Modification of critical current density properties in high-T_c superconductors by tuning columnar defect morphologies in different directions

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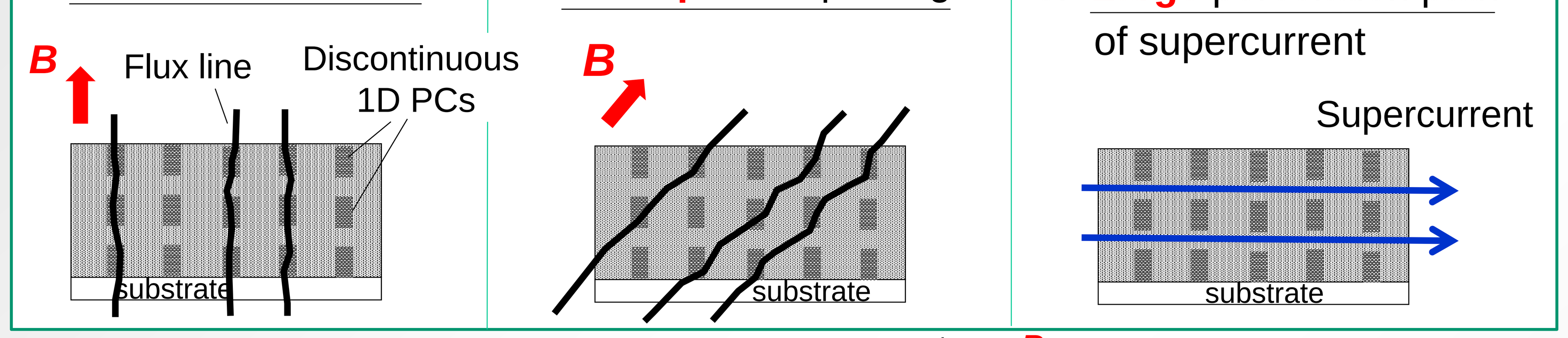
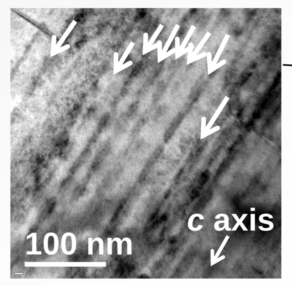
1. Introduction

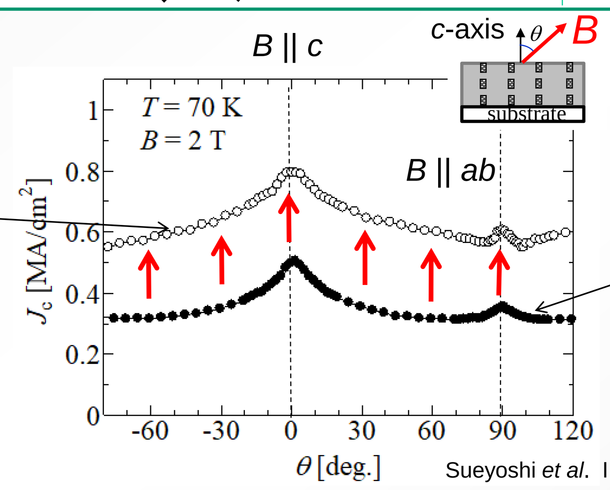
Flux pinning by discontinuous columnar defects (CDs) in high-T_c superconductors



GdBa$_2$Cu$_3$Oy coated conductor irradiated with 80 MeV Xe ions

➡ Discontinuous CDs





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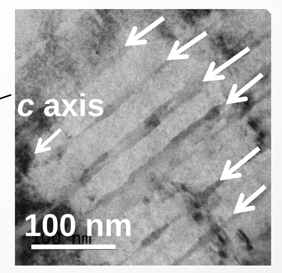
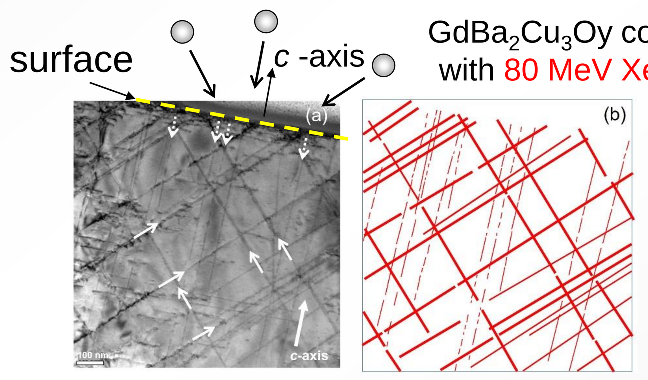
GdBa$_2$Cu$_3$Oy coated conductor irradiated with 270 MeV Xe ions

➡ Continuous CDs





GdBa$_2$Cu$_3$Oy coated conductor irradiated with 80 MeV Xe ions at θ_i = 0° and ±45°

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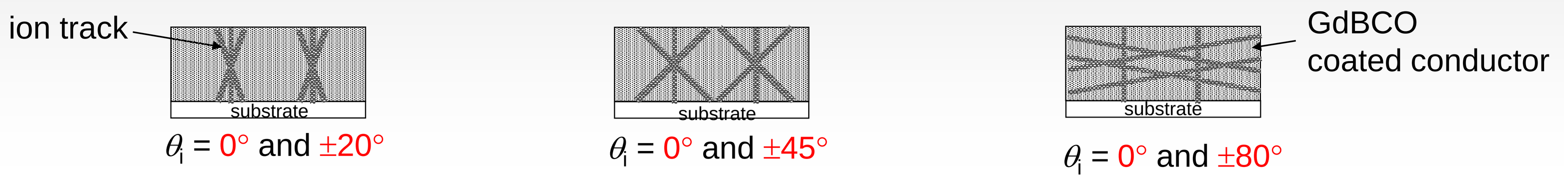
➡ Directional dependent morphology of CDs

- ✓ *C*-axis direction: discontinuous CDs
- ✓ At θ_i = 45° : continuous CDs

by the same ion beam of 80 MeV Xe ions

This work

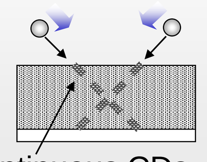
1. Systematic investigation of the morphology of CDs installed at different angles by using 80 MeV Xe ions on GdBCO coated conductors



➡ Clarify the mechanism of the directional dependent morphology of CDs, for tuning the morphology of CDs in every direction in a controlled manner.

2. Demonstration of the formation of discontinuous CDs at ±45° relative to the *c*-axis

➡ Investigate the effect of direction-dispersion of discontinuous CDs on the critical current density J_c properties in YBCO thin films



2. Experimental

○ Samples : GdBa$_2$Cu$_3$O$_y$ coated conductors (Fujikura ltd.) for TEM analysis
Thickness : 2.2 μm (superconducting layer) 5mm-width, I_c = 280 A

YBa$_2$Cu$_3$O$_y$ thin films (Ceraco ltd.) for TEM and transport measurement
Thickness : 400nm, prepared by co-evaporation method

○ Heavy-ion irradiation procedure: Tandem accelerator at JAEA Tokai, Japan

Ions : 80 MeV Xe^{11+} S_e = 20.1 keV/nm (for TEM and transport measurement)

200 MeV Xe^{14+} S_e = 27.8 keV/nm (for transport measurement)

50 MeV Kr^{7+} S_e = 14.5 keV/nm (for TEM and transport measurement)

Direction of irradiation : tilted at θ_i relative to *c*-axis

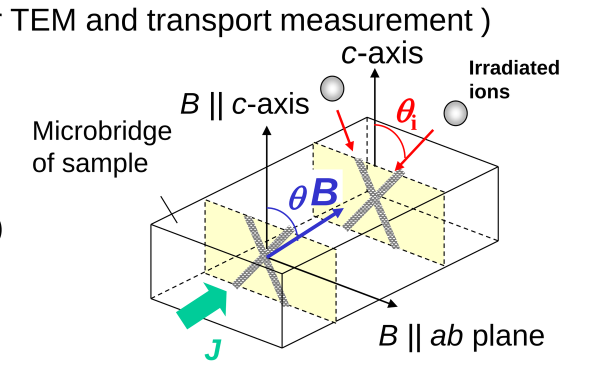
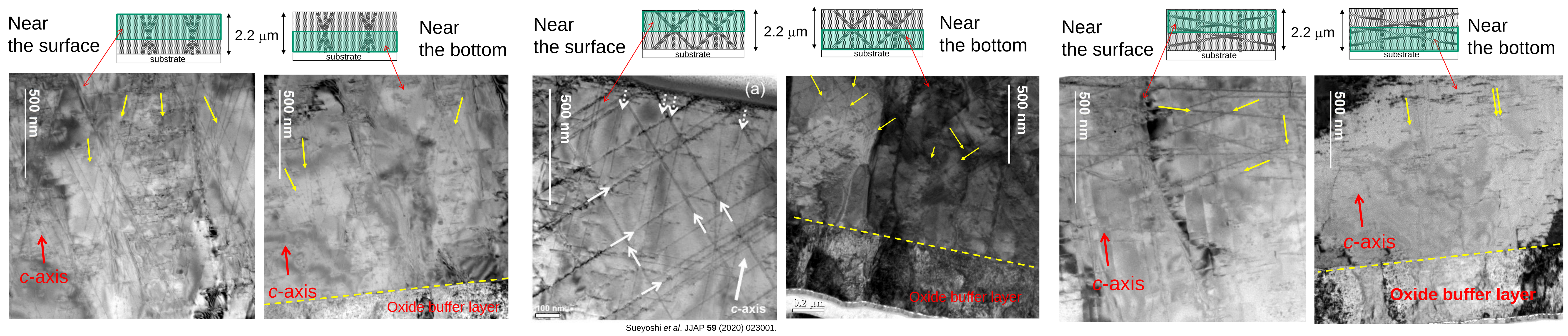


Table Samples in this study.

Sample	θ_i	Irradiated Ions, [MeV] / B_ϕ [T]	Measurement(s)
GdBCO	0°, ±20°	Xe, 80 / 0.5 × 3	TEM
GdBCO	0°, ±45°	Xe, 80 / 0.5 × 3	TEM
GdBCO	0°, ±80°	Xe, 80 / 0.5 × 3	TEM
YBCO	0°	Xe, 200 / 1.5	SQUID-J_c
YBCO	±45°	Xe, 200 / 0.75 × 2	SQUID-J_c
YBCO	0°	Kr, 50 / 1.5	TEM / SQUID-J_c
YBCO	±45°	Kr, 50 / 0.75 × 2	TEM / SQUID-J_c

3. Results

Microstructures of GdBCO coated conductors irradiated with 80MeV Xe ions at different angles



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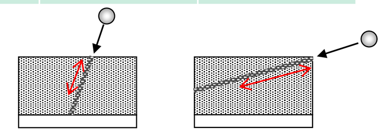
Morphology of CDs at a depth from the surface

Depth from surface	θ_i = 0°	θ_i = ±20°	θ_i = ±45°	θ_i = ±80°
500 nm	Discont.	Continuous	Continuous	Continuous
1000 nm	Discont.	Discont.	Continuous	—
1500 nm	Discont.	Discont.	Discont.	—
2000 nm	Discont.	Discont.	Discont.	—

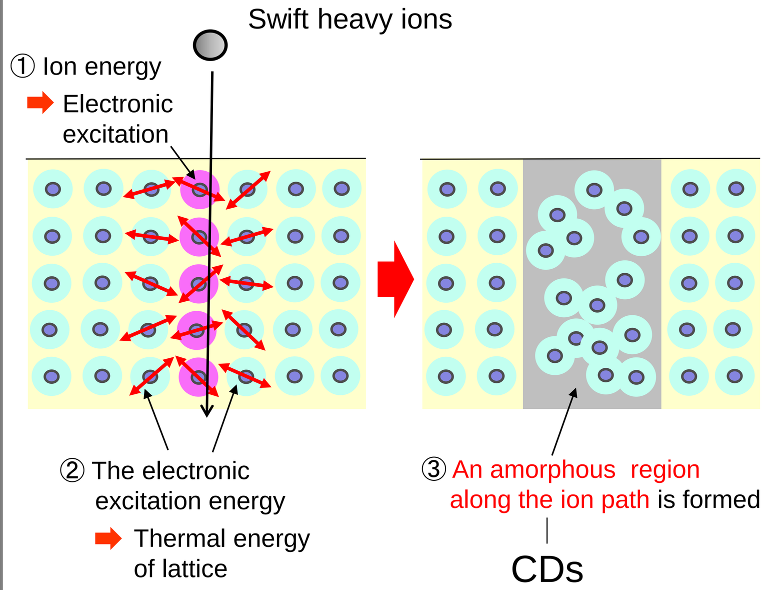
Electronic stopping power S_e [keV/nm] at a depth from the surface

Depth from surface	θ_i = 0°	θ_i = ±20°	θ_i = ±45°	θ_i = ±80°
0 nm	20.3	20.3	20.3	20.3
500 nm	19.1	19.0 (532)	18.5 (707)	11.8 (2879)
1000 nm	17.7	17.5 (1064)	16.5 (1414)	— (5759)
1500 nm	16.3	16.0 (1596)	14.3 (2121)	— (8638)
2000 nm	14.9	14.3 (2128)	12.0 (2828)	—(11518)

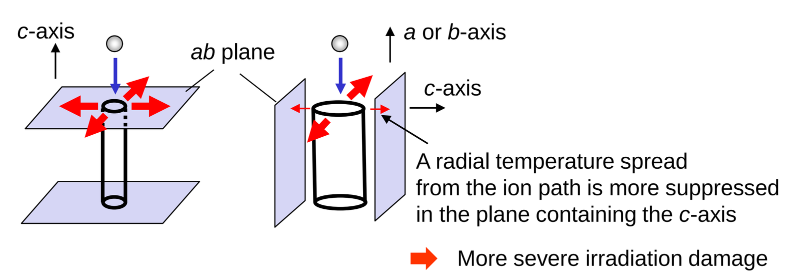
*The values in ( ) are the ion path length at the depth [nm].



Mechanism of the formation of CDs by the thermal spike model



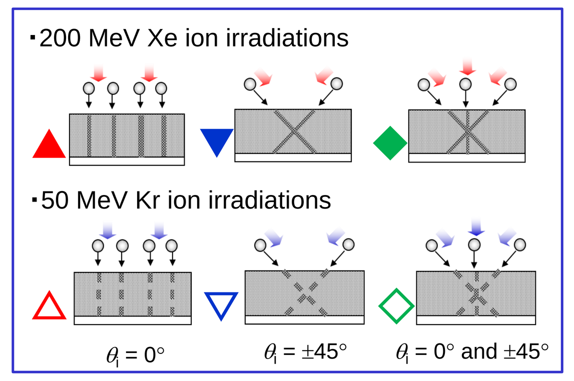
Thermal diffusivity D in high-T_c superconductors
$D_c < D_{ab}$



Anisotropy of thermal diffusivity
➡ Directional dependence of CD morphology

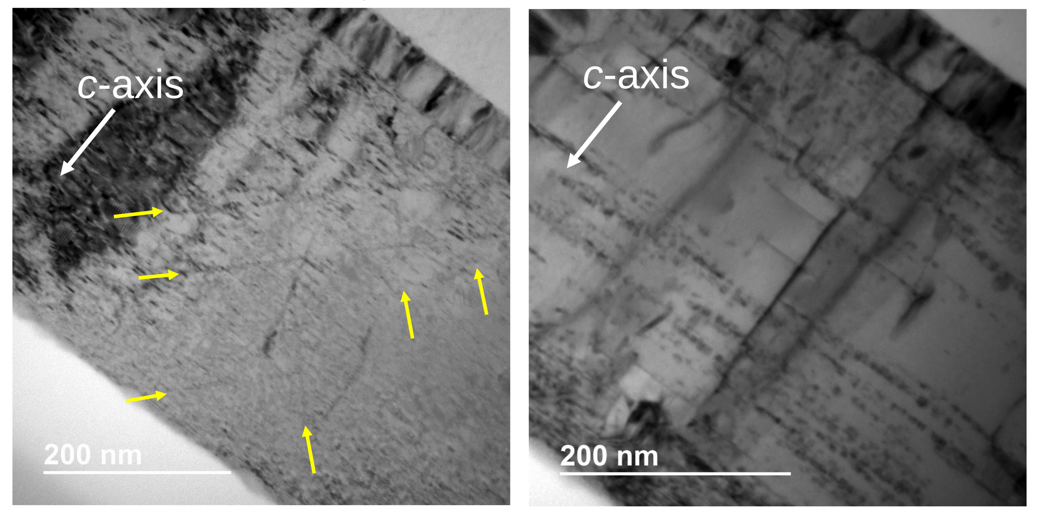
Introduction of discontinuous CDs at θi = ± 45° by using 50 MeV Kr ions

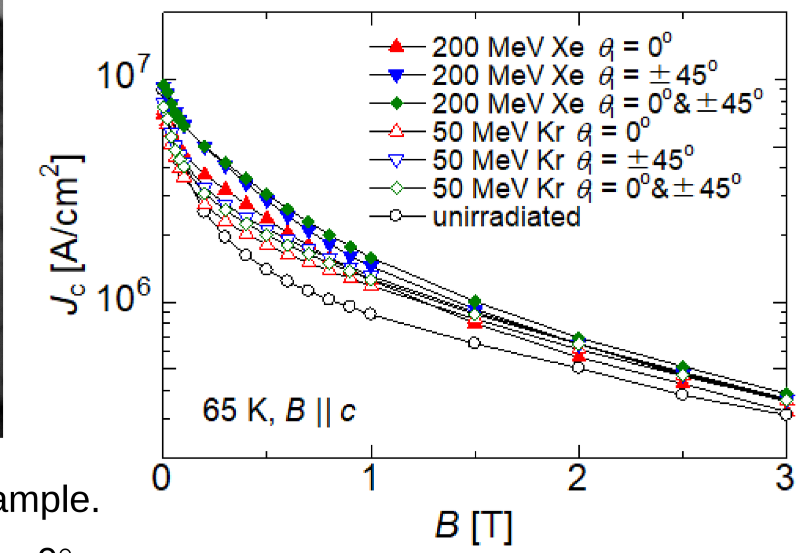
50 MeV Kr irradiation to YBCO has a value of S_e = 14.5 keV/nm, which is the irradiation condition for the appearance of discontinuous CDs at θ_i = ±45° suggested by TEM observations.



YBCO thin films irradiated with 50 MeV Kr at θ_i = ±45°

YBCO thin films irradiated with 50 MeV Kr at θ_i = 0°





- ✓ Discontinuous CDs are formed at θ_i = ±45° through the sample.
- ✓ No visible irradiation defects exists for the irradiation at θ_i = 0°.
- ✓ Direction-dispersion of the ion tracks is effective even for the flux pinning by discontinuous CDs.

4. Conclusions

Microstructures of GdBCO irradiated by 80 MeV Xe ions at various angles θ_i relative to the c-axis

- Not Discontinuous CDs but continuous ones are easily formed for the irradiation more tilted from the *c*-axis.
- CDs are turned from continuous shape to discontinuous one at a deeper depth for the irradiation more tilted from the *c*-axis.
- The TEM observations enabled us to identify the irradiation condition for the formation of discontinuous CDs at θ_i = 45°.

Effect of direction-dispersion of discontinuous CDs on J_c properties in YBCO thin films

- The flux pinning by discontinuous CDs is improved by the direction-dispersion of the ion tracks.
- The irradiation defects by 50 MeV Kr were too small to provide superior J_c properties to continuous CDs by 200 MeV Xe.