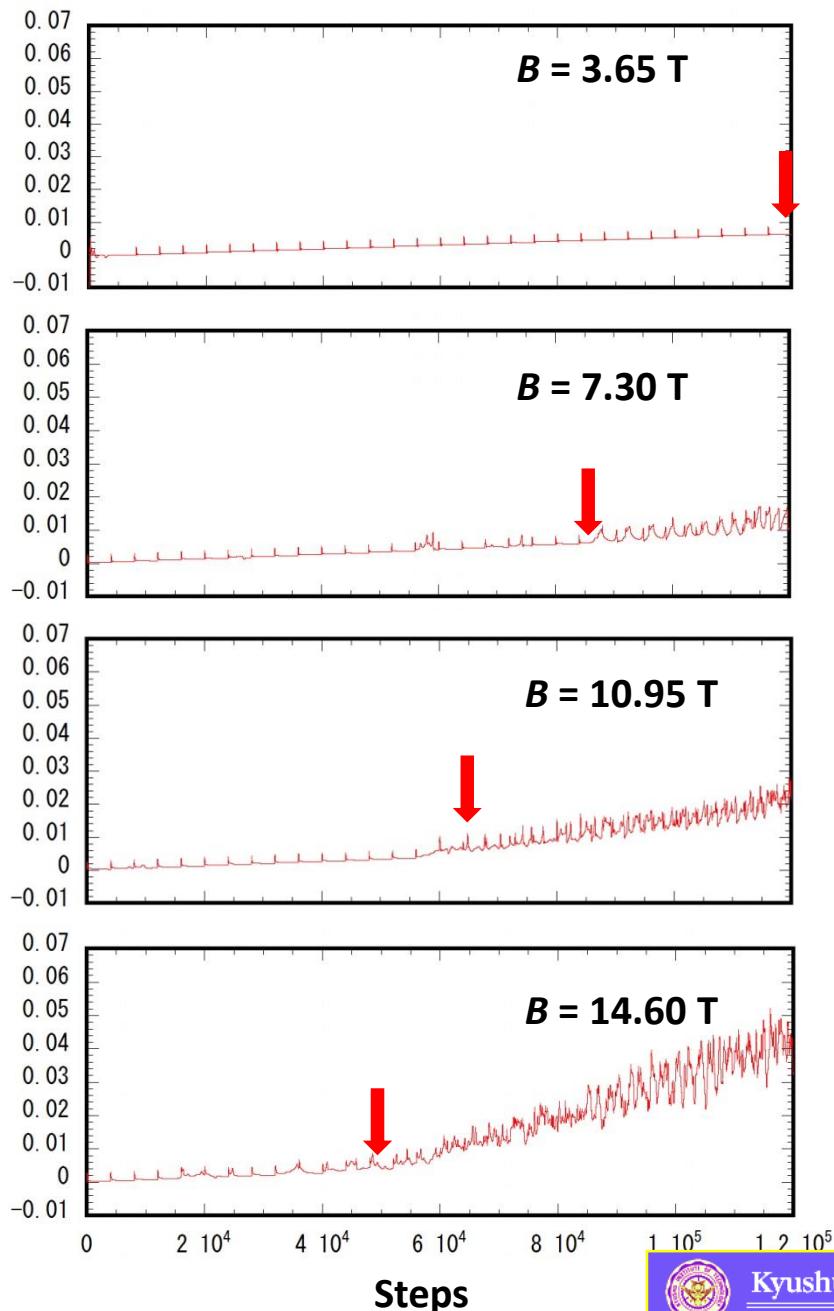


- $T = 0 \text{ K}$
- $B = 10 \text{ T}$
- High kappa $\kappa_{\text{GL}} \gg 1$
- $\zeta(0) = 1.5 \text{ nm}$
- Nanorod Dia.
= 6 nm
- Density = 10 %
- $B_\phi = 7.3 \text{ T}$
- Ave. distance
= 16.8 nm



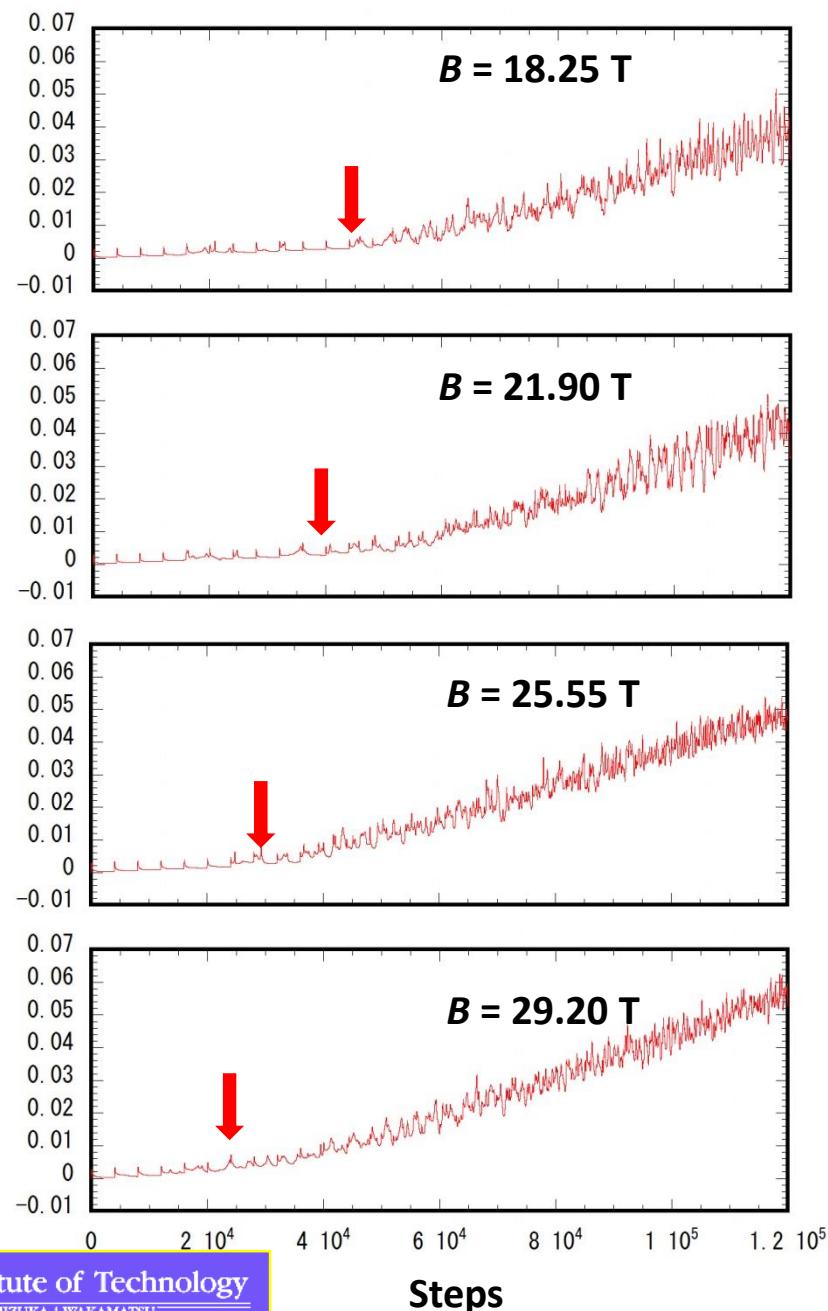
Simulation results of I-V characteristics by TDGL at 0 K

Normalized voltage



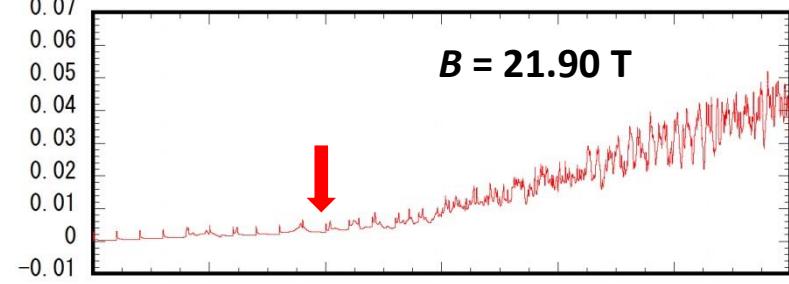
$B = 3.65$ T

Normalized voltage



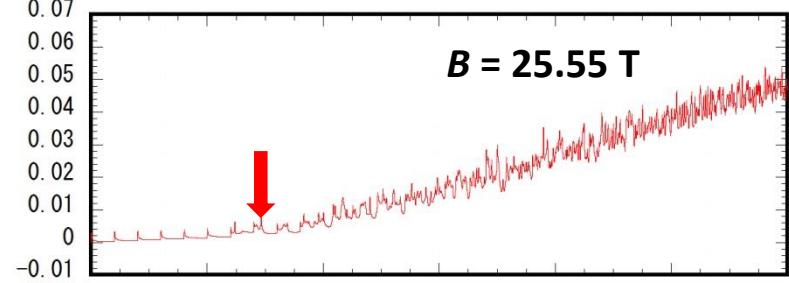
$B = 18.25$ T

Normalized voltage



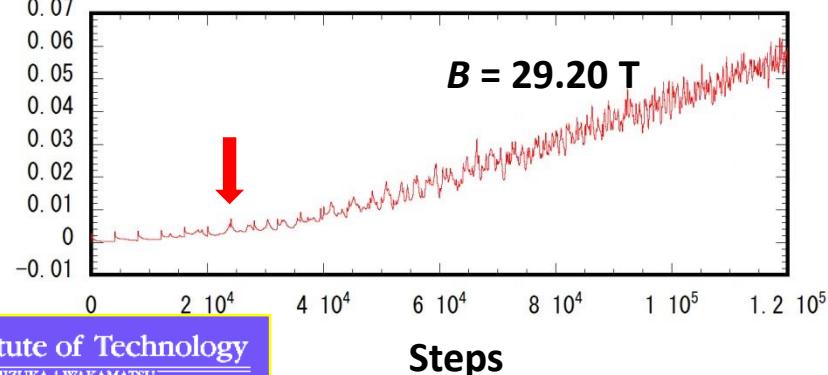
$B = 21.90$ T

Normalized voltage



$B = 25.55$ T

Normalized voltage



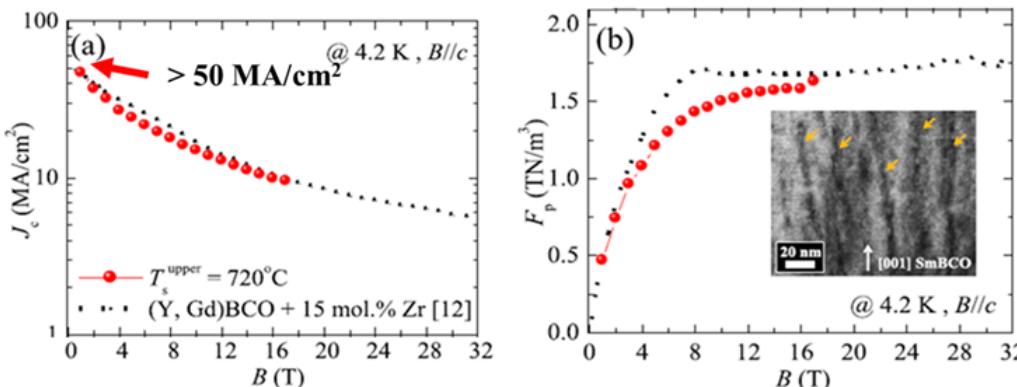
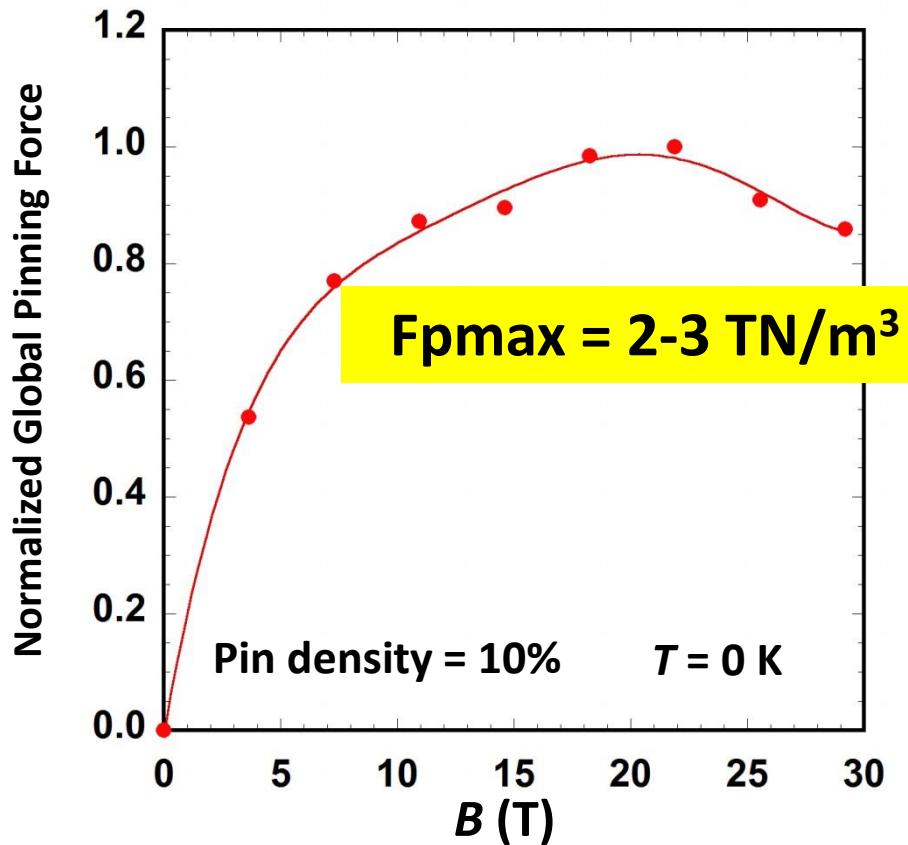
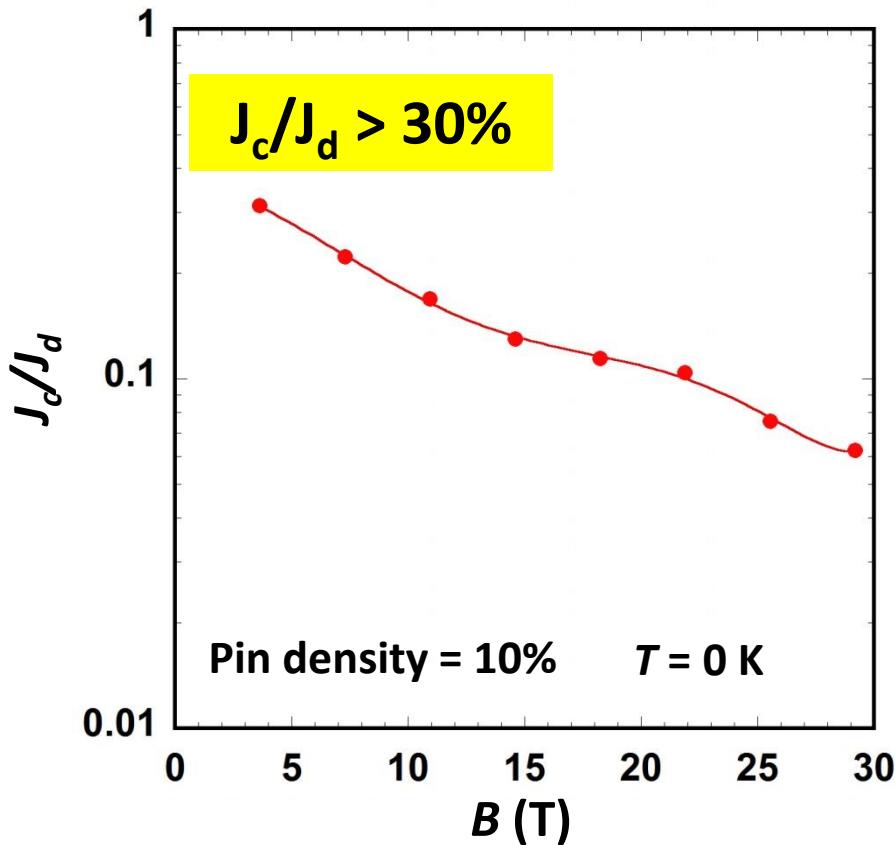
$B = 29.20$ T

Steps



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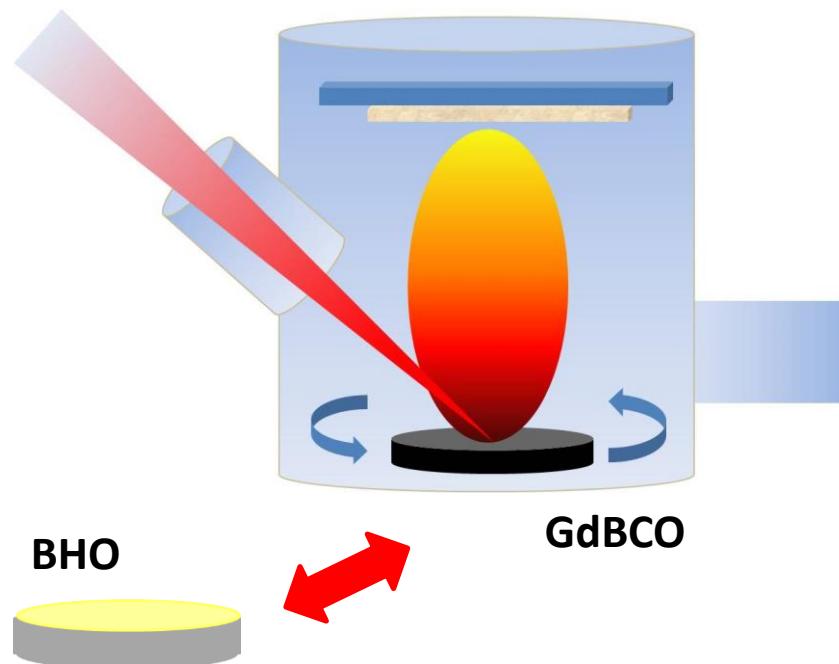
Comparison with experimental results of Jc-B and Fp-B



Pin density = 3-5%
 $T = 4.2$ K
"Similar behaviors are expected"



Experiment on temperature dependent J_c with nanorods



Alternating target method

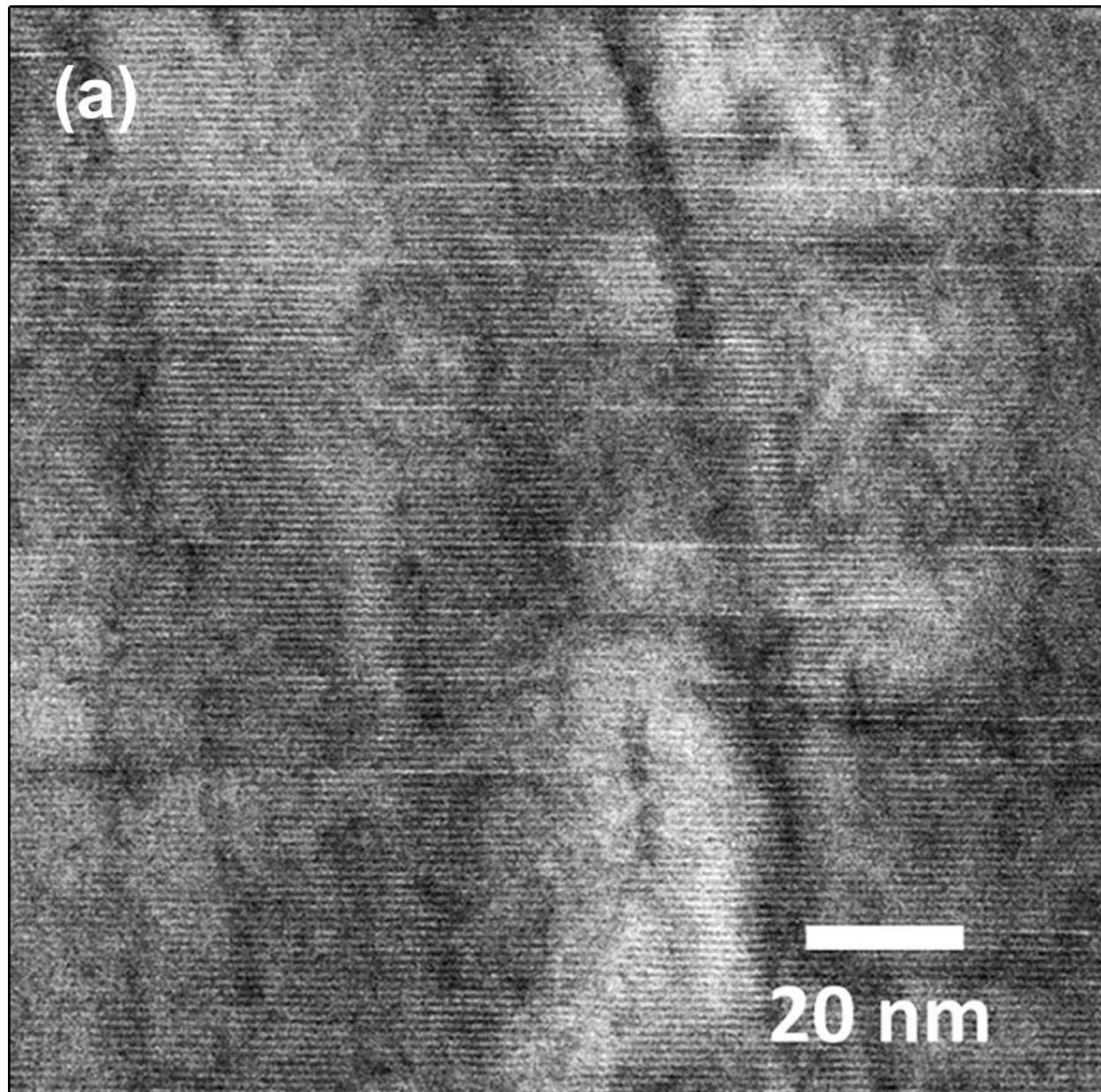
Growth temperature	780°C
Distance	70 mm
Frequency	1–10 Hz
pO ₂	400 mTorr
Substrate	LaAlO ₃ (100)
Pulse number	6000
Energy density	1.5 J/cm ²

	0 vol%	4 vol%	5 vol%			6 vol%	10 vol%		
Sample	pure	25:1	20:1	39:2	78:4	15:1	20:2	39:4	78:8
GdBCO (pulse)	6000	5770	5714	5707	5707	5625	5456	5442	5442
BHO (pulse)	0	230	286	293	293	375	545	558	558
Thickness (nm)	254	243	150	178	238	243	150	141	165

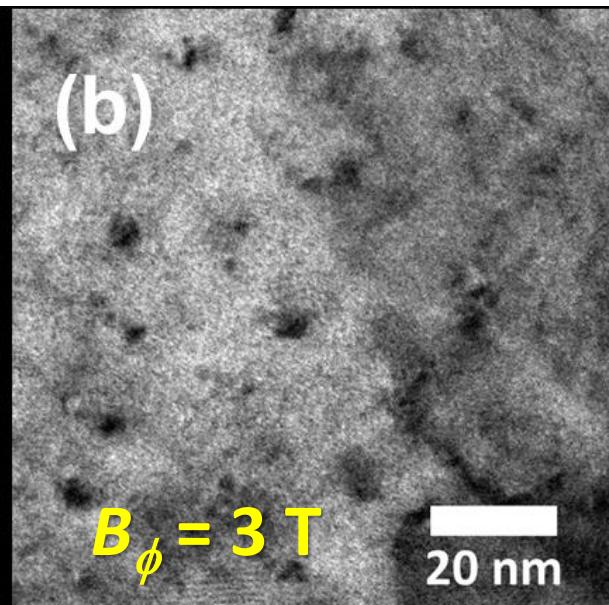


TEM photograph of BHO doped GdBCO thin films

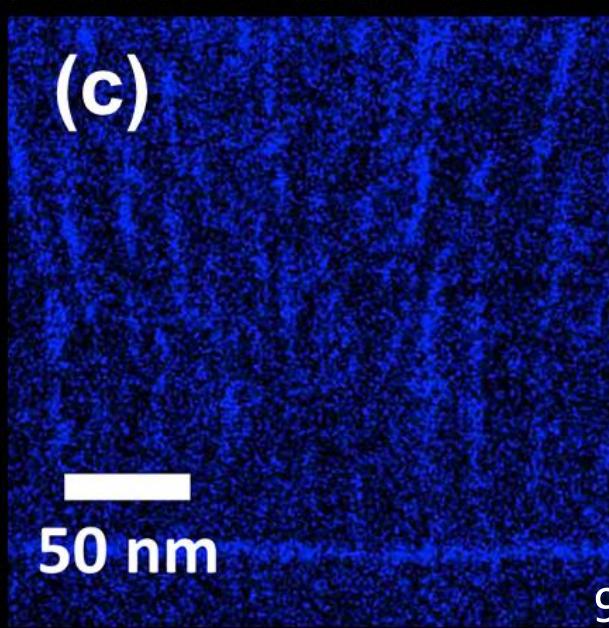
(a)



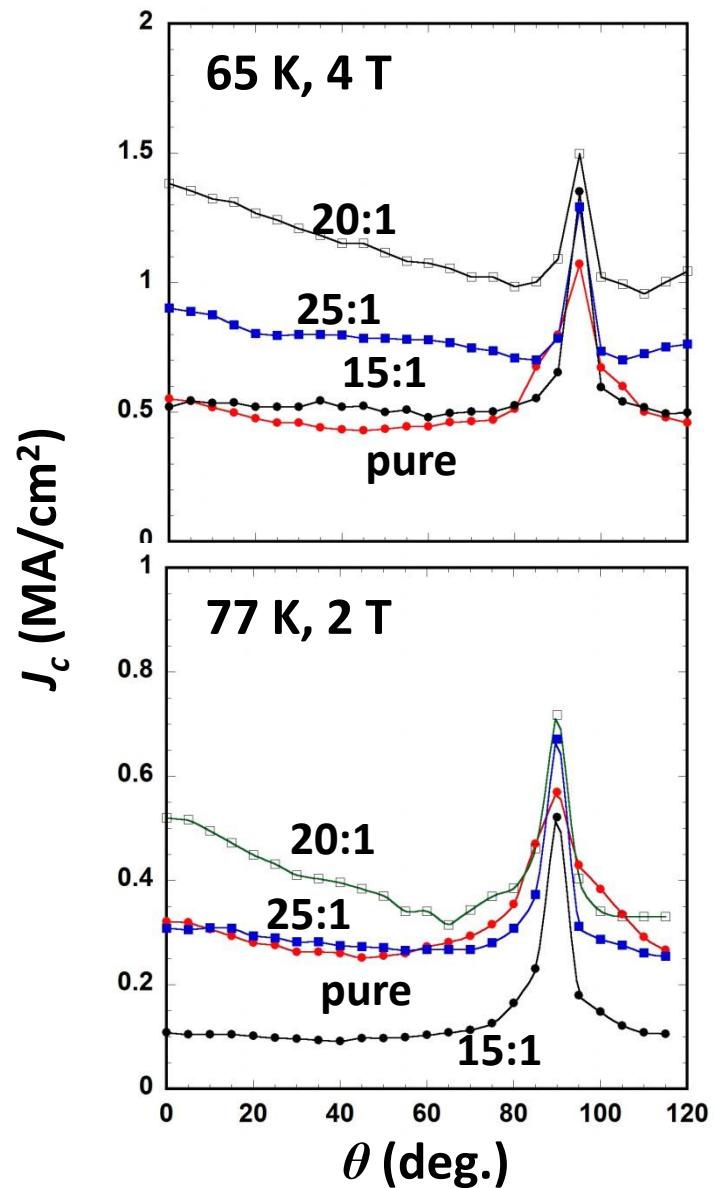
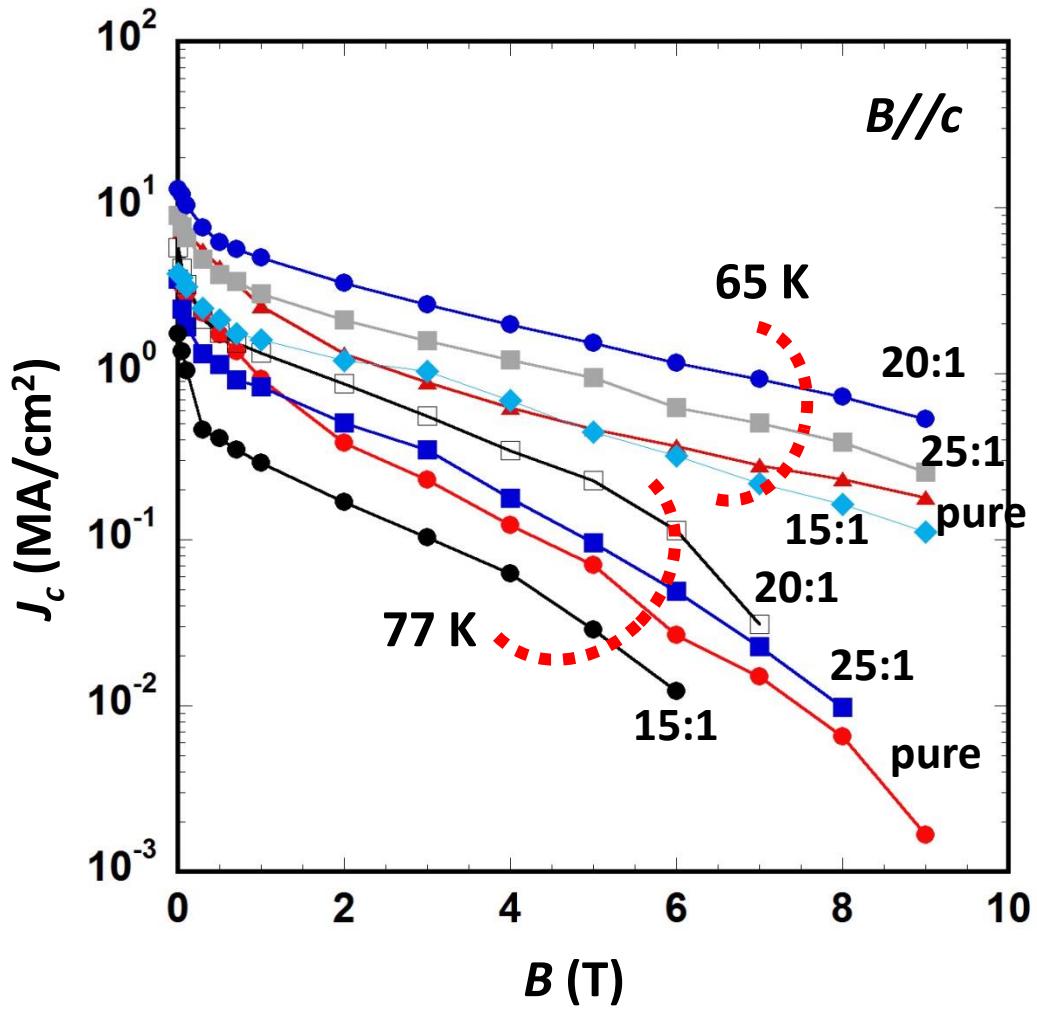
(b)



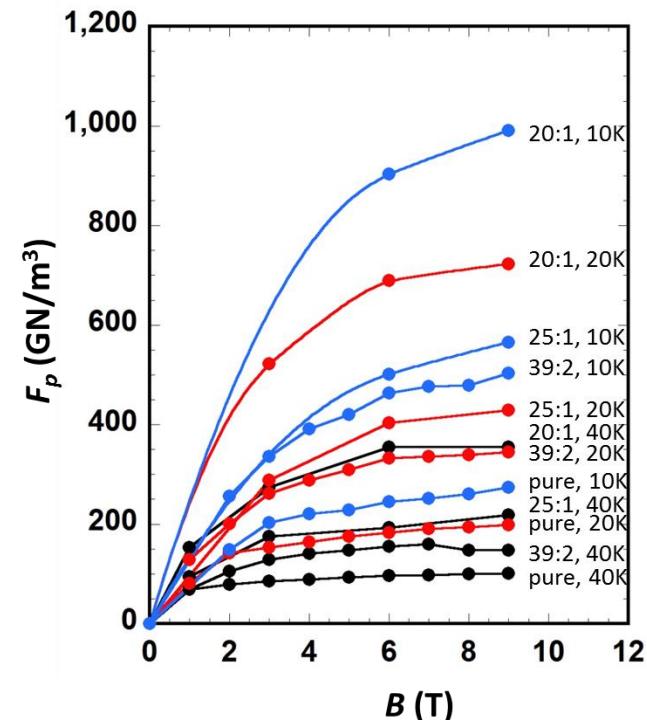
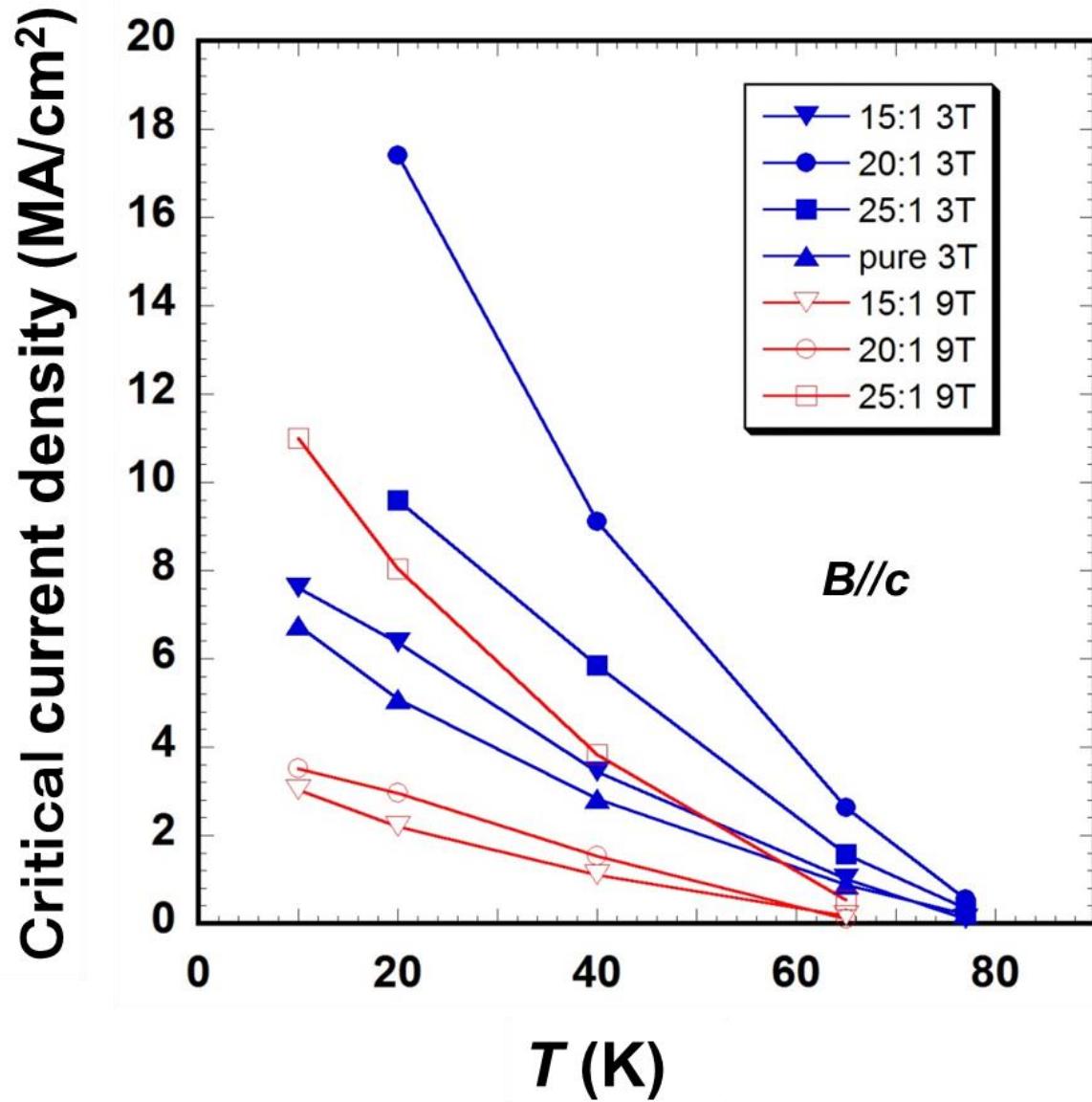
(c)



Jc properties of BHO doped GdBCO films at 65 K and 77 K



Temperature dependence of J_c of BHO doped GdBCO films



" F_p reached about 1 TN/m^3 at 10 K, $B//c$ "



δl pinning and δT_c pinning mechanism

$$F_{GL}(r) = F_L(\psi(r)) + F_{grad}(r)$$

$$F_L(\psi(r)) = \alpha |\psi|^2 + \frac{\beta}{2} |\psi|^4 \quad F_{grad}(r) = \frac{\hbar^2}{2m} |\nabla \psi|^2$$

$$\begin{aligned}\delta T_c \text{ pinning: } & \quad 1 - |\psi(r)|^2 \\ \delta l \text{ pinning: } & \quad \xi^2 |\nabla \psi(r)|^2\end{aligned}$$

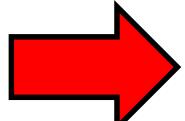
Blatter et al., 1994
Griessen et al., 1994

$$J_c(t)/J_c(0) = (1-t^2)^{7/6} (1+t^2)^{-5/6}$$

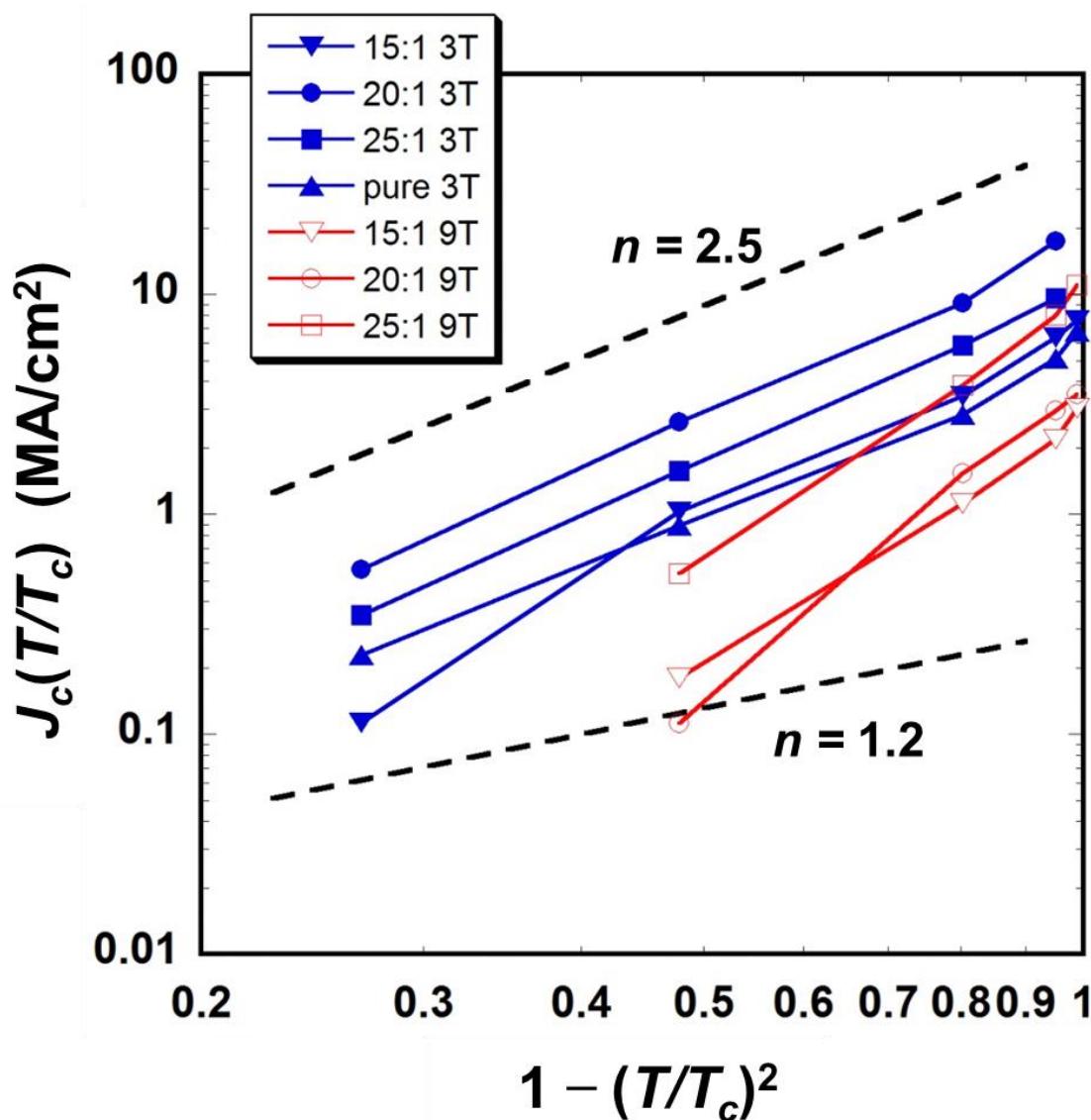
δT_c pinning

$$J_c(t)/J_c(0) = (1-t^2)^{5/2} (1+t^2)^{-1/3}$$

δl pinning



Analysis of temperature dependent J_c by Griessen's model



$$J_c(T) \propto \left\{1 - (T/T_c)^2\right\}^n$$

δl pinning : $n = 5/2$

δT_c pinning : $n = 7/6$

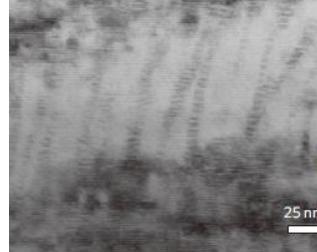
N. Haberkorn et al., PRB 85, 014522 (2012)

“Contrary to the prediction, the experimental results show that the δ pinning mechanism is dominant”

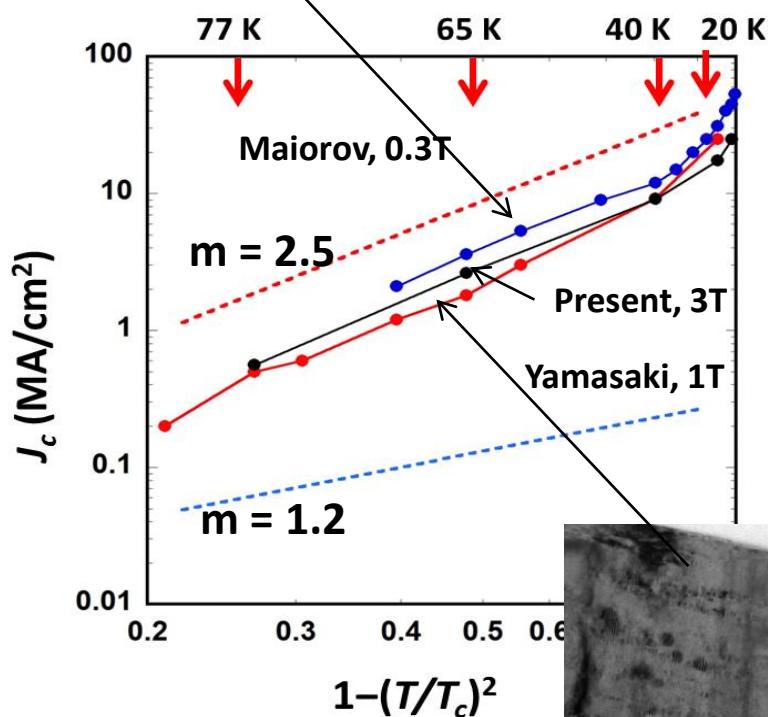


Comparison with experimental results of other groups

785 °C
BZO nanorods

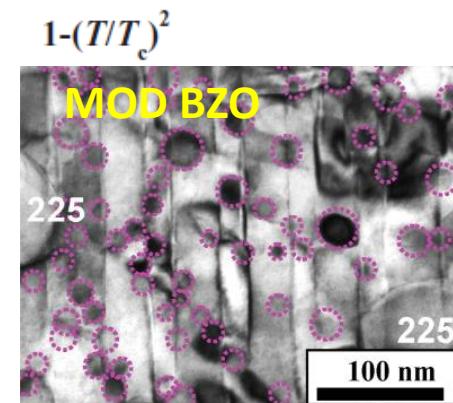
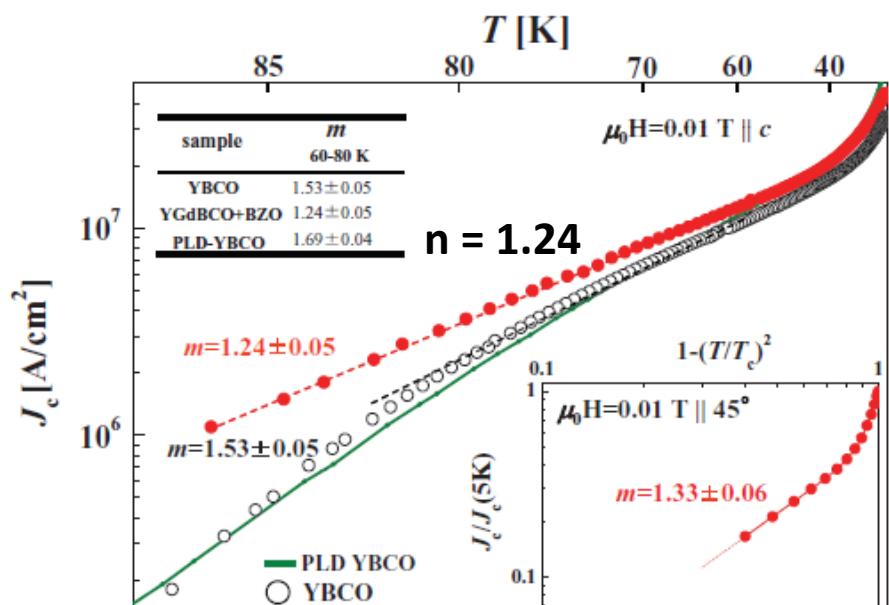


B. Maioriv et al., nature mater. 8, 398 (2009)



H. Yamazaki, SUST 29, 065005 (2016)

Y₂O₃ nanoparticles



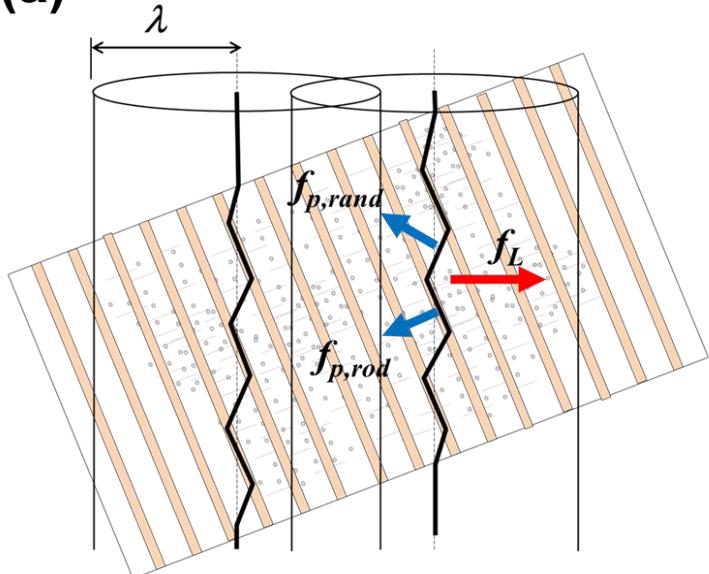
M. Miura, PRB 83, 184519 (2011)



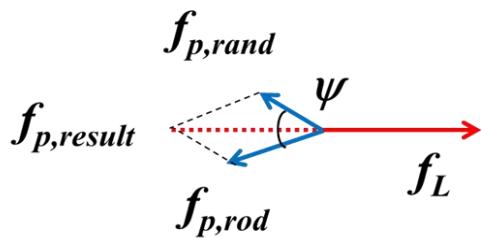
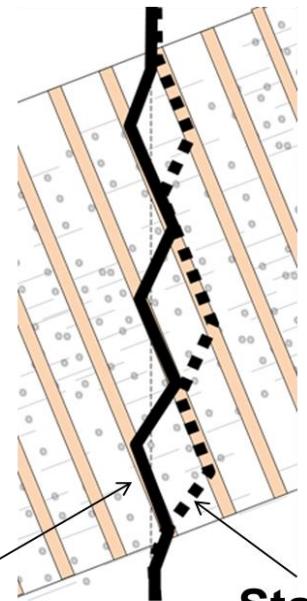
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Importance of background random pins in GdBCO thin films

(a)



(b)



$$f_{p,result} = \left(f_{p,rod}^2 + f_{p,rand}^2 + 2f_{p,rod} \cdot f_{p,rand} \cos \psi \right)^{1/2}$$

Summary

- Nanorods in REBCO thin films have excellent pinning force and their J_c characteristics can be evaluated using Nelson's Bose Glass model
- By using the TDGL simulation, it is possible to quantitatively predict the J_c characteristic of an ideal nanorod at low temperatures
- From the measured temperature dependent J_c , it was predicted that the δl pinning mechanism is dominant in the nanorod doped REBCO thin films