Superconductivity

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1.Introduction of superconductivity

1. Properties of superconductor

1. Brief history

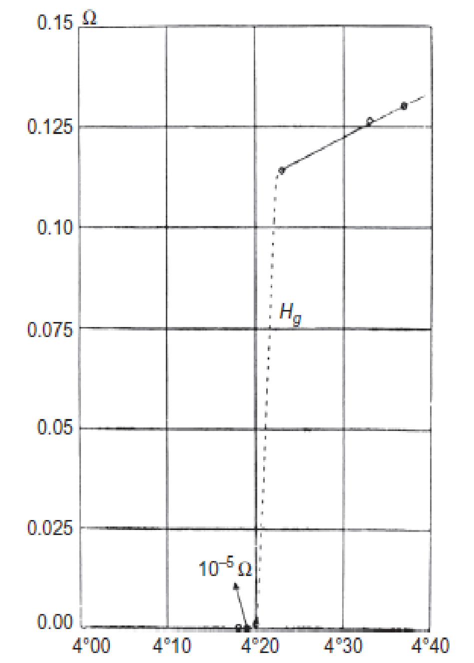
1. Main theories of superconductivity

1.1 Properties of superconductor

- A perfect superconductor is a material that exhibits two characteristic
  - **Zero electrical resistance**
  - **perfect diamagnetism**

- **Zero electrical resistance**
  exhibit perfect electrical conductivity

- Under a low temperatures (**Transition temperatures or Critical temperatures** (T_c))



-Poole, Charles P. et al. Superconductivity. San Diego: Elsevier, 2014. Print.

1.1 Properties of superconductor:

Perfect diamagnetism: Two aspects, relevant to **Meissner effect**

1.Flux exclusion:

material in the normal state **cooled below Tc** to the superconducting state **without** any **magnetic** field(zero-field-cooled (ZFC)). Then placed in an **external magnetic field**, the field will be **excluded** from the superconductor

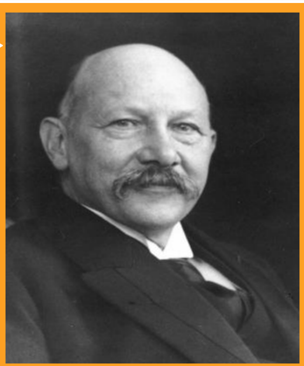
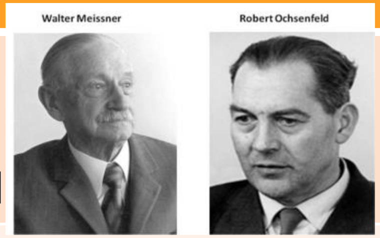
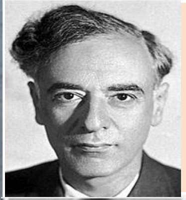
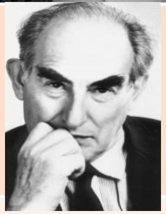
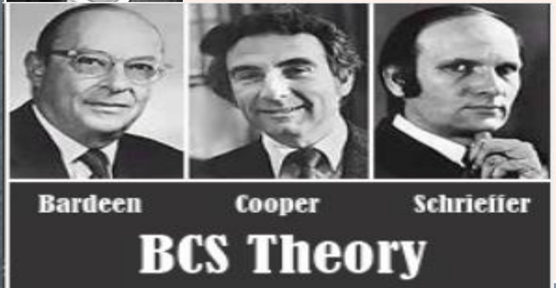
1.1 Properties of superconductor:

<u>Perfect diamagnetism:</u>

2. <u>Flux expulsion</u>:

material in the <u>normal state</u> placed in an **<u>external magnetic field</u>** first. Then **<u>cooled below Tc</u>** in the presence of this field, the field will be **<u>expelled</u>** from the material.

1.2 Brief history:

Heike Kamerlingh Onnes → 	**1911: Dc resistance of mercury dropped to zero when temperature below 4.15 K** **1912: strong axial magnetic field restored the resistance to its normal value.** **1913: lead was found to be superconducting at 7.2 K.**
 Walther Meissner and Robert Ochsenfeld	1933: Meissner effect
London brothers, Fritz(right) and Heinz(left) 	1935 :developed London equations explain to Meissner effect
 ← Lev Davidovich Landau Vitaly Lazarevich Ginzburg → 	1950 Ginzburg-Landau theory: describe superconductivity in terms of an order parameter
	1957 Bardeen–Cooper–Schrieffer theory (BCS theory)

1.2 Brief history:

- **Superconducting Transition Temperature Records Through the Years:**

Material	T_c (K)	Year
Hg	4.1	1911
Pb	7.2	1913
Nb	9.2	1930
$NbN0_{0.96}$	15.2	1950
Nb_3Sn	18.1	1954
$Nb_3\ (Al_{\frac{3}{4}}Ge_{\frac{1}{4}})$	20–21	1966
Nb_3Ga	20.3	1971
Nb_3Ge	23.2	1973
$Ba_xLa_{5-x}Cu_5O_y$	30–35	1986
$(La_{0\cdot 9}Ba_{0.1})_2CuO_{4-\delta}$ at 1 GPa	52	1986
$YBa_2Cu_3O_{7-\delta}$	95	1987
$Bi_2Sr_2Ca_2Cu_3O_{10}$	110	1988
$Tl_2Ba_2Ca_2Cu_3O_{10}$	125	1988
$Tl_2Ba_2Ca_2Cu_3O_{10}$ at 7 GPa	131	1993
$HgBa_2Ca_2Cu_3O_{8-\delta}$	133	1993
$HgBa_2Ca_2Cu_3O_{8-\delta}$ at 25 GPa	155	1993
$Hg_{0.8}Pb_{0.2}Ba_2Ca_2Cu_3O_x$	133	1994
$HgBa_2Ca_2Cu_3O_{8-\delta}$ at 30 GPa	164	1994

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Discuss Ba-La-Cu-O system later.

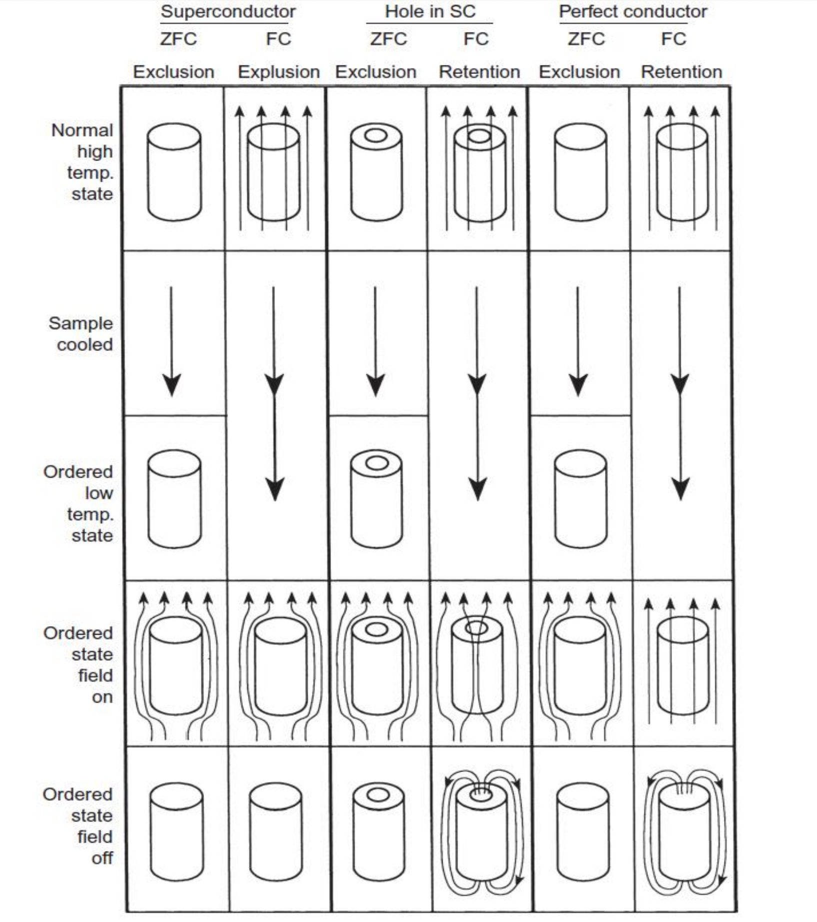
1.3 Main theories of superconductivity

- **<u>Meissner effect and London equations</u>**

- Ginzburg-Landau theory(GL theory)

- **<u>Bardeen–Cooper–Schrieffer theory (BCS theory)</u>**

Meissner effect and London equations:



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$$\frac{\partial \mathbf{j}_s}{\partial t} = \frac{n_s e^2}{m}\mathbf{E} \quad .....(1)$$

$$\nabla \times \mathbf{j}_s = -\frac{n_s e^2}{m}\mathbf{B} \quad .....(2)$$

Combined into a single London Equation in terms of A_s, which is vector potential

$$\mathbf{j}_s = -\frac{n_s e^2}{m}\mathbf{A}_s$$

Bardeen–Cooper–Schrieffer theory (BCS theory)

- Microscopic theory of superconductivity
- Explained successfully about low-temperature superconductivity

$$H_{BCS} = \sum_k \varepsilon_k \left(c_k^+ c_k + c_{-k}^+ c_{-k} \right) - \sum_{kk'} V_{kk'} c_{k'}^+ c_{-k'}^+ c_{-k} c_k$$

2.Different type of superconductor:

1. Depend on Magnetic field: Type I and Type II
2. Depend on Temperature: High Tc and Low Tc

2.1 Magnetic field:

When applied **<u>magnetic field(critical field(Hc))</u>** become large, superconductivity will breaks down.

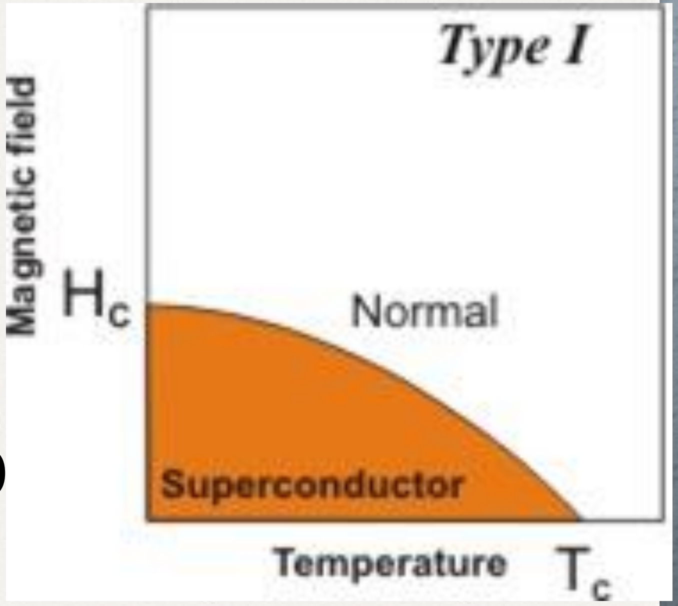
- Type I: The superconductors that are $TaSi_2$ and metal elements except for Nb & V
- Type II: The superconductors that are Nb, V, alloys & compounds

2.1 Magnetic field (Type I:)

- Only 1 **critical field(Hc) ,** which is usually small
- **Critical field** affected by the Temperatures: For T= Tc, the **critical field(Hc) =0**

$$H_c(T) = H_c(0)[1 - (T/T_c)^2]$$

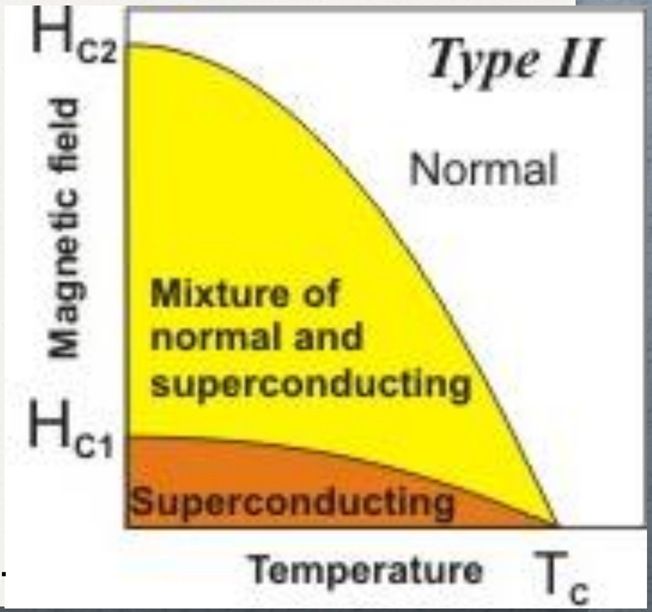
- When $H<H_c$,Perfect conductor ($\rho = 0$) and Meissner's effect ($B = 0$)
- When $H_c<H$, normal state $\rho \neq 0$ and $B \neq 0$



-Poole, Charles P. et al. Superconductivity. San Diego: Elsevier, 2014. Print.

2.1Magnetic field (Type II):

- 2 critical fields:H_{C1} and H_{C2} , which $H_{C2}>H_{C1}$
- When $0 < H < H_{C1}$, same as Type I($\rho = 0$ and $B = 0$)
- When $H_{C1} < H < H_{C2}$, mixed state ($\rho = 0$ but $B \neq 0$)
- When $H_{C2} < H$, normal state($\rho \neq 0$ and $B \neq 0$)



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2.2Temperature: High T_c and Low T_c

- **High-temperature superconductors(**High T_c **):** T_c>77K
- 77K is the boiling point of liquid nitrogen. For high temperature superconductors, liquid nitrogen can be used for superconductivity

- **Low-temperature superconductors(**Low T_c **):** T_c<77K
- For low temperature superconductors, required other method for superconductivity (eg. at high pressure)

3.Challenge in early days of superconductor

1. How early days look like

2. What’s the problem?

3.1 Early days of superconductor

- Transition-metal alloy compounds
  - A-15

    Ideal formula with A_3B

    (A is transition metal, B is right side of the periodic table)

e.g. Nb_3Ge

- Linear extrapolation
- 1000 years
- Room temperature

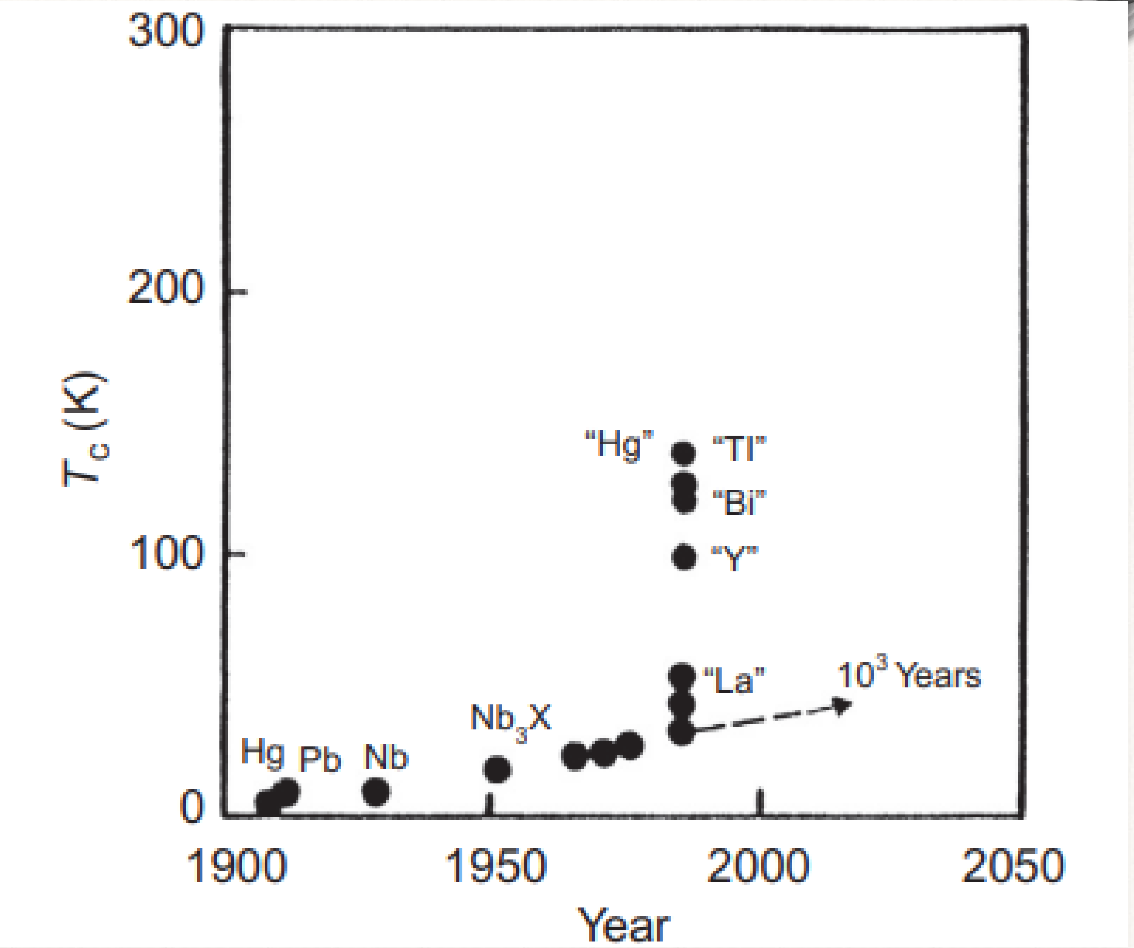


Figure: Increase in the superconducting transition temperature with time
Source:Poole et al., Copper Oxide Superconductors. Wiley, New York,NY. 1988.

3.2What’s the problem?

- Expensive!!!!
  - Using liquid helium to be coolant

- Not Useful at all
  - Require low temperatures

4.Ba - La- Cu- O System

1. What is Ba-La-Cu-O System
2. Why it is so important

4.1Ba - La- Cu- o System

- First ceramic material “high temperature” superconductor

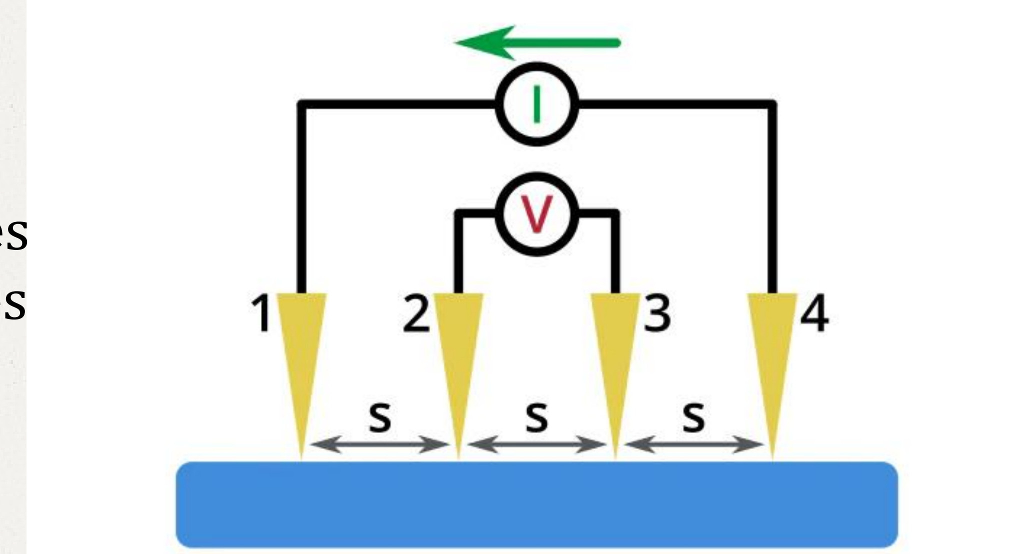
- Metallic oxygen-deficient compounds

  - With Composition $Ba_xLa_{5-x}Cu_5O5(3-y)$

4.1Method of measurement

- Four point method

$$R_S = \frac{\pi}{\ln(2)}\frac{\Delta V}{I} = 4.53236\frac{\Delta V}{I}$$ ......(3)



From Ossila Calculate Sheet Resistance Using the Four-Probe Method

R_S is sheet resistance
ΔV is change in voltage between inner probes
I is current applied between the outer probes

$$\rho = R_S . t$$ ......(4)

ρ is resistivity
T is the thickness of material

4.1Result

Resistivity drop rapidly At around T=30

superconductor

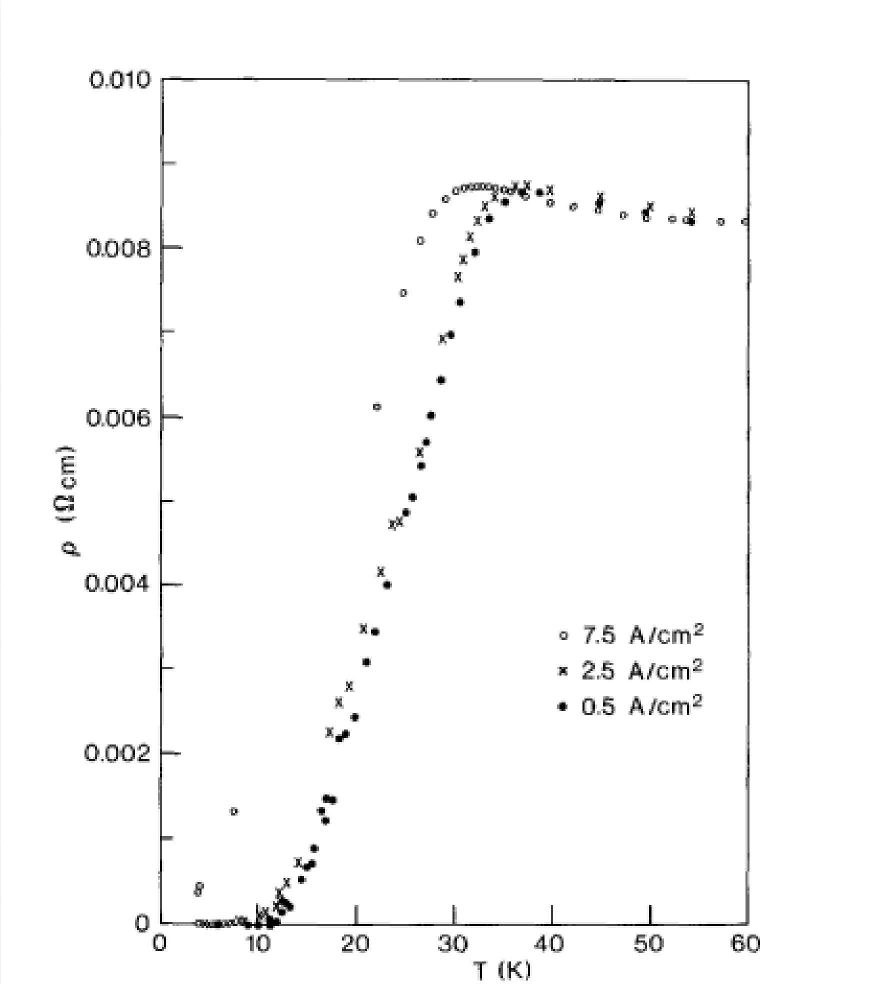
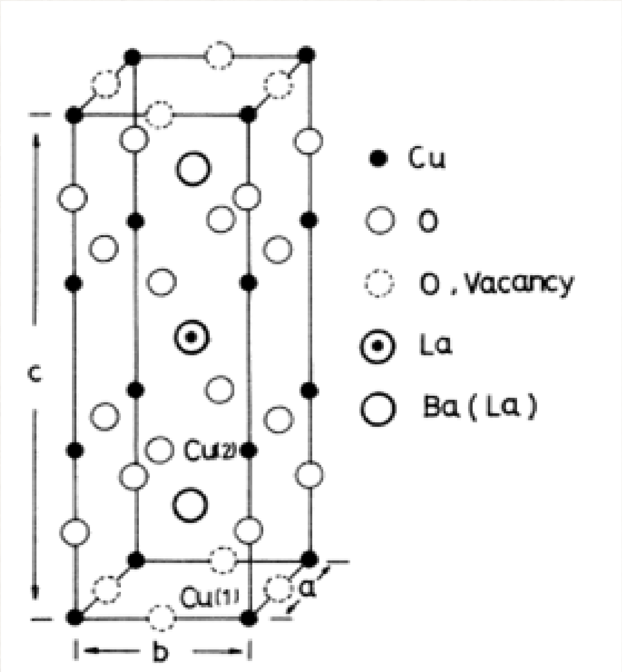


Fig. Resistivity in low temperature (x=0.75) with different current densities
–J.G. Bednorz and K.A. Miiller , "Possible High T c Superconductivity in the Ba - La- Cu- 0 System ", Phys. B - Condensed Matter 64, 189-193 (1986)

3D Structure

layer structure

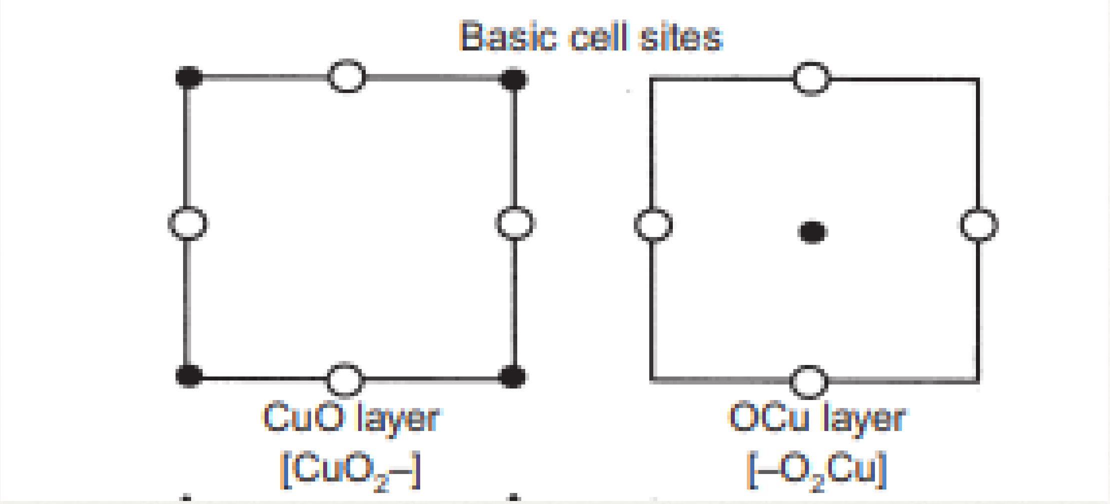


Unit cell Ba-La-Cu-O system
With lattice constant a=b=c/3

-Cheng Dong et al, “ Superconductivity and Crystal Structure in
the La-Ba-Cu-O System “, Physical review. B, Condensed matter (1988)

2D Structure

Cu-O plane



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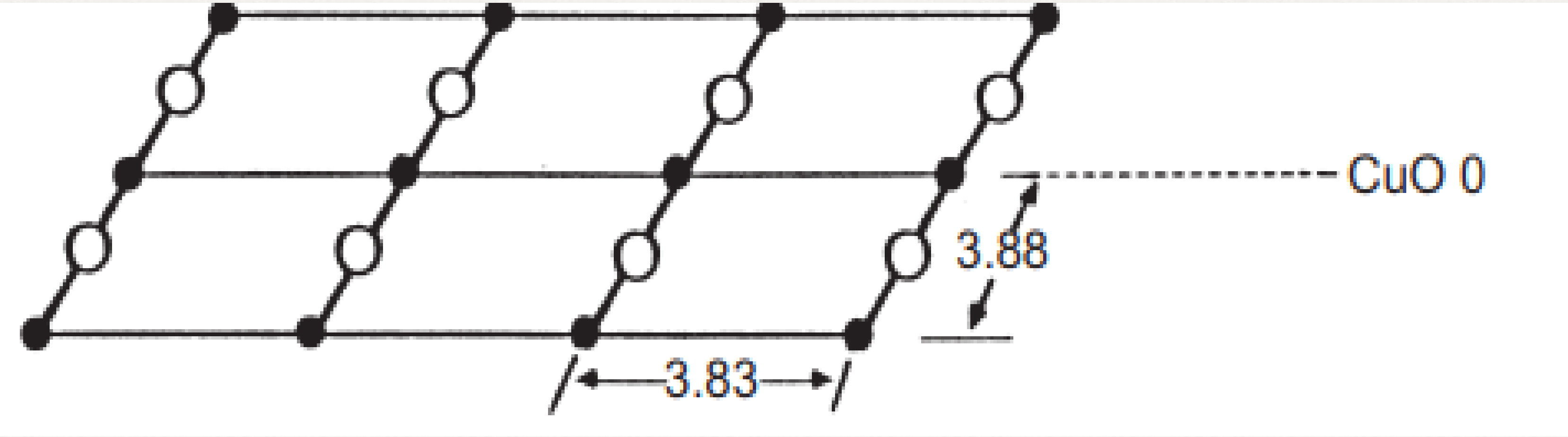
1D Structure

- Fence-like CuO Chain



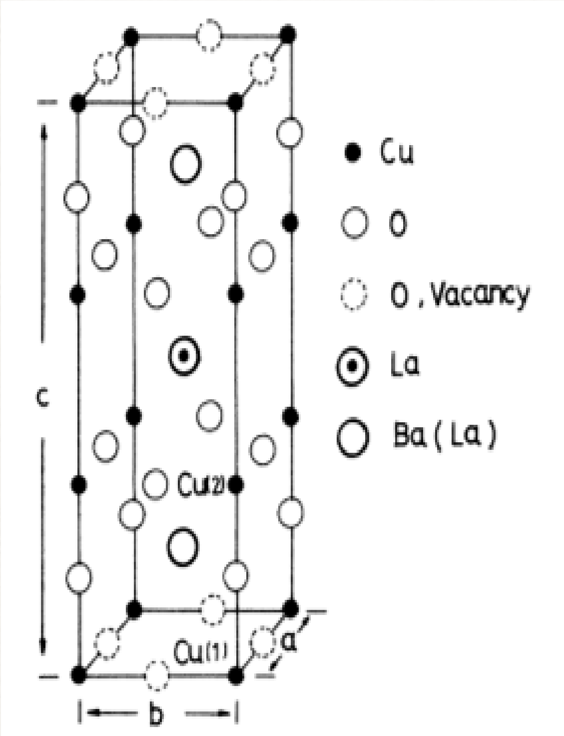
Source:Poole et al., Copper Oxide Superconductors. Wiley, New York,NY. 1988

Structure

Oxygen locate in b

Become orthorhombic

Superconductor



Unit cell Ba-La-Cu-O system
With lattice constant a=b=c/3

-Cheng Dong et al, " Superconductivity and Crystal Structure in the La-Ba-Cu-O System ", Physical review. B, Condensed matter (1988)

Cuprate superconductors

- Tc 10 times of A-15 in 8 years
- $HgBa_2Ca_2Cu_3O_{8-\delta}$ at 30 Gpa
- 164K

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Hg	4.1	1911
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5.Application

- Electric power equipment

Increase the Flux destiny

↓

Reducing the size

↓

Increase the efficiency

5.Application

2022 April Hong Kong

Electricity consumption:$1.7x10^{16}$ J

0.01%=$1.7x\ 10^{12}$ J

Reference

- Poole, Charles P. et al. Superconductivity. San Diego: Elsevier, 2014. Print. (Ch 2,4,5,6,7)
- https://archive.nptel.ac.in/content/storage2/courses/113104005/lecture33/33_4.html
- Poole et al., Copper Oxide Superconductors. Wiley, New York,NY. 1988
- Cheng Dong et al, " Superconductivity and Crystal Structure in the La-Ba-Cu-O System ", Physical review. B, Condensed matter (1988)
- J.G. Bednorz and K.A. Miiller , "Possible High T c Superconductivity in the Ba - La- Cu- 0 System ", Phys. B - Condensed Matter 64, 189-193 (1986)