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FACULTÉ DES SCIENCES

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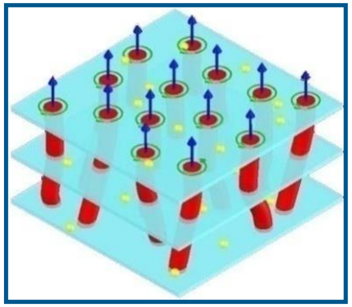
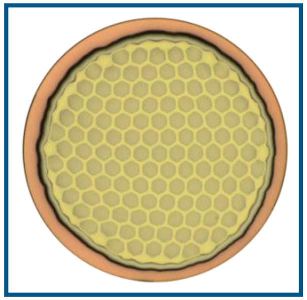
Superconductivity and its applications

Lecture 8





Carmine SENATORE

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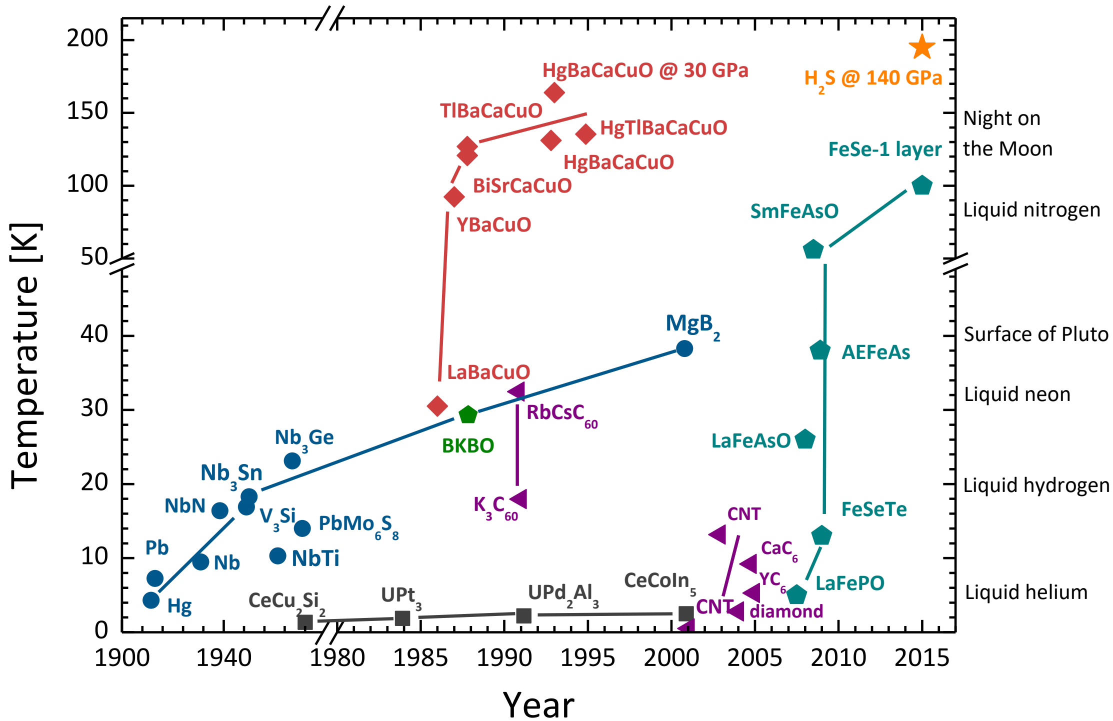
Previously, in lecture 7

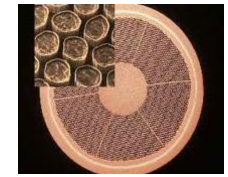
From superconducting materials…

…to technical superconductors

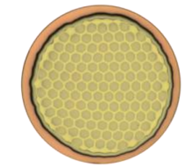


1. *Superconducting ?* *10'000*
2. *T_c>4.2K & B_{c2}>10T ?* *100*
3. *J_c>1000 A/mm^2 ?* *~10*

NbTi



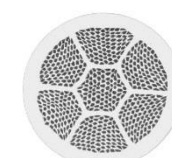
Nb$_3$Sn



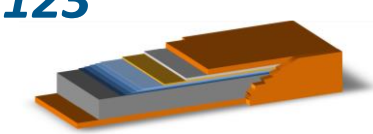
MgB$_2$

Bi2223

Bi2212



Y123



Previously, in lecture 7

	T_c [K]	B_{c2} [T]
NbTi	9.8	10.5
Nb_3Sn	18.0	30+
MgB_2	39.0	10-60

NbTi:
- Alloy
- Easy to produce in multifilamentary wires
- Wires does not need reaction heat treatment

Nb_3Sn, MgB_2:
- Intermetallic compounds
- Three different fabrication technologies
- Wires must be reacted after fabrication

Key parameter for J_c optimization

NbTi $\rightarrow$ α-Ti precipitates acts as pinning centers

Nb_3Sn $\rightarrow$ Grain morphology (pinning) and composition/doping (B_{c2})

MgB_2 $\rightarrow$ Doping (B_{c2}) and connectivity (densification)

Previously, in lecture 7

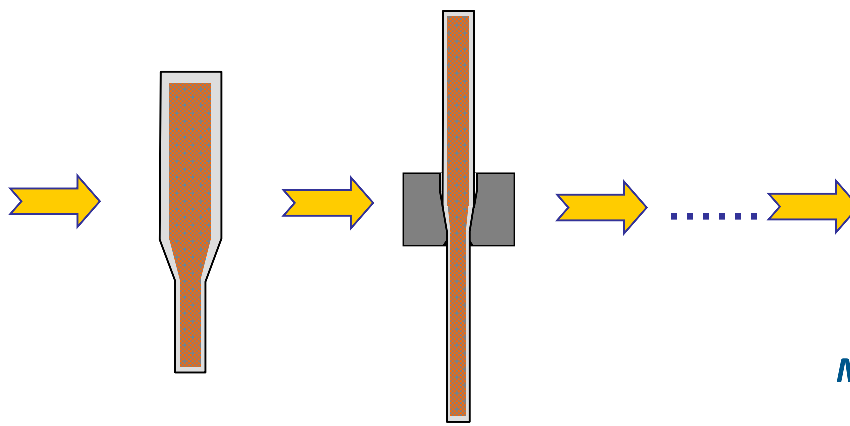
MgB_2 wires: fabrication by powder metallurgy

MgB_2 powders *ex-situ*

or

Mg + 2B powders *in-situ*

Swaging Drawing



Multifilamentary wire

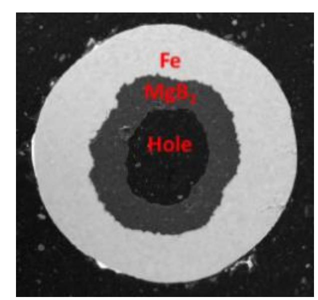
B powders

Mg rod

Internal Magnesium Diffusion (IMD)

In IMD wires, Mg diffuses into B powders during the heat treatment and forms very dense MgB_2

Drawback: a hole is left at the place of the Mg rod



Monofilamentary wire

Previously, in lecture 7
Relevant HTS families

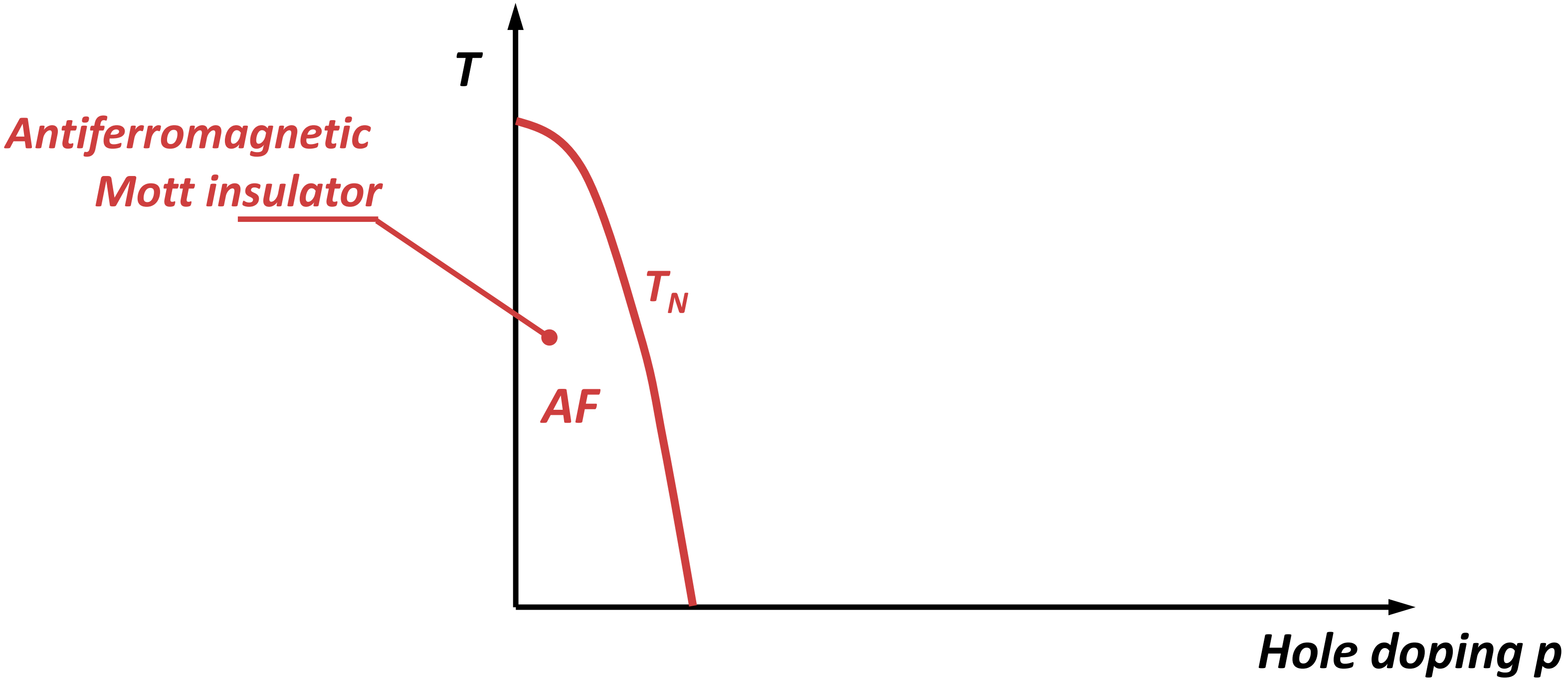
hole-doped: REBCO, Bi family, Tl families, Hg family

electron-doped

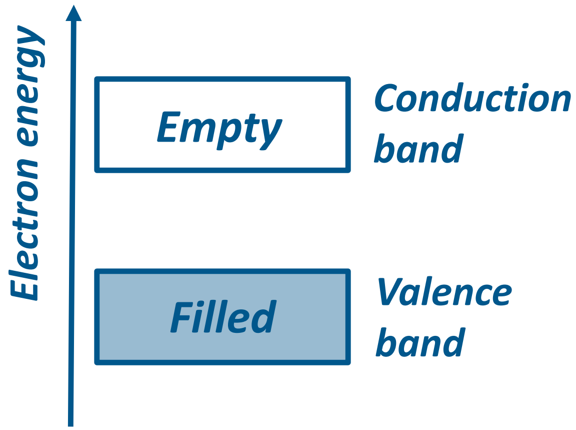
Compound	T_c [K]	Short name
$La_{1.85}Sr_{0.15}CuO_4$	39	LaSCO
$YBa_2Cu_3O_7$	92	Y123 or YBCO
$Bi_2Sr_2CuO_6$	15	Bi2201
$Bi_2Sr_2CaCu_2O_8$	91	Bi2212
$Bi_2Sr_2Ca_2Cu_3O_{10}$	110	Bi2223 or BSCCO
$Tl_2Ba_2CuO_6$	90	
$Tl_2Ba_2CaCu_2O_8$	110	
$Tl_2Ba_2Ca_2Cu_3O_{10}$	125	Tl2223 or TBCCO
$TlBa_2CaCu_2O_7$	91	
$TlBa_2Ca_2Cu_3O_9$	116	
$TlBa_2Ca_3Cu_4O_{11}$	122	
$HgBa_2CuO_4$	95	
$HgBa_2CaCu_2O_6$	122	
$HgBa_2Ca_2Cu_3O_8$	133	Hg1223
$Nd_{1.85}Ce_{0.15}CuO_4$	25	NCCO

Record T_c of ~165 K under high pressure

A quick introduction to the HTS phase diagram



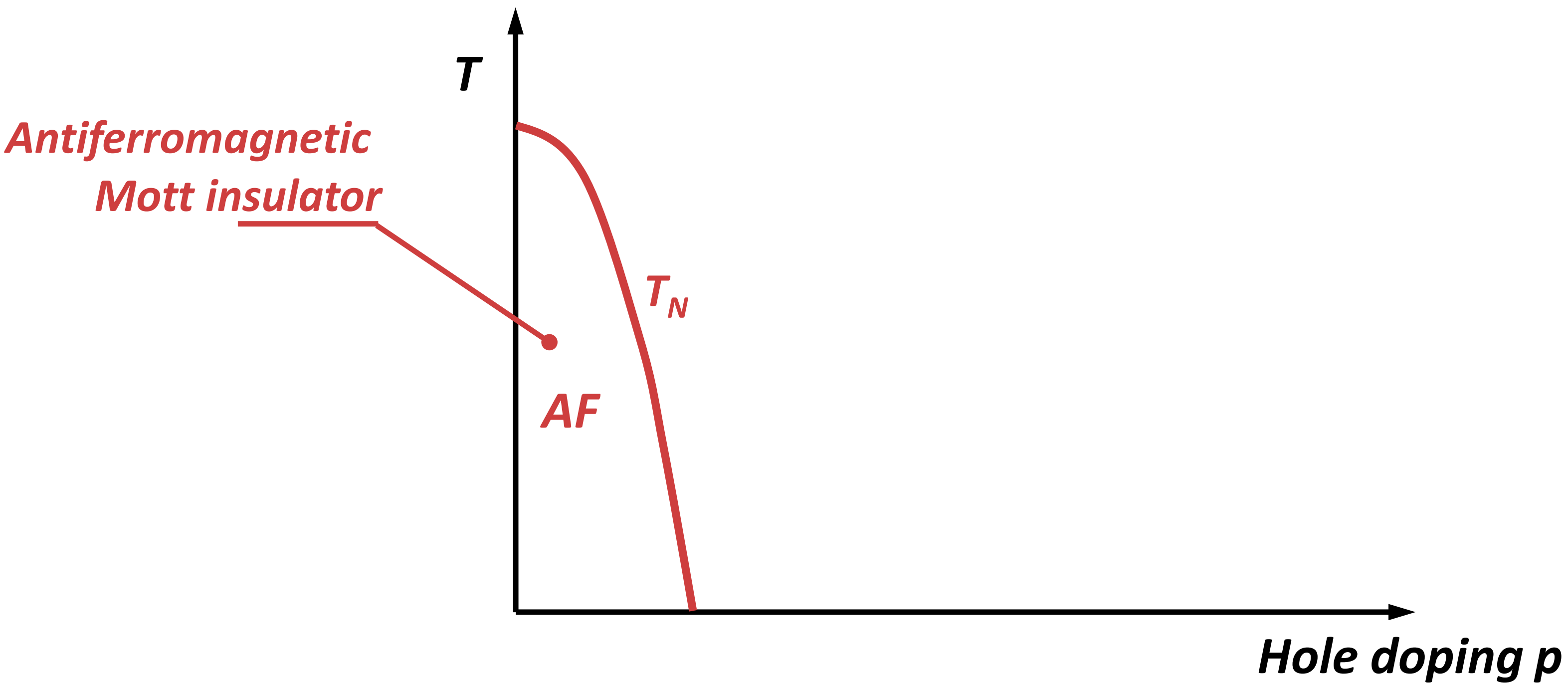
Band (Bloch-Wilson) insulator



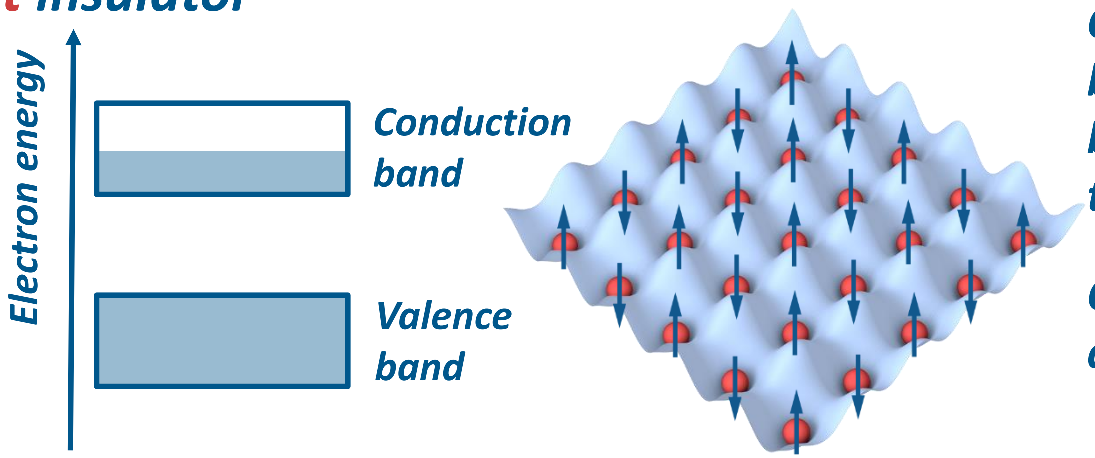
HTS are copper oxides

The undoped parent compounds are antiferromagnetic Mott insulators

A quick introduction to the HTS phase diagram



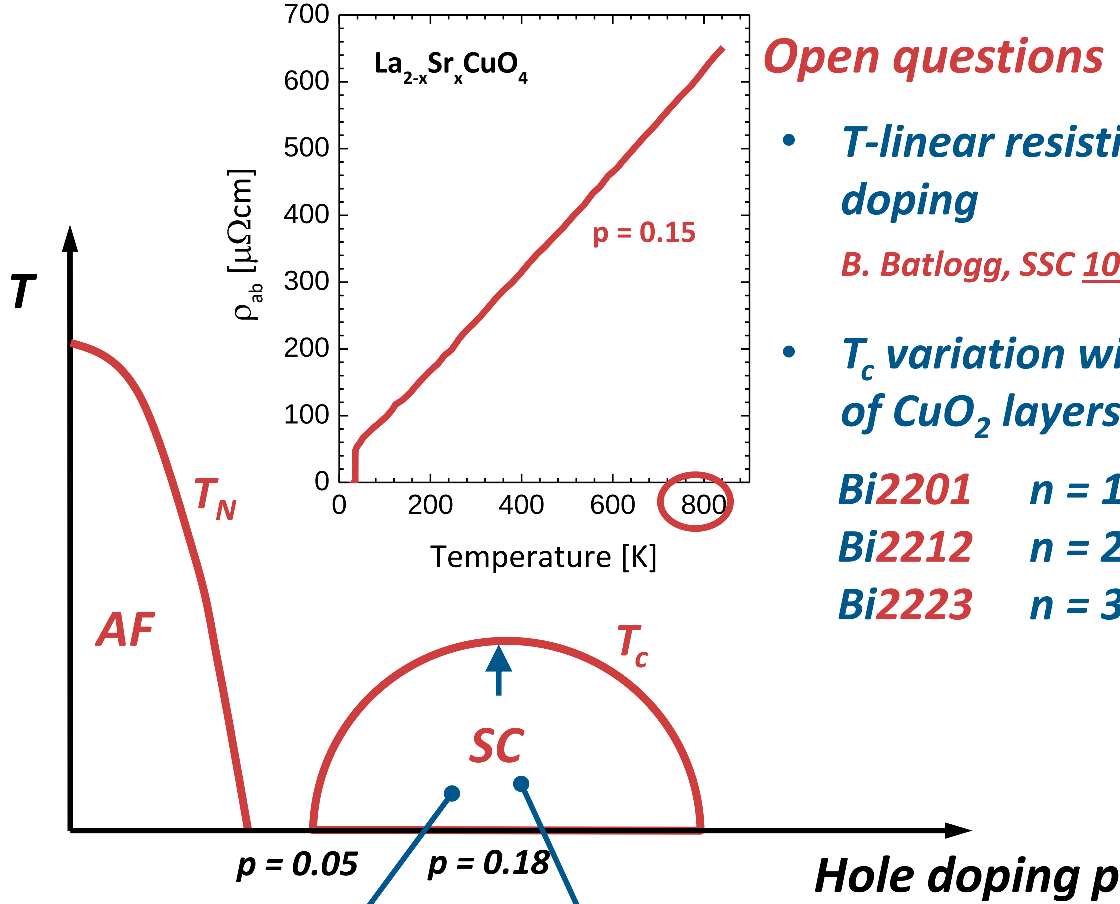
Mott insulator



Only one electron per site
but the strong Coulomb repulsion
between the electrons impedes
their flow

On the top of that the
antiferromagnetic interaction

A quick introduction to the HTS phase diagram



Open questions

- *T-linear resistivity at optimal doping*

  B. Batlogg, SSC 107 (1998) 639

- *T_c variation with the number of CuO_2 layers*

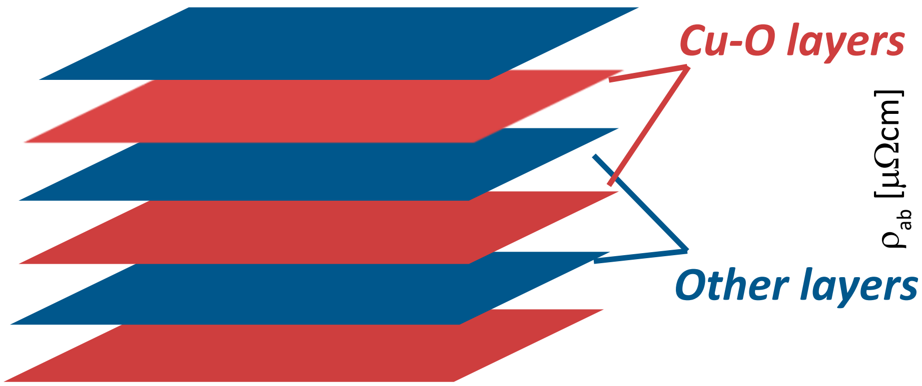
Bi2201	n = 1	T_c = 15 K
Bi2212	n = 2	T_c = 91 K
Bi2223	n = 3	T_c = 110 K

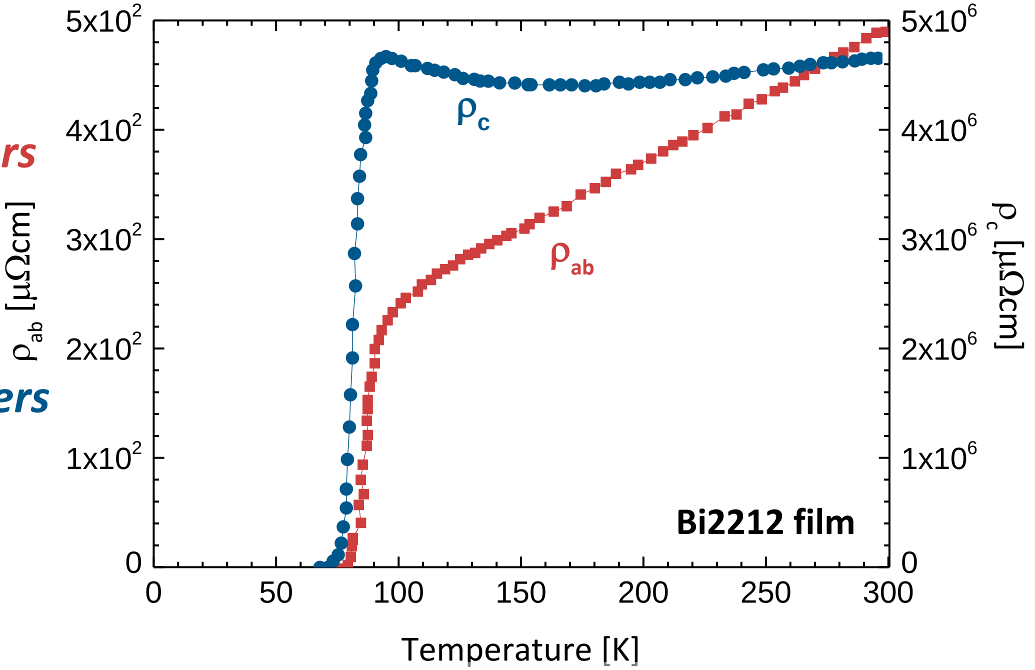
Superconductivity arises in the CuO_2 planes

Macroscopic Ginzburg-Landau describes the electromagnetic properties

Layered structure and Anisotropy

$\rho = \frac{m}{ne^2\tau}$





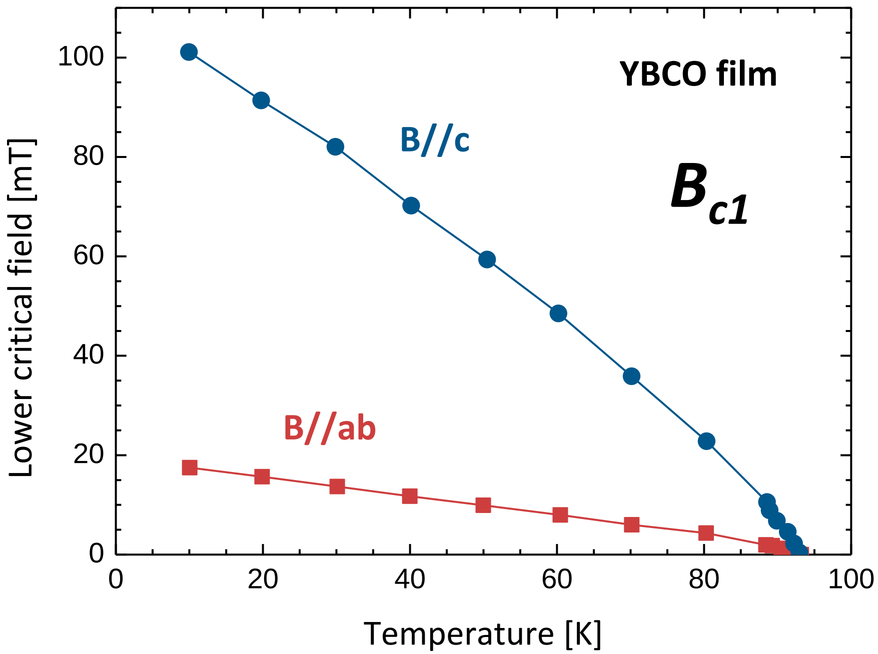
Raffy et al., Physica C 460-462 (2007) 851

Charge carriers have effective masses that depend on the crystallographic orientation

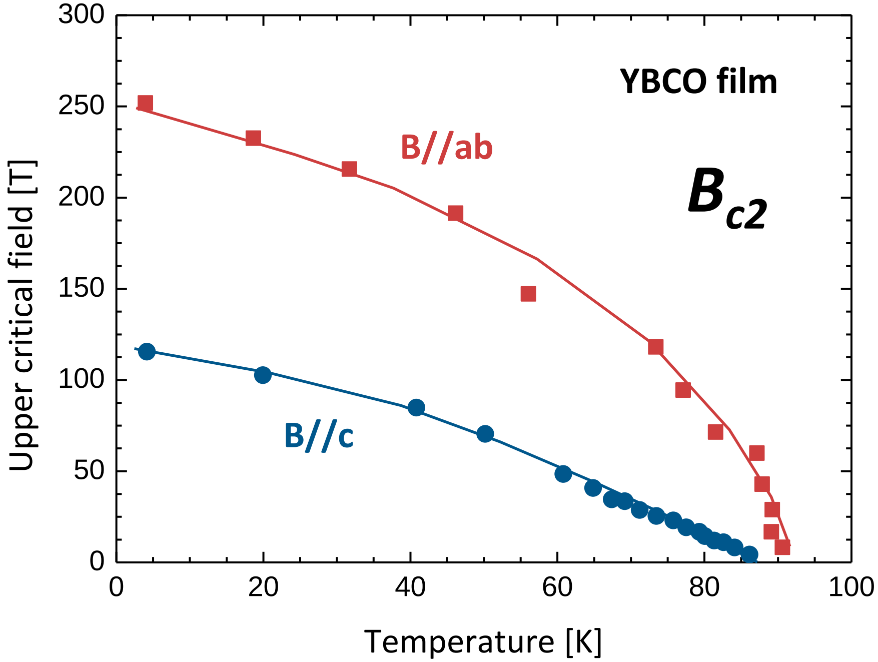
$\frac{m_c}{m_{ab}}$ ***ranges between 50 and 10'000 in cuprates***

The superconductor lengths depend on the carrier mass: $\xi \propto \frac{1}{\sqrt{m}}$ ***and*** $\lambda \propto \sqrt{m}$

Anisotropy of the critical fields B_{c1} and B_{c2}



Liang et al., PRB 50 (1994) 4212



Nagakawa et al., JPCM 10 (1998) 11571

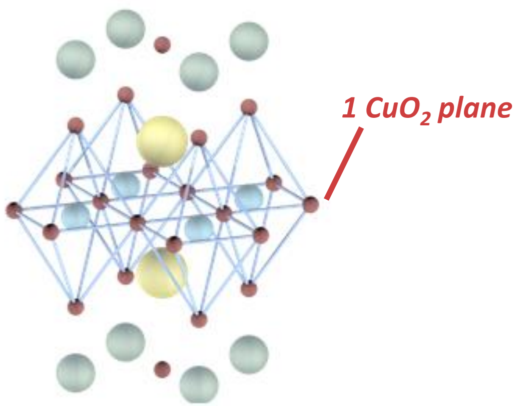
Sekitani et al., NJP 9 (2007) 47

The superconductor anisotropy parameter

$$\gamma = \sqrt{\frac{m_c}{m_{ab}}} = \frac{\lambda_c}{\lambda_{ab}} = \frac{\xi_{ab}}{\xi_c}$$

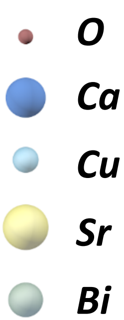
	Bi2212	Bi2223	Y123
γ	~150	~30	~7

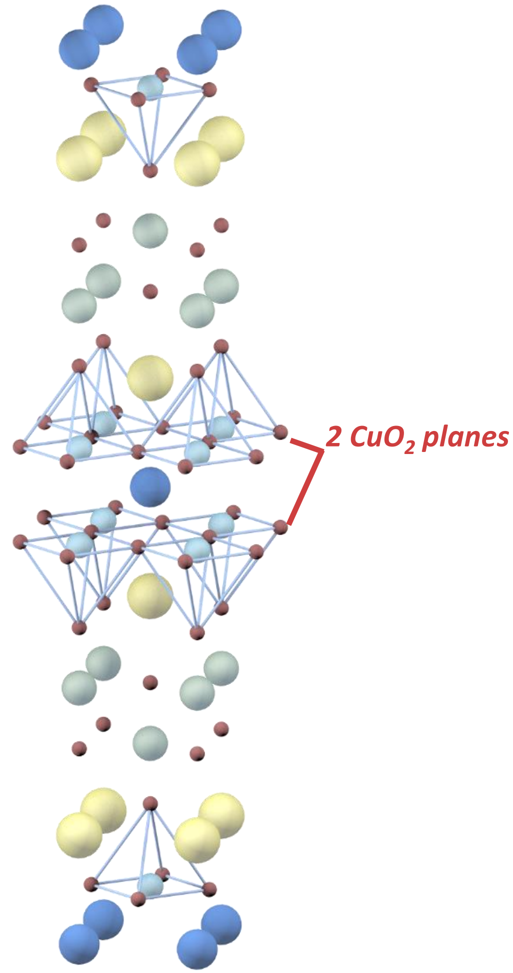
The BiSrCaCuO (BSCCO) family



Bi2201

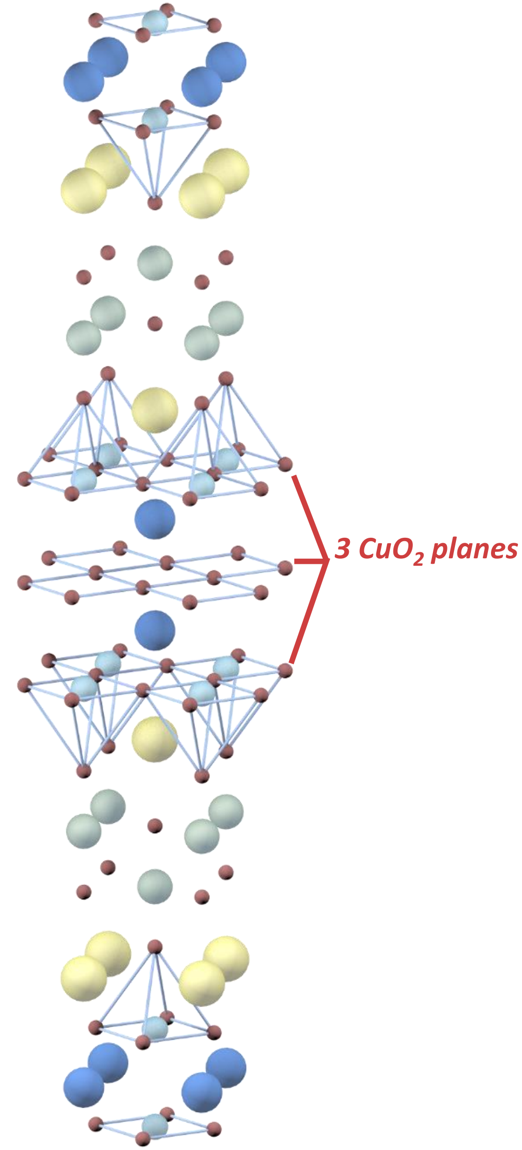
$Bi_2Sr_2CuO_{6+x}$





Bi2212

$Bi_2Sr_2CaCu_2O_{8+x}$



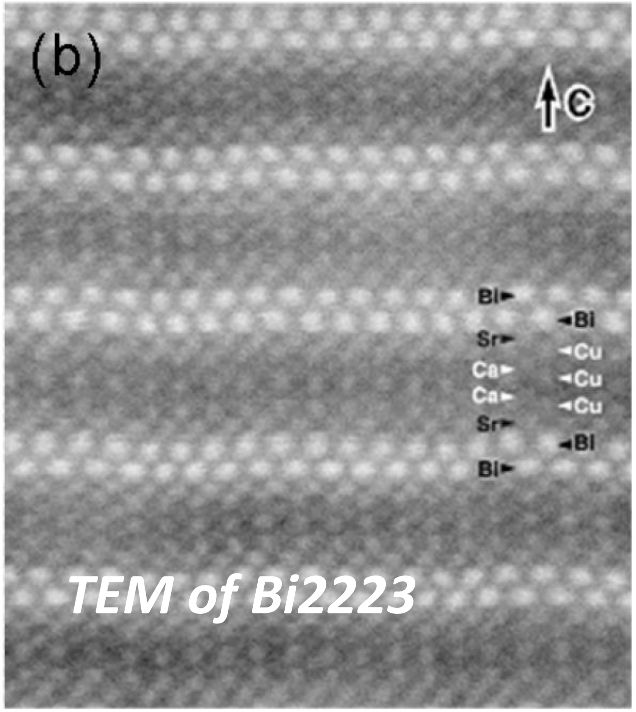
Bi2223

$Bi_2Sr_2Ca_2Cu_3O_{10+x}$

The BiSrCaCuO (BSCCO) family

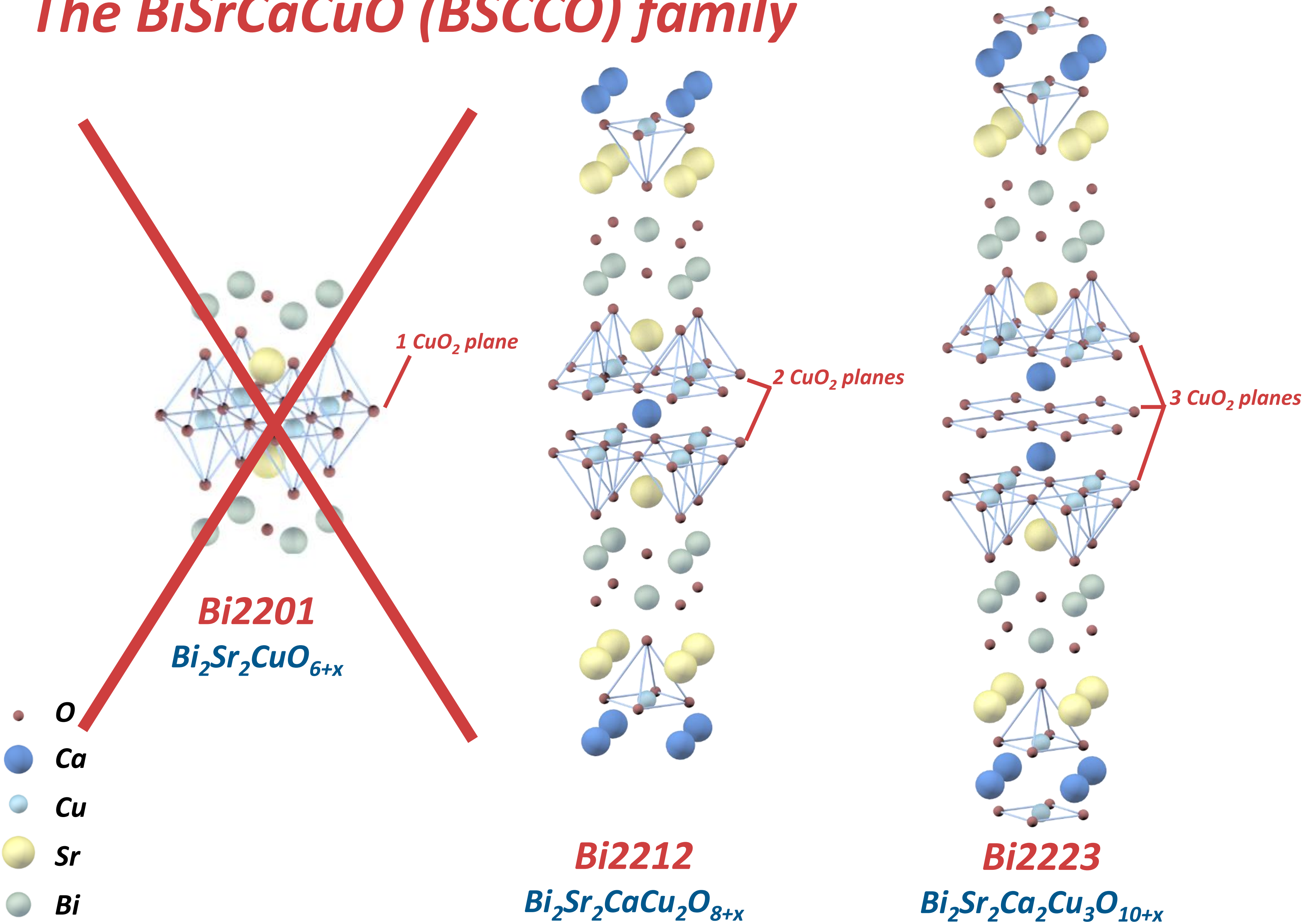
	Bi2201	Bi2212	Bi2223
a [Å]	5.362	5.415	5.413
b [Å]	5.374	5.421	5.421
c [Å]	24.622	30.880	37.010
# of adiacent CuO_2 planes	1	2	3
T_c [K]	15	91	110
$B_{c2}^{//ab}$ [T]	15-20	>100	>100
Anisotropy γ	>150	150	30

These 2 parameters are correlated



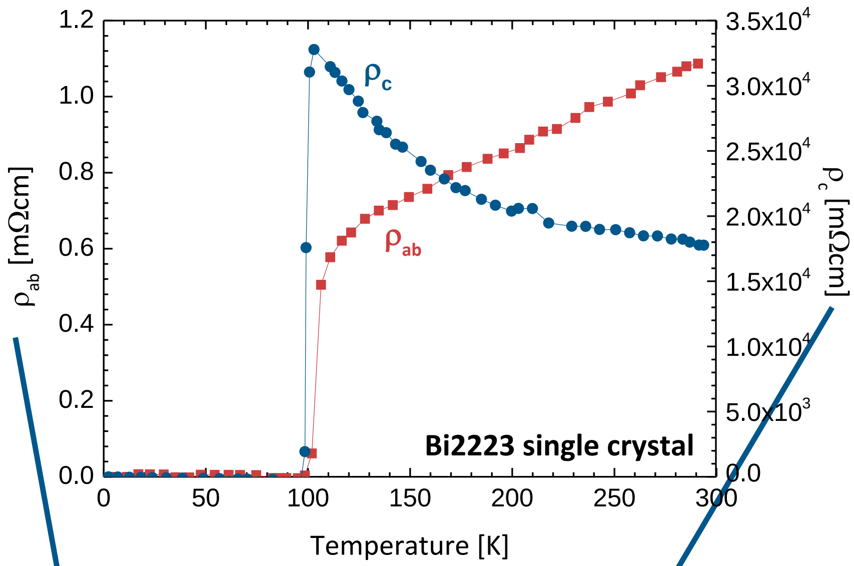
$$\gamma = \sqrt{\frac{m_c}{m_{ab}}} = \frac{B_{c1}^{ab}}{B_{c1}^{c}} = \frac{B_{c2}^{c}}{B_{c2}^{ab}}$$

The BiSrCaCuO (BSCCO) family

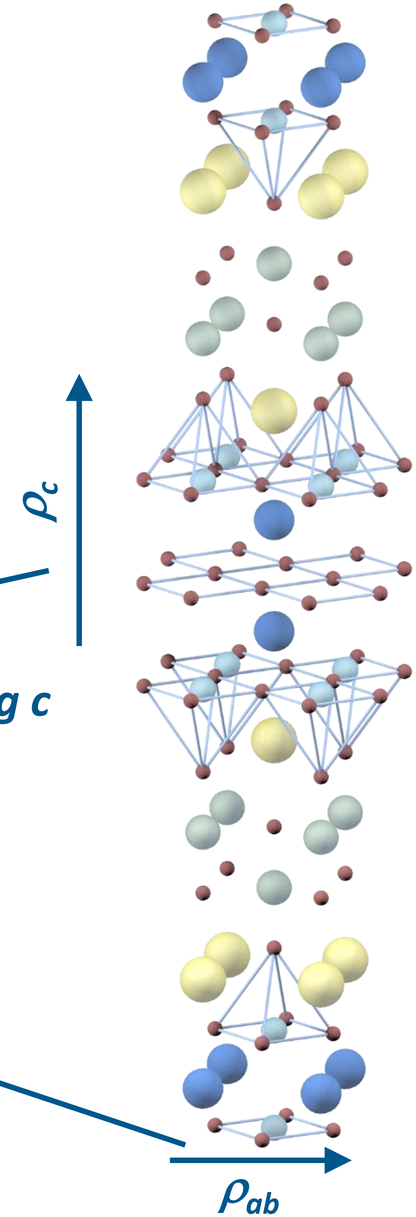


Bi2223: anisotropy of the electrical properties

$$\rho = \frac{m}{ne^2\tau}$$



Liang et al., Physica C 383 (2002) 75



High resistivity when current flows along c
Low J_c // c in the superconducting state

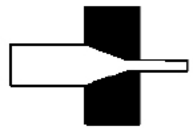
Low resistivity when current flows in the ab plane
High J_c // ab in the superconducting state

Grains in the Bi2223 conductors must have defined orientation !!

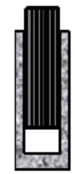
Bi2223 conductor technology
Powder-in-Tube fabrication process (PIT)

Hikata et al., Jap. J. App. Phys. 28 (1989) 82

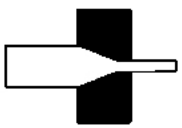
1- Oxide precursor powder packed into Ag tube



2 - Ag/oxide composite drawn to wire

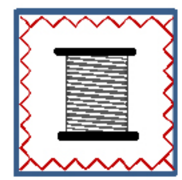


3 - Ag/oxide wire cut and re-bundled into Ag tube



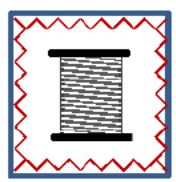
4 - Multi-filamentary composite drawn to wire

5 - Round wire deformed to tape

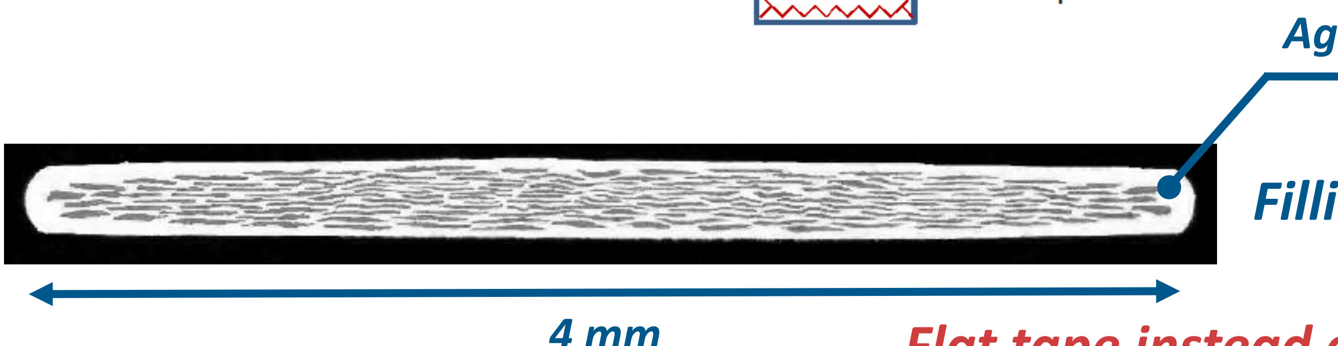


6 - Thermal process forms HTS phase

7 - Deformation process densifies ceramic core



8 - Thermal process completes conversion to HTS phase



Filling factor is ~40%

Flat tape instead of round wire !!

Bi2223 conductor technology
Precursor powders preparation

1. Mixture of $CuC_2O_4 \cdot 2.5H_2O$, $Bi_2(C_2O_4)+H_2O$, PbC_2O_4, $CaC_2O_4 \cdot H_2O$ and $SrC_2O_4 \cdot 2.5H_2O$

2. Repeated calcinations to decompose oxalates and eliminate carbon and water (thermal treatment in air at 300-500°C for 1 to 5 hours)

3. Multiple steps of hand grinding and reaction at 700-800°C in air

1, 2 and 3 are necessary to eliminate the carbon impurities, obtain Bi2212 (!) as main phase and limit the grain size to about 2-5 μm

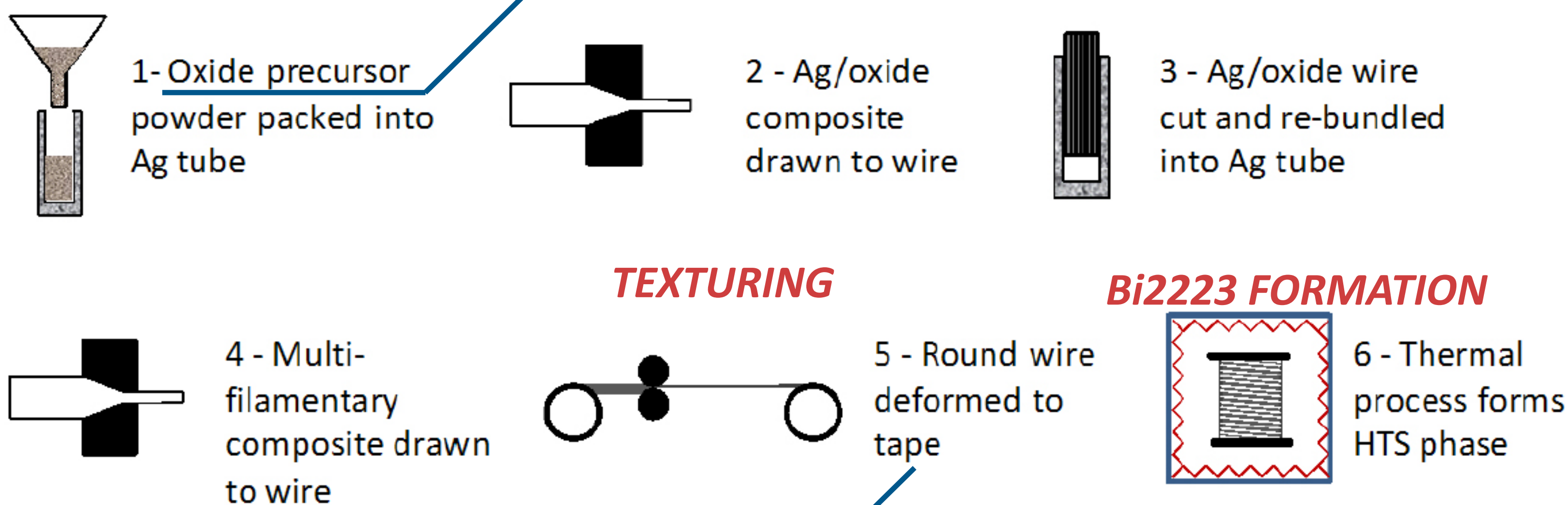
The result is a mixture of Bi2212 (75-80%), Bi2201 (~5%), Ca_2PbO_4 (10%) and CuO

Overall composition close to $Bi_2Sr_2Ca_2Cu_3O_{10}$

Bi2223 conductor technology

Ag is permeable to O_2

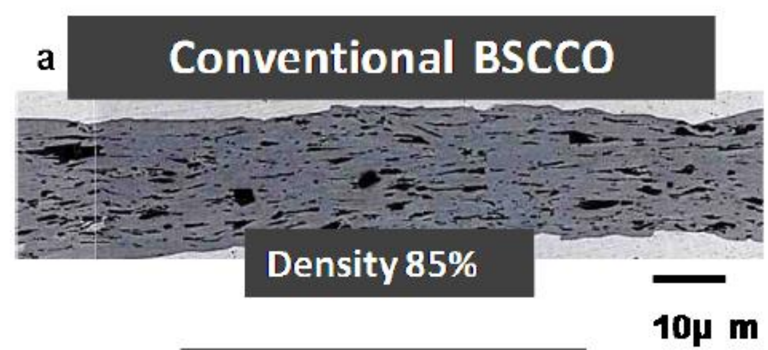
Bi2212 (75-80%), Bi2201 (~5%), Ca_2PbO_4 (10%) and CuO in a Ag tube



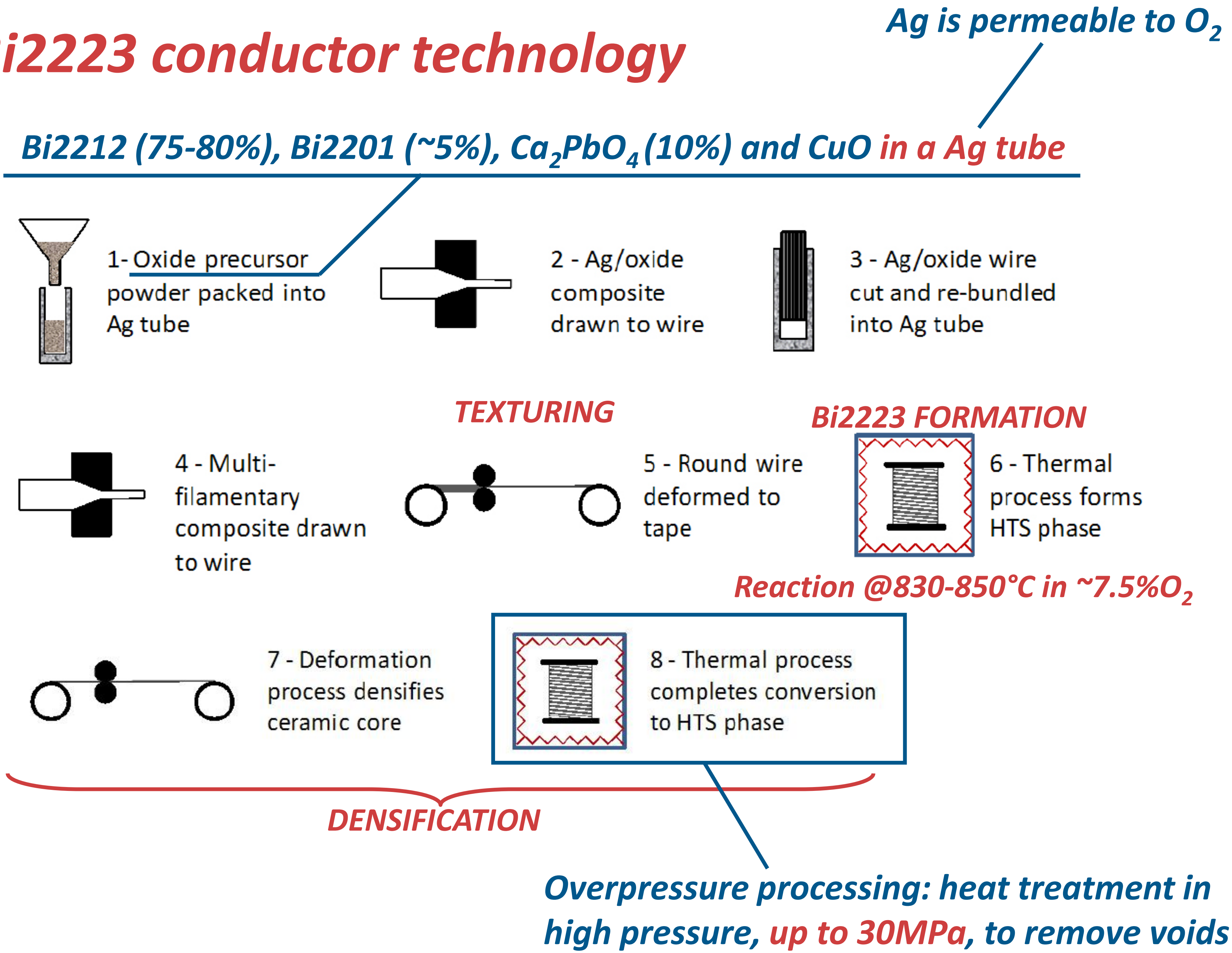
Reaction @830-850°C in ~7.5%O_2

Platelet-like Bi2212 grains are aligned with parallel c-axis (texturing) during the wire-to-tape (rolling) deformation

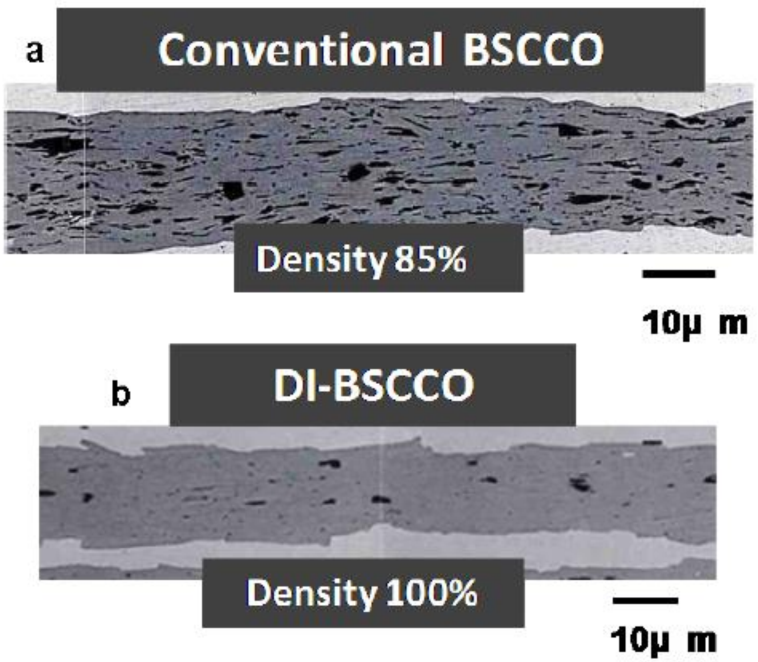
Reaction also leads to the CO_2 formation in the filaments ⇒ bubbles ⇒ de-densification

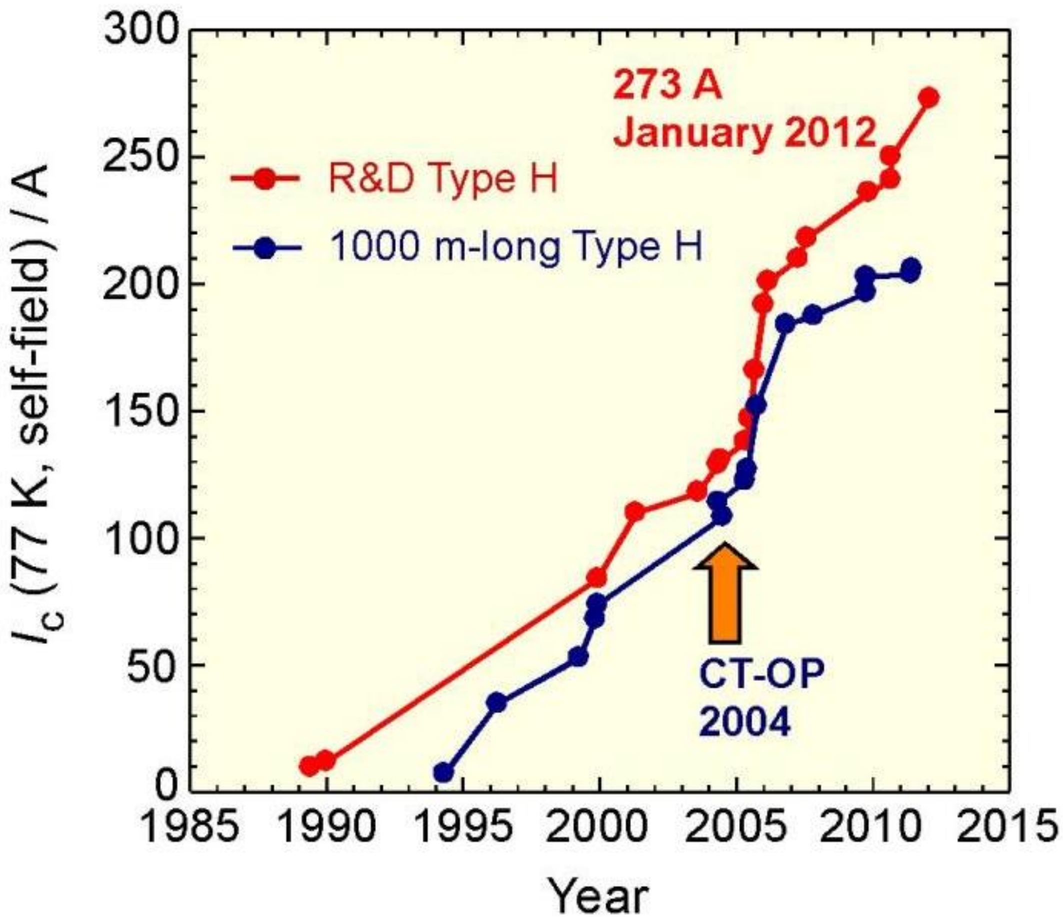


Bi2223 conductor technology



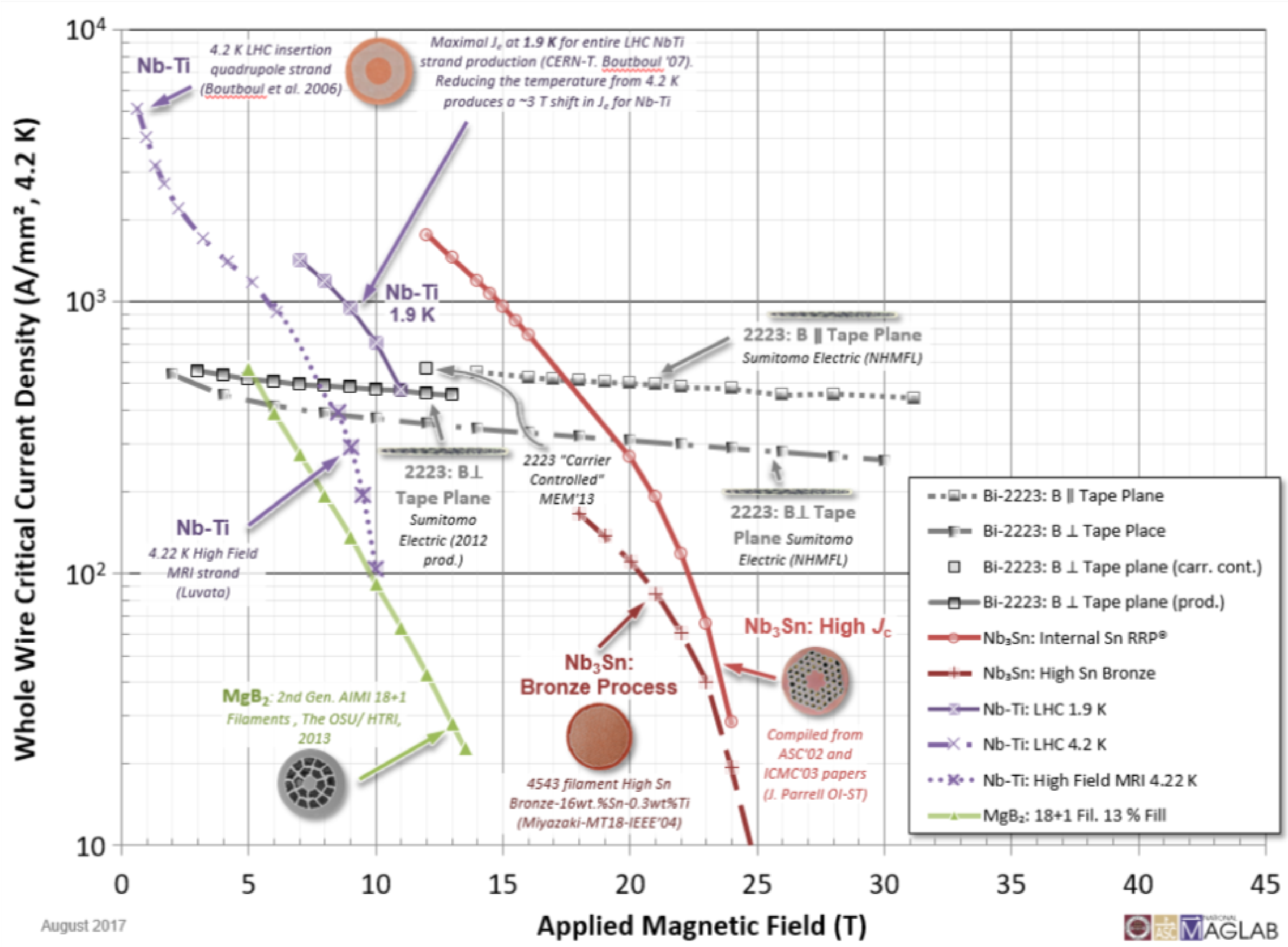
Bi2223 tapes: evolution of I_c vs. year (77K, self-field)





SUMITOMO ELECTRIC

Bi2223 tapes: engineering critical current density J_e

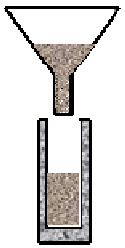


http://fs.magnet.fsu.edu/~lee/plot/plot.htm

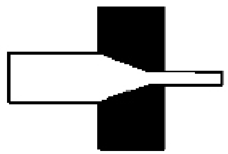
Bi2212 conductor technology

Heine et al., APL 55 (1989) 2441
Enomoto et al., Jap. J. App. Phys. 29 (1990) L447

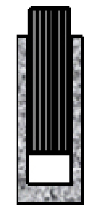
Bi2212 powders in a Ag tube — **Ag is permeable to O_2**



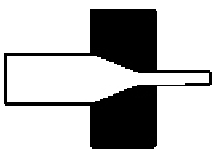
1- Oxide precursor powder packed into Ag tube



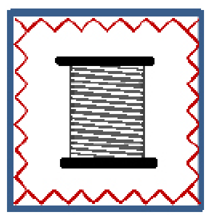
2 - Ag/oxide composite drawn to wire



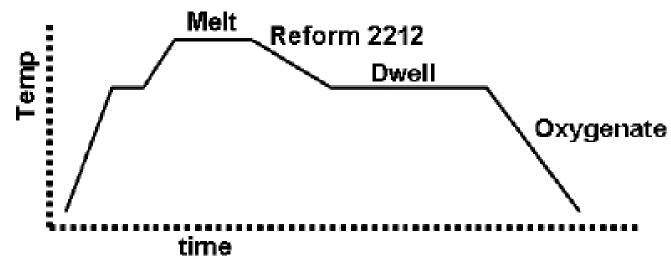
3 - Ag/oxide wire cut and re-bundled into Ag tube



4 - Multi-filamentary composite drawn to wire



5 - Thermal process forms HTS phase



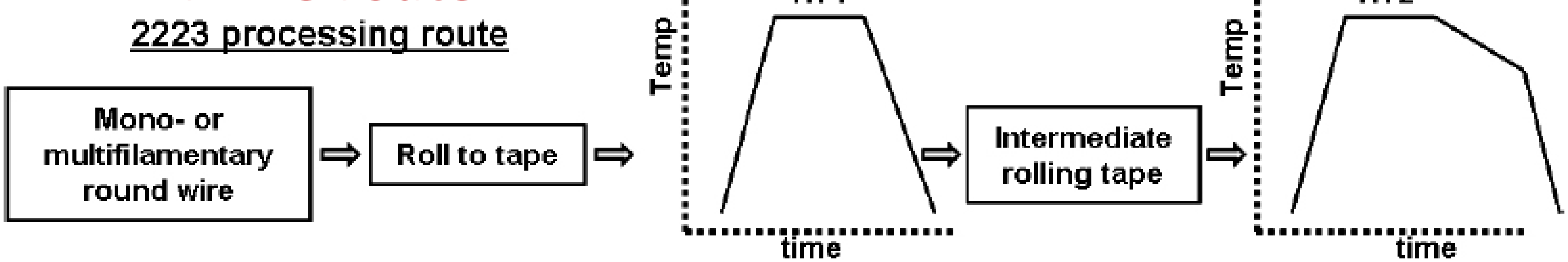
$$\text{Bi2212 powders} \xrightarrow{\text{HEATING}} \text{Bi2212 liquid} + \underbrace{(Sr,Ca)_{14}Cu_{24}O_x}_{\text{AEC}} + \underbrace{Bi_9(Sr,Ca)_{16}O_x}_{\text{CF}} \xrightarrow{\text{COOLING}} \text{Bi2212}$$

Bi2212 conductor technology

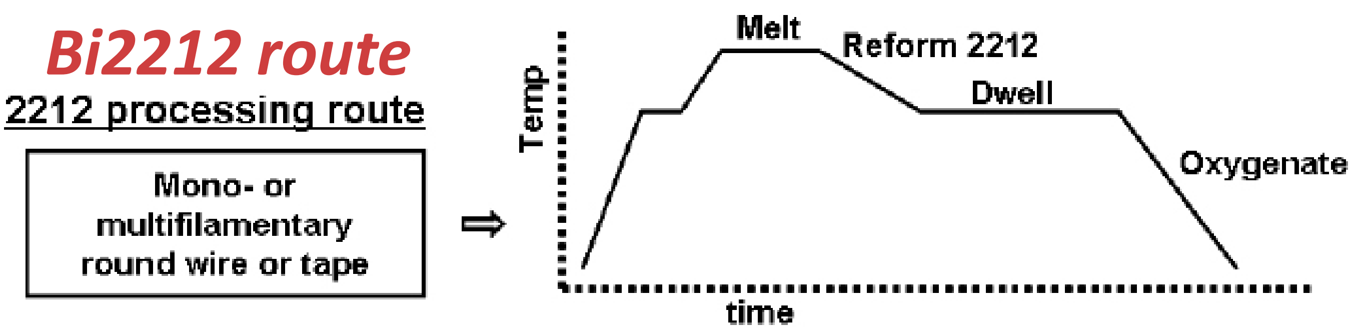
Heine et al., APL 55 (1989) 2441

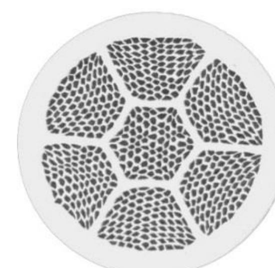
Enomoto et al., Jap. J. App. Phys. 29 (1990) L447

Bi2223 route



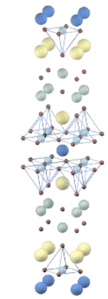
Bi2212 route





Bi2212 conductors are multifilamentary round wires

Bi2212 Powder-In-Tube round wires: Some facts



Heine et al., APL 55 (1989) 2441
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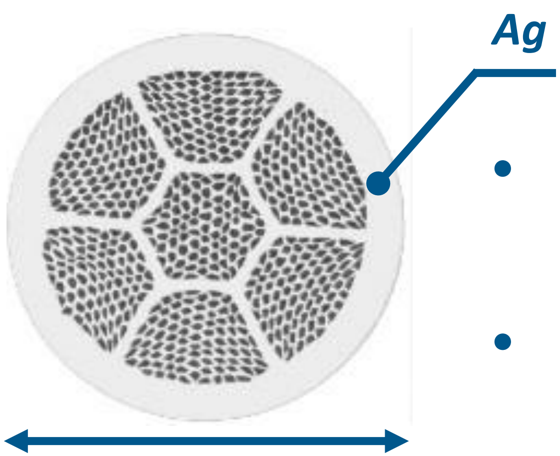
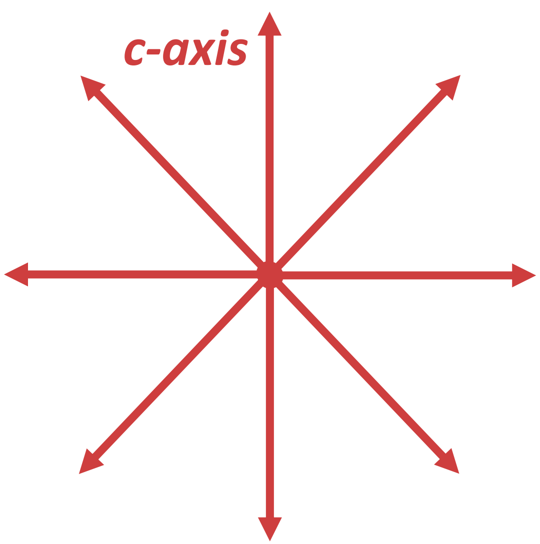
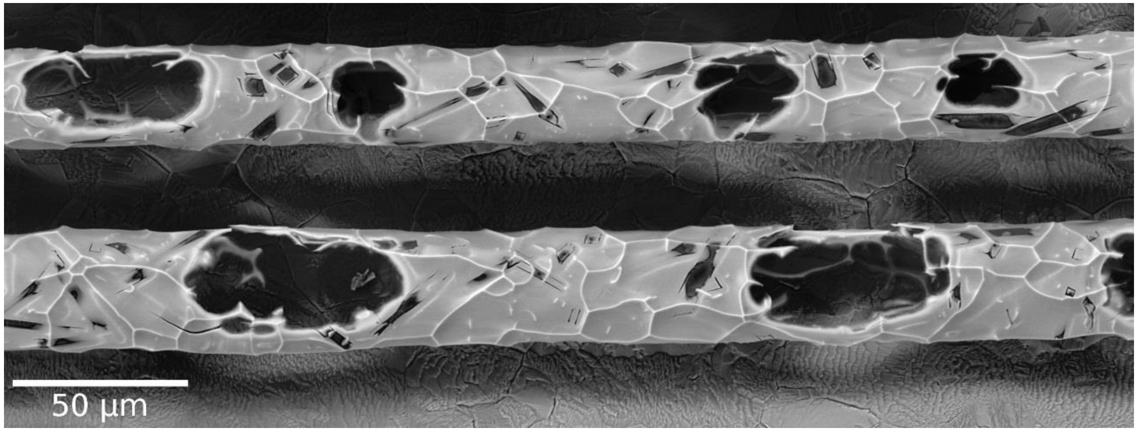


0.8 mm
Filling factor is ~25-30%

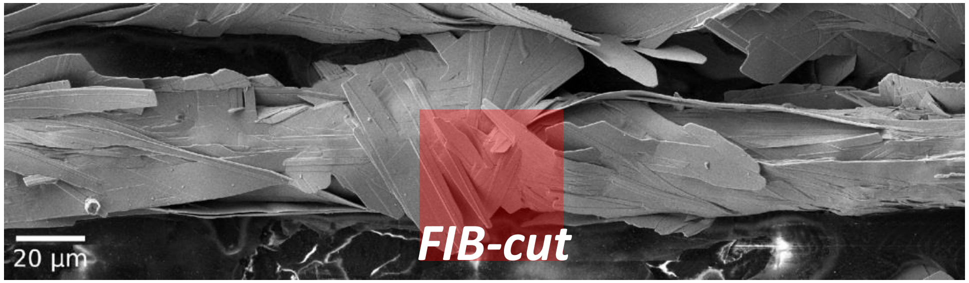


- The intrinsic anisotropy of Bi2212 is higher compared to Bi2223
- However, it is not necessary to deform the Bi2212 conductors to flat tapes in order to get high J_c
- Melting and recrystallization during the heat treatment determines a gradual rotation of the c-axis of grains around the wire axis
- The advantage is that Bi2212 conductors do not have preferential orientation with respect to the magnetic field
- The disadvantage is that Bi2212 can usefully operate only up to ~20K, while Bi2223 can operate at 77K, s.f.

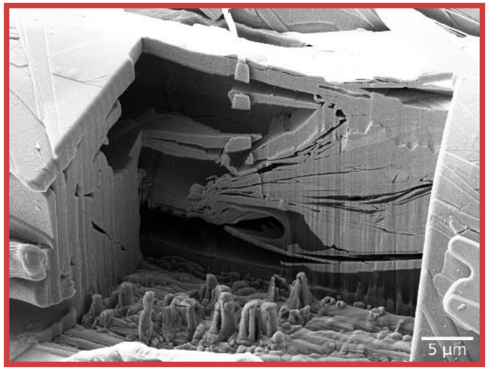
Bi2212: Powder-In-Tube round wires
Filament structure



Large bubbles form on melting and holding at T_{max} during the heat treatment



Bubbles can be partially filled on resolidification and Bi2212 reformation, but many voids remain



F. Kametani et al., SuST 24 (2011) 075009

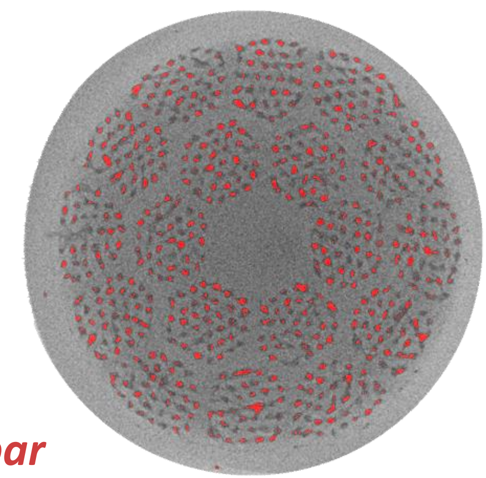
How do we get high J_c in Bi2212 wires ?

The "secret" of its recent success

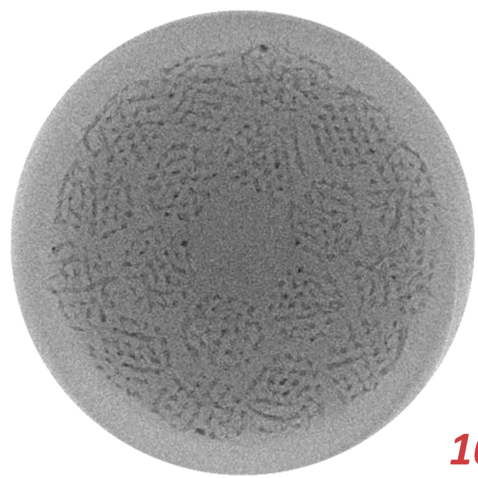
OVERPRESSURE (up to 100 bar) during the heat treatment prevents the formation of bubbles

To increase the current carrying cross section

Larbalestier et al., Nat. Mat. 13 (2014) 375



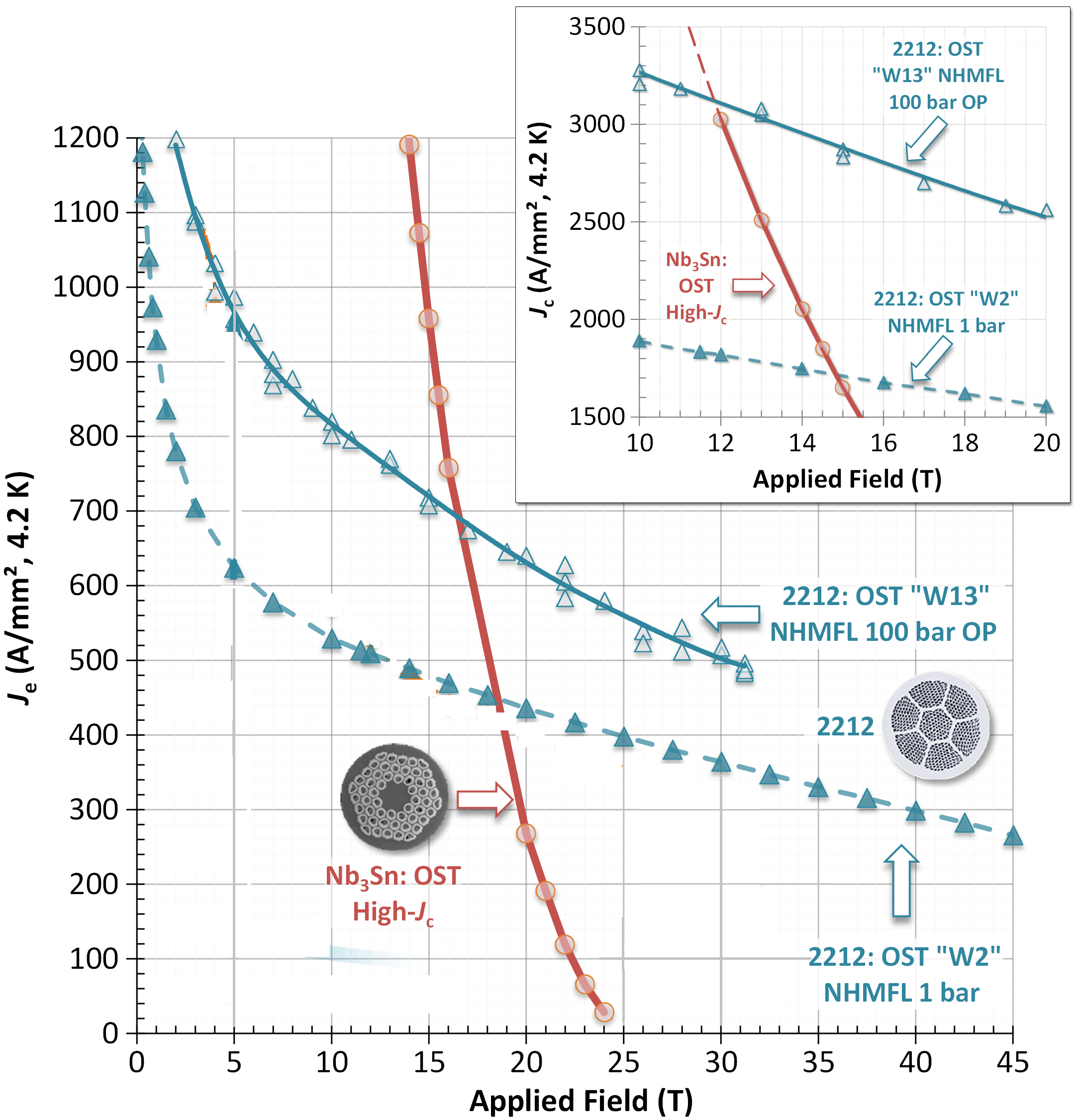
10 bar



100 bar

Bi2212: reaction in overpressure (OP)

Enhancement of J_c: 2500 A/mm² at 20 T and 4.2 K



Reaction in OP is very effective to reduce porosity and thus raise J_c

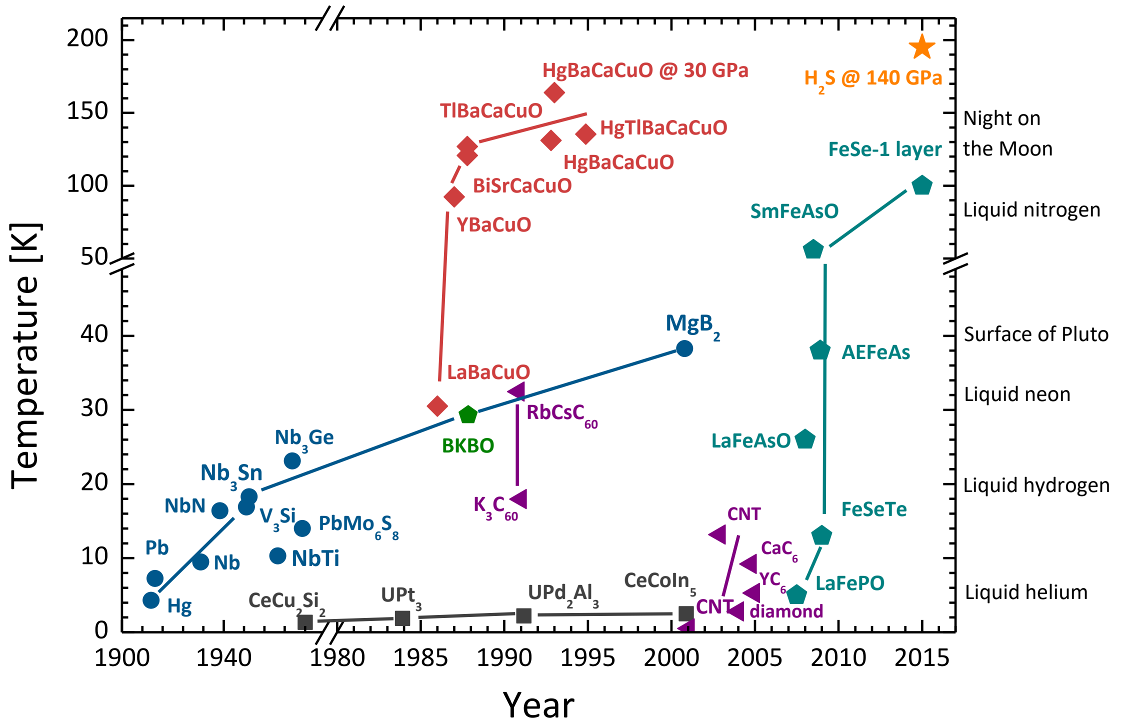
Related papers:

D. Larbalestier et al., Nat. Mat. 13 (2014) 375
J. Jiang et al., IEEE TAS 23 (2013) 6400206
J. Jiang et al., SuST 24 (2011) 082001

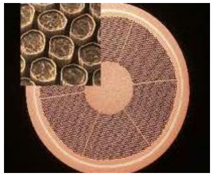
Previously, in lecture 7

From superconducting materials…

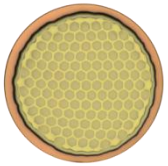
…to technical superconductors



NbTi

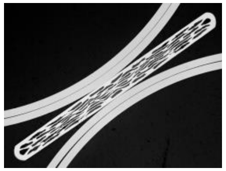


Nb_3Sn

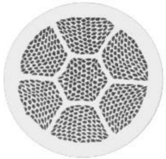


MgB_2

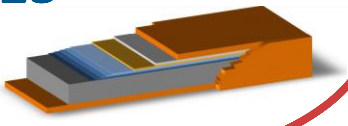
Bi2223



Bi2212

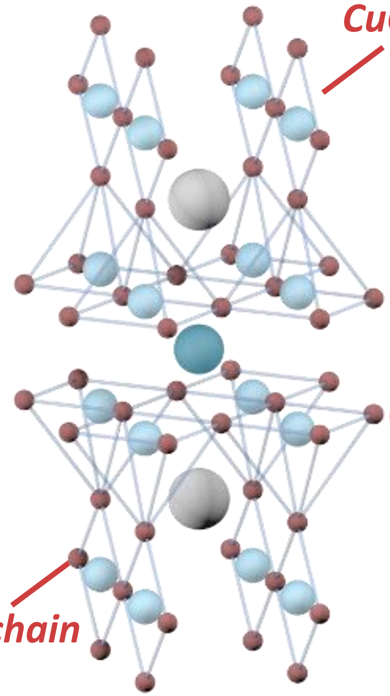


Y123



1. Superconducting ? 10'000
2. T_c>4.2K & B_{c2}>10T ? 100
3. J_c>1000 A/mm² ? ~10

YBCO – Y123 – $YBa_2Cu_3O_{7-x}$: Some facts



- *Discovered by C. P. Chu soon after Bednorz&Müller LaBaCuO*
- *1st material with T_c > 77K*
- *SC @ 92K not only with Y, but with many RE*

	Y123
a [Å]	3.8227
b [Å]	3.8872
c [Å]	11.680
# of adjacent CuO_2 planes	2
T_c [K]	92
$B_{c2}^{//ab}$ [T]	>100
anisotropy γ	7-8

$$\gamma = \sqrt{\frac{m_c}{m_{ab}}} = \frac{B_{c1}^{ab}}{B_{c1}^{c}} = \frac{B_{c2}^{c}}{B_{c2}^{ab}}$$

$$\frac{b}{a} \approx 1.001 \text{ in BSCCO, whereas } \frac{b}{a} \approx 1.02 \text{ in YBCO}$$

Bibliography

Rogalla & Kes
100 Years of Superconductivity
Chapter 11 Section 4 (Bi2223 & Bi2212)

Fosshein & Sudbø
Superconductivity: Physics and Applications
Chapter 2

Papers cited in the slides