Materials Aspects and Application of Superconductivity

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- Brief introduction to Superconductivity
- Materials Aspects
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Brief introduction to superconductivity

Electrical Resistance (Resistivity)

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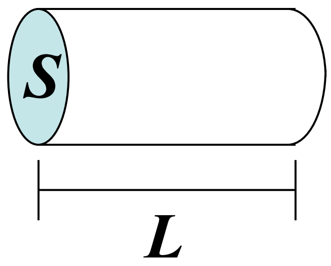
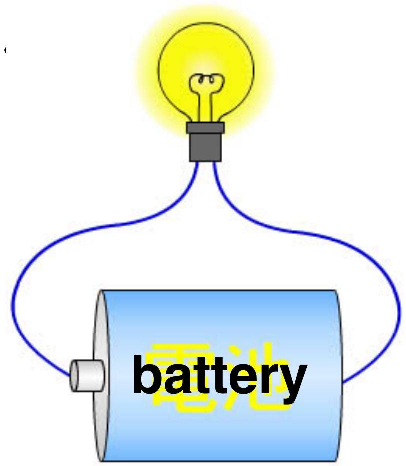
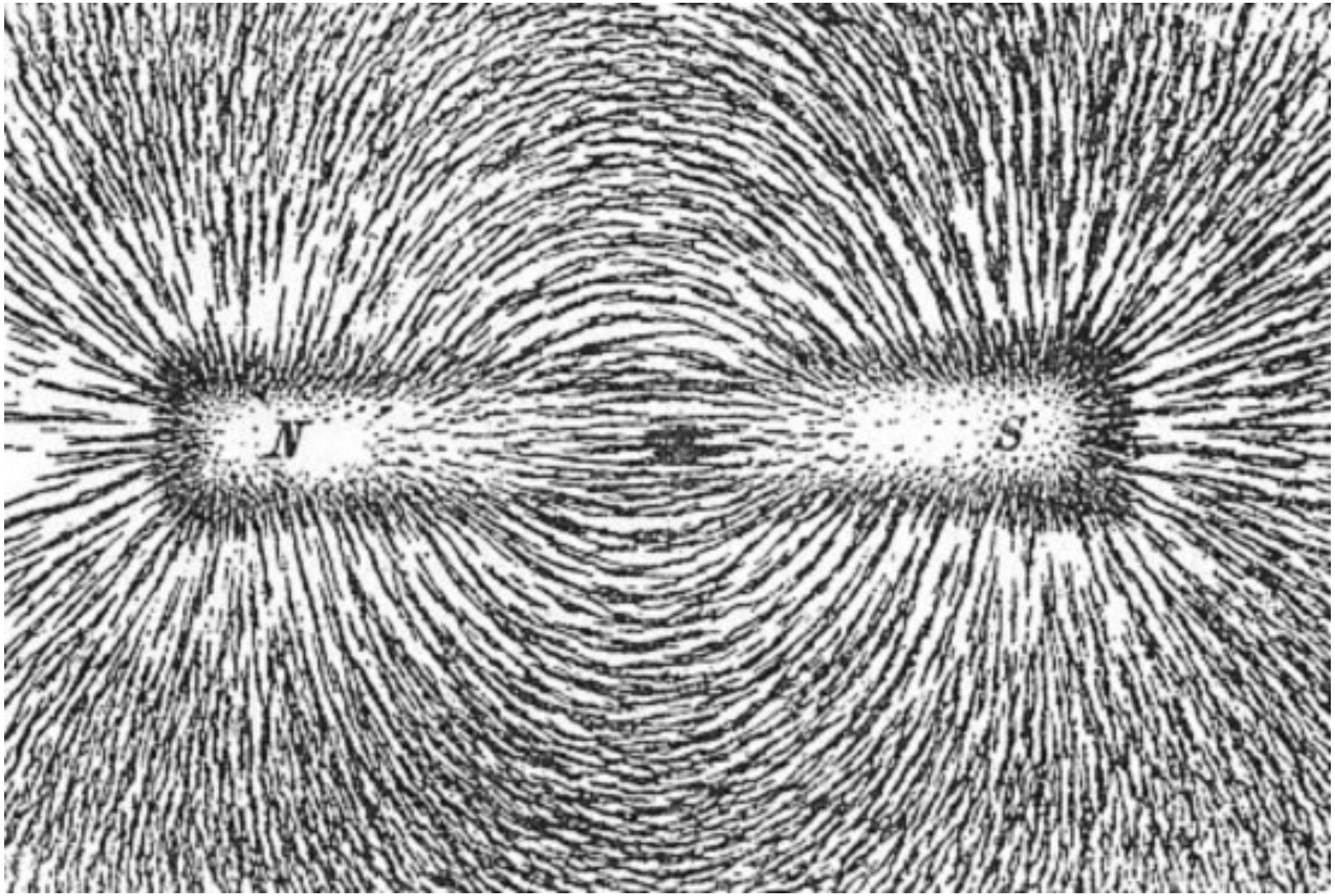
- Ohm's law: $V=RI$
  - V: voltage, I: current, R: resistance
  - R depends on amount of material.
- $R=\rho L/S$
  - ρ: resistivity, L: length, S: cross-section
  - ρ is material constant.
- Joule heat (energy)
  - $W=I^2R$





Magnetic force lines



What is superconductivity?

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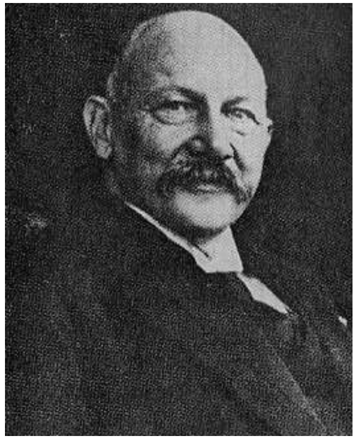
- In some materials, electrical resistance is absolutely zero below a certain temperature. This phenomenon is called "superconductivity" and this characteristic temperature is called "critical temperature" or "superconductivity transition temperature" (T_c).
- T_c is very low in our normal sense (its present world record at ambient pressure is 133 K (-140˚C)), however, if T_c is higher than 77 K (-196˚C), we can use cheap liquid nitrogen instead of too expensive liquid helium (4.2 K) for cooling.

1911: discovered by H. K. Onnes

(Leiden Univ., Netherland)



- Resistivity of metals
  - decreases as temperature (*T*) lowers.
- At absolute zero (0 K, -273˚C), does it go down to zero or diverge to infinity?
  - Using highly pure metal (mercury; Hg) and liquid helium (liq. He), Onnes measured temperature-dependence of resistivity, and then, discovered "Superconductivity".
  - Hg is liquid at room-temperature, so Hg is easily vaporized. By re-condensation, highly pure Hg can be obtained.

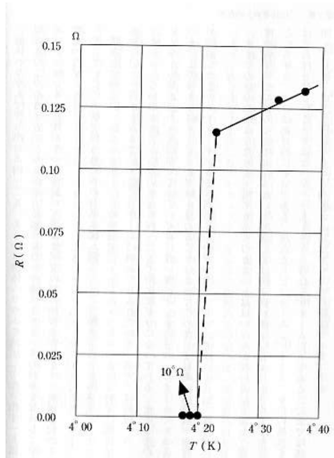


図3.2 カメリン・オンネス教授の超電導の発見
(10^{-5}Ωは計測器限界を表示している)
H.Kamerlingh Onnes, Leiden Communications, No124 (1911)

Characterics
(on the standpoint of Physics)

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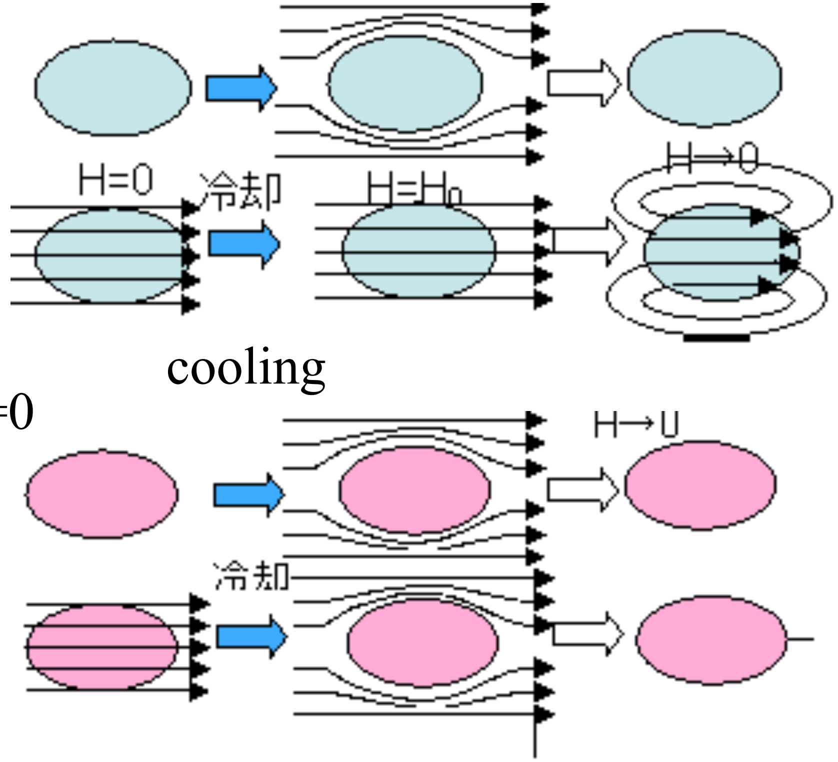
- Characteristics of superconductivity is not only "zero resistance" but also •••
  - zero Joule loss: energy saving
- Perfect Diamagnetism: type I superconductor
  - exclude magnetic flux
  - In type II, this is "imperfect".
- Quantum Vortex
- Josephson Effect

Type I Superconductor ≠ Perfect conductor

room-temperature



cooling

H=0

normal state

superconducting state

perfect conductor

$$\frac{\partial \boldsymbol{B}}{\partial t} = 0$$

superconductor

$$\frac{\partial \boldsymbol{B}}{\partial t} = 0$$

$$\boldsymbol{B} = 0$$

by London

Superconductor ≠ Perfect conductor

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- Maxwell's equations

$$\nabla \bullet \boldsymbol{D} = \rho$$

$$\nabla \times \boldsymbol{E} = -\frac{\partial \boldsymbol{B}}{\partial t}$$

$$\nabla \bullet \boldsymbol{B} = 0$$

$$\nabla \times \boldsymbol{H} = -\frac{\partial \boldsymbol{D}}{\partial t} + \boldsymbol{J}$$

  - $\boldsymbol{D}=\varepsilon_0\boldsymbol{E}+\boldsymbol{P}=\varepsilon_r\varepsilon_0\boldsymbol{E}=\varepsilon\boldsymbol{E}$, $\boldsymbol{B}=\mu_0\boldsymbol{H}+\boldsymbol{M}=\mu_r\mu_0\boldsymbol{H}=\mu\boldsymbol{H}$

- We can conclude that "*superconducting state*" and "*normal state*" are different phases from each other.

Why superconductivity: Application

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- Zero-resistance
  - very strong electromagnet (NMR, MRI ••••)
  - energy storage (SMES; superconducting magnetic energy storage)
- Diamagnetism
  - magnetic shielding
- Quantum Vortex
  - highly sensitive magnetic sensor (SQUID *etc.*)
- Josephson effect
  - highly sensitive magnetic sensor (SQUID *etc.*)

3 critical parameters

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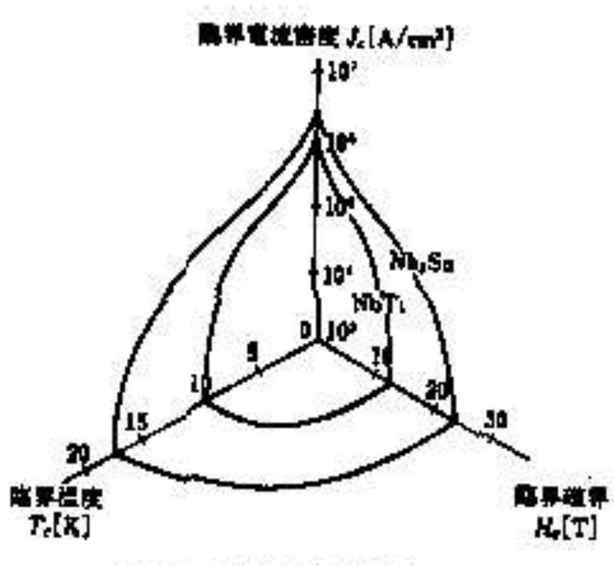
- Critical temperature (T_c)
- Critical field (H_{c1}, H_{c2})
- Critical current (J_c)
  - the most important parameter for practical application



Brief History of Superconductivity

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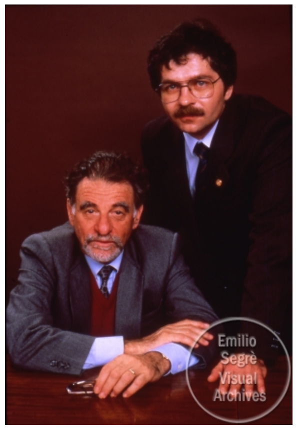
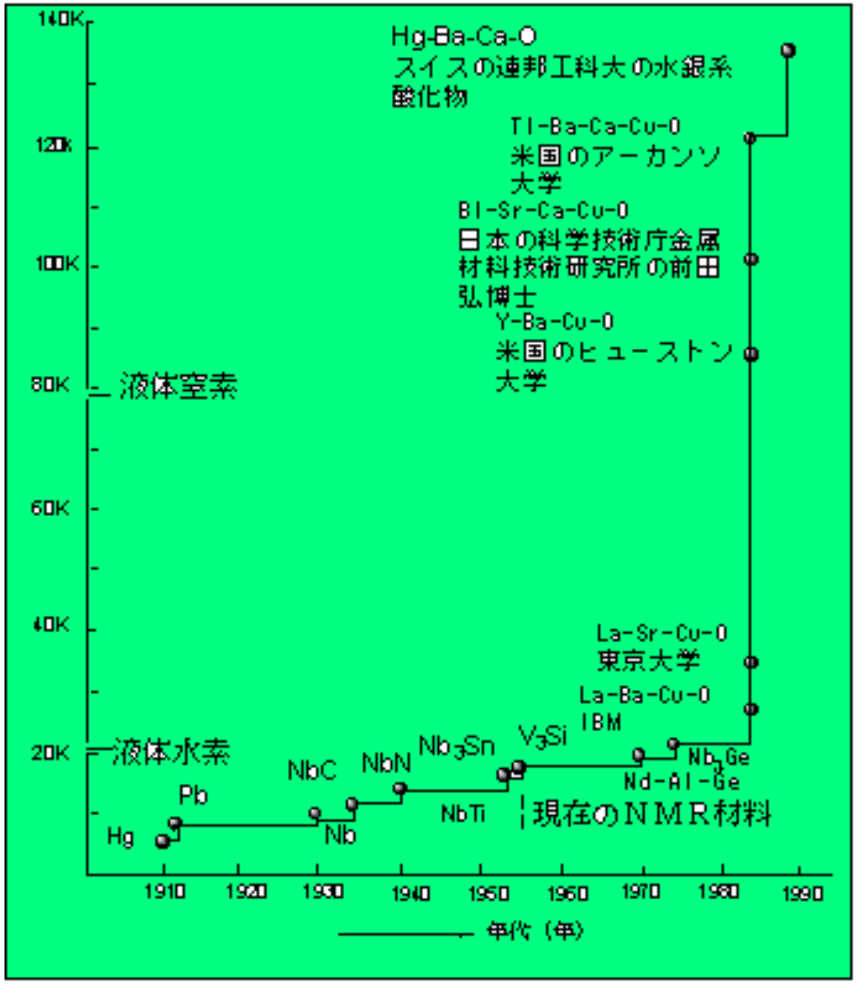
- 1908: Liquid Helium
- 1911: discovery of Superconductivity (Hg, Sn, Pb)
- 1933: Meissner effect
- 1935: London equation
- 1935-37: Type II Superconductor
- 1954: Nb_3Sn (18.5 K)
- 1960: GL theory
- 1961: Quantum Vortex
- 1961: NbTi (9.8 K)
- 1957: BCS theory
- 1962: Josephson effect
- 1974: Nb_3Ge (23.2 K)
- 1986: discovery of High-Temperature Superconductivity



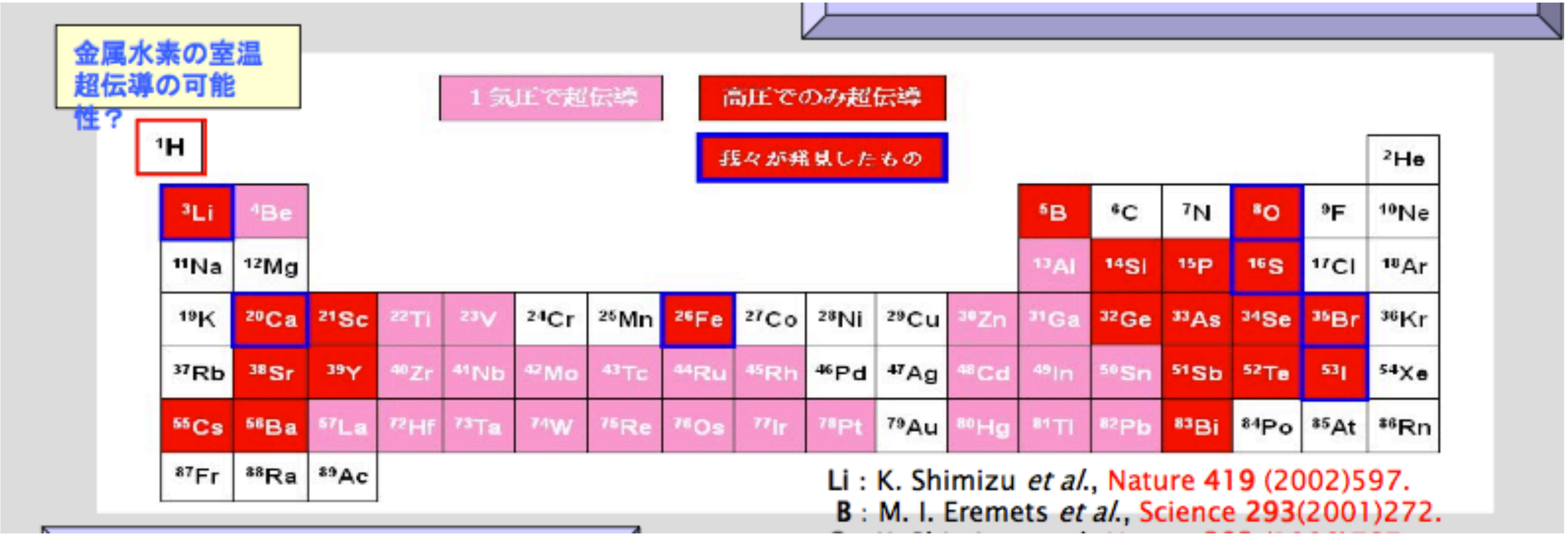
Increasing T_c: HTSC



Materials Aspects

Element superconductors

- Many elements exhibit superconductivity at 1 atm.
  - Hg, Pb, Sn, Nb, ••• (30 elements)
  - Under high-pressure, much more!)

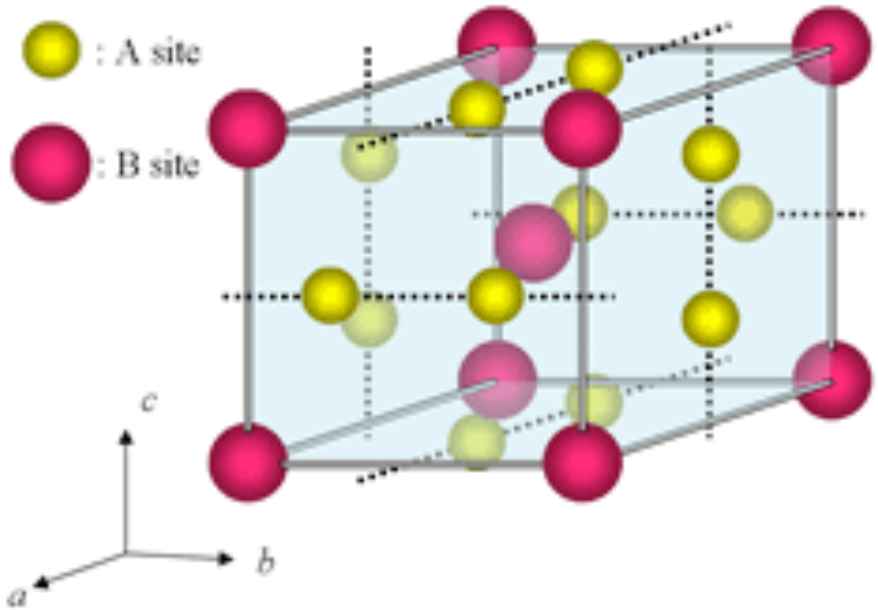


Other (Compound) superconductors

- Alloys: NbTi *etc.*
- Intermetallic compounds: Nb_3Sn, Nb_3Al *etc.*
- Organic compounds: $(TMTSF)_2PF_6$ *etc.*
- Sulfides: $PbMo_6S_8$ *etc.*
- Oxides (Cuprates: high-temperature superconductors)
  - $SrTiO_3$, $Ba(Pb,Bi)O_3$ *etc.*
  - $(La,Ba)Cu_2O_4$
  - $YBa_2Cu_3O_7$
  - $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$, $Tl_2Ba_2Ca_{n-1}Cu_nO_{2n+4}$ *etc.*
  - Fe-based Oxides (Arsenides): new comers

Conventional Superconductors

- At present, superconductors used for practical application are NbTi (bcc) and Nb_3Ti only.



Nb_3Sn: A15 structure

$YBa_2Cu_3O_z$

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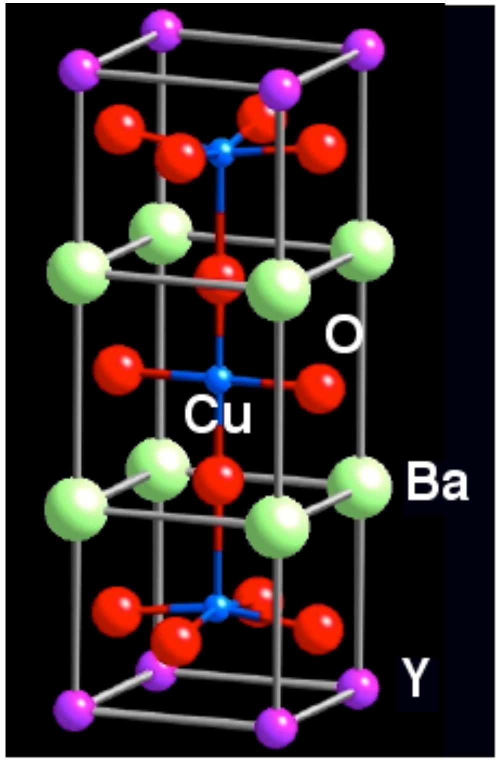
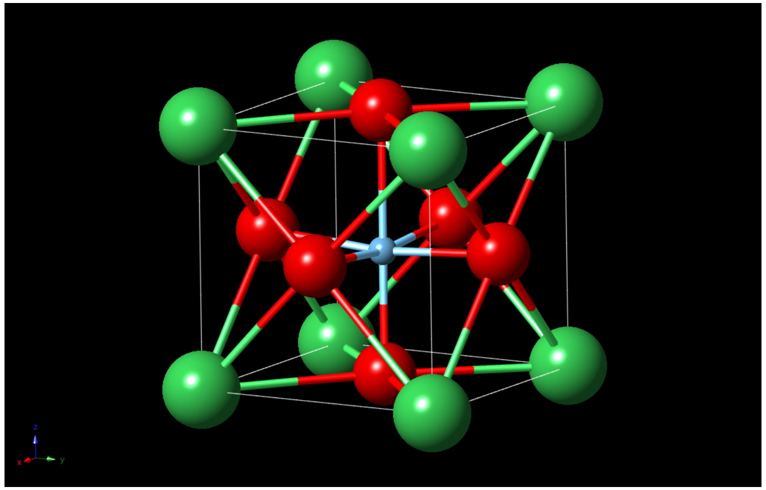
- The first material having T_c higher than 77 K (T_c≈90 K for z≈7; quite sensitive on z value).

- The structure is oxygen-deficient triple perovskite.



Perovskite structure

- Ionic crystal with chemical formula of ABO_3.
- Many functional oxides with 3d transition metals.
- The most famous one is (probably) $BaTiO_3$ in which TiO_6 octahedron is slightly distorted.



Examples of Application

Labo. application

High-field magnet

SQUID

NMR

Medical application (MRI)

- Magnetic Resonance Inspection

Transportation (MAGLEV)

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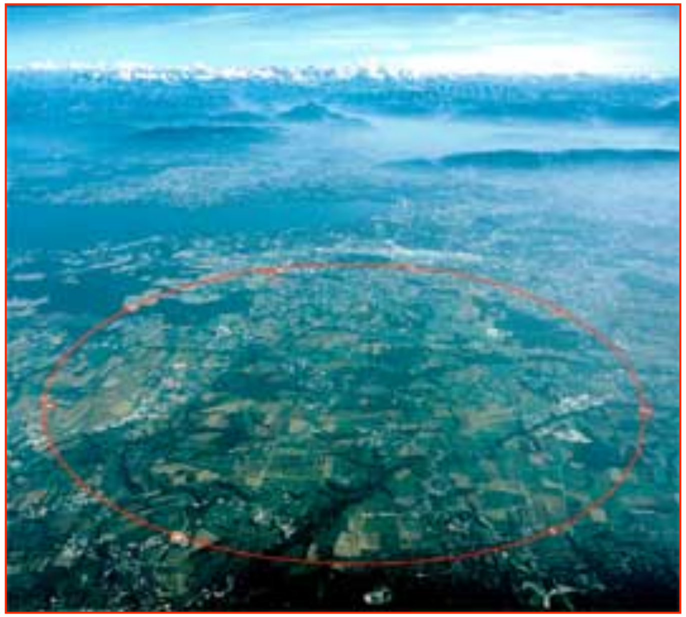
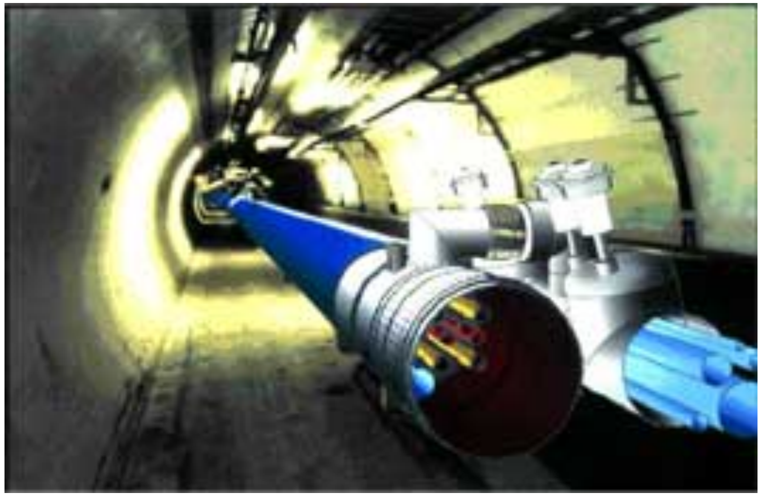
Magnetically Levitation Train

Apr. 21, 2015: World record: 603 km/h

Large scale application

- **LHC: Large hadron collider (CERN)**
  - **Nobel prize in 2013**
  - **Japanese suppliers contribute a lot.**





On going R&D

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Superconducting power cable

1st generation wire: Ag-sheathed $Bi_2Sr_2Ca_2Cu_3O_{10}$: powder sintering

2nd generation wire (epitaxial thin film)

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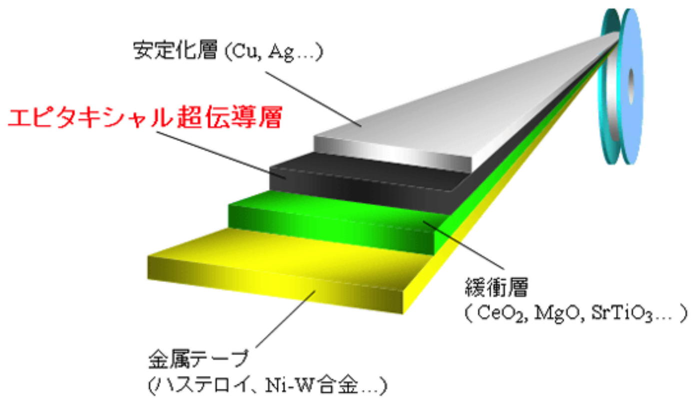
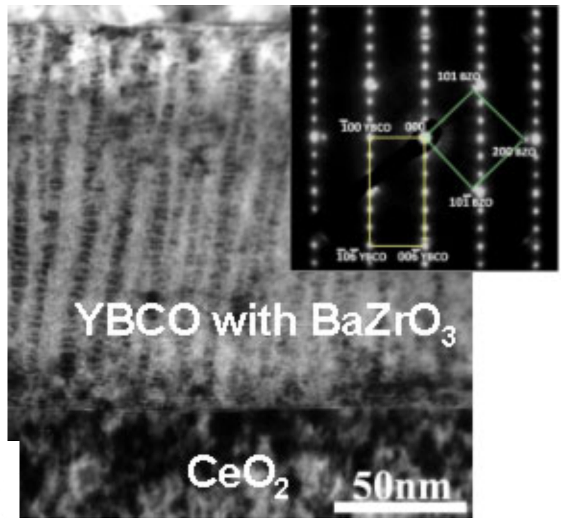
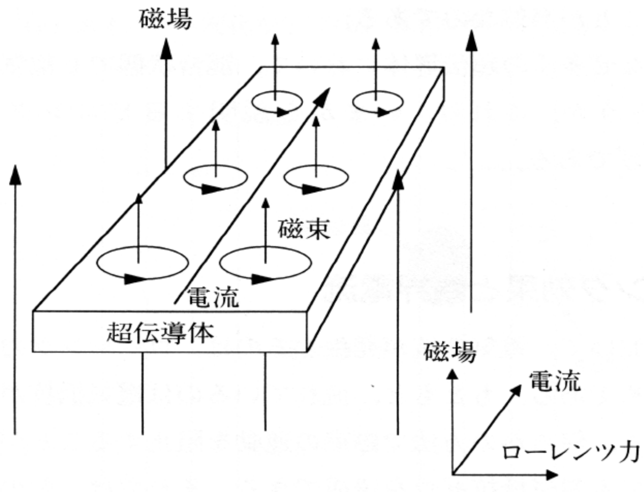
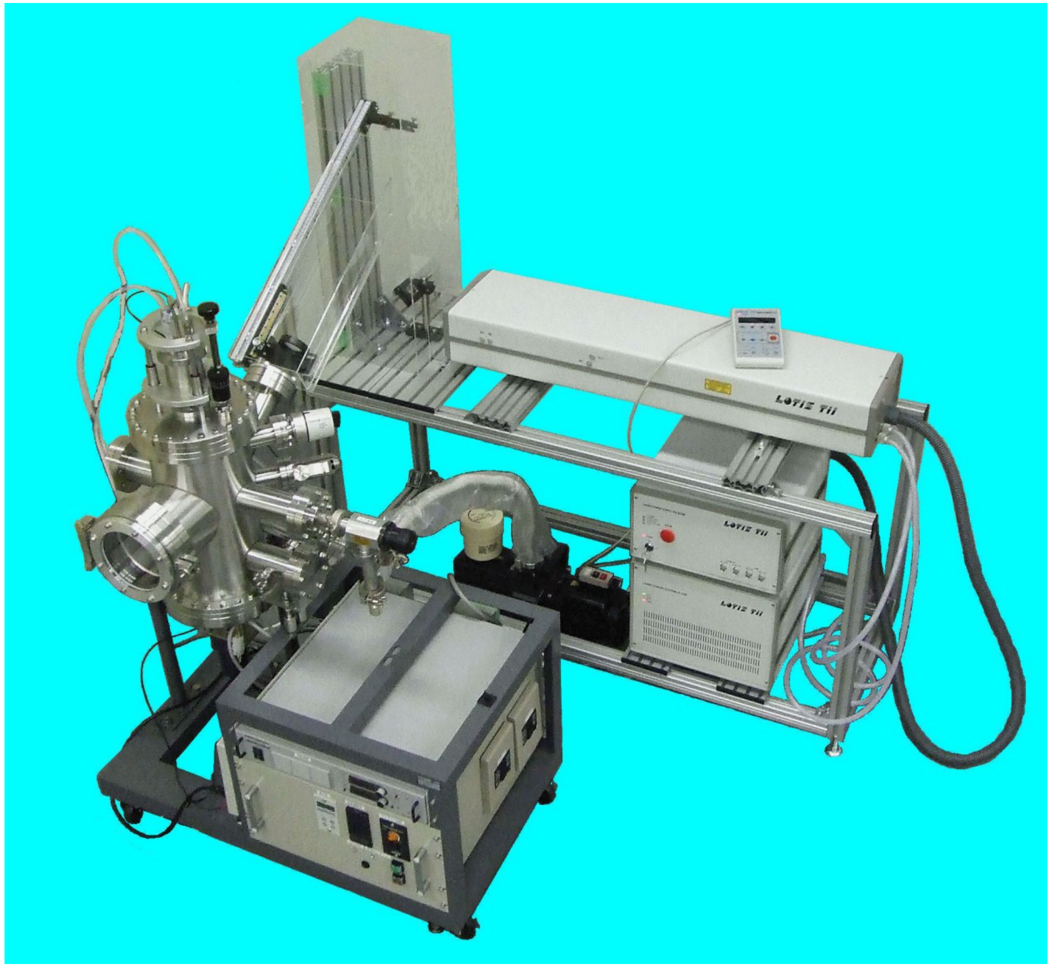


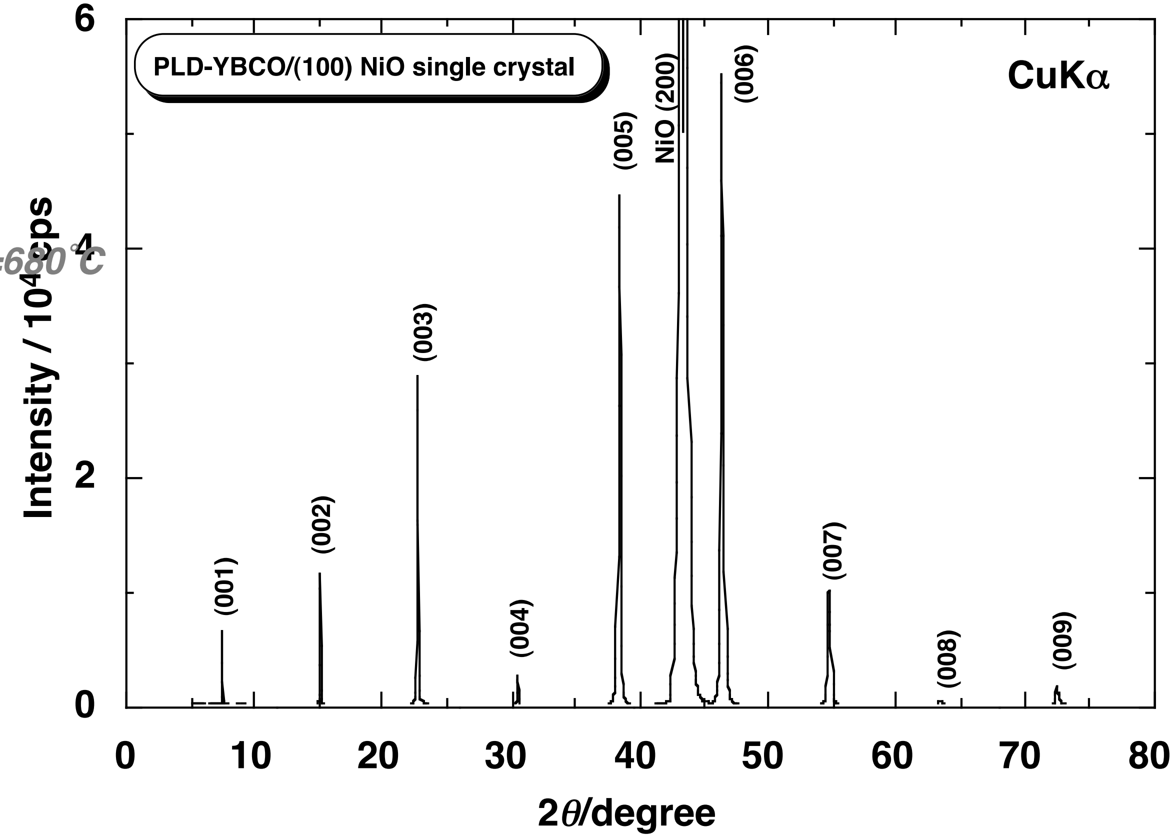




PLD apparatus



XRD profile of YBCO film



T_{sub}=680℃

Pole figure

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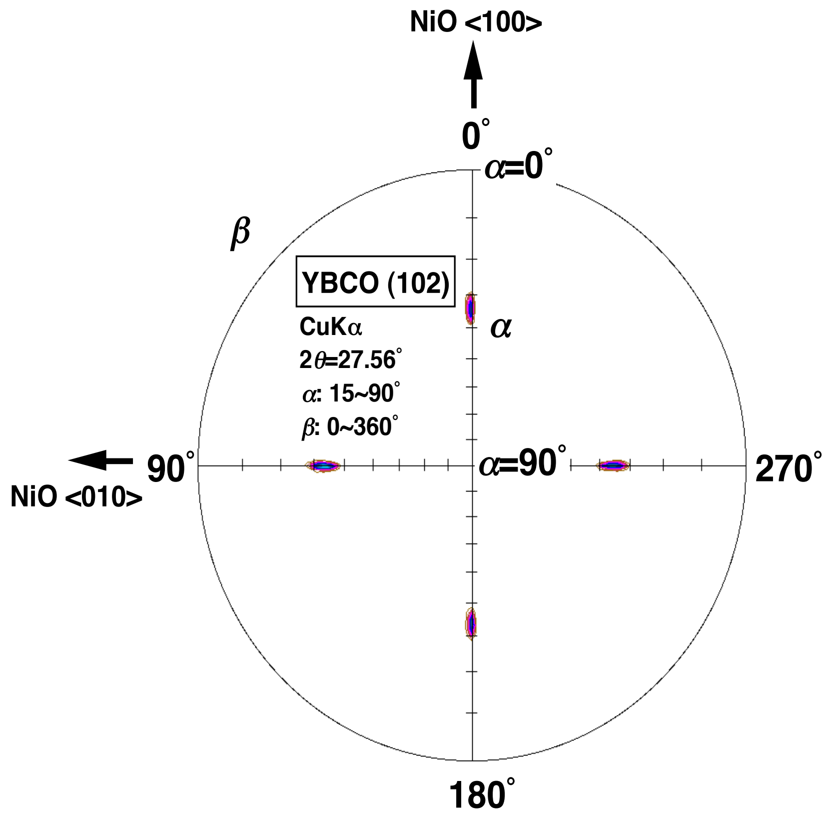

β-scan profile

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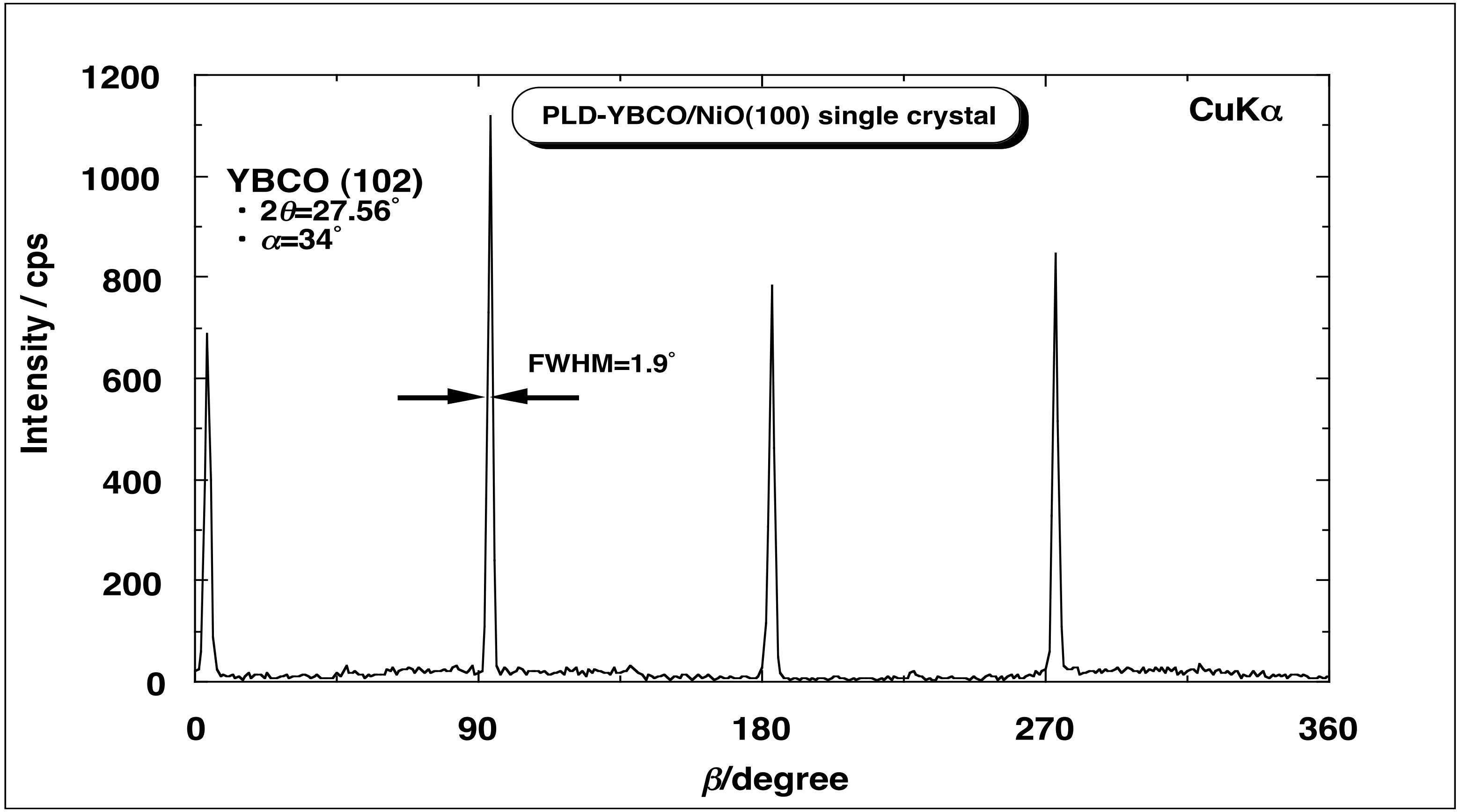
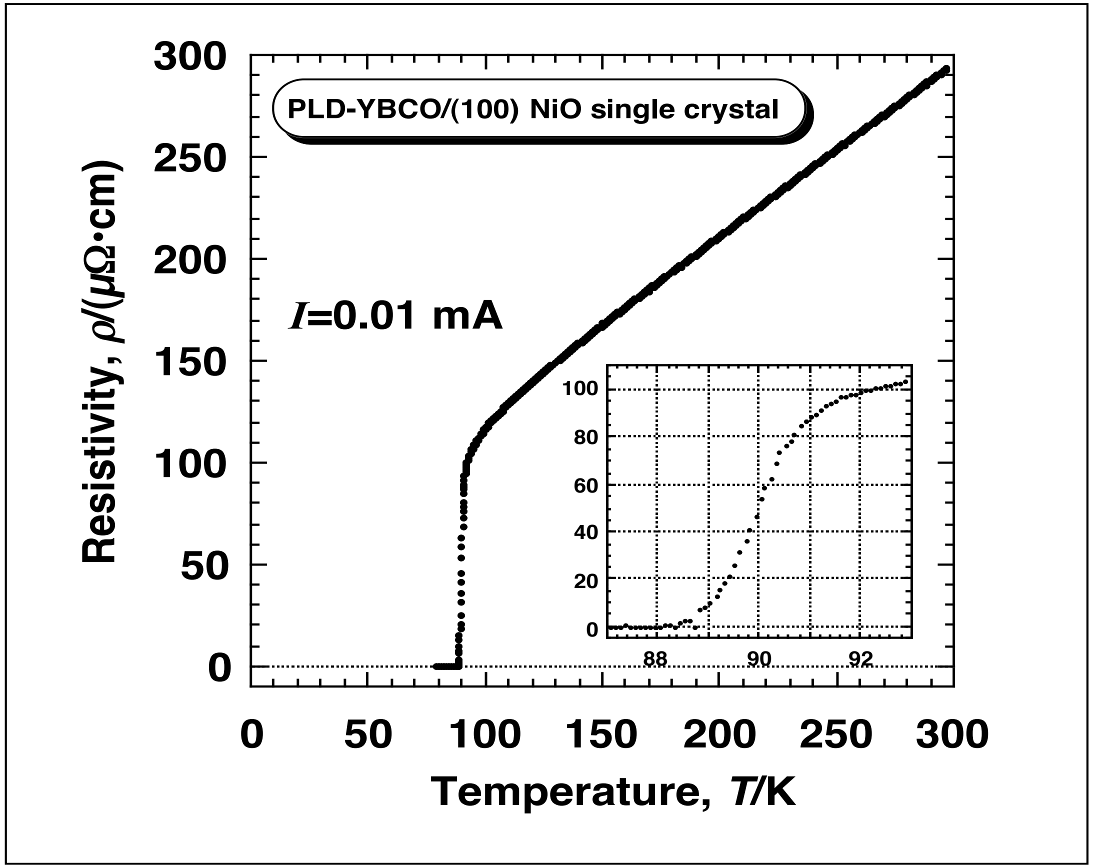
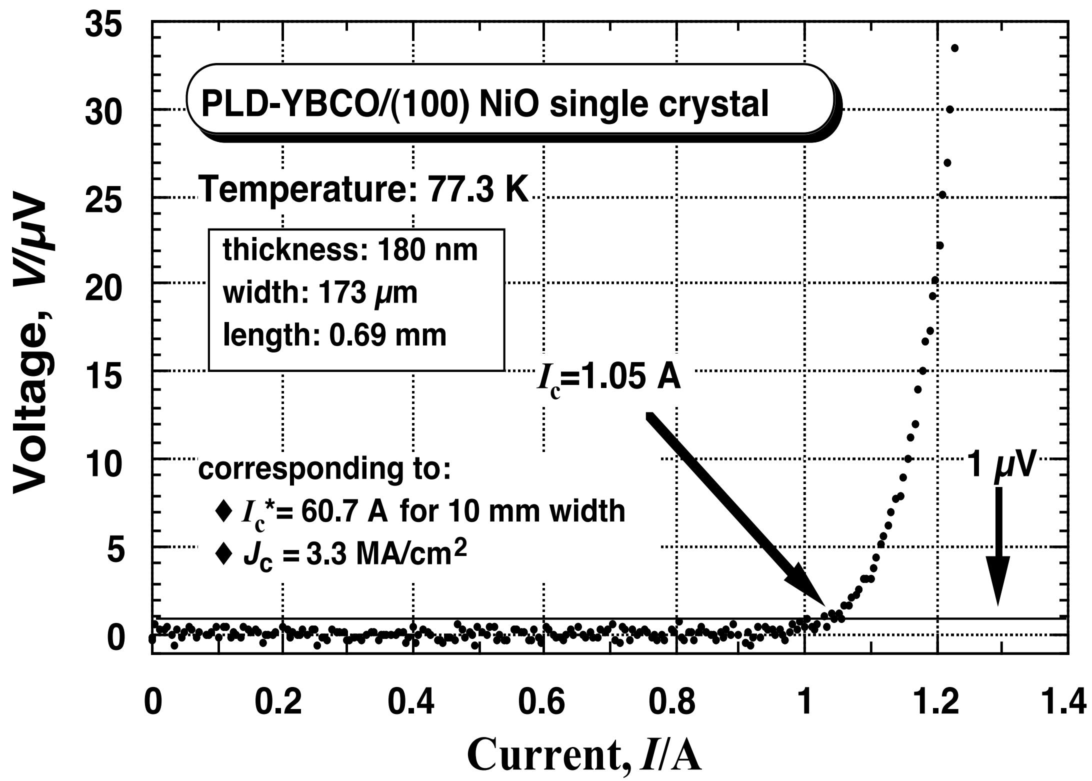


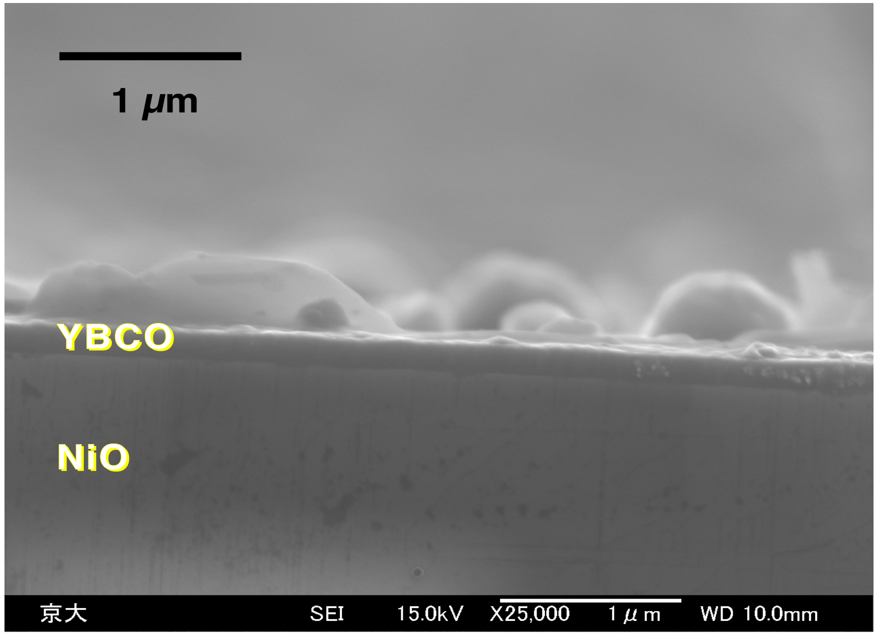
Temperature dependence of resistivity

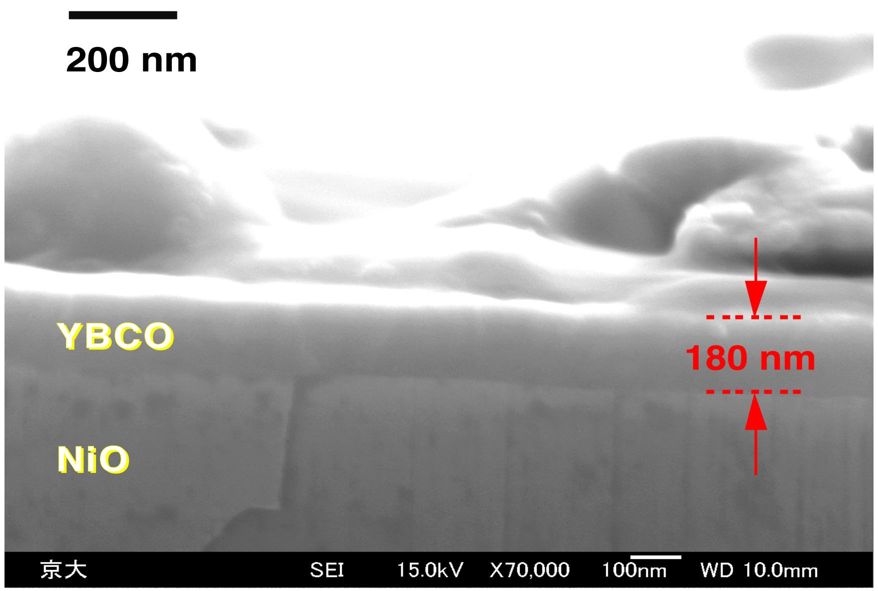


I-V characterics at 77 K



Cross sectional HRSEM images of fractured surface for PLD-YBCO/NiO structure





(taken by Kyoto Univ.)

TEM image of interface structure of PLD-YBCO/(100) NiO single crystal

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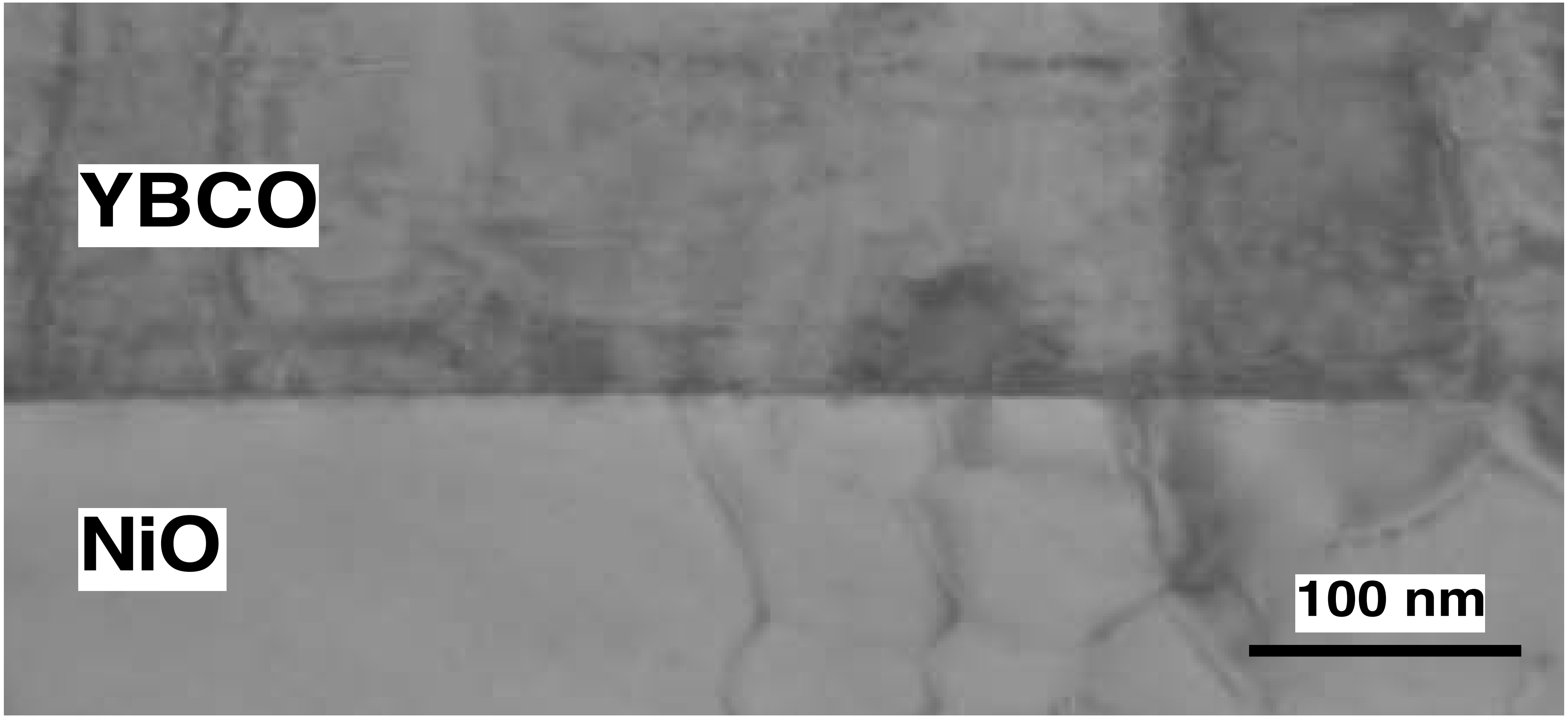

Summary

- **Superconductivity**
  - **hopeful**
  - **interesting**
  - **cute**

That's all !!

Thank you for your attention !!

Submit your report at the beginning of next lecture.