Defect formation and improved critical current density in YBCO superconducting films by electron beam irradiation

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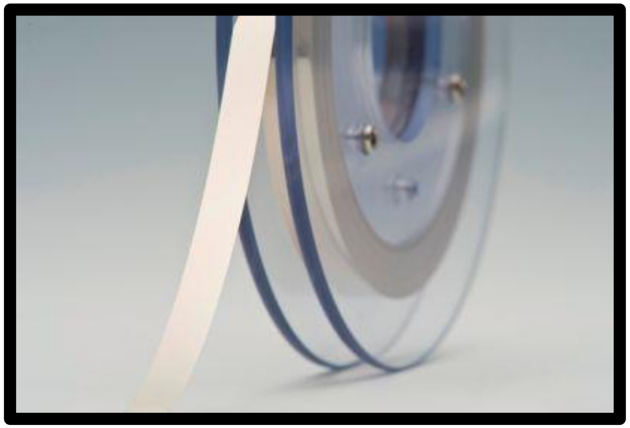
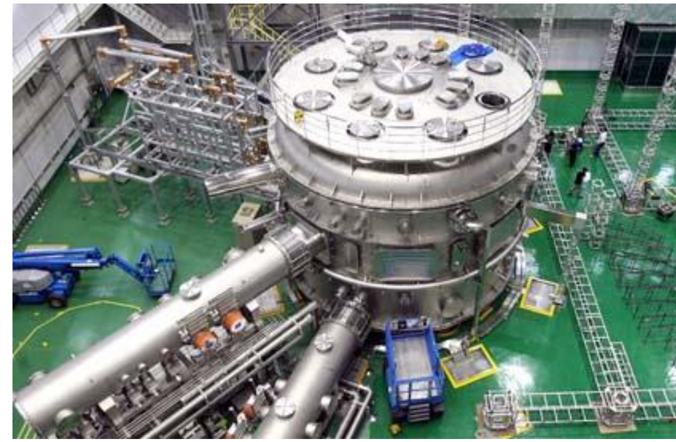
Applications of superconducting wires/tapes



HTS tape: coated conductor

Superconducting cable

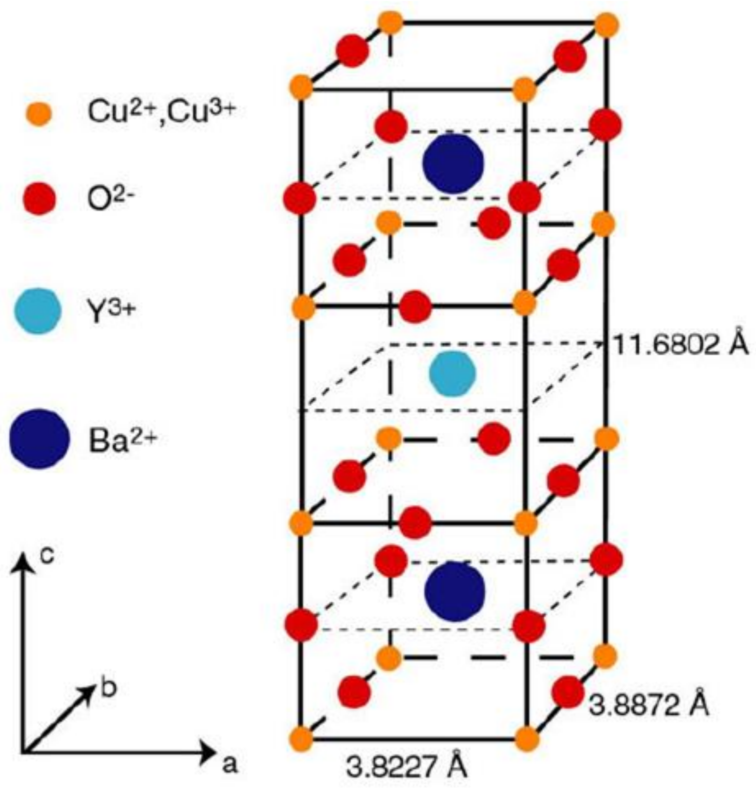


Magnet for nuclear fusion

Generator

Magnet for levitation transportation

$YBa_2Cu_3O_{7-y}$ (YBCO) superconductor

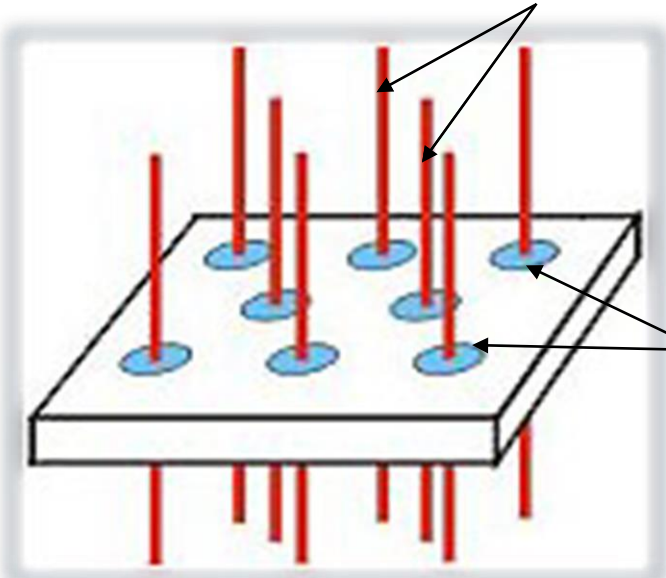


<Crystal structure of YBCO>

- **High superconducting transition temperature(T_c) of 91 K**
- **Critical current density(J_c) of 10^5~10^7A/cm^2 at 77 K, self-field**
- **Short coherent length**
- **Weakly linked grain boundary**
- **High current anisotropy: high J_c along the *a-b* plane but low J_c along the *c* direction**

How to enhance flux pinning capability

Magnetic flux trapped at defects



Chemical method

- **Addition of second phase (ex, Y_2BaCuO_5(Y211))**
- **Chemical doping (Fe or Ni to Cu)**

Physical method

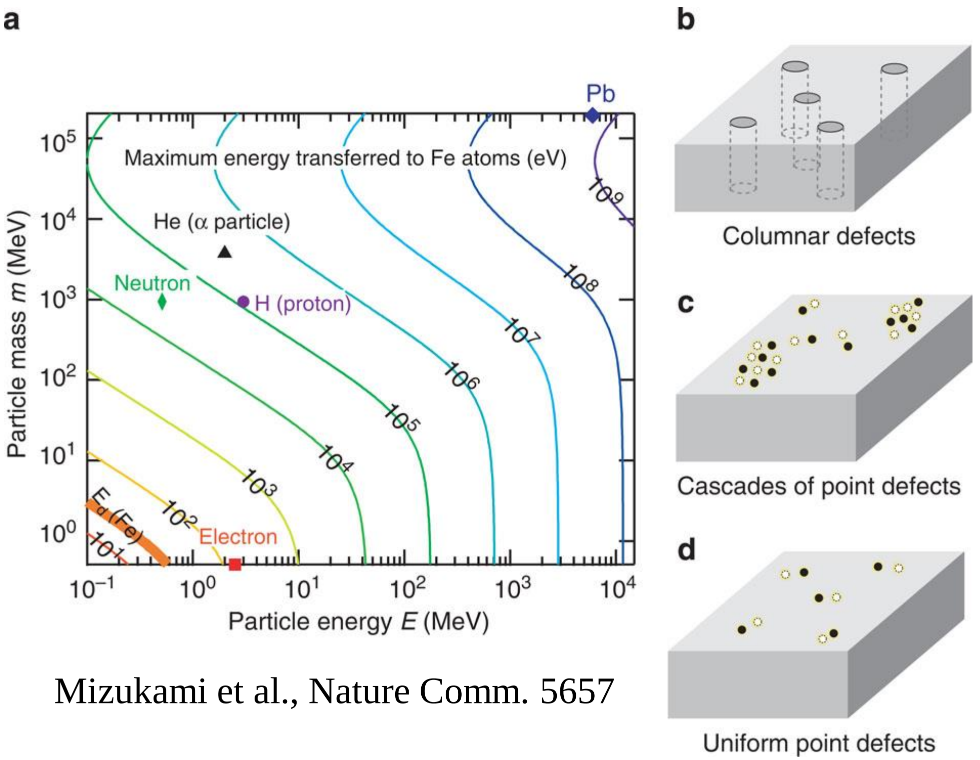
- **Particle irradiation (neutron, electron, proton, ion etc.)**

The defects such as vacancy, twin, dislocation and stacking faults can act as flux pinning centers.

Physical method : particle irradiation

Type of irradiation

- Heavy ion
- He particle
- Neutron
- Electron
- Proton

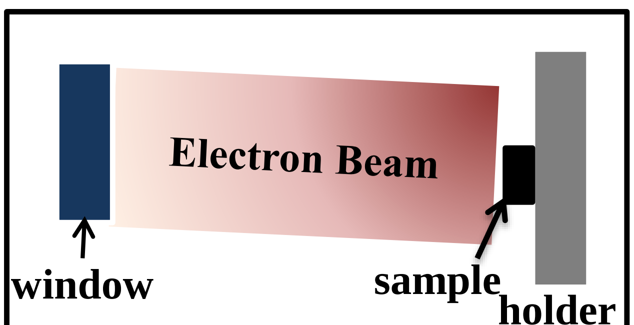


Mizukami et al., Nature Comm. 5657

In this study, electron beam irradiation was attempted to form defects for the YBCO films with an aim of the enhancement of J_c.

Electron beam (EB) irradiation

EB accelerator in KAERI



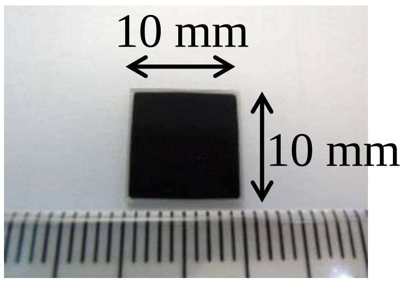
EB irradiation

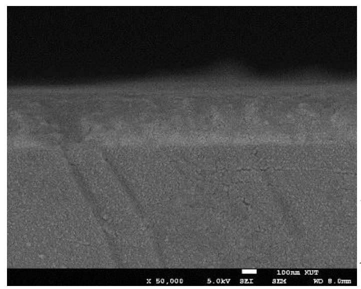
EB Irradiation Condition

- Acceleration Energy : 0.2 MeV
- Acceleration Current : 1 mA

YBCO films used for EB irradiation

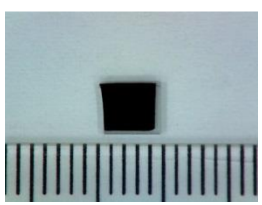
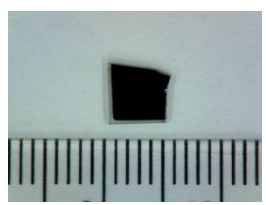
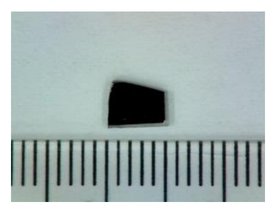
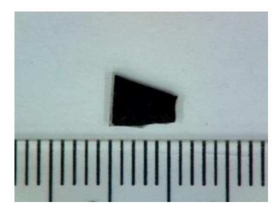
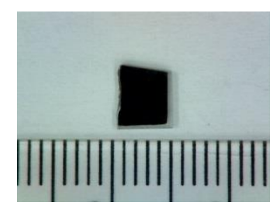
YBCO film/CeO_2 buffer/Al_2O_3 substrate





◆ **CERACO**

- **10 mm x 10 mm**
- **YBCO : 300 nm**
- **CeO_2 : ~ 65 nm**

Dose(e/cm²)	**0**	**0.75×10^{16}**	**2.25×10^{16}**	**0.52×10^{17}**	**0.75×10^{17}**
Time(min)	**0**	**1**	**3**	**7**	**10**
Picture					
Area (cm²)	**0.1568**	**0.2014**	**0.1453**	**0.1676**	**0.1873**

Property measurement

HR-XRD

High-Resolution X-ray Diffraction

- Phase analysis
- Lattice parameter calculation
- Rocking curve

MPMS

Magnetic Property Measurement System

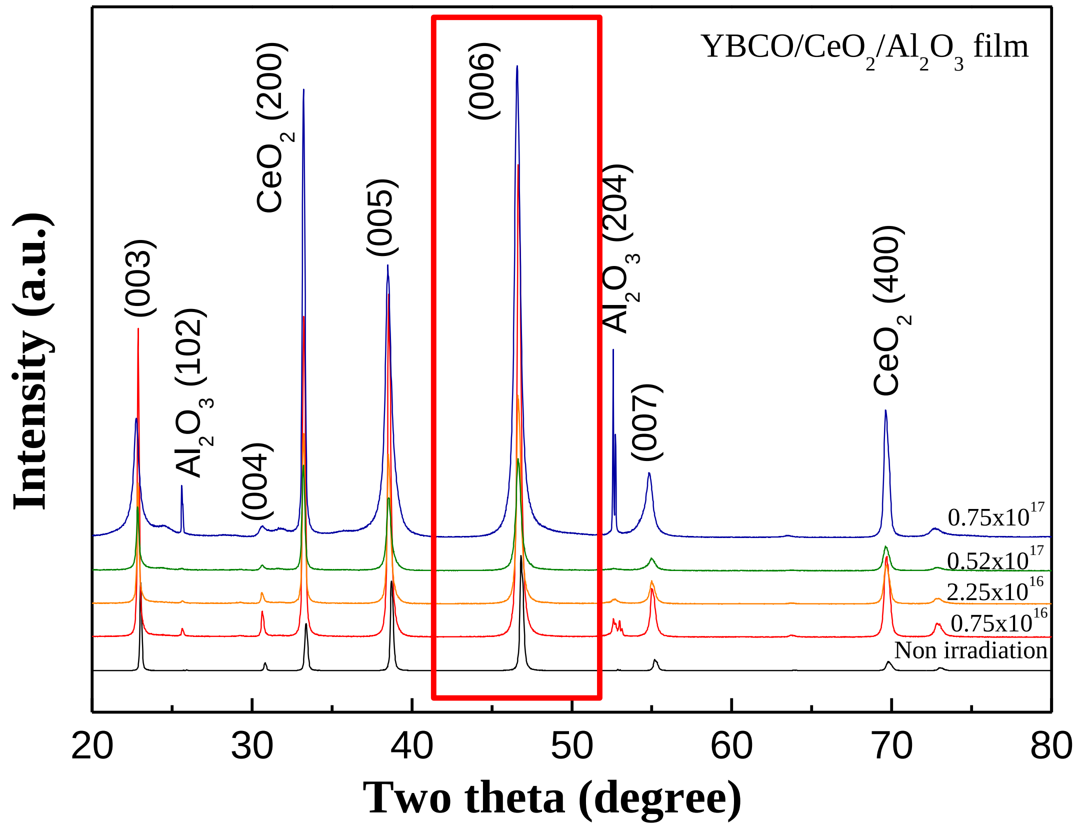
- Critical temperature (T_c)
- Critical current density (J_c) using Bean's model

TEM

Transmission Electron Microscopy

- Microstructure analysis (defects)

XRD patterns of YBCO films after EB irradiation



- **All the YBCO films were grown to the *c*-axis direction on the CeO_2 buffered Al_2O_3 substrate. The (006) peak was selected to investigate the EB effect on the crystal structure.**

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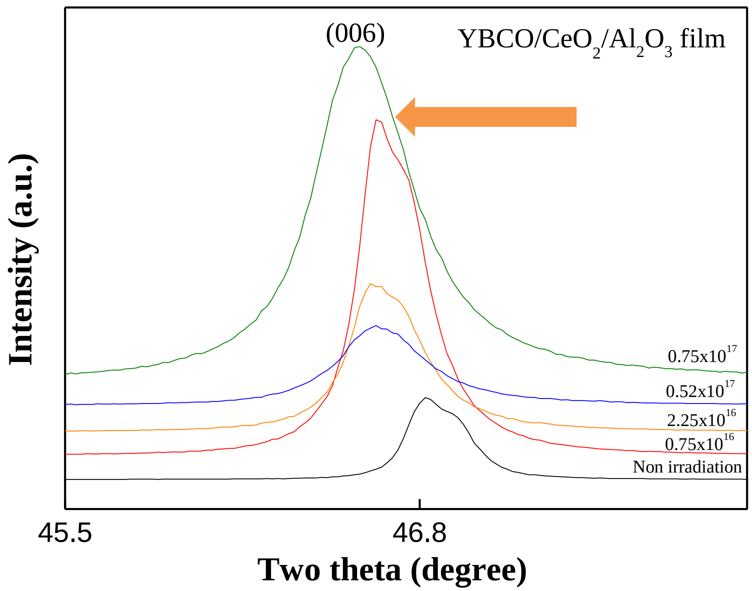
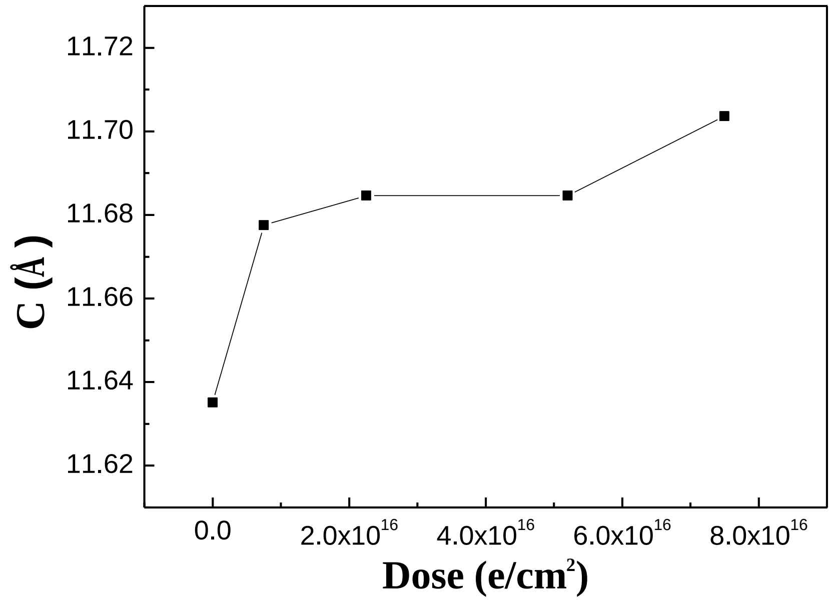
c lattice parameter change by EB irradiation

(006) peak shift



Lattice parameter, *c*



- **As the EB dose increased, (006) peak shifted to low angle, which indicated the increase of *c* lattice parameter.**
- ***c* lattice parameter is a function of an oxygen content.** *(E.D. Specht, et.al , Phys. Rev. B, vol. 37, pp. 7426, 1988)*

Formula

$$\frac{1}{d^2} = \frac{h^2}{a^2} + \frac{k^2}{b^2} + \frac{l^2}{c^2} \quad \text{(Orthorhombic)}$$

$$2d\sin\theta = n\lambda \quad \text{(Bragg's law)}$$

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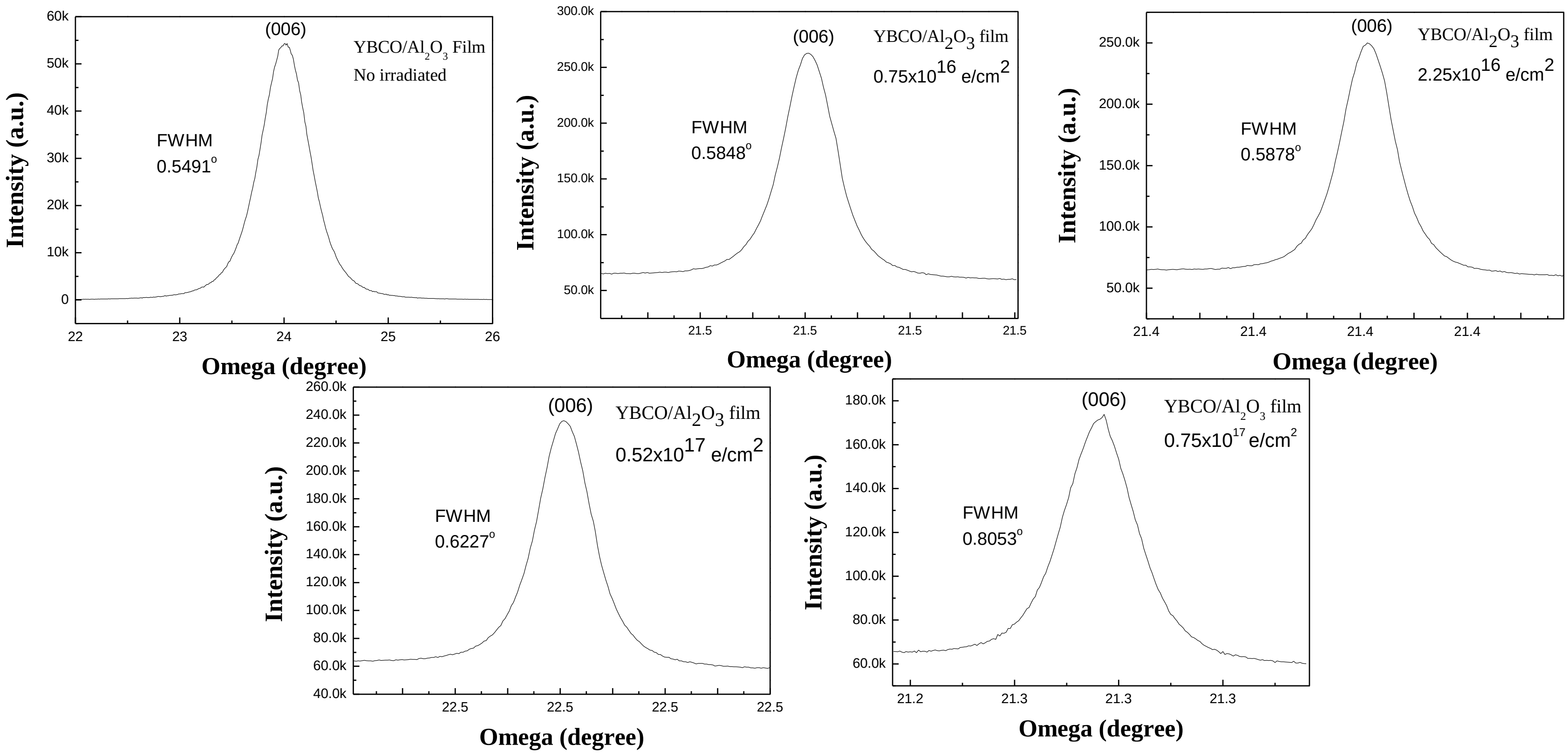
FWHM broadening by EB irradiation ; Rocking curve for (006) peak



dose(e/cm^2)	0	$0.75x10^{16}$	$2.25x10^{16}$	$0.52x10^{17}$	$0.75x10^{17}$
FWHM (°)	0.5491	0.5848	0.5878	0.6227	0.8053

FWHM increase → lattice distortion by irradiation → Crystallinity deterioration

Dose ∝ Lattice distortion

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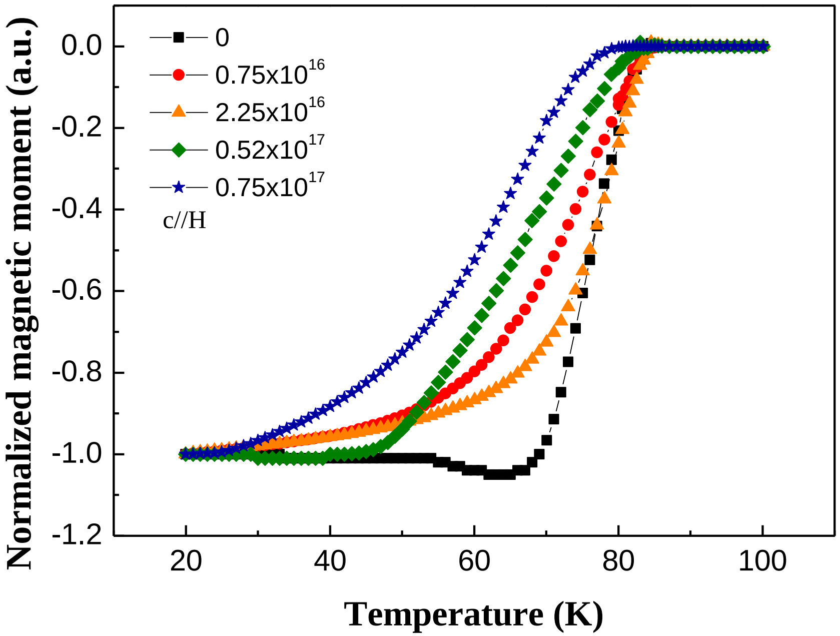
Superconducting critical temperature (T_c) vs. EB dose



- As an EB dose increased, the critical temperature(T_c) decreased: the $T_{c,onset}$ of non-irradiated YBCO was 84.5 K and the $T_{c,onset}$ of YBCO irradiated with an EB dose of 0.75×10^{17} was 80.5 K.
- Moreover, the transition temperature width (ΔT_c) became broad by EB irradiation, which indicates the lattice distortion by EB irradiation.

Dose (e/cm^2)	0	0.75×10^{16}	2.25×10^{16}	0.52×10^{17}	0.75×10^{17}
$T_{c,onset}$	84.5 K	84.3 K	84.5 K	80.8 K	80.5 K
$T_{c,mid}$	76.4 K	71.7 K	76 K	66.7 K	60.7 K
ΔT_c	8.1 K	12.6 K	8.5 K	14.1 K	19.8 K

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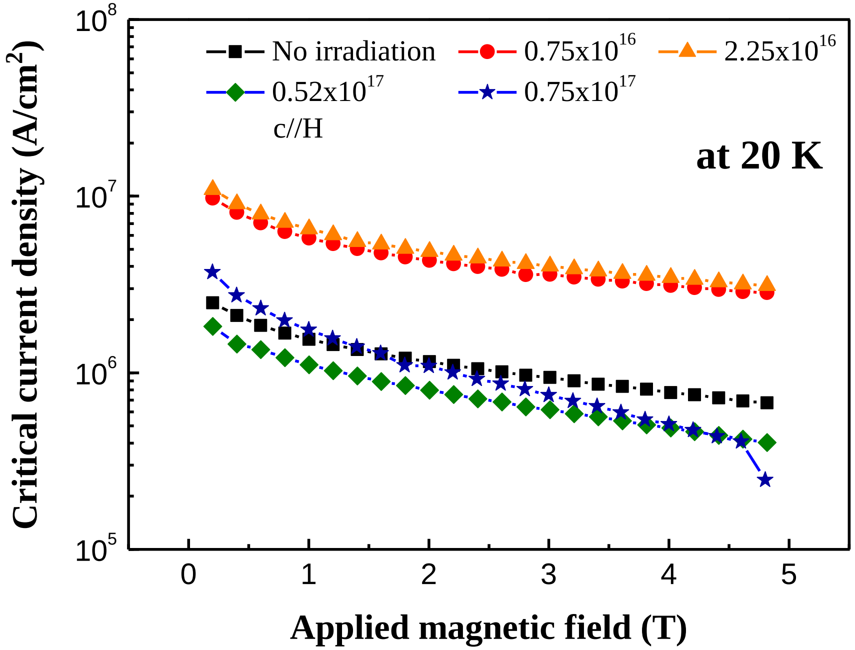
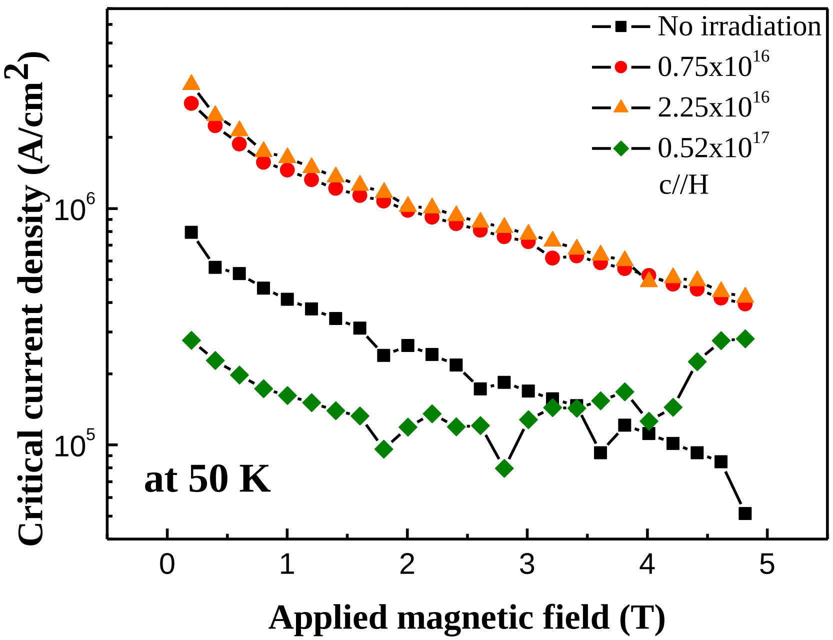
Critical current density (J_c) at 20 K vs. EB dose

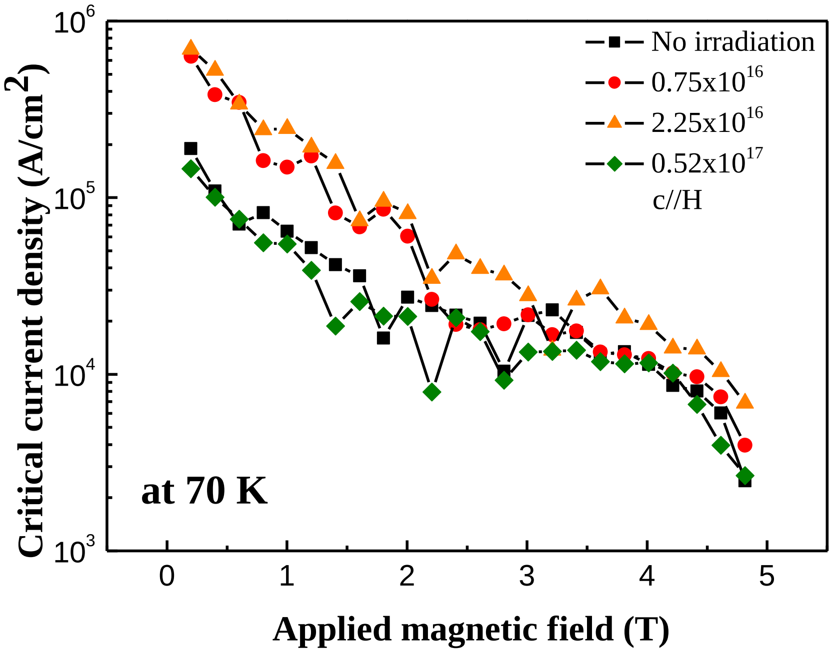


- **The critical current density(J_c) of YBCO increased with the EB doses of 0.75×10^{16} - 2.25×10^{16} e/cm^2.**
- **The EB dose exceeding 2.25×10^{16} e/cm^2 decreased J_c.**
- **There is an optimum EB dose for increasing J_c.**

Dose (e/cm^2)	0	0.75×10^{16}	2.25×10^{16}	0.52×10^{17}	0.75×10^{17}
J_c at 1T (A/cm^2)	1.54×10^6	5.77×10^6	6.52×10^6	1.11×10^6	1.75×10^6
J_c at 3T (A/cm^2)	9.38×10^5	3.59×10^6	4.01×10^6	6.17×10^5	7.45×10^5

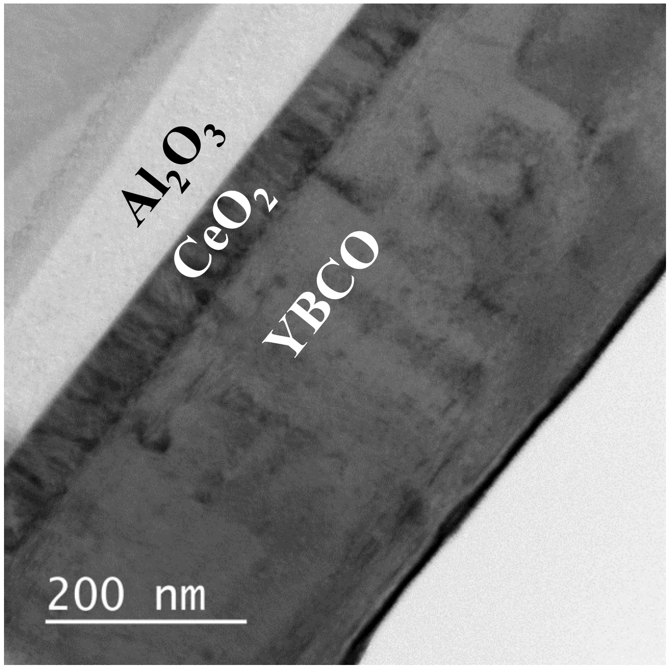
J_c at 50 and 70 K vs. EB dose

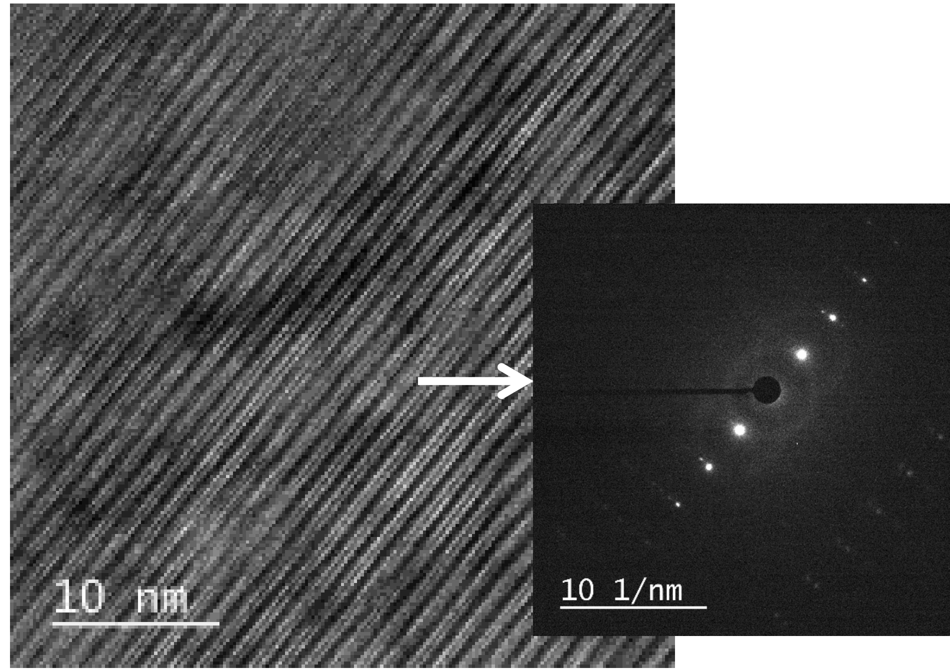




- J_c trends with various EB doses at 50 and 70 K were similar to that at 20 K
- The defects formed by EB irradiation act as flux pinning centers in the temperature range of 20-70 K

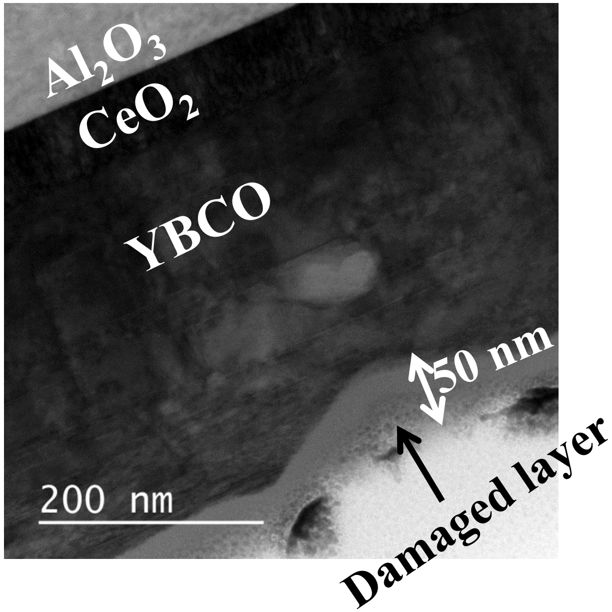
TEM image for non-irradiated YBCO film

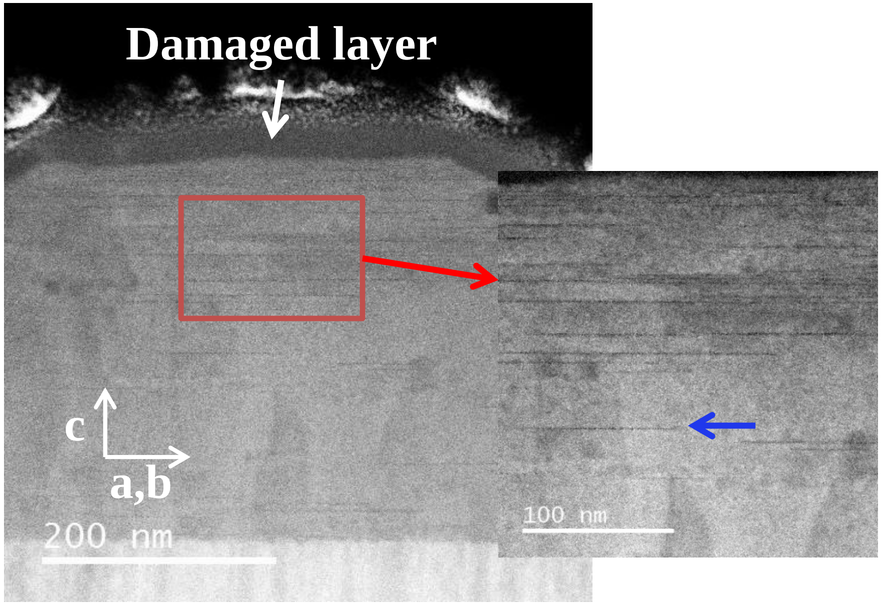




- **Epitaxial growth of YBCO thin film on the CeO_2/Al_2O_3 substrate.**
- **TEM image of non-irradiated YBCO film showed a crystalline structure.**

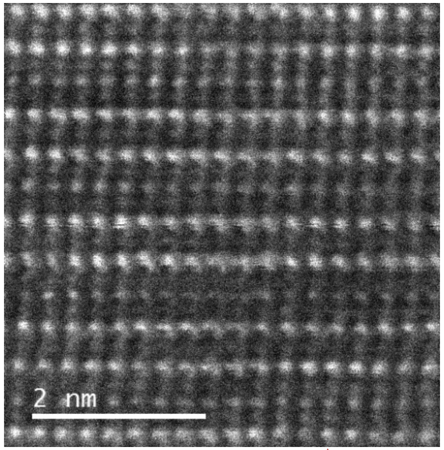
TEM image of YBCO film irradiated with 2.25×10^{16} e/cm^2

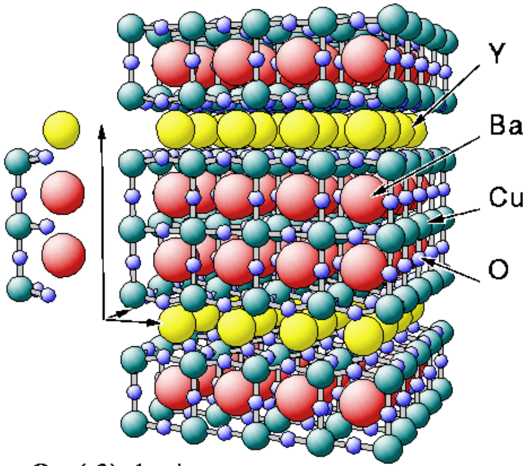




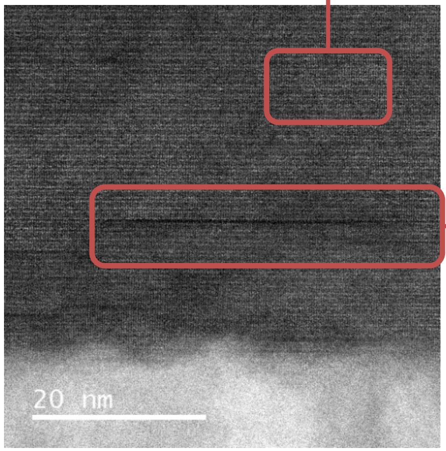
- The film irradiated with this EB dose showed J_c increase.
- EB damaged layer of about 50 nm thickness was observed near the surface.
- Many striation lines normal to *c*-axis were observed in the interior of the film.

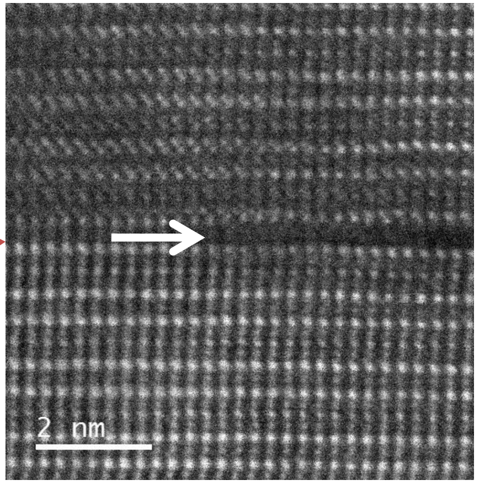
STEM image for the striations





$YBa_2Cu_3O_7$ (.3) lattice





Element	Number	Mass(g/mol)
Y	39	88.91
Ba	56	137.33
Cu	29	63.55
O	8	15.99

- **The striations are thought to be the stacking faults (Cu-deficient layers) formed by heating due to the electron bombardment.**
- **It was reported that the stacking faults were formed during low temperature annealing.**

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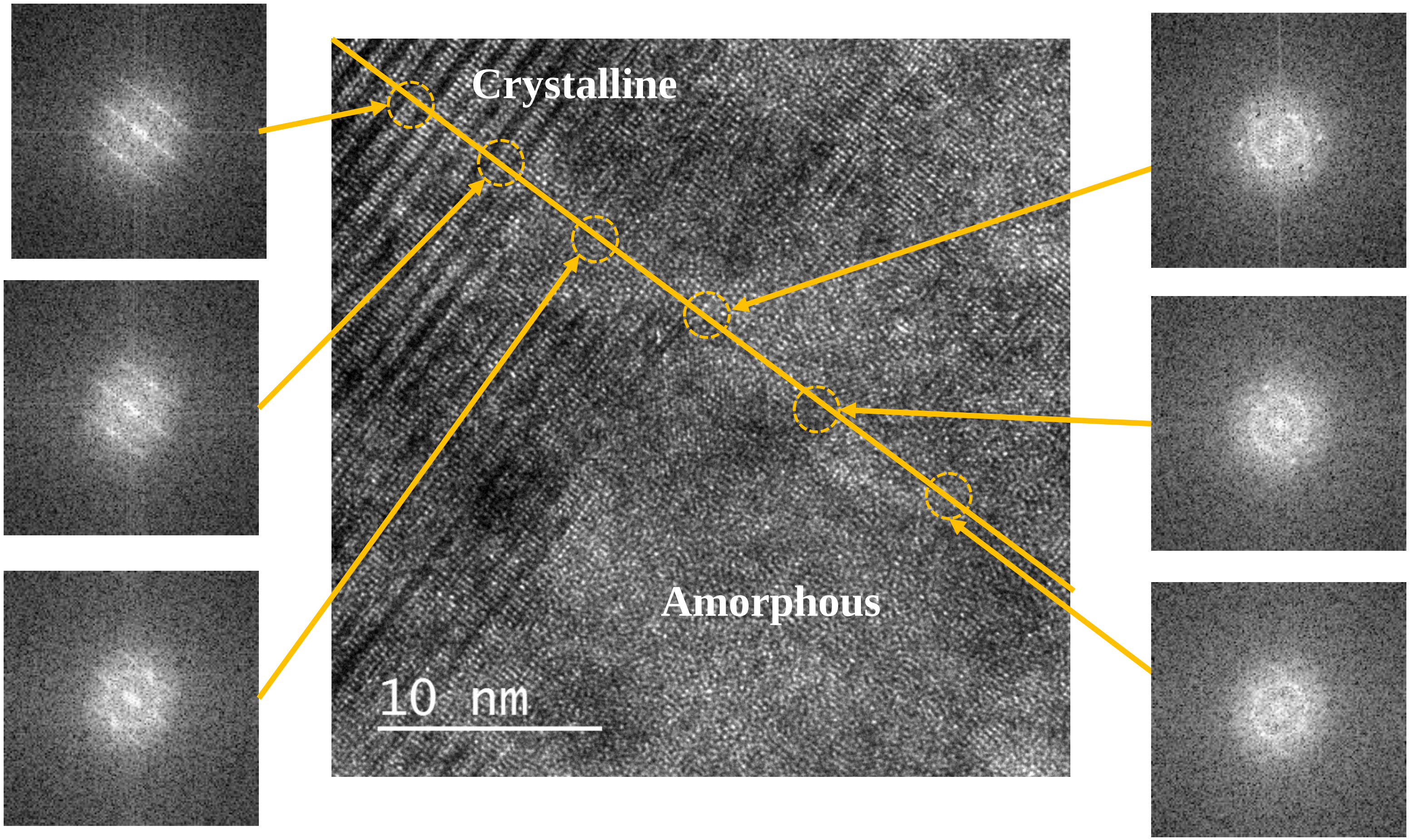
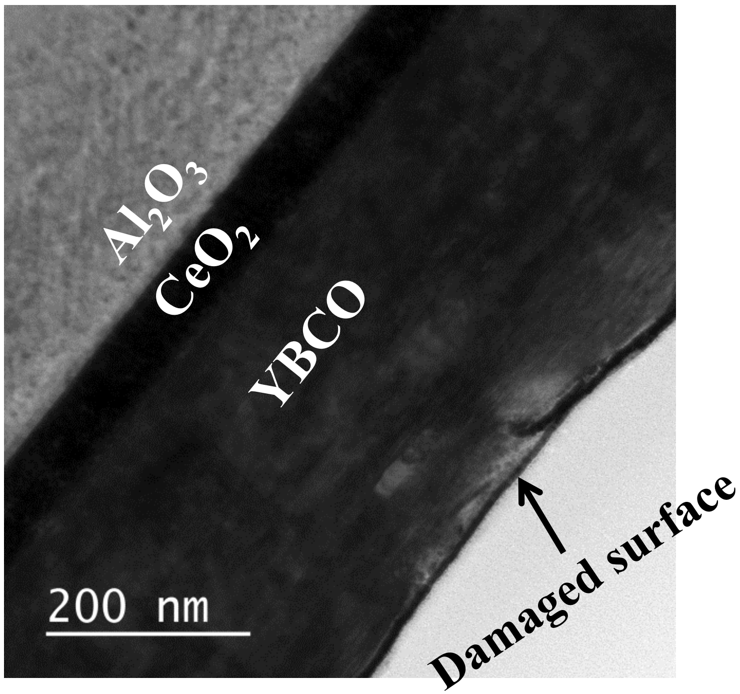
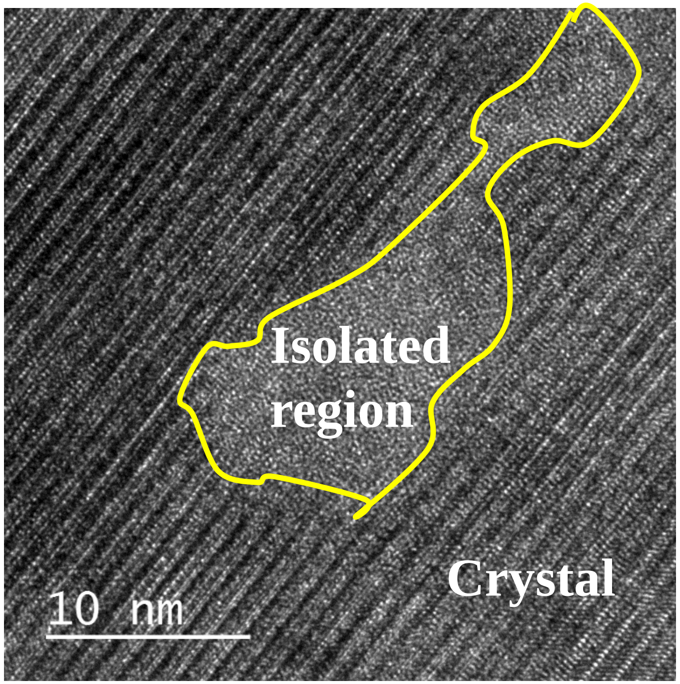
TEM image of YBCO film irradiated with 0.75×10^{17} e/cm^2



- **Amorphous phase regions were extended near film surface.**
  → The volume fraction of superconducting phase decreased.

TEM image of YBCO film irradiated with 0.75×10^{17} e/cm^2



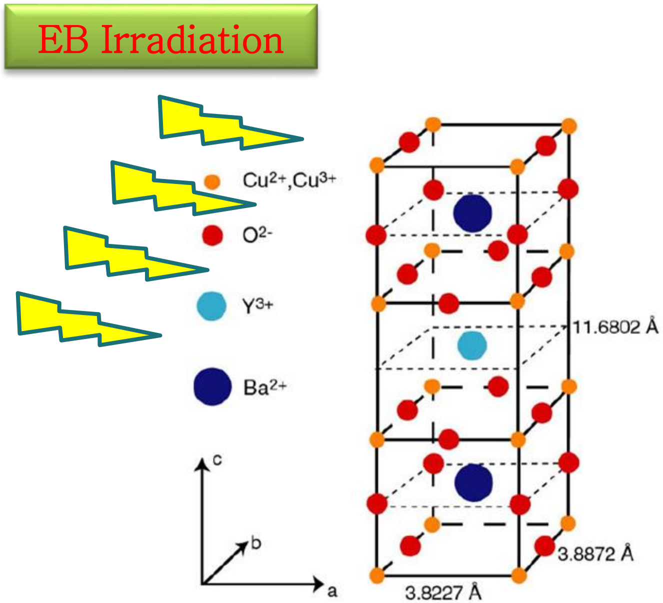


- The amorphous phase in a form of isolated region was often observed in the interior of the crystalline YBCO film.

Summary

J_c enhancement by EB irradiation

- J_c increase factor (at 0.75×10^{16}, 2.25×10^{16} e/cm^2)
  - Lattice distortion (FWHM)
  - Oxygen vacancies (*c*-axis)
  - Stacking faults (linear striation)
  - Point defect, dislocation etc.



- J_c decrease at the high level of EB dose
  - Extended amorphous phase
    → Reduced superconducting volume

Conclusions

- **As the electron dose increases, the T_c of YBCO film decreased, whereas the J_c increased : maximum J_c at the dose of 2.25×10^{16} e/cm^2. Further increase of EB dose decreased the J_c of YBCO films: There is an optimum level of an EB dose for enhancing J_c.**
- **The TEM image and XRD analysis for the irradiated YBCO films showed that the lattice distortion (the increase of *c*-lattice parameter and stacking faults) was observed, which appeared to be the cause for J_c increase.**
- **As the EB dose increased, the amorphous layer formed near the film surface and the volume fraction of amorphous layer increased. The extension of the amorphous layer, which reduces the volume fraction of a superconducting phase, was the cause for the J_c decrease of YBCO films at the high level EB dose.**

Thank you for your attention!