Superconducting Materials

APPLIED SUPERCONDUCTIVITY
(Superconducting materials)

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and

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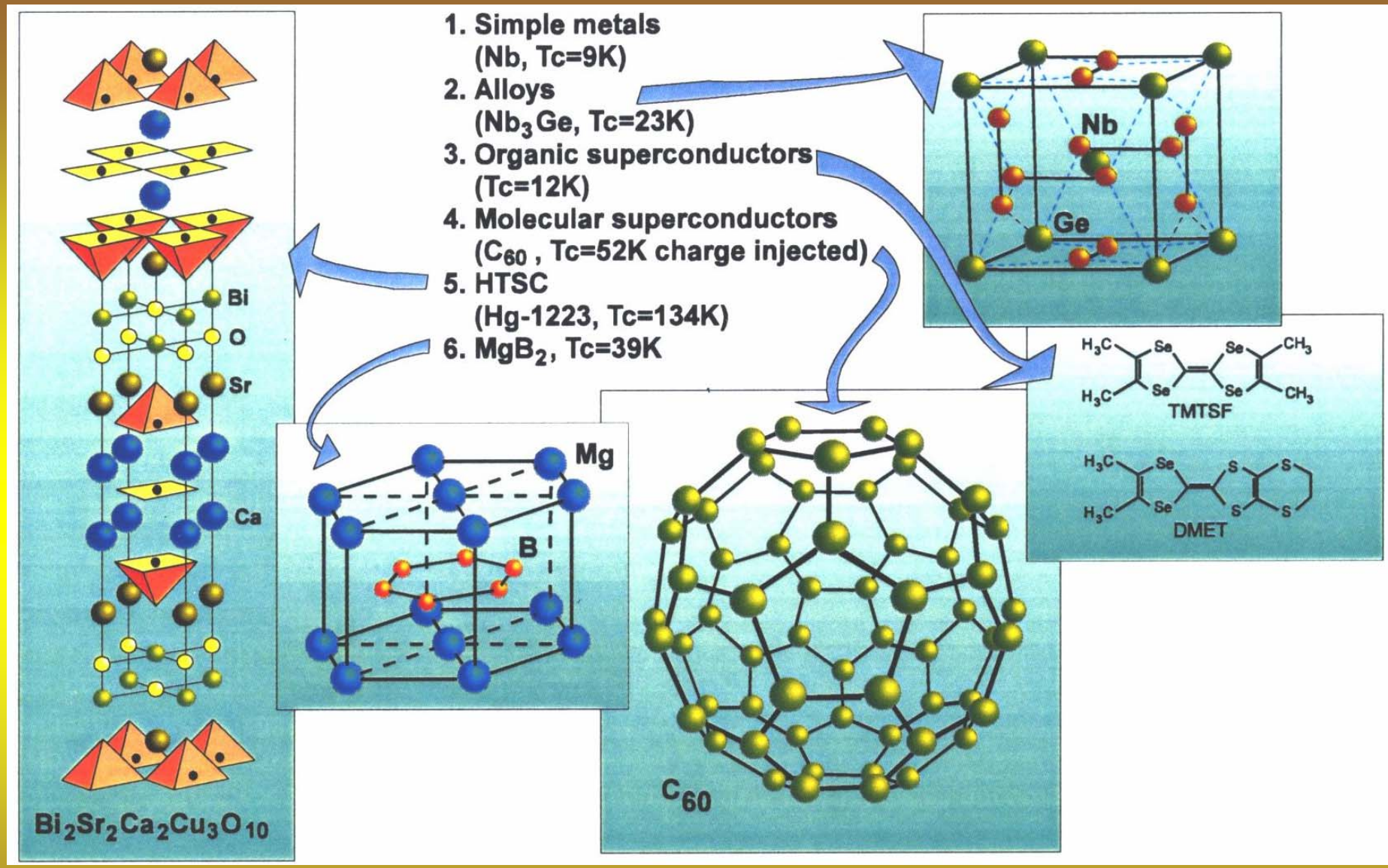
Material Science and Engineering

CERN, Academic Training, Jan 19 2007

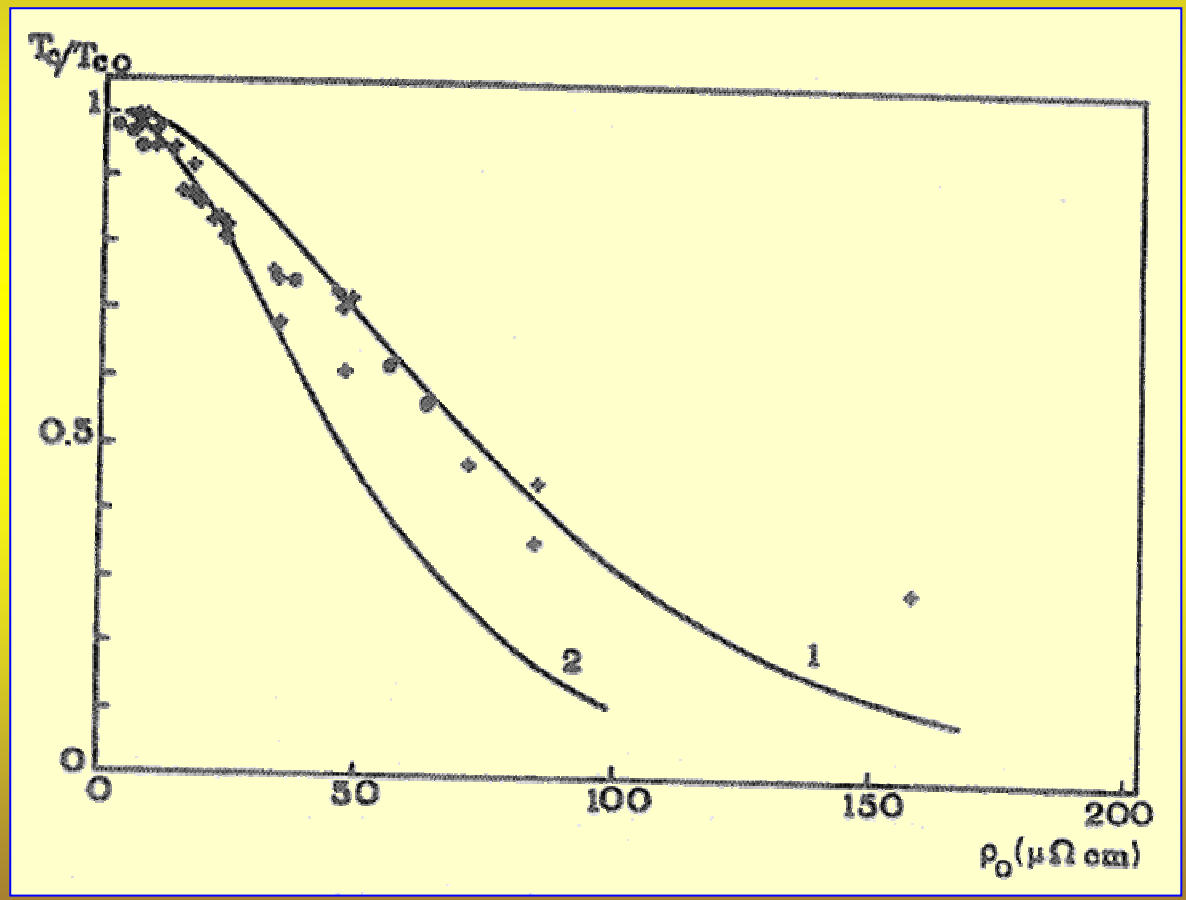
Lecture 3 of 3



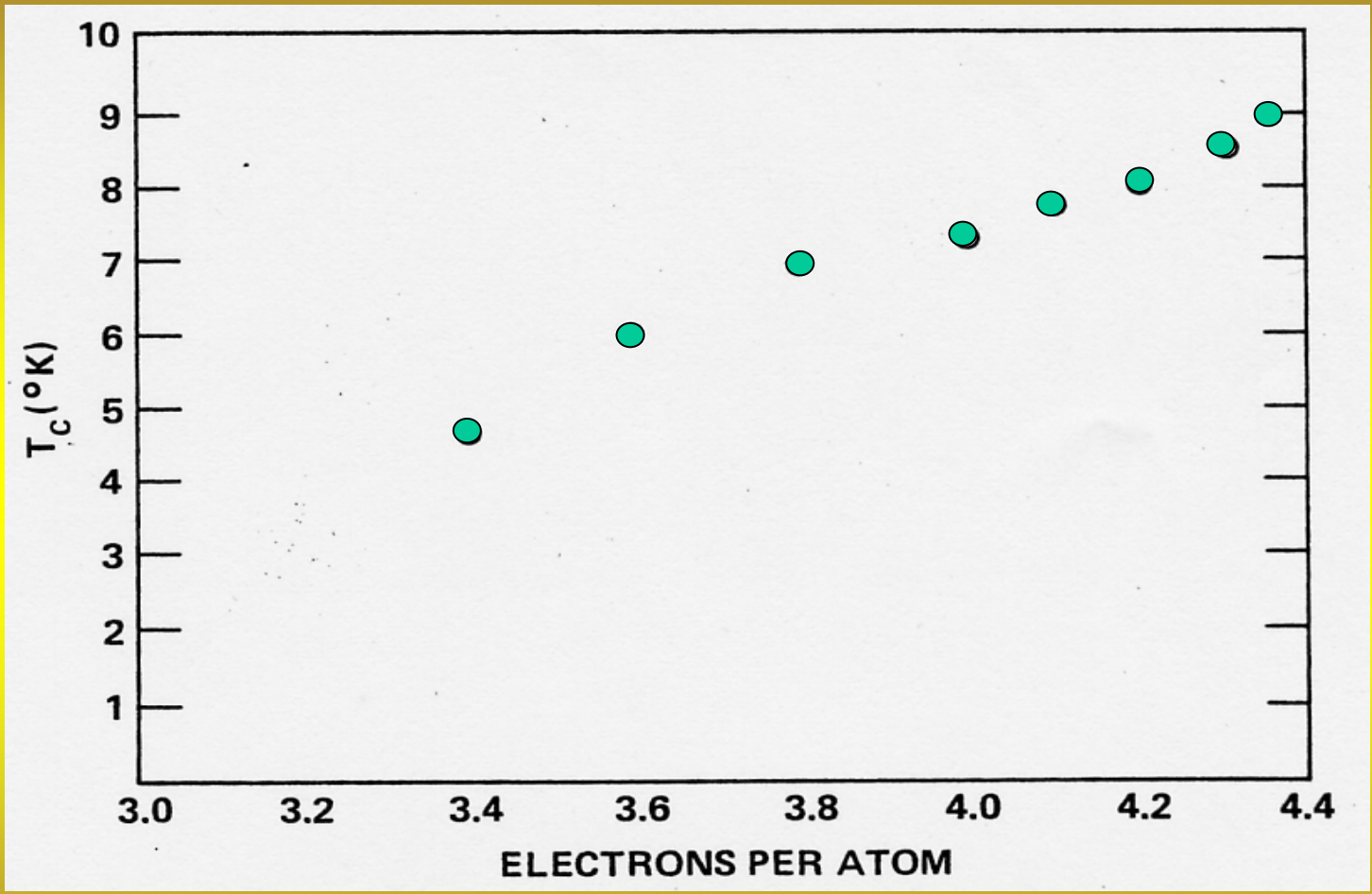
Different classes of superconductors (after Buzea and Yamashita).

		T_c (K)	$H_c(0)$ (GAUSS)
Al		1.196	99
Cd		0.56	30
Ga		1.091	51
Hf		0.09	—
Hg	α (rhomb)	4.15	411
	β	3.95	339
In		3.40	293
Ir		0.14	19
La	α (hcp)	4.9	798
	β (fcc)	6.06	1096
Mo		0.92	98
Nb		9.26	1980
Os		0.655	65
Pa		1.4	—
Pb		7.19	803
Re		1.698	198
Ru		0.49	66
Sn		3.72	305
Ta		4.48	830
Tc		7.77	1410
Th		1.368	162
Ti		0.39	100
Tl		2.39	171
U	α	0.68	—
	γ	1.80	—
V		5.30	1020
W		0.012	1
Zn		0.875	53
Zr		0.65	47

Disorder effect on TC



In the **Tl-Pb-Bi** System, the mass can be held almost constant and the variation of $\mathbf{T_C}$ with **e/a** can be studied in a continuous fashion even up to **9 K**



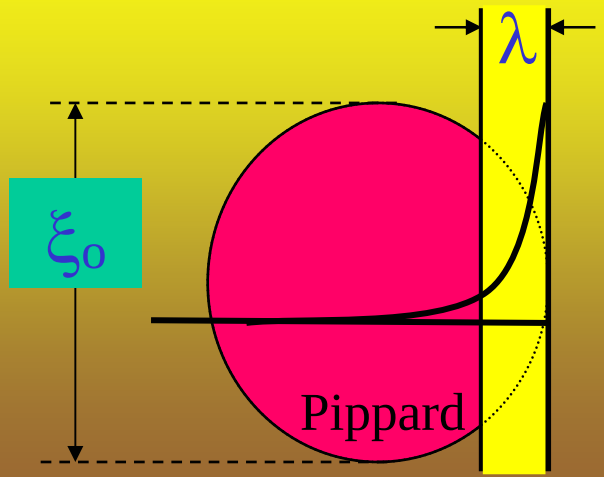
Variation of Transition Temperature with electrons-to-atom ratio in the Tl-Pb-Bi alloy family.

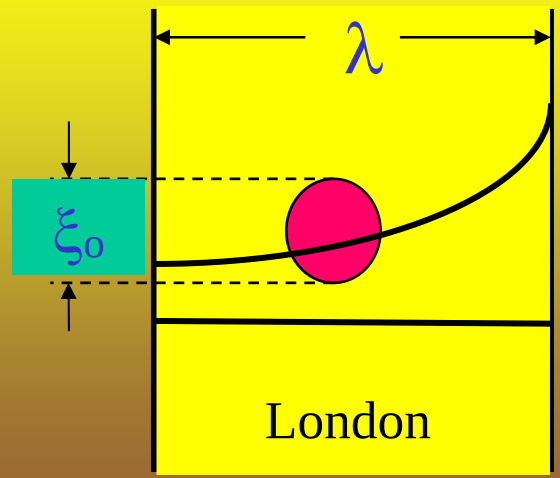
After Dynes and Rowell, Phys. Rev. B 11,1884 (1975)

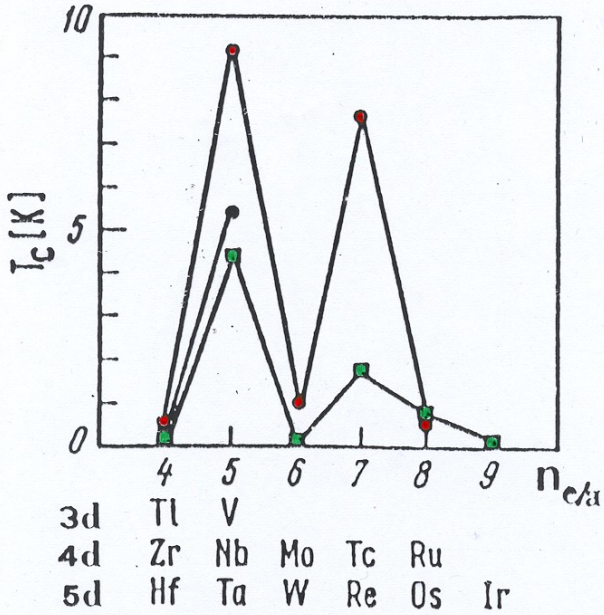
Strong Correlations among Superelectrons within a coherence length ξ_0

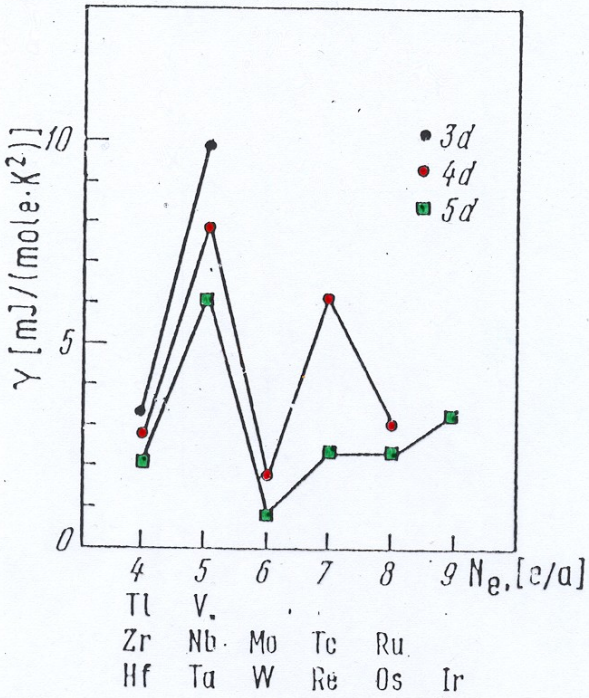
$$\vec{J}_s(\vec{r}) = \int_{\xi_0} f(\vec{r}_1 - \vec{r}) \cdot \vec{A}(\vec{r}_1) d\vec{r}_1$$

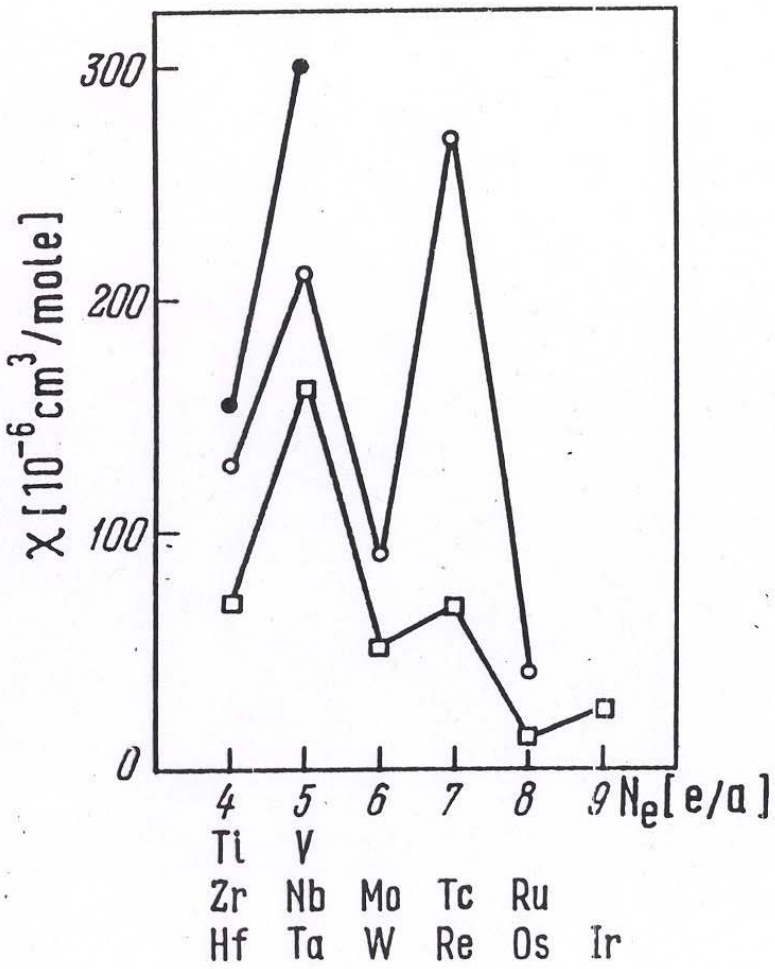
instead of $\vec{J}_s = -\dfrac{\vec{A}}{\lambda_L^{\,2} \mu_0}$

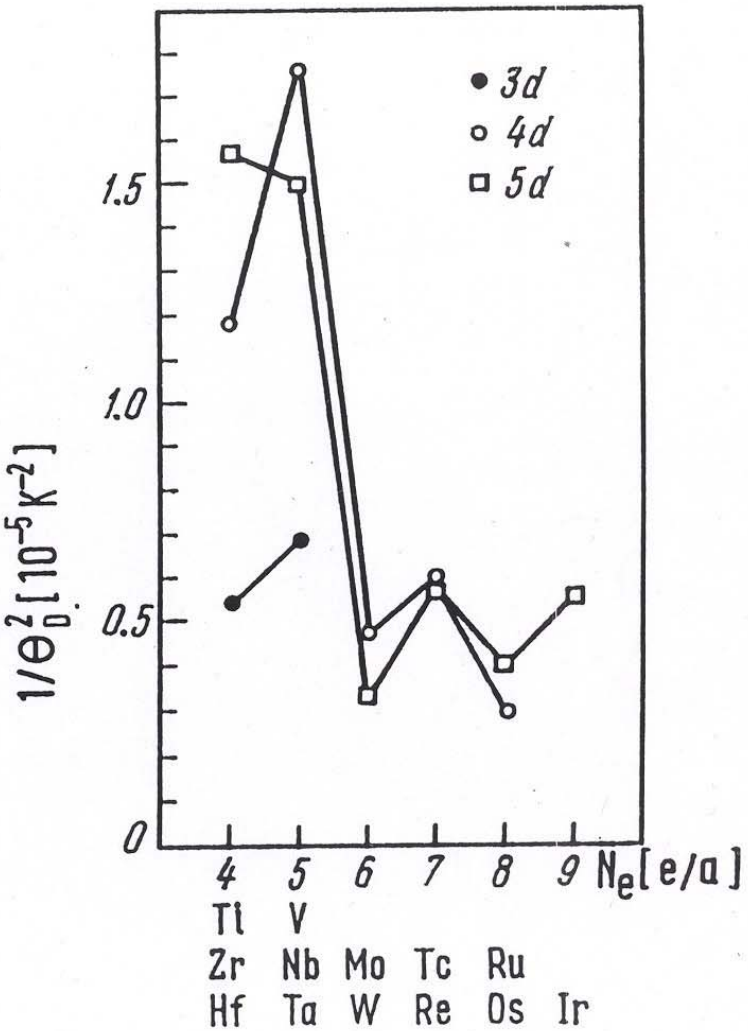





10
5
0
T_c [K]
4 5 6 7 8 9 $n_{e/a}$
3d Tl V
4d Zr Nb Mo Tc Ru
5d Hf Ta W Re Os Ir


10
5
0
γ [mJ/(mole·K²)]
3d
4d
5d
4 5 6 7 8 9 N_e, [e/a]
Tl V
Zr Nb Mo Tc Ru
Hf Ta W Re Os Ir


χ [10⁻⁶cm³/mole]
300
200
100
0
4 5 6 7 8 9 Ne[e/a]
Ti V
Zr Nb Mo Tc Ru
Hf Ta W Re Os Ir


1/θ_D² [10⁻⁵K⁻²]
1.5
1.0
0.5
0
3d
4d
5d
4 5 6 7 8 9 Ne[e/a]
Ti V
Zr Nb Mo Tc Ru
Hf Ta W Re Os Ir

$N(E_F)$ ↗ T_C ↗

$$T_c = 1.14\Theta_D e^{-1/\left(N(E_F)V-\mu^*\right)}$$

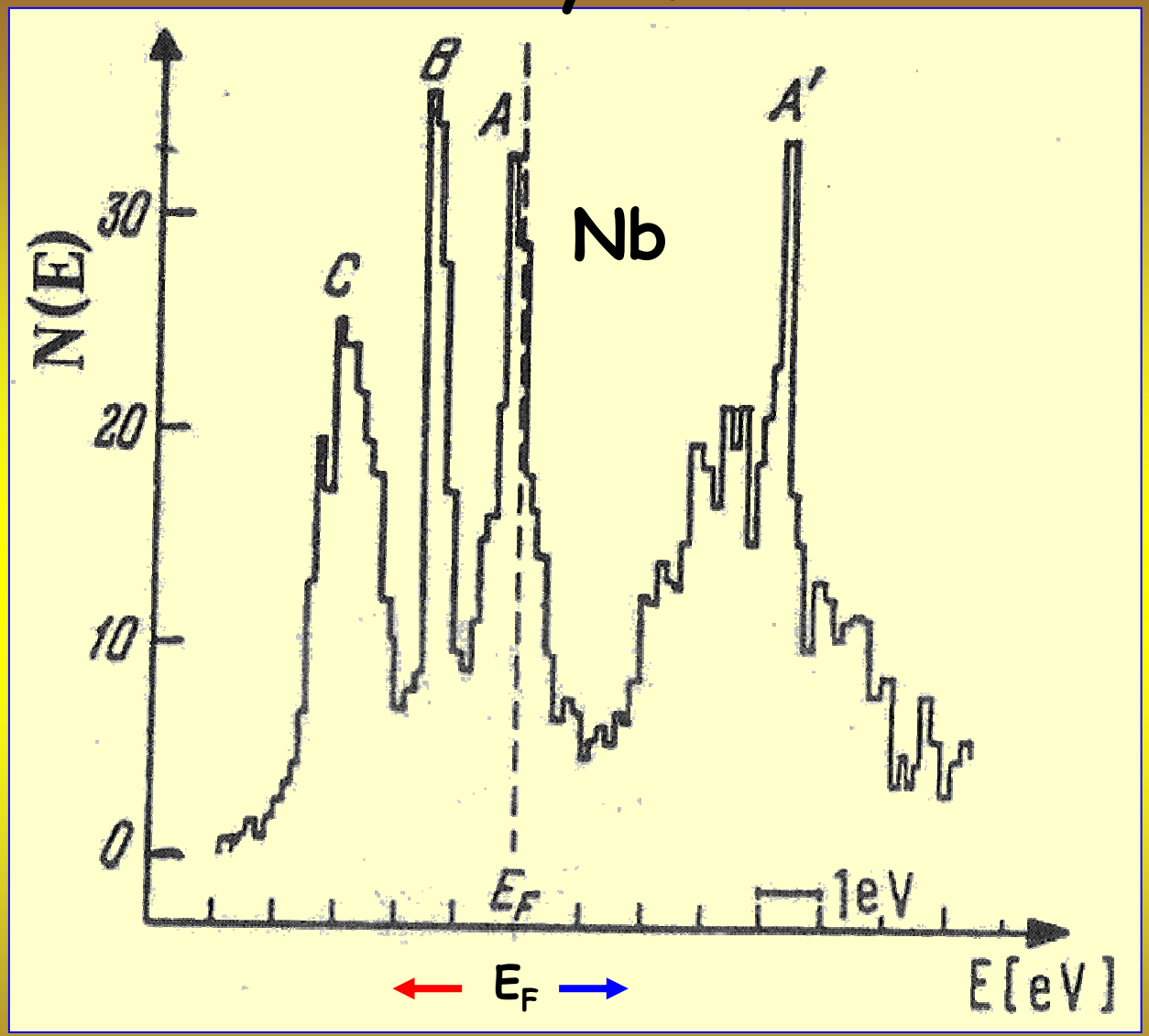
Θ_D= Debye Temperature (for TM 250÷450 K)

$N(E_F)$ = Electronic density of states at the Fermi level

V = attractive potential (phonon-mediated)

μ^*= coulombian pseudo-potential

Electronic density of states



$N(E_F)$ ↗ T_C ↗

$$E_F = (n_{e/a})^{\frac{3}{2}}$$

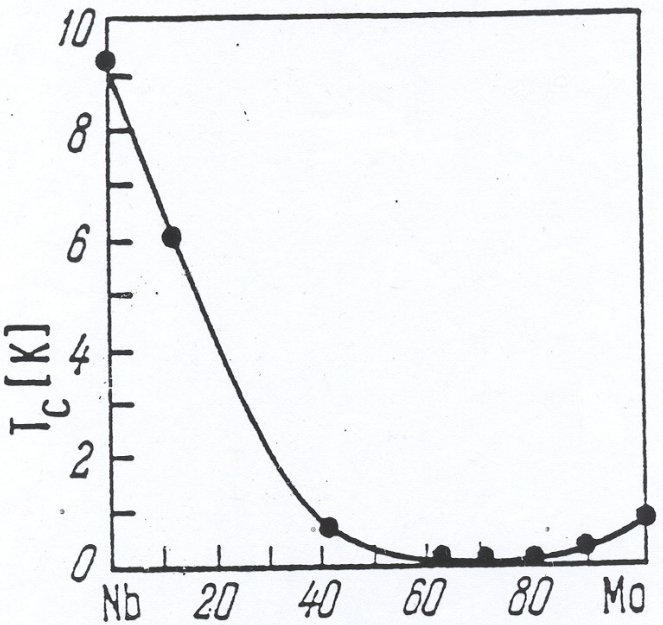
Calore spElectronic specific heat

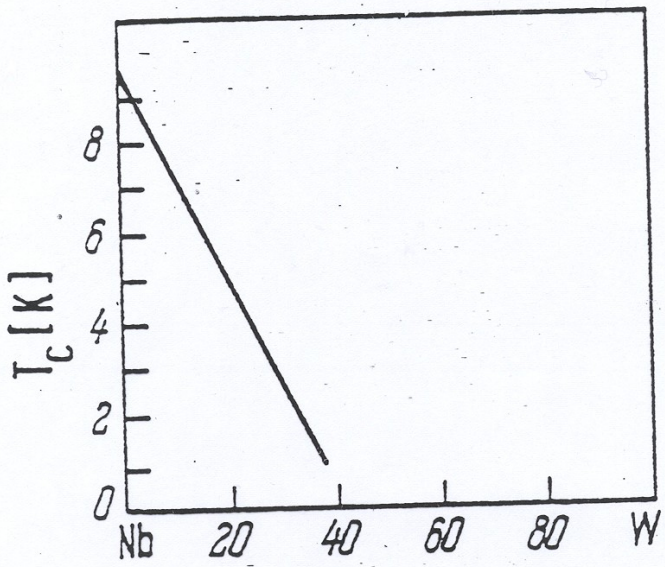
$N(E_F)$ can be calculated from:

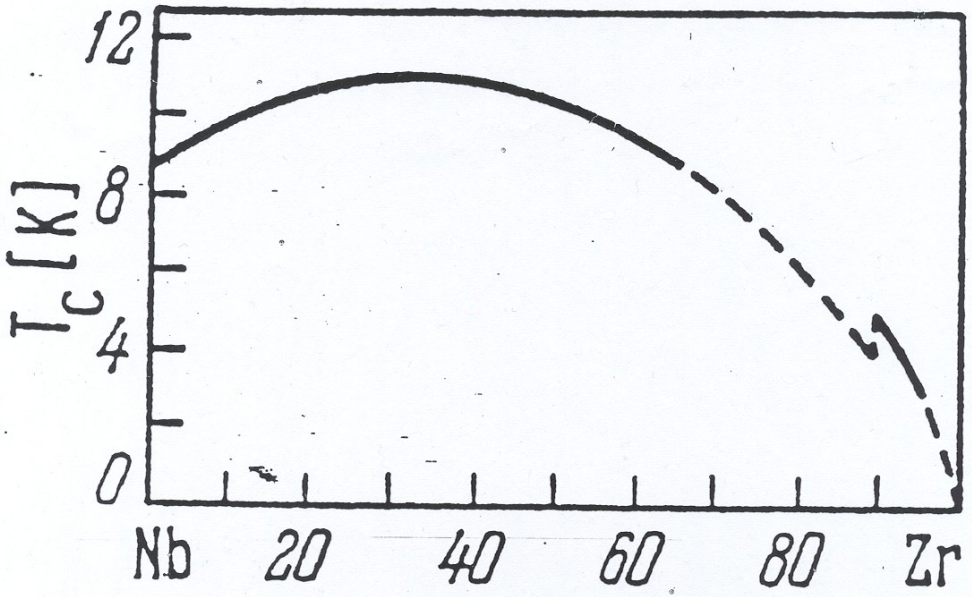
$$C_e = \gamma \cdot T$$

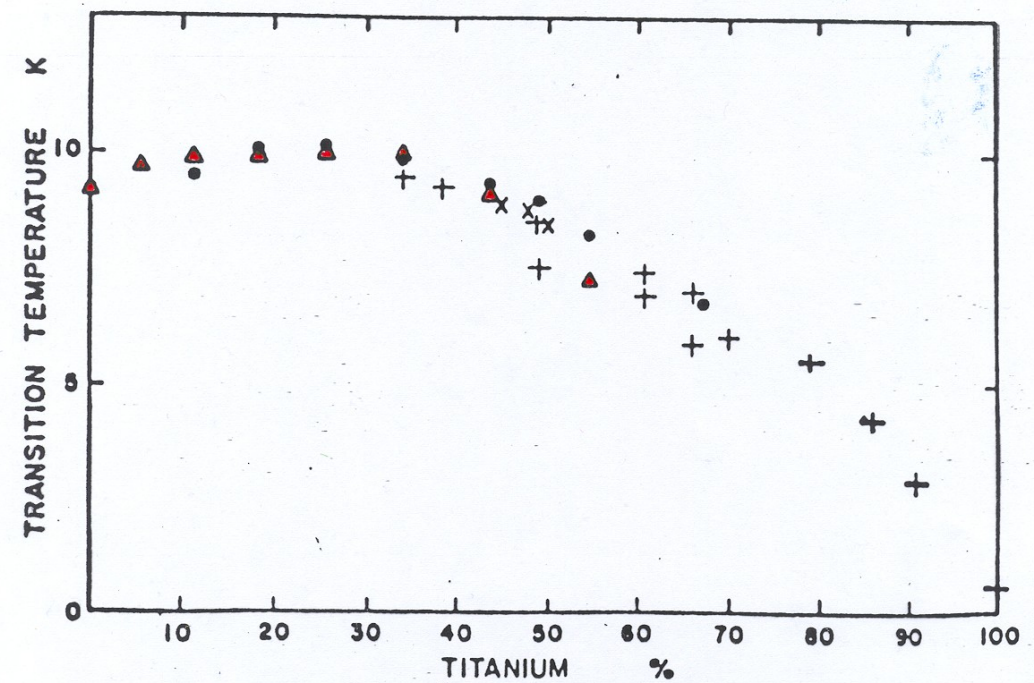
being

$$\gamma = \frac{\pi^2}{3} \cdot k_B^2 \cdot N\left(E_F\right)$$


10
8
6
4
2
0
T_c [K]
Nb
20
40
60
80
Mo

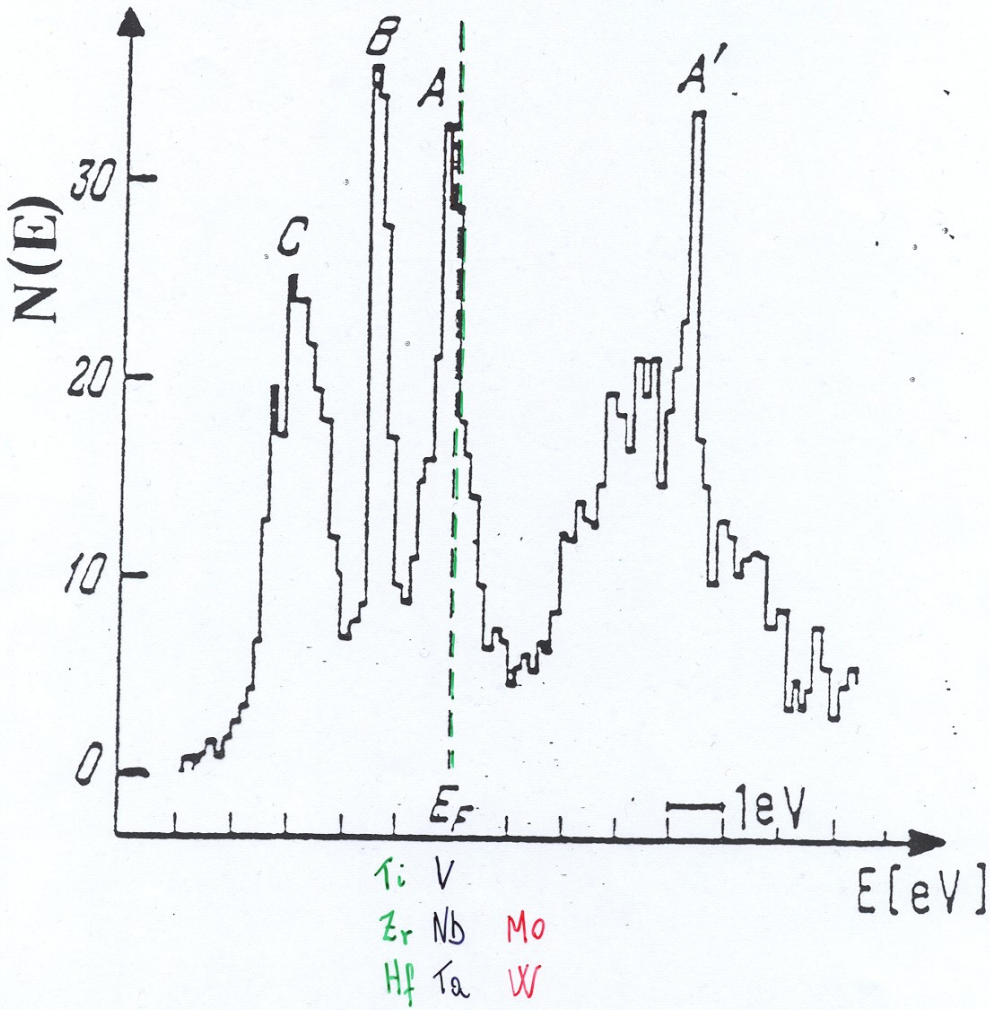

8
6
4
2
0
T_c [K]
Nb
20
40
60
80
W


12
8
4
0
T_c [K]
Nb
20
40
60
80
Zr

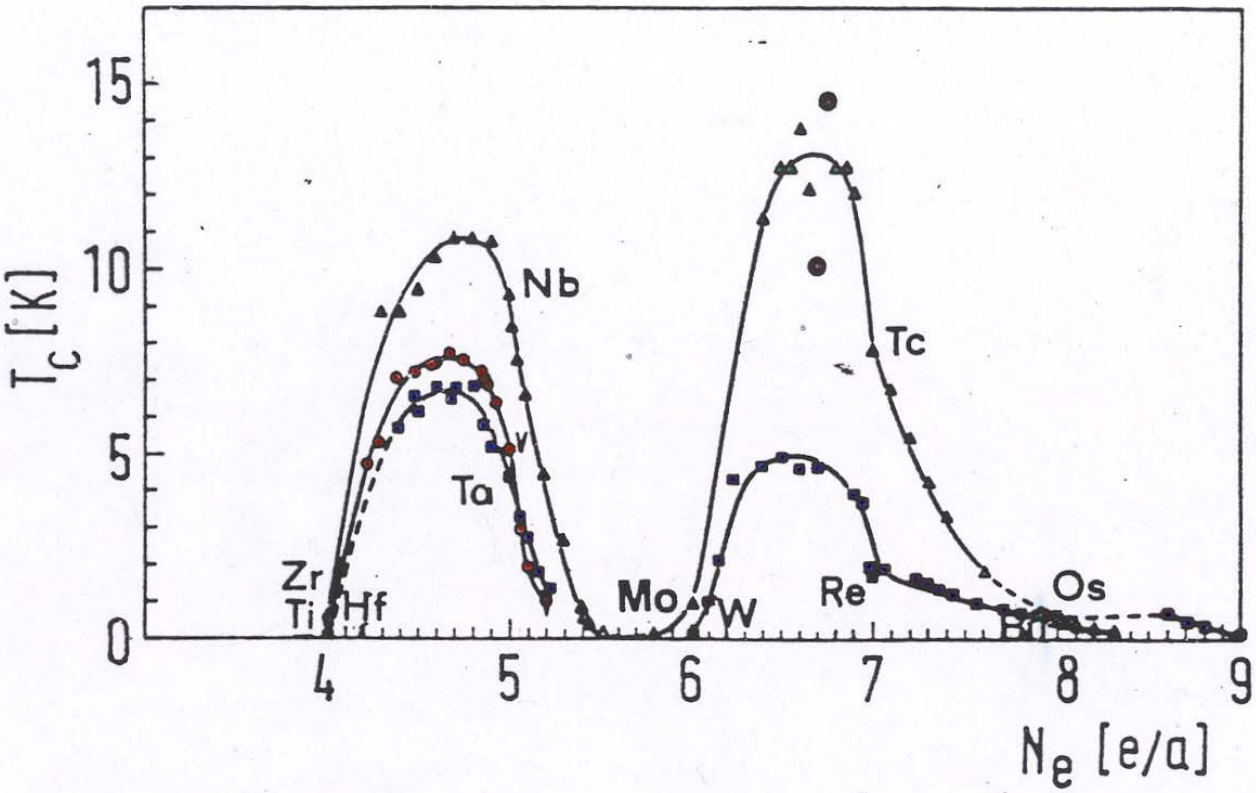

TRANSITION TEMPERATURE K
10
5
0
10
20
30
40
50
60
70
80
90
100
TITANIUM %

for solid solutions AB

$$E_F^{3/2} = n_{e/a}(AB) = C_A\, n_{e/a}(A) + C_B\, n_{e/a}(B)$$



Matthias empirical rule



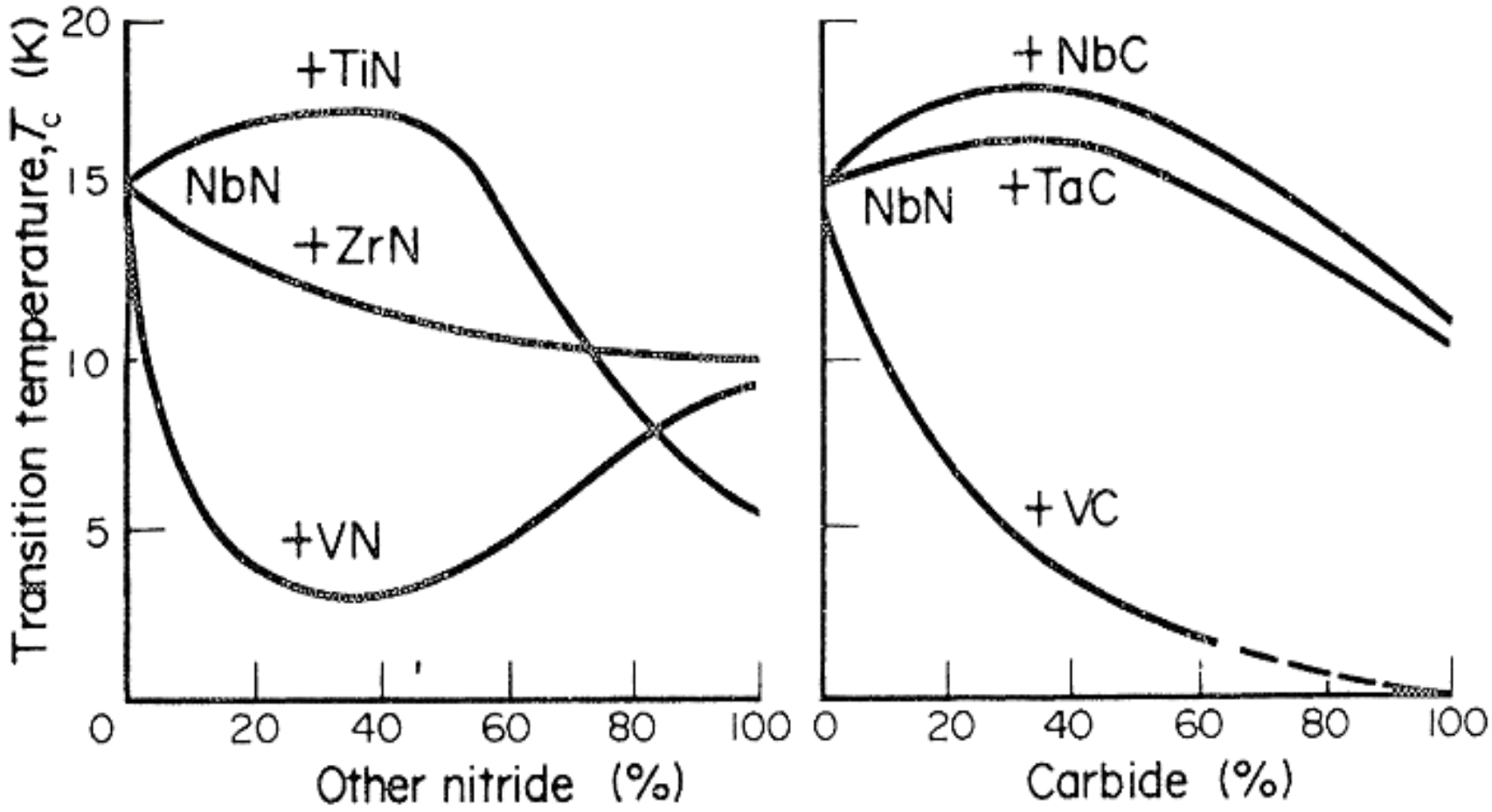
It works only for neighbourhood elements in per. table.

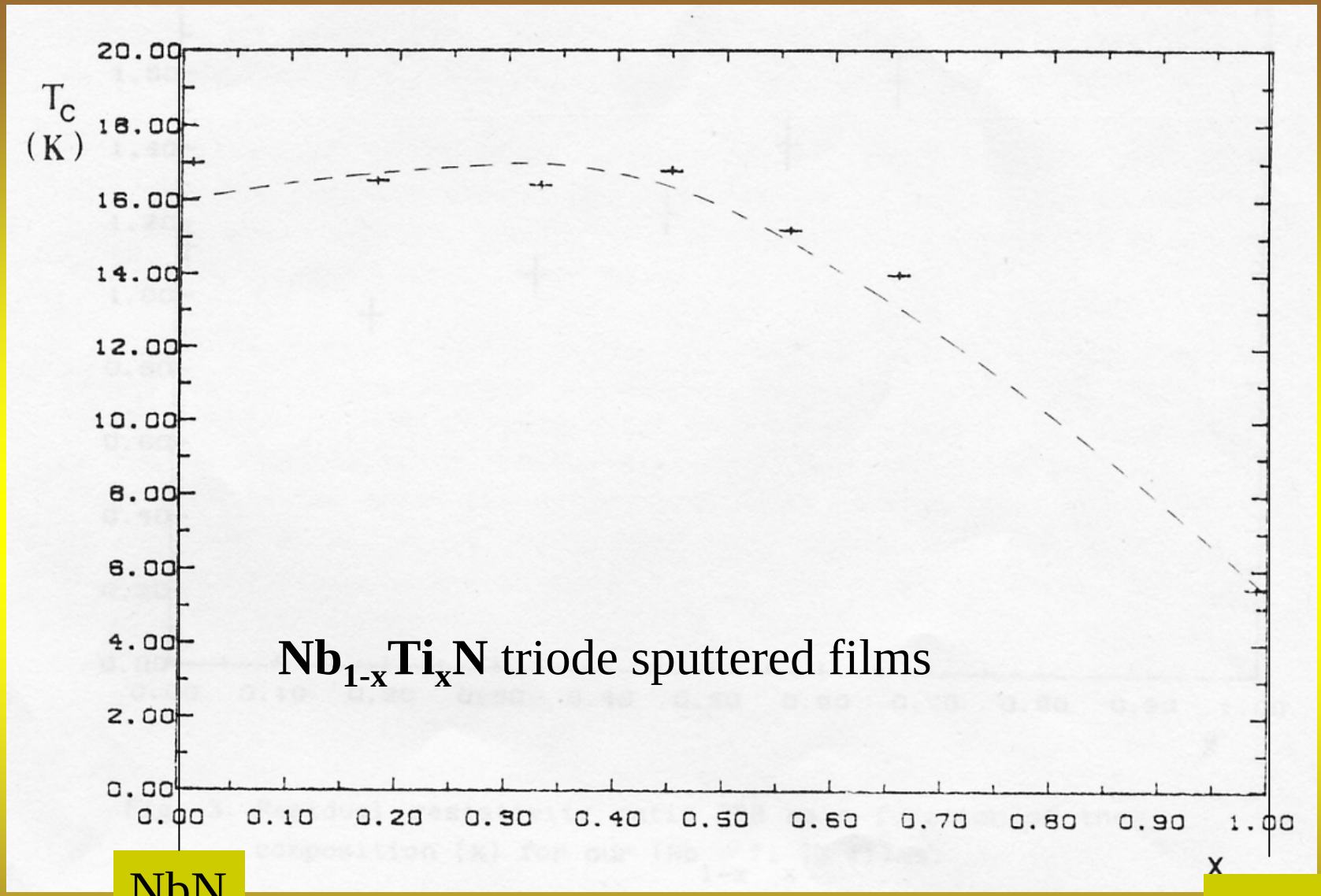
Critical Temperature of compounds with NaCl structure

A / B	Sc	Y	La	Ti	Zr	Hf	V	Nb	Ta	Cr	Mo	W	Re
B					3.4	3.1							
C	<1.38	<1.38		3.42	<0.3	<1.20	0.03 3.2*	12	10.35		14.3	10.0	3.4
N	<1.38	<1.4	1.35	5.49	10.7	8.83	8.5	17.3	6.5	<1.28	5.0	<1.38	
P			<1.68										
Sb		<1.02	<1.02										
O				2.0			<0.3	1.39					
S	<0.33	1.9	0.87		3.3								
Se	<0.33	2.5	1.02										
Te		2.05	1.48										

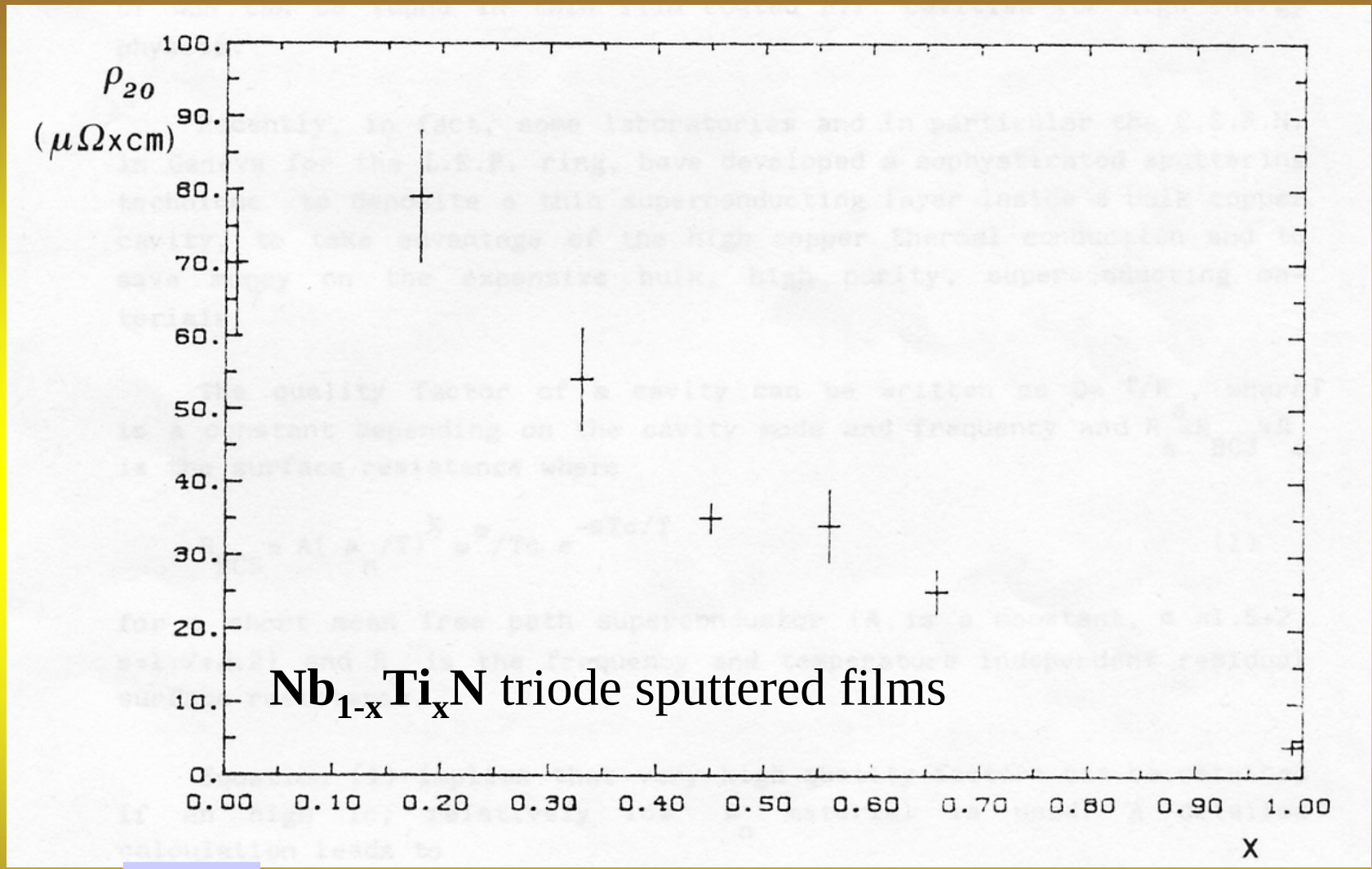
* $T_c = 3.2$ K was registered in vanadium carbide after implantation of C^+ ions

Critical temperature vs composition for nitride and carbide ***addition to NbN***





A.Nigro, G.Nobile, V.Palmieri, R.Vaglio, "PROPERTIES OF NIOBIUM-TITANIUM NITRIDE SUPERCONDUCTING THIN FILMS", **Adv. Cryog. Eng. Mat., vol. 34, (1988) 813**



NbN

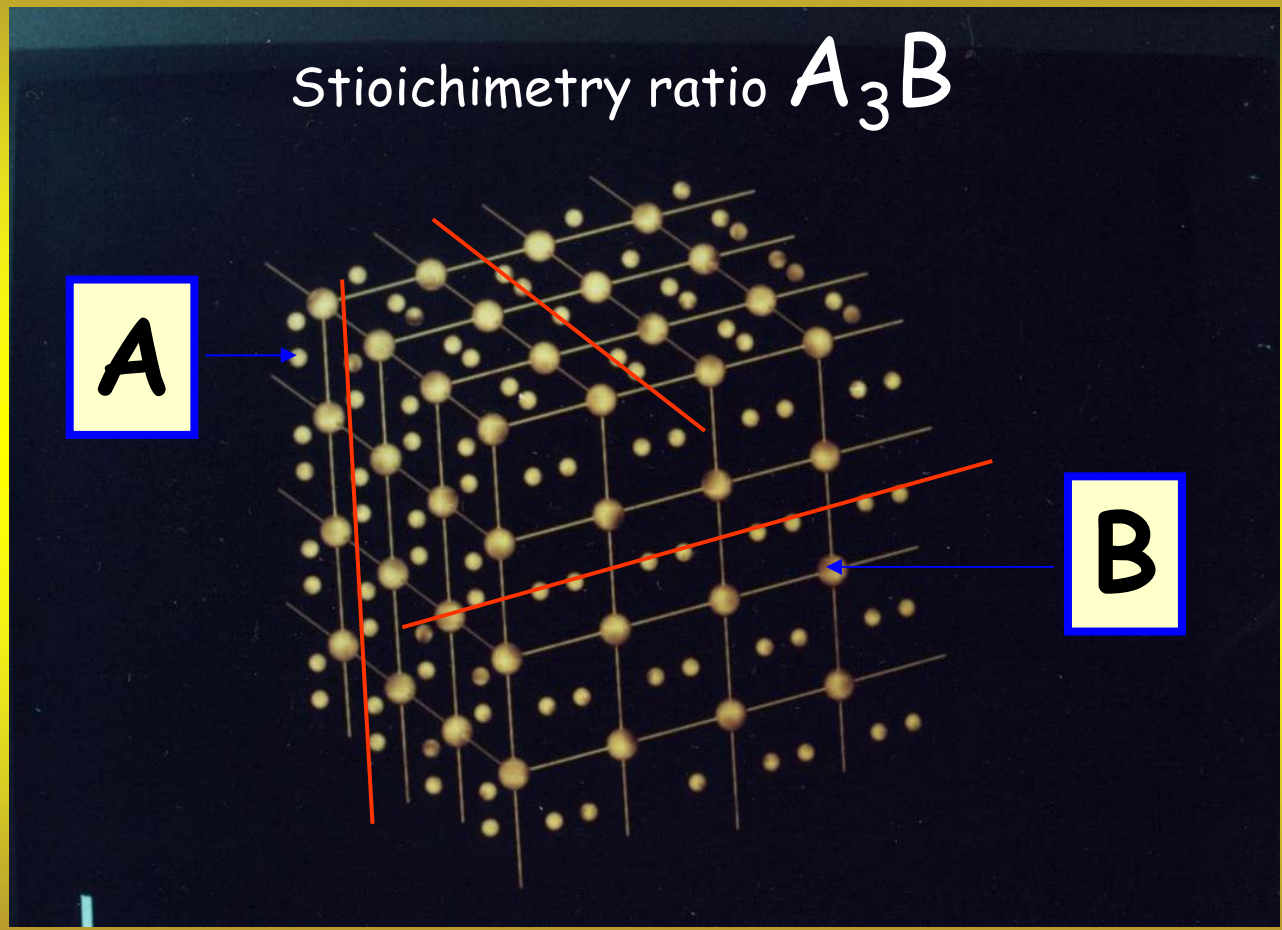
TiN

A.Nigro, G.Nobile, V.Palmieri, R.Vaglio, "PROPERTIES OF NIOBIUM-TITANIUM NITRIDE SUPERCONDUCTING THIN FILMS", **Adv. Cryog. Eng. Mat., vol. 34, (1988) 813**

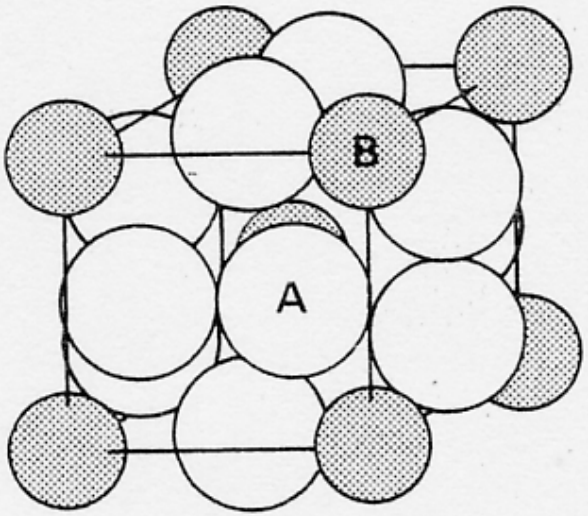
PdH is a very famous material for the reversal isotope effect and it has low resistivity

And Hydrides of Pd-Ag and Pd-Cu display Tc up to 15K!!!

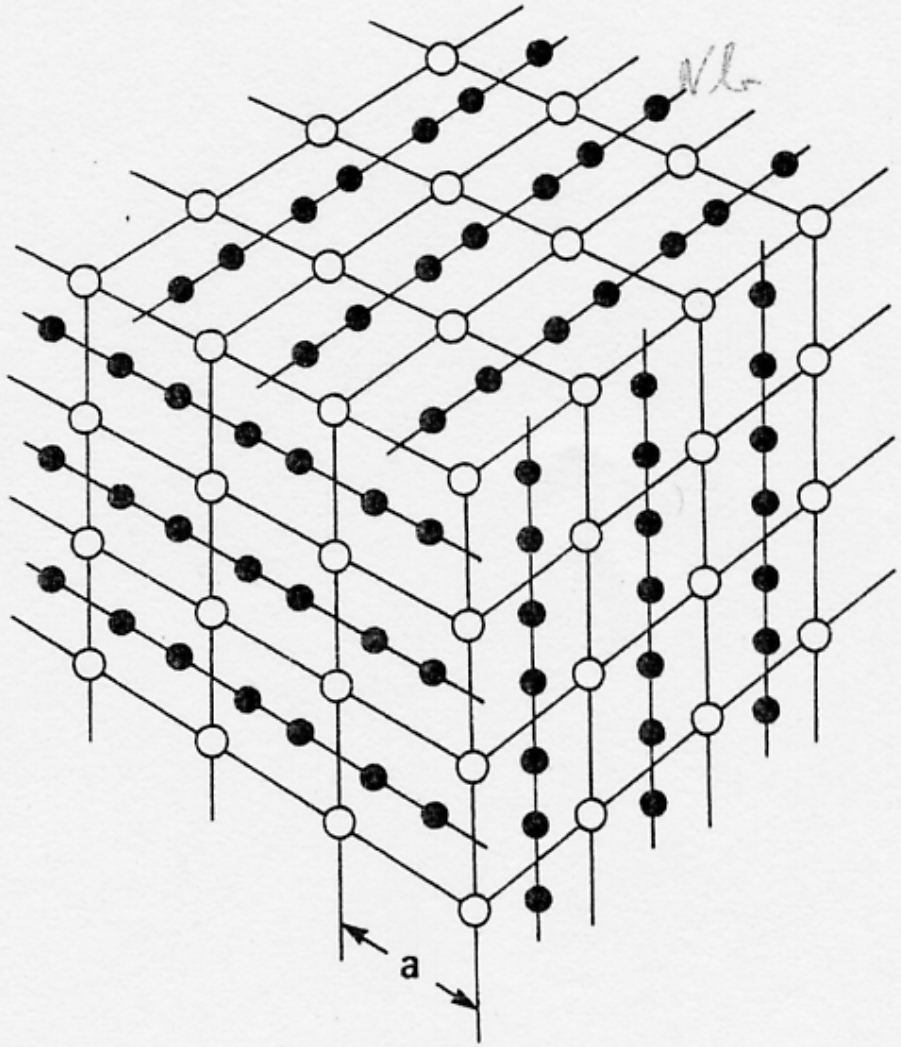
A15 compounds



The **A** atoms form linear chains parallel to the [100], [010], [001] directions

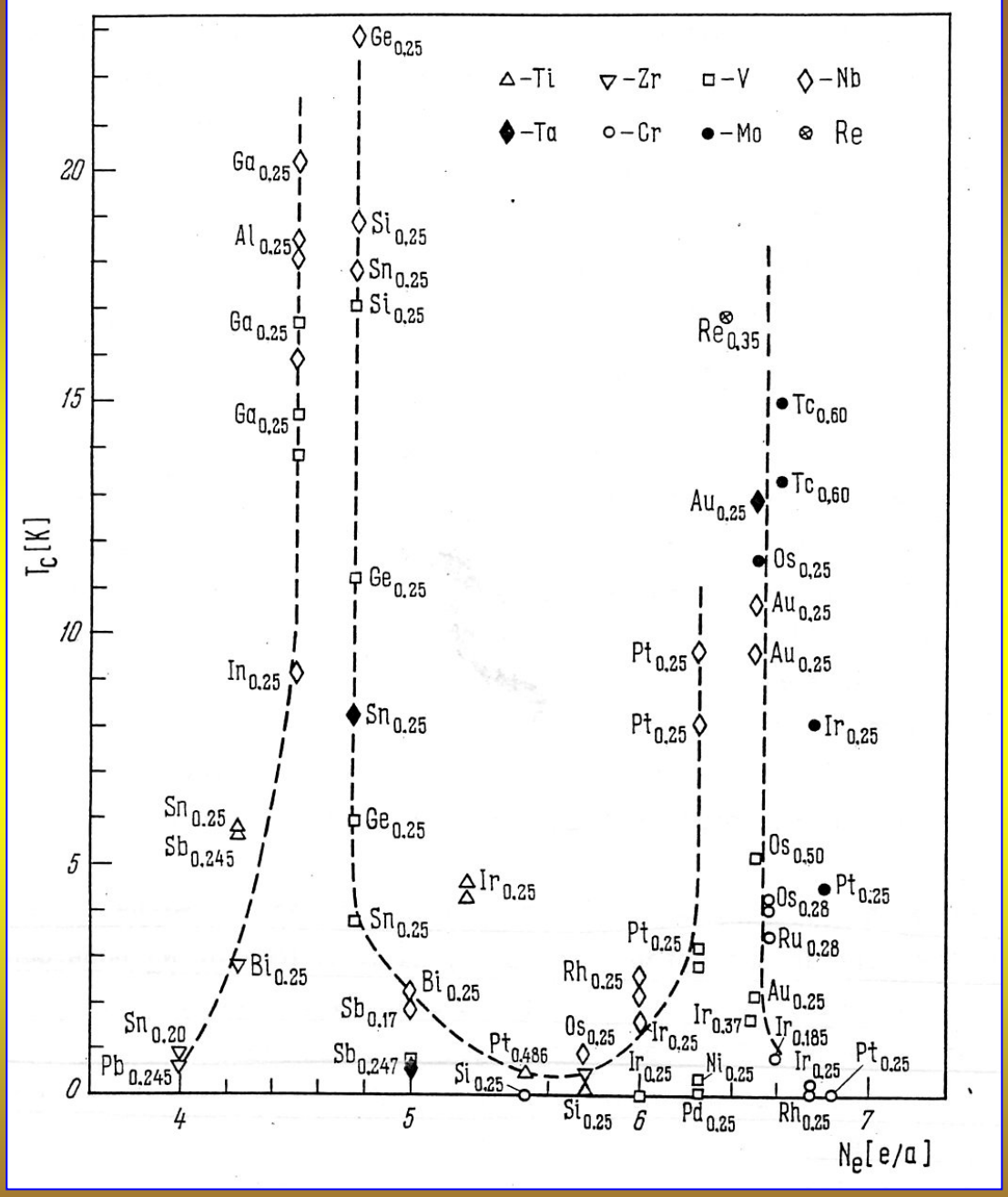


A-15 (OR β-W)
A_3B

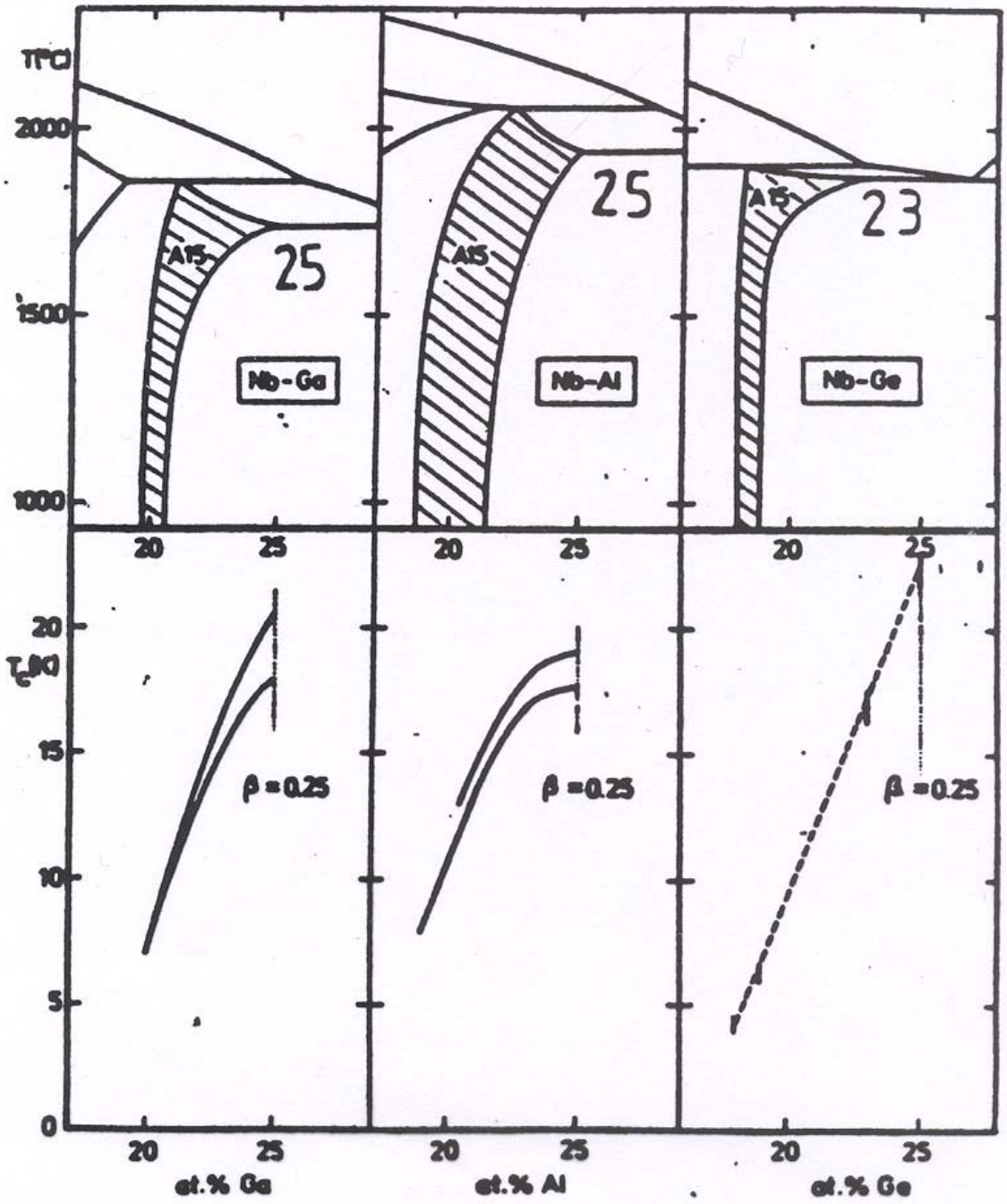


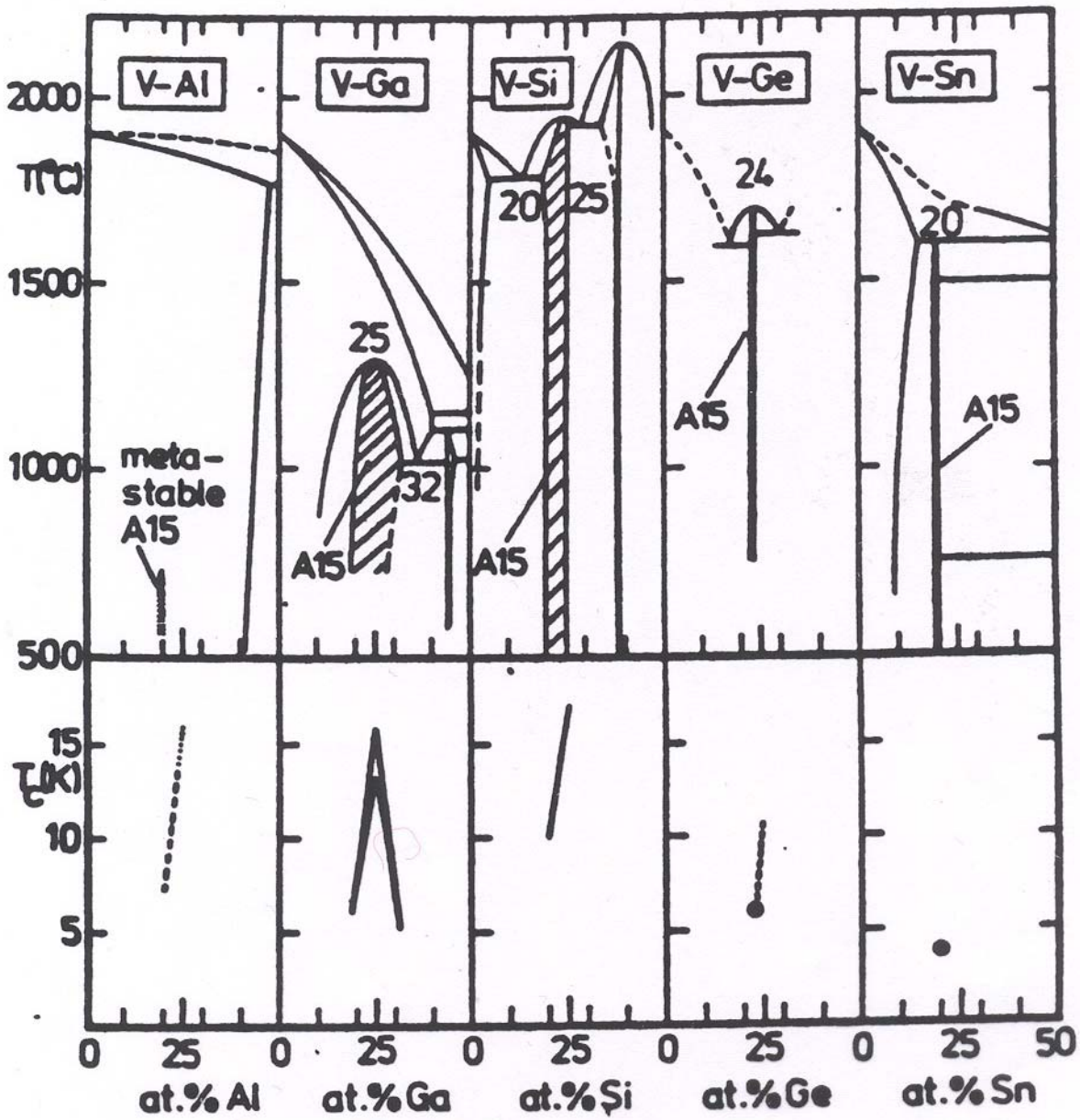
Nontransition elements	T_c (K)	Transition elements	T_c (K)
Ti_3Sb	6.5	Ti_3Ir	4.2
		Ti_3Pt	0.5
$Zr_{80}Sn_{20}$[a]	0.92		
Zr–Pb	0.76	Zr_3Au	0.9
$Zr_{\sim 3}Bi$[b]	3.4		
		$V_{29}Re_{71}$	8.4
V–Al[c]	14	$V_{50}Os_{50}$	5.7
V_3Ga	15.9	$V_{65}Rh_{35}$	$\simeq 1$
V_3Si	17.0	$V_{63}Ir_{37}$	1.7
$V_{\sim 3}Ge$	6	$V_{\sim 3}Pd$	0.08
$V_{\sim 3}Ge$[c]	11	V_3Pt	3.7
$V_{\sim 79}Sn_{\sim 21}$	3.8	$V_{76}Au_{24}$	3
$V_{77}As_{23}$	0.2	$Nb_{75}Os_{25}$	1.0
$V_{76}Sb_{24}$	0.8	$Nb_{75}Rh_{25}$	2.6
		$Nb_{72}Ir_{28}$	3.2
Nb_3Al	19.1	Nb_3Pt	11
Nb_3Ga	20.7	$Nb_{\sim 3}Au$	11.5
$Nb_{\sim 3}In$[b]	9.2		
$Nb_{82}Si_{18}$[a]	4.4	$Ta_{85}Pt_{15}$	0.4
		$Ta_{\sim 80}Au_{20}$	0.55
Nb–Si[c]	11–17		
Nb–Ge[a]	17	$Cr_{72}Ru_{28}$	3.4
Nb–Ge[c]	23	$Cr_{73}Os_{27}$	4.7
Nb_3Sn	18	$Cr_{78}Rh_{22}$	0.07
Nb–Sb	2	$Cr_{82}Ir_{18}$	0.75
$Nb_{\sim 3}Bi$[b]	3		
		$Mo_{40}Tc_{60}$	13.4
$Ta_{\sim 3}Ge$[c]	8	$Mo_{\sim 65}Re_{\sim 35}$[c]	$\simeq 15$
$Ta_{\sim 3}Sn$	8.3	$Mo_{75}Os_{25}$	13.1
$Ta_{\sim 3}Sb$	0.7	$Mo_{78}Ir_{22}$	8.5
		$Mo_{82}Pt_{18}$	4.6
Mo_3Al	0.58		
Mo_3Ga	0.76	$W_{\sim 60}Re_{\sim 40}$[c]	11
$Mo_{77}Si_{23}$	1.7		
$Mo_{77}Ge_{23}$	1.8		

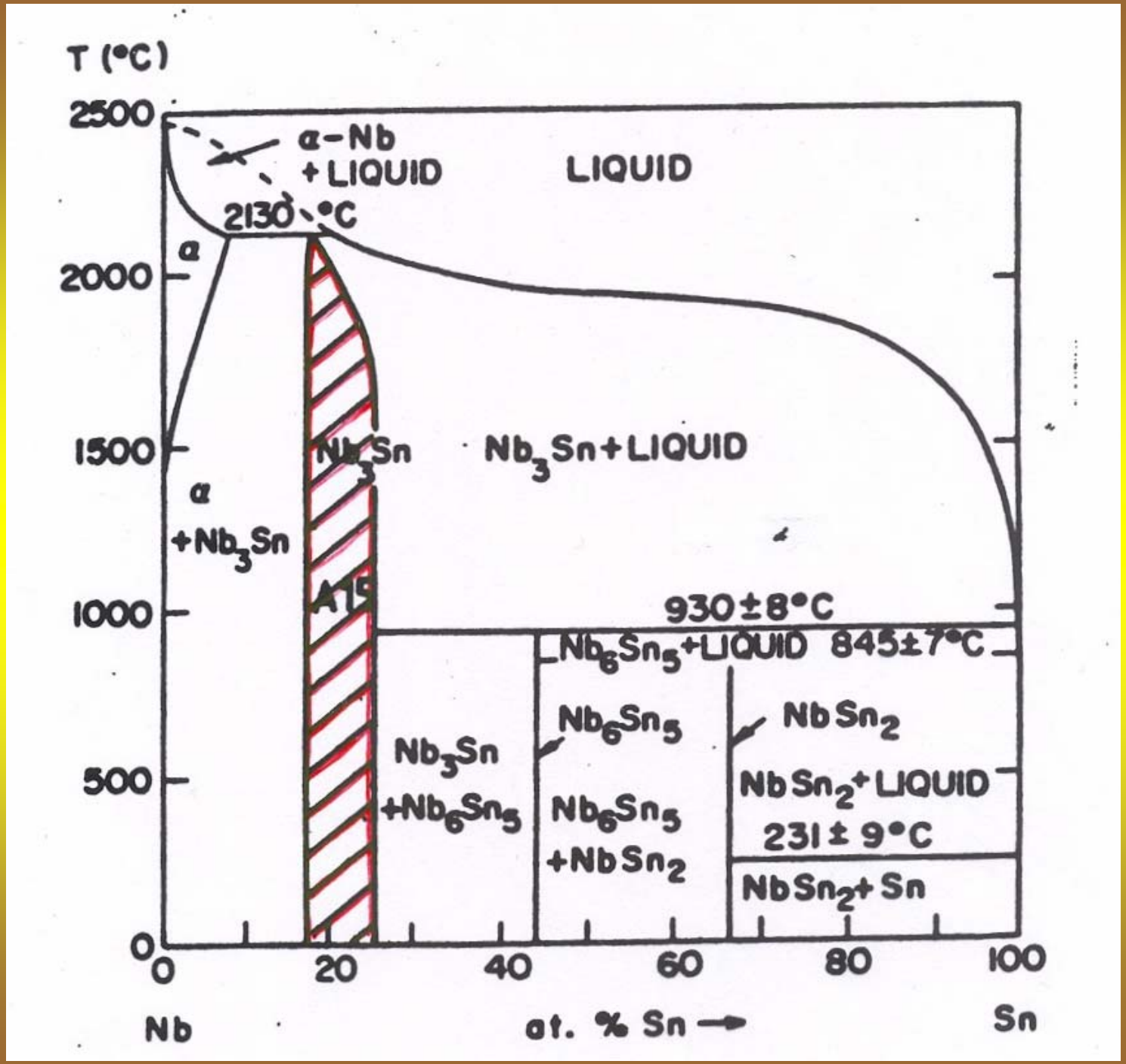
a Rapid quenching b High-pressure synthesis c Film deposition techniques


△-Ti ▽-Zr □-V ◇-Nb
◆-Ta ○-Cr ●-Mo ⊗ Re
T_c[K]
N_e[e/a]
0
5
10
15
20
4
5
6
7
$Ge_{0.25}$
$Ga_{0.25}$
$Al_{0.25}$
$Si_{0.25}$
$Sn_{0.25}$
$Re_{0.35}$
$Tc_{0.60}$
$Au_{0.25}$
$Os_{0.25}$
$In_{0.25}$
$Pt_{0.25}$
$Ir_{0.25}$
$Sn_{0.25}$
$Sb_{0.245}$
$Bi_{0.25}$
$Os_{0.50}$
$Os_{0.28}$
$Ru_{0.28}$
$Rh_{0.25}$
$Sn_{0.20}$
$Pb_{0.245}$
$Sb_{0.17}$
$Sb_{0.247}$
$Pt_{0.486}$
$Ir_{0.37}$
$Ir_{0.185}$
$Ni_{0.25}$
$Pd_{0.25}$
$Rh_{0.25}$

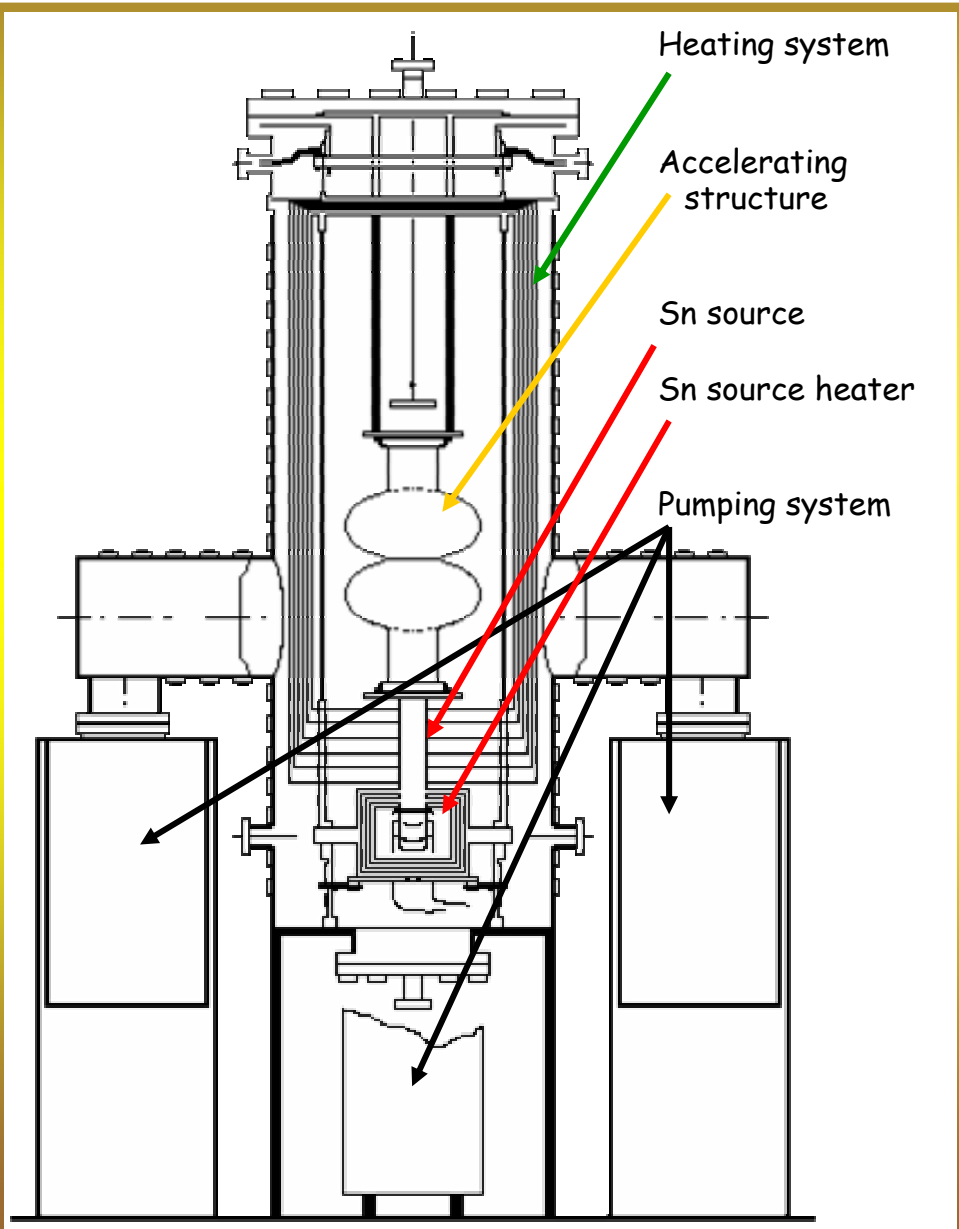
E_F


T(K)
2000
1500
1000
A15
25
Nb-Ga
A15
25
Nb-Al
A15
23
Nb-Ge
20
25
T_c(K)
20
15
10
5
0
β =0.25
β =0.25
β =0.25
at.% Ga
at.% Al
at.% Ge


V-Al
V-Ga
V-Si
V-Ge
V-Sn
2000
T(°C)
1500
1000
500
meta-
stable
A15
25
32
A15
A15
20
25
24
A15
20
A15
15
T_c(K)
10
5
0
25
0
25
0
25
0
25
0
25
50
at.% Al
at.% Ga
at.% Si
at.% Ge
at.% Sn


T (°C)
2500
2000
1500
1000
500
0
α-Nb
+ LIQUID
LIQUID
2130 °C
α
α
+Nb3Sn
Nb3Sn
A15
Nb3Sn+LIQUID
930±8°C
Nb6Sn5+LIQUID 845±7°C
Nb3Sn
+Nb6Sn5
Nb6Sn5
Nb6Sn5
+NbSn2
NbSn2
NbSn2+LIQUID
231±9°C
NbSn2+Sn
0
20
40
60
80
100
Nb
at. % Sn →
Sn

Vapor Sn Diffusion



Procedure

1) Cavity manufactoring
2) Formation of nucleation centers of Nb_3Sn (Nb Surface Anodization + $SnCl_2$ Treatment)
3) Nb_3Sn film growth in a Sn atmosphere (T = 1050-1250°C, t = dozens of h, p(Sn) ~ 10^{-3}mbar)
4) Cool down and unwanted phases Chemical removal (anodizaton + HF 48%)

Technique Choice Reasons

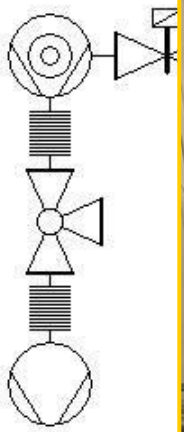
Liquid Sn Diffusion?

Bulk Nb substrate dipping in a liquid Tin bath → Sample Annealing

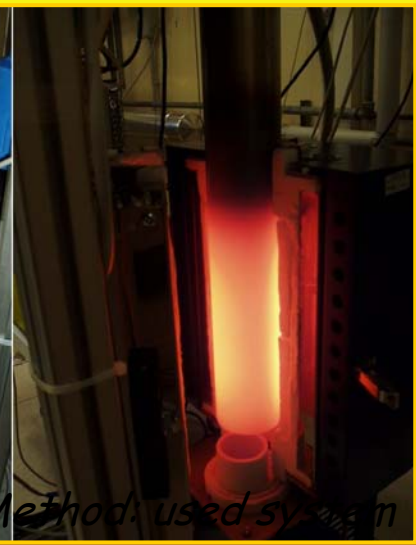
- No nucleation sites on Nb are required
- Fast growth of Nb_3Sn layer
- Deasirable uniform thickness

Used System

Linear feedtrou



Liquid Sn



Method: used system

SEM Image

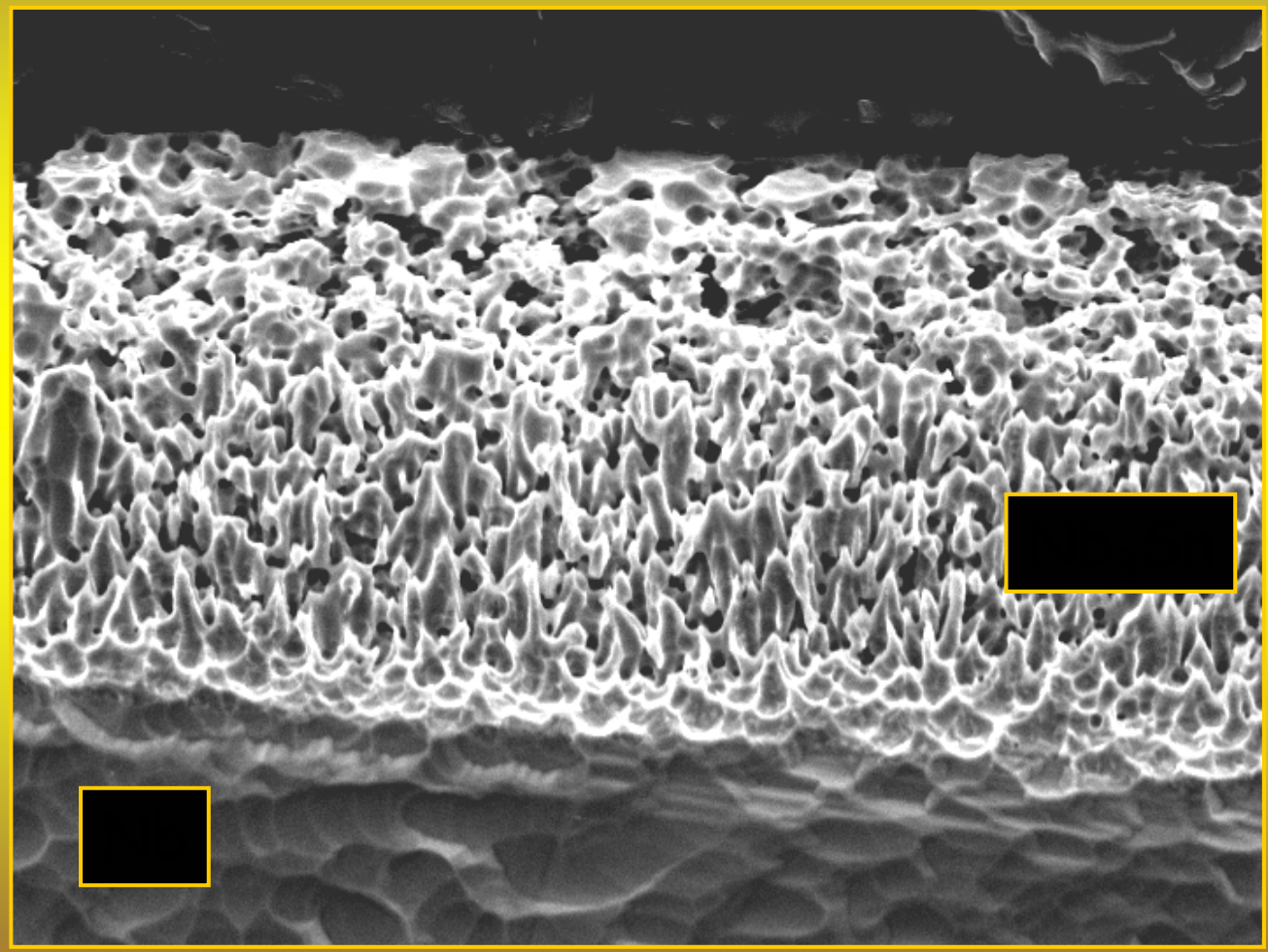
Process T = 1000°C

Dipping t = 120'

Annealing t = 14h

Post annealing:

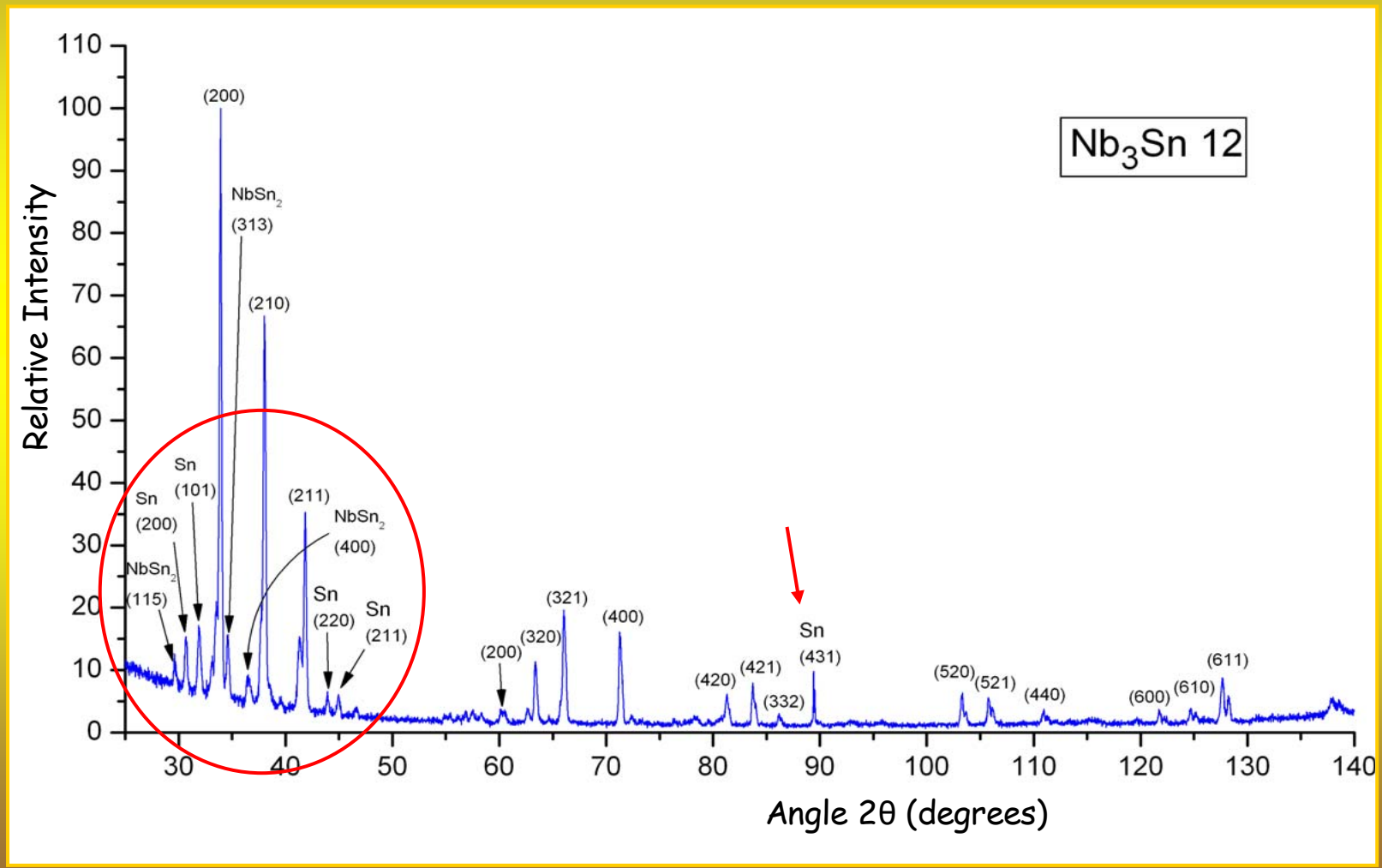
5h at 500°C



Method: "1 step" process

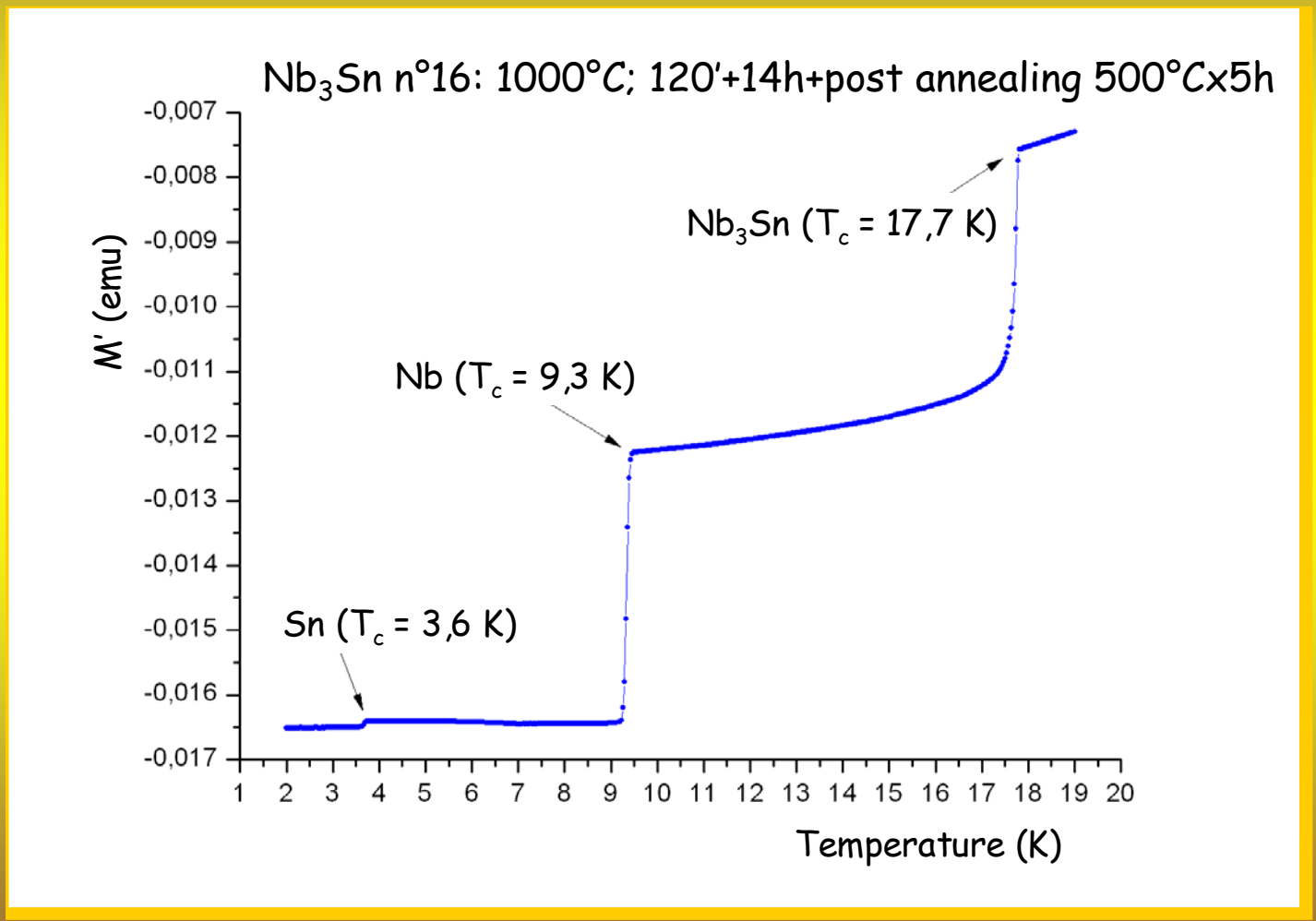
XRD spectrum

Process T = 1000°C, Dipping t = 30', Annealing t = 10h



Method: "1 step" process

A Superconductive Transition Curve



Method: "1 step" process

Francesco Todescato, Thesis 2004,
Material Science Dept, Padua University

Synthesis of Niobium Pentakis(dimethilammide)

The reaction happens in two different steps:

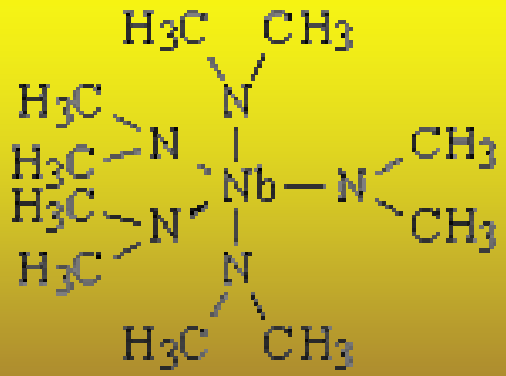
First the Me_2NH 50 mL is bubbled for around 90 minutes in LiBu:

$$Me_2NH + LiBu \rightarrow LiNMe_2 + BuH$$

Than the butane is evaporated and the product obtained is suspended in pentane and treated by $NbCl_5$

pentane

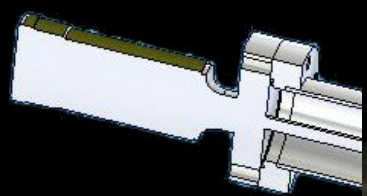
$$NbCl_5 + 5\,LiNMe_2 \rightarrow Nb(NMe_2)_5 + 5\,LiCl$$



The Ammide is a brrownish powder that sublimes at 130°C

Experimental setup: sputtering

Section view of experimental device



sputtering system

- ✓Balanced Magnetron sources
- ✓Target-Substrate distance 60 mm
- ✓2 inches target diameter

Thin film grown

Condition of deposition

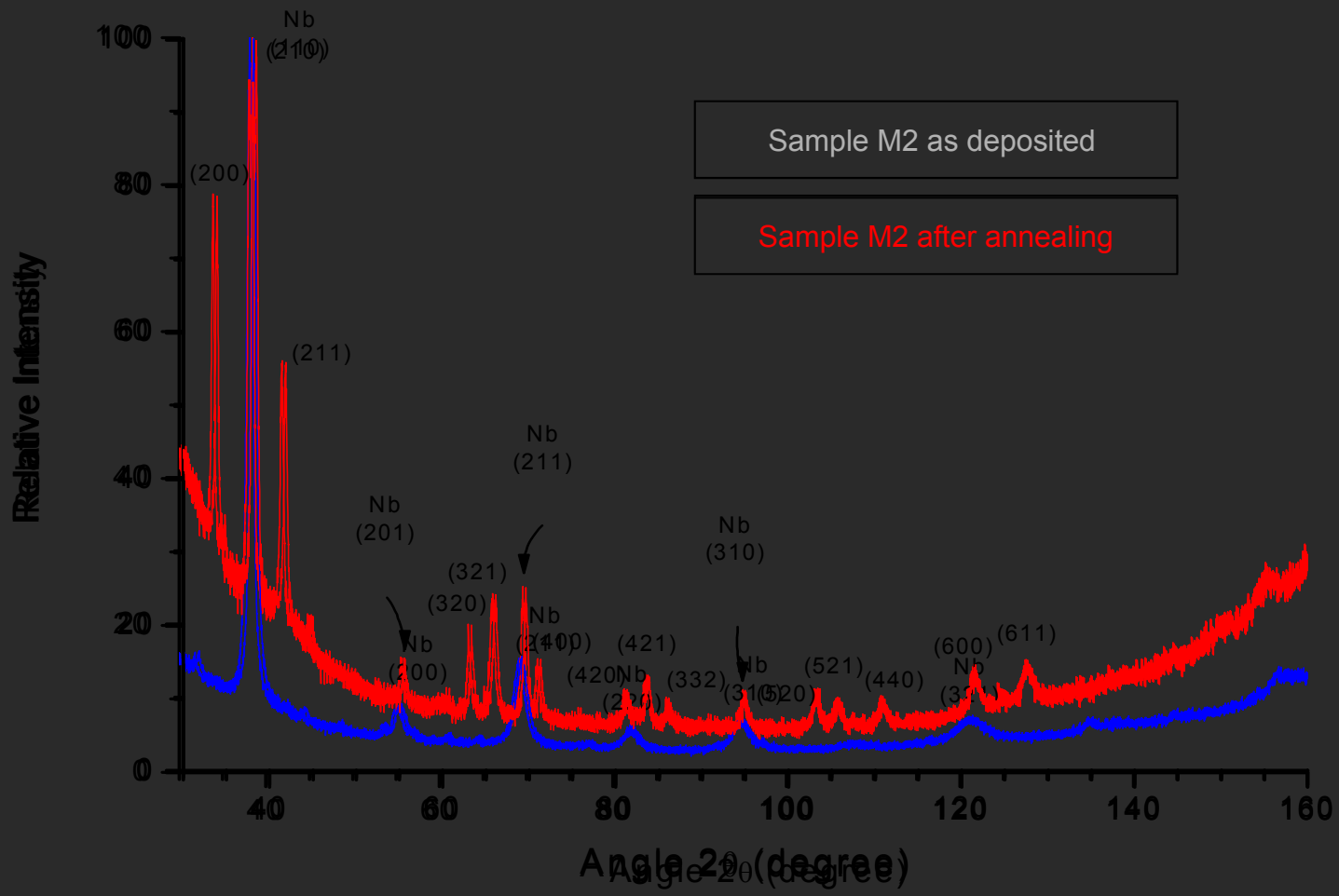
P base = 1.5×10^{-6} mbar
P sputtering = 4.0×10^{-3} mbar

Sputtering Target	Voltage (V)	Current (A)	Power (W)
Sn			
Nb			

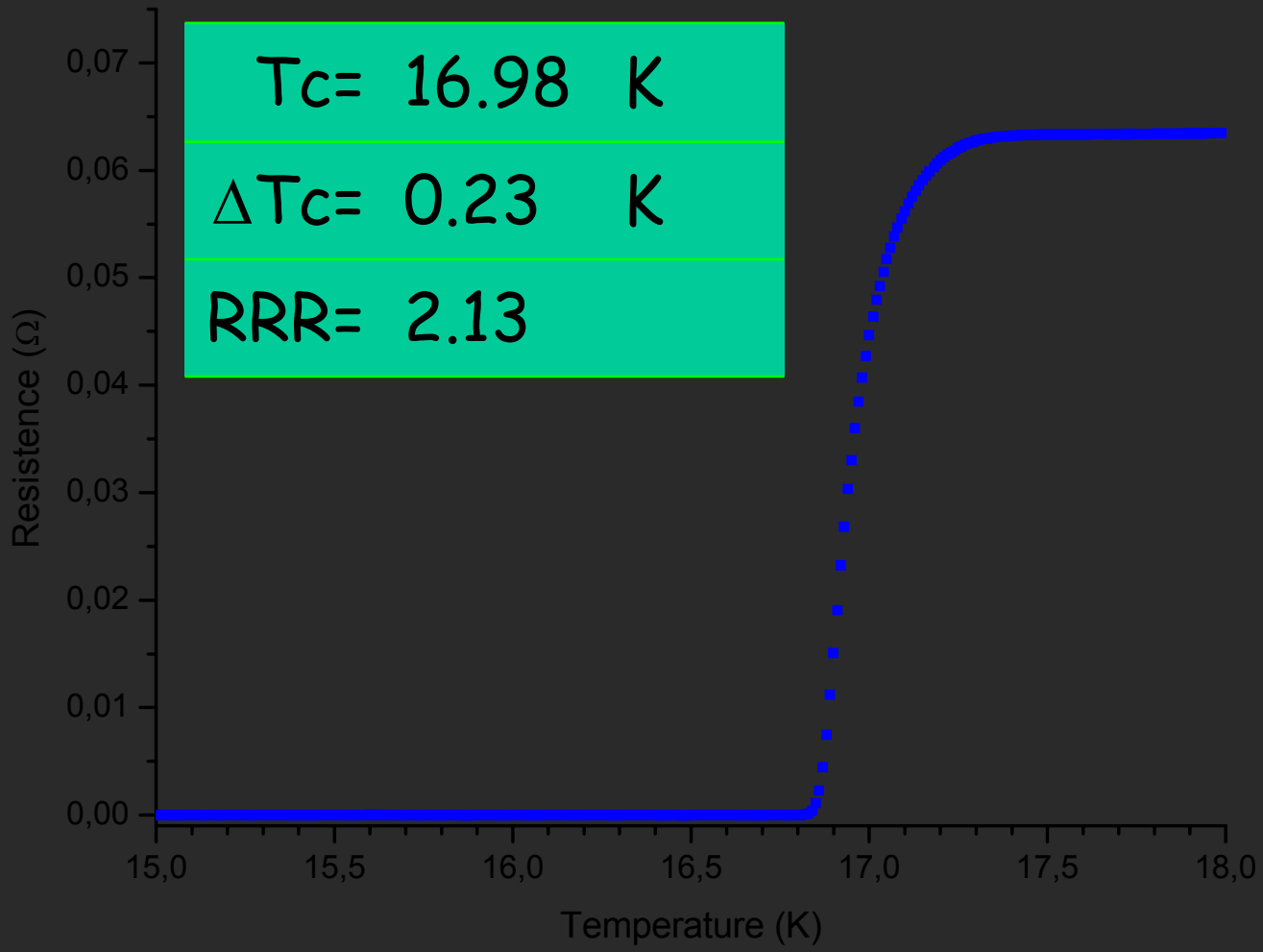
Thickness Nb = 4.5 Thickness Sn

Annealed after sputtering
for 3 hours at 975 °C

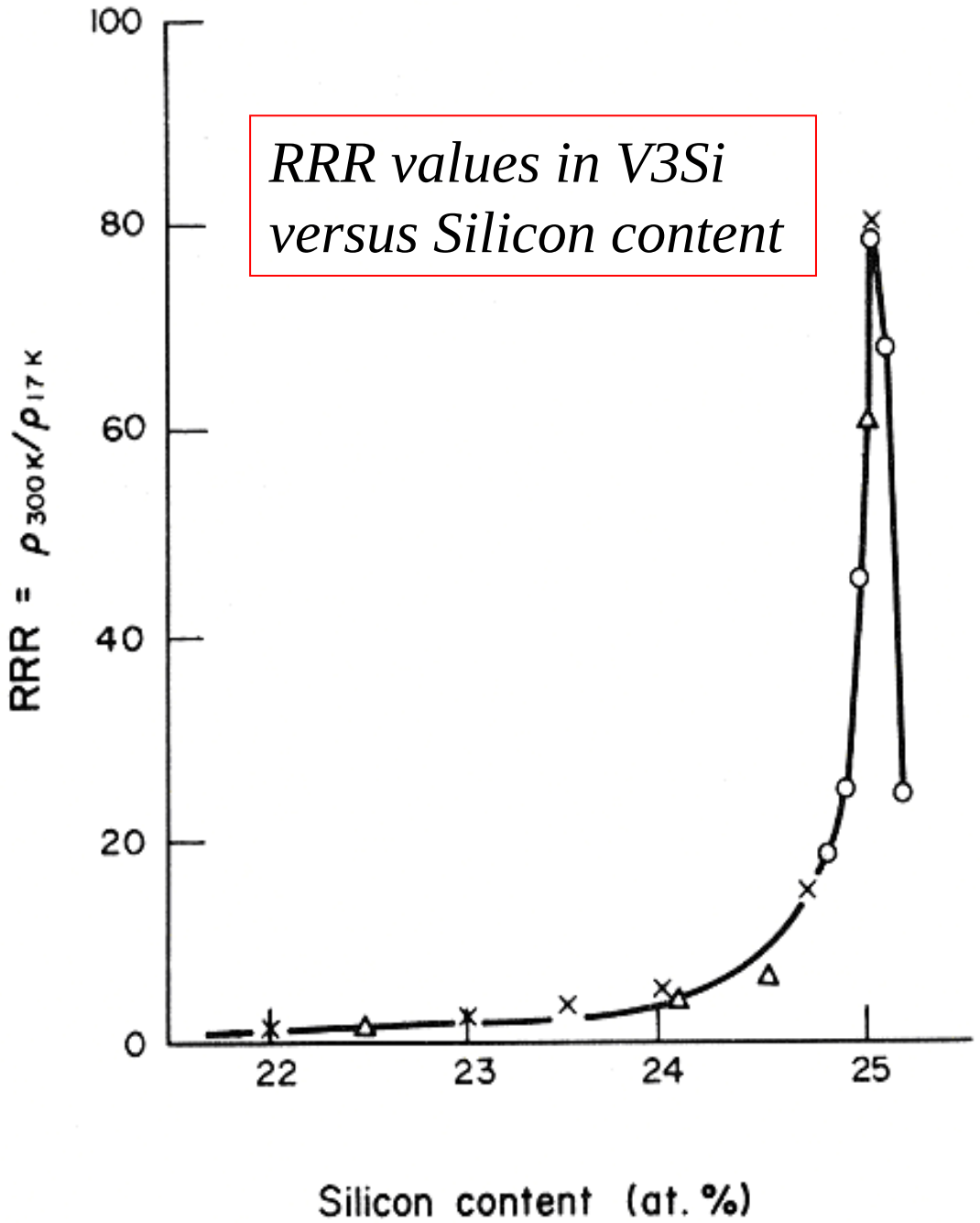
Results: X-ray diffraction



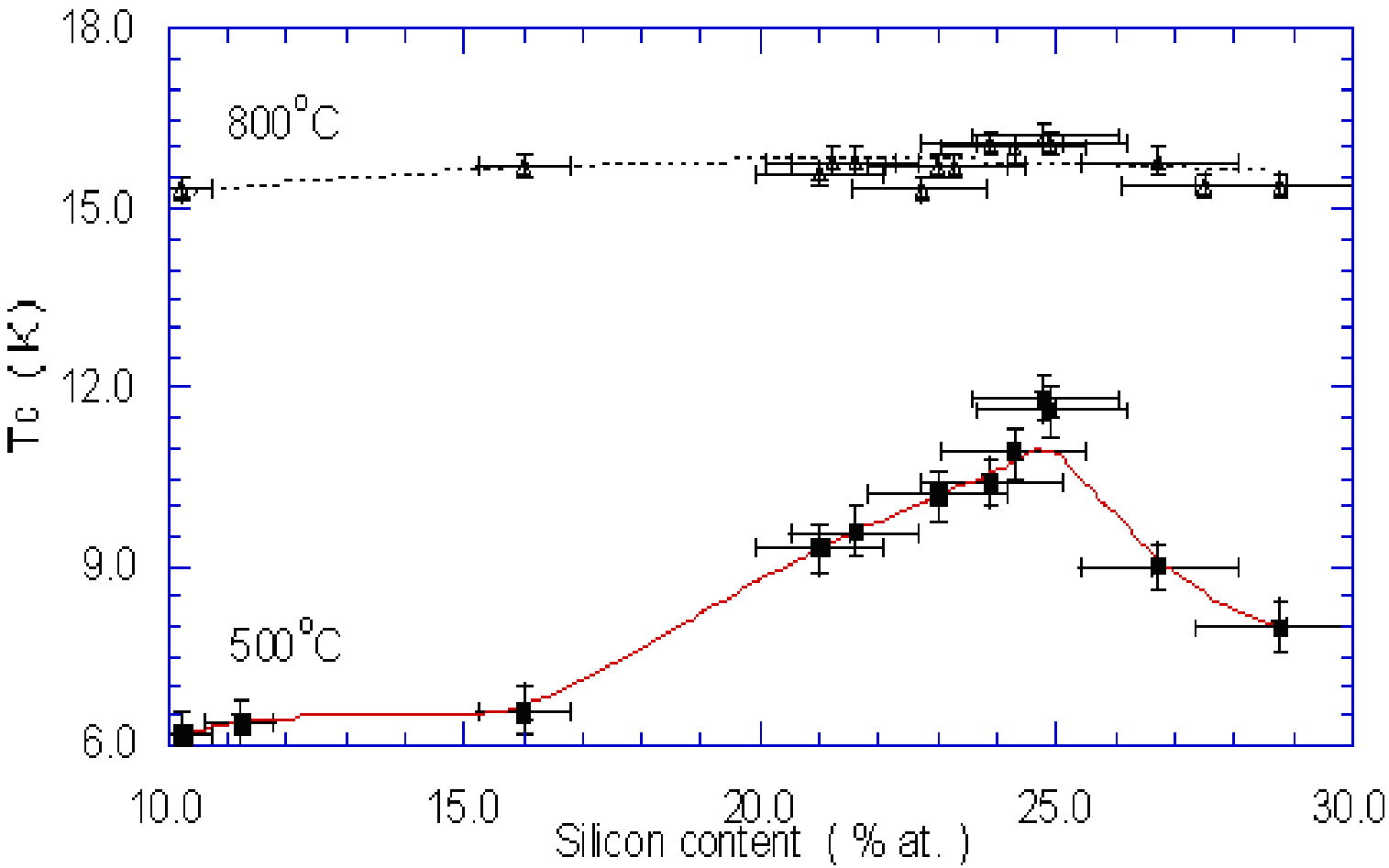
Results: Superconductive characteristic



RRR values in V3Si versus Silicon content



Tc vs Si content for sputtered films before and after in situ post-annealing in SiH4 atmosphere



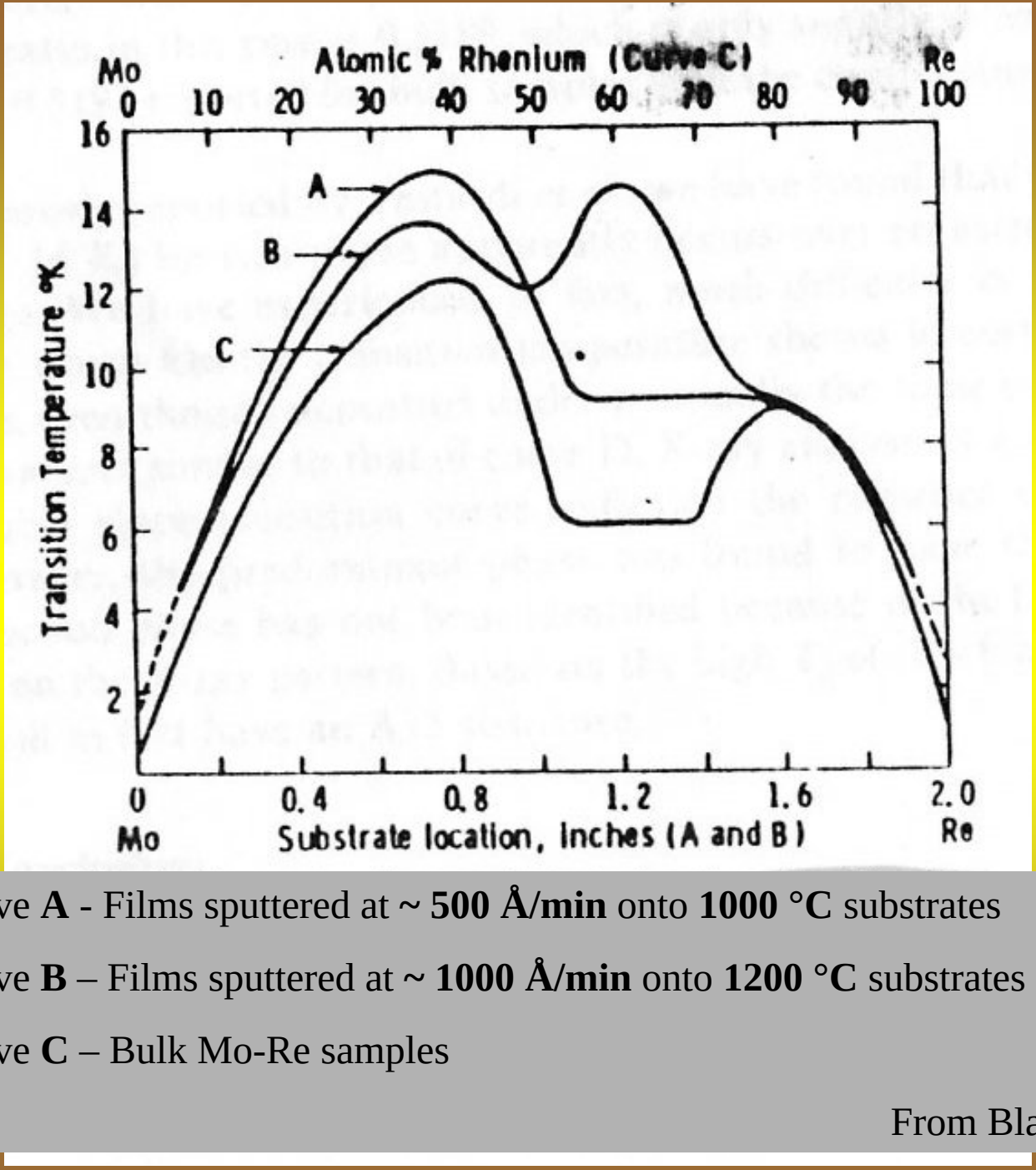
Y. Zhang, V. Palmieri, W. Venturini, F. Stivanello, R. Preciso, **LNL-INFN (REP) 157/2000**

Molybdenum-Rhenium

Most commonly known as **Moly-Rhenium**, and used extensively throughout many industries -from medicine to defense and pure research to production welding, this material is a less costly alternative to pure rhenium.

Possessing excellent thermal and mechanical properties, **Moly-Rhenium** is used as welding wire, wires for numerous medical applications, components and parts for the aerospace and defense industries, and grids for electronic applications.

Density, g/cm^3	**13.52**
Melting Point, °C	**2550**
Thermal Conductivity, W/m at 20°C	**36.8**
Linear Coefficient of Thermal Expansion, µm/m·K from 20-1000°C	**5.7**
Ductile Brittle Transition Temperature (DBBT), °C	**(-273)-(-173)**
Critical Superconducting temperature, K	**10.9**
Electrical Resistivity, µΩ·m at 20°C	**0.220**
Elastic Modulus in Tension, GPa	**373**



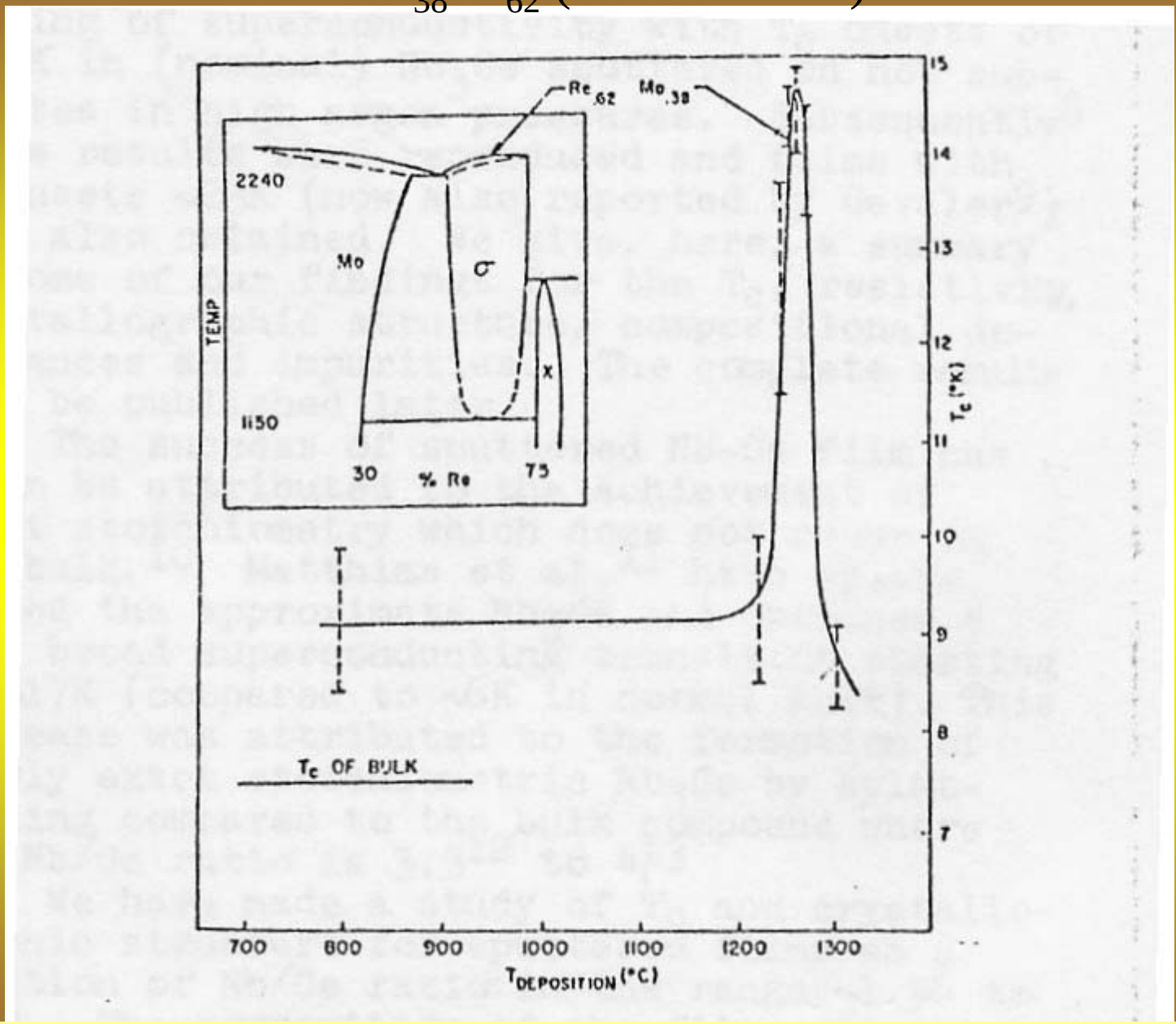
Curve **A** - Films sputtered at **~ 500 Å/min** onto **1000 °C** substrates

Curve **B** – Films sputtered at **~ 1000 Å/min** onto **1200 °C** substrates

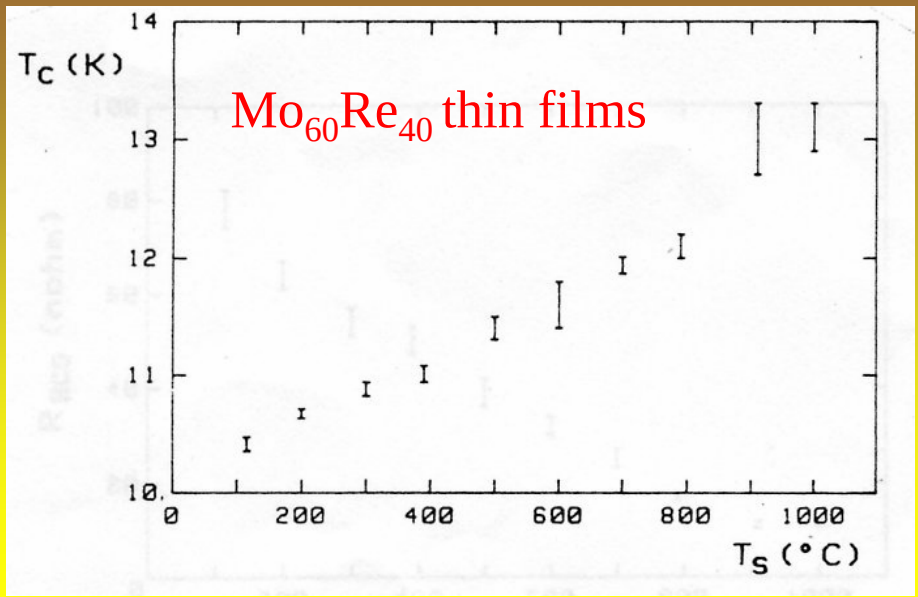
Curve **C** – Bulk Mo-Re samples

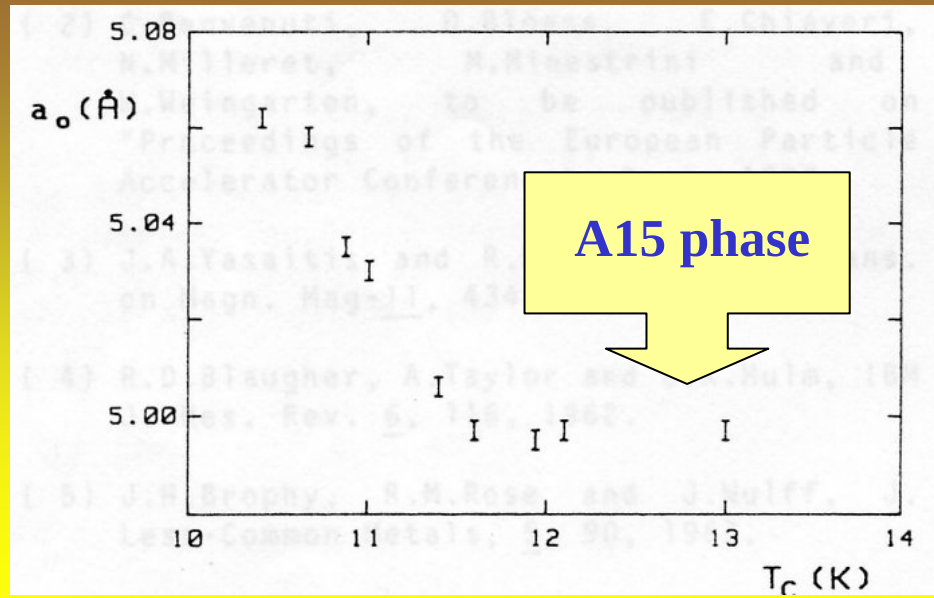
From Blaugher et al

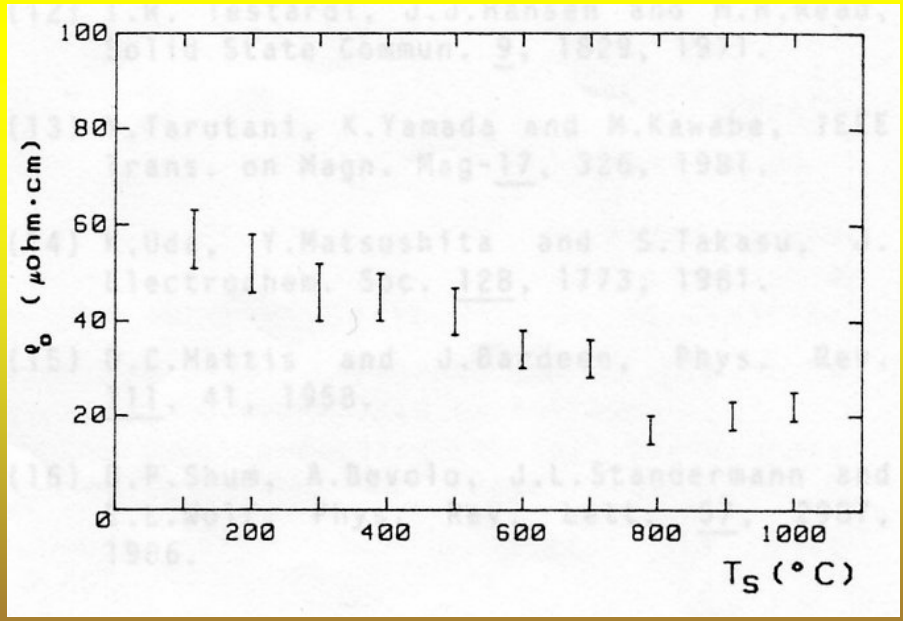
$Mo_{38}Re_{62}$ (after Testardi)

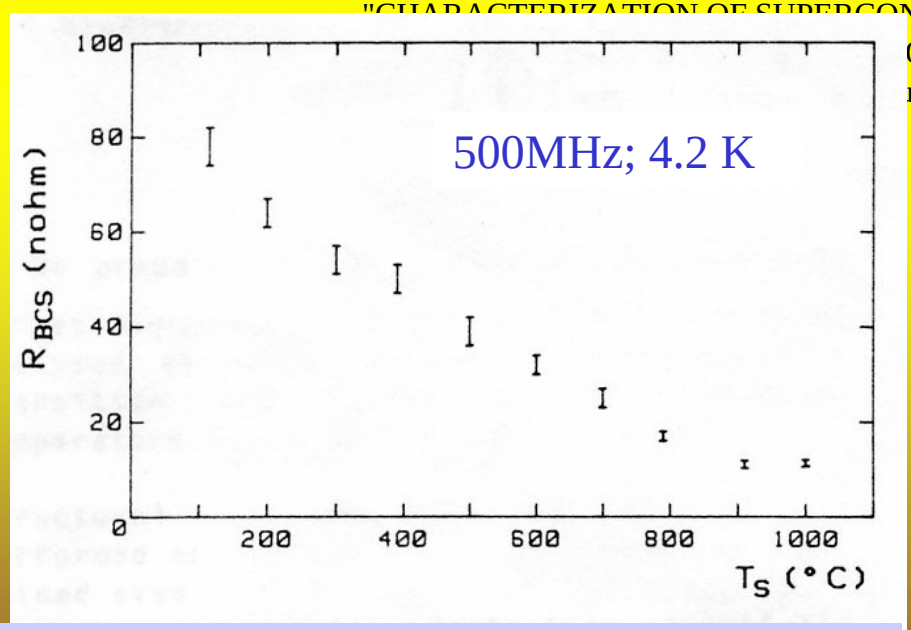


(The author communicates that the Temperature was 150 C lower than reported in the picture)

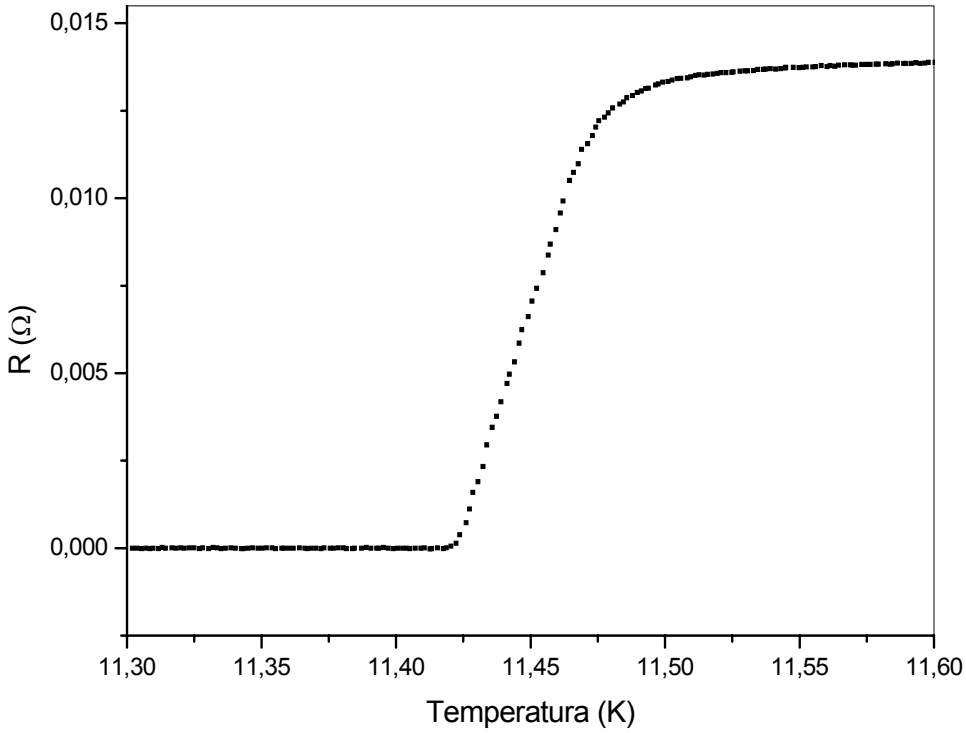






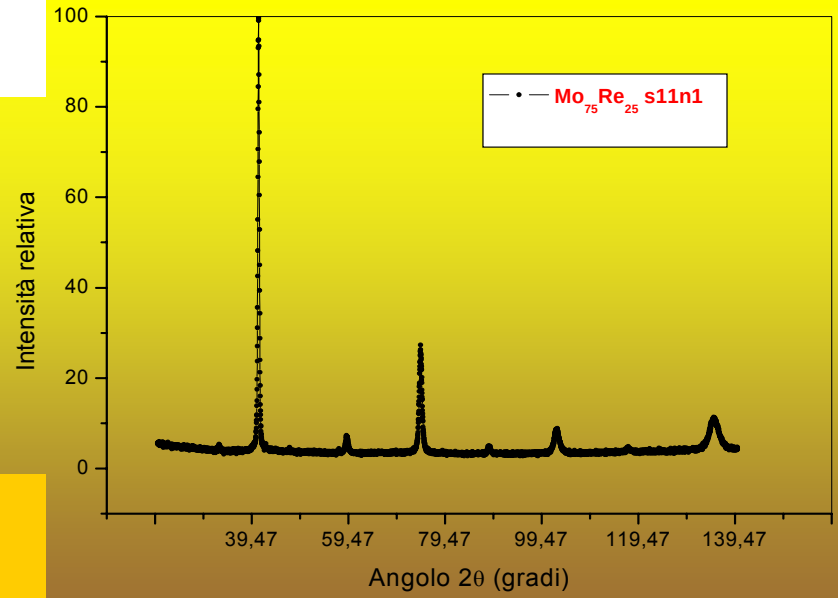


A.Andreone, A.Barone, A.Di Chiara, G.Mascolo, V.Palmieri, G.Peluso, U.Scotti, "Mo-Re Superconducting Thin Films by Single Target Magnetron Sputtering", **IEEE Trans. Mag., 25, 2, (1989) 1972**



Sputtered films from $Mo_{75}Re_{25}$ arc melted target

$\Delta T_C = 0.02$ K



Silvia Deambrosis, Thesis 2004,
Material Science Dept, Padua University

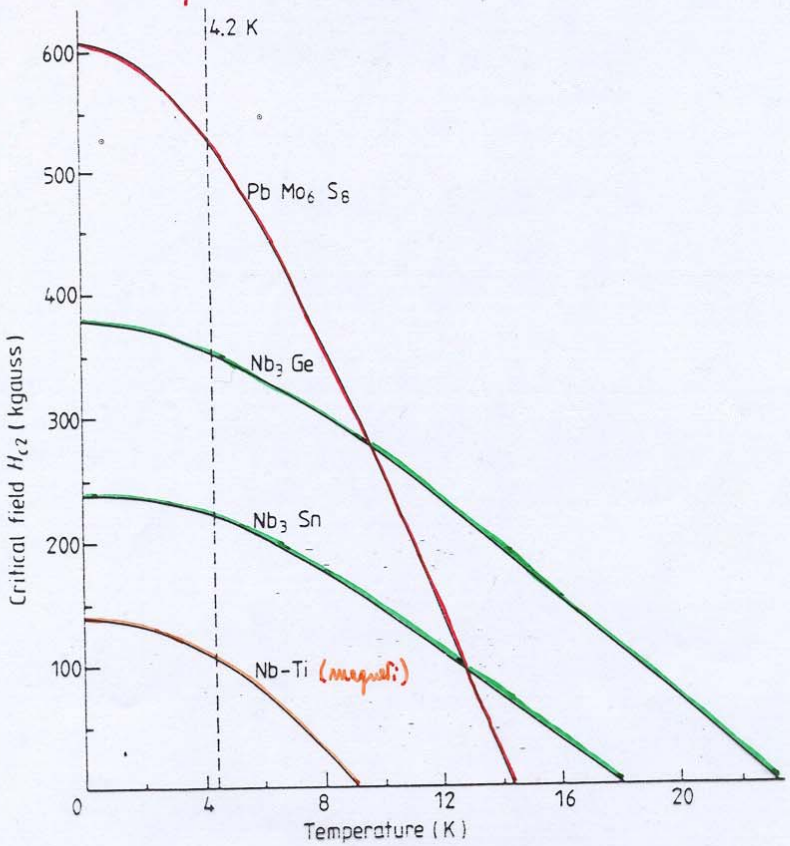
Chevrel Phases

$A_x Mo_6 Y_8$

$Y = S, Se, Te$

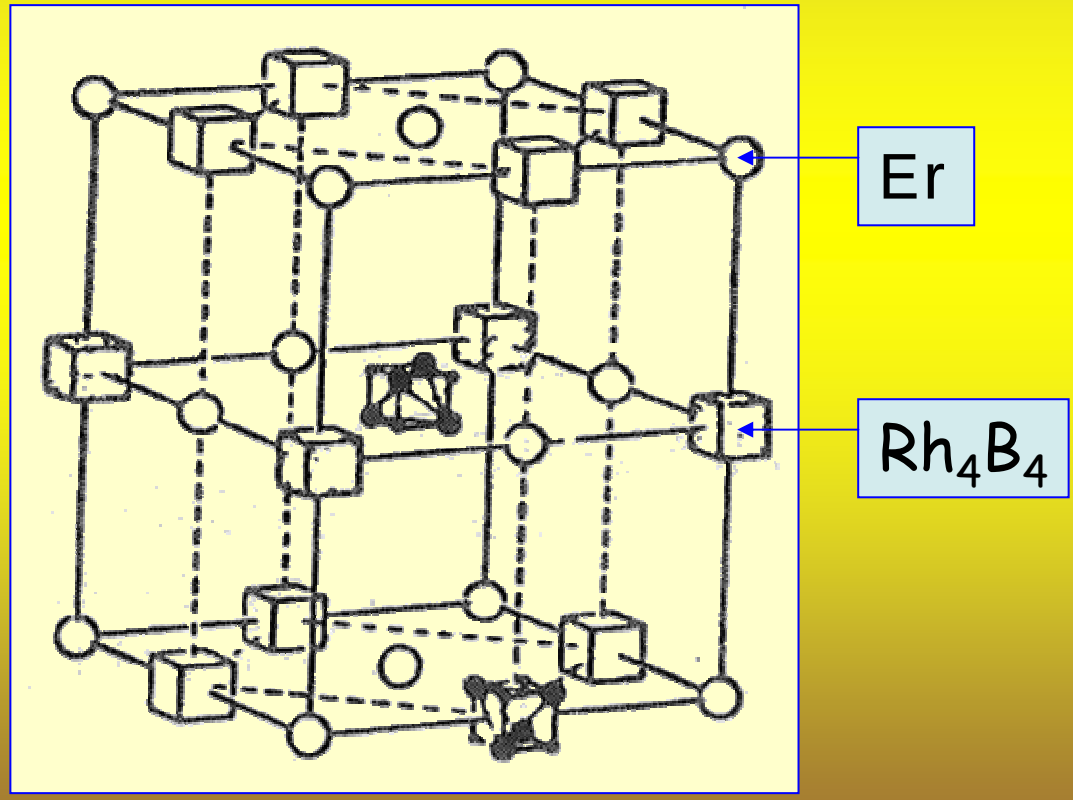
A = almost any

Formula	T_c(K)	Formula	T_c(K)
Mo_6S_8	1.7	Mo_6Se_8	6.3
$Cu_2Mo_6S_8$	10.6	$Cu_{1.4}Mo_6Se_8$	5.8
		$Cu_{2.6}Mo_6Se_8$	4.6
$AgMo_6S_8$	8.5	$AgMo_6Se_8$	5.8
$SnMo_6S_8$	11.8–14.5	$SnMo_6Se_8$	4.8
$PbMo_6S_8$	12.5–14.7	$PbMo_6Se_8$	3.6
$NaMo_6S_8$	8.5		
$LaMo_6S_8$	7.0	$LaMo_6Se_8$	11.2
$PrMo_6S_8$	2.6	$PrMo_6Se_8$	8.9
$NdMo_6S_8$	3.5	$NdMo_6Se_8$	8.0
$SmMo_6S_8$	2.4	$SmMo_6Se_8$	6.6
$GdMo_6S_8$	1.4	$GdMo_6Se_8$	5.4
$YbMo_6S_8$	8.5	$YbMo_6Se_8$	5.2

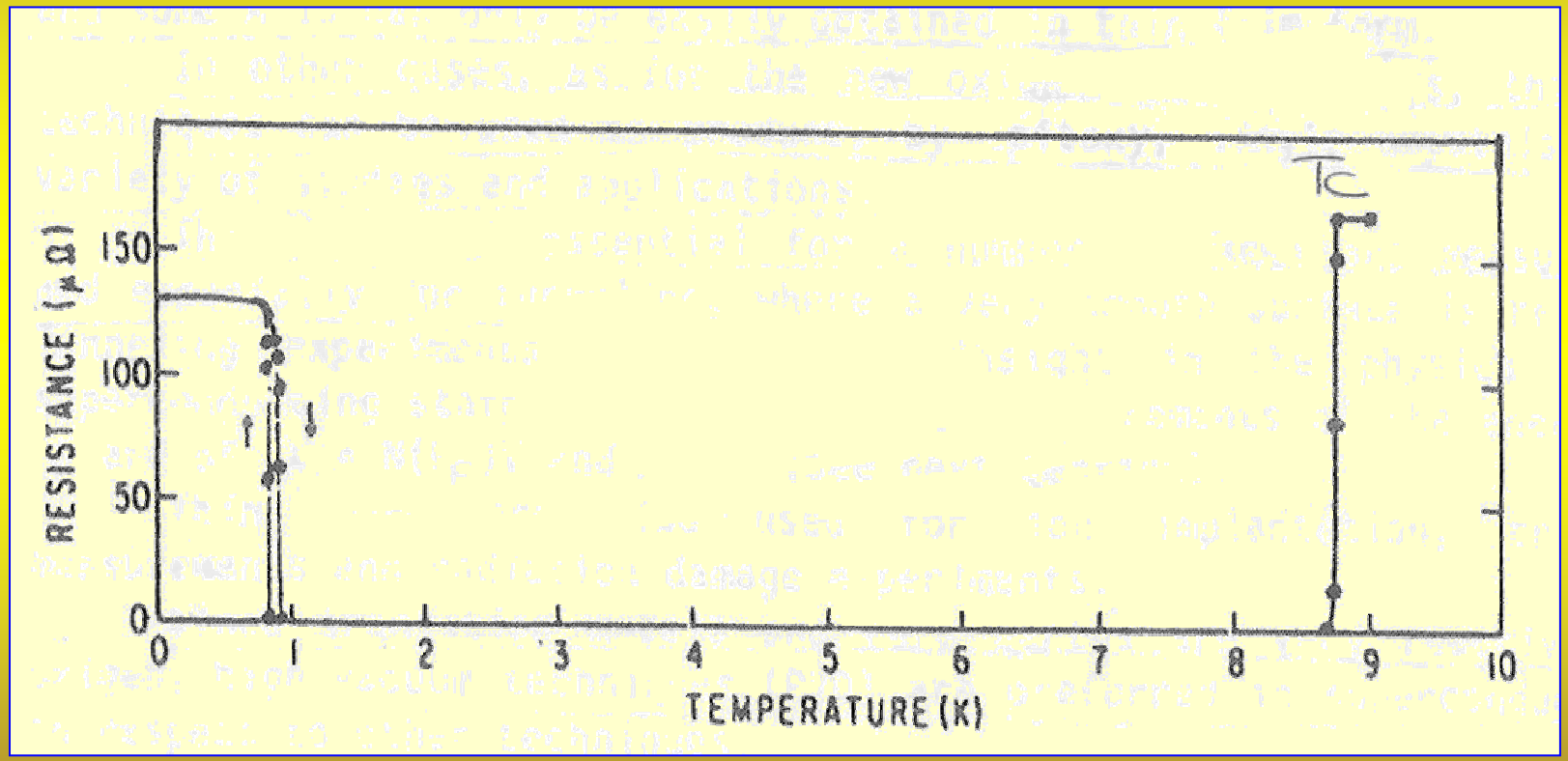


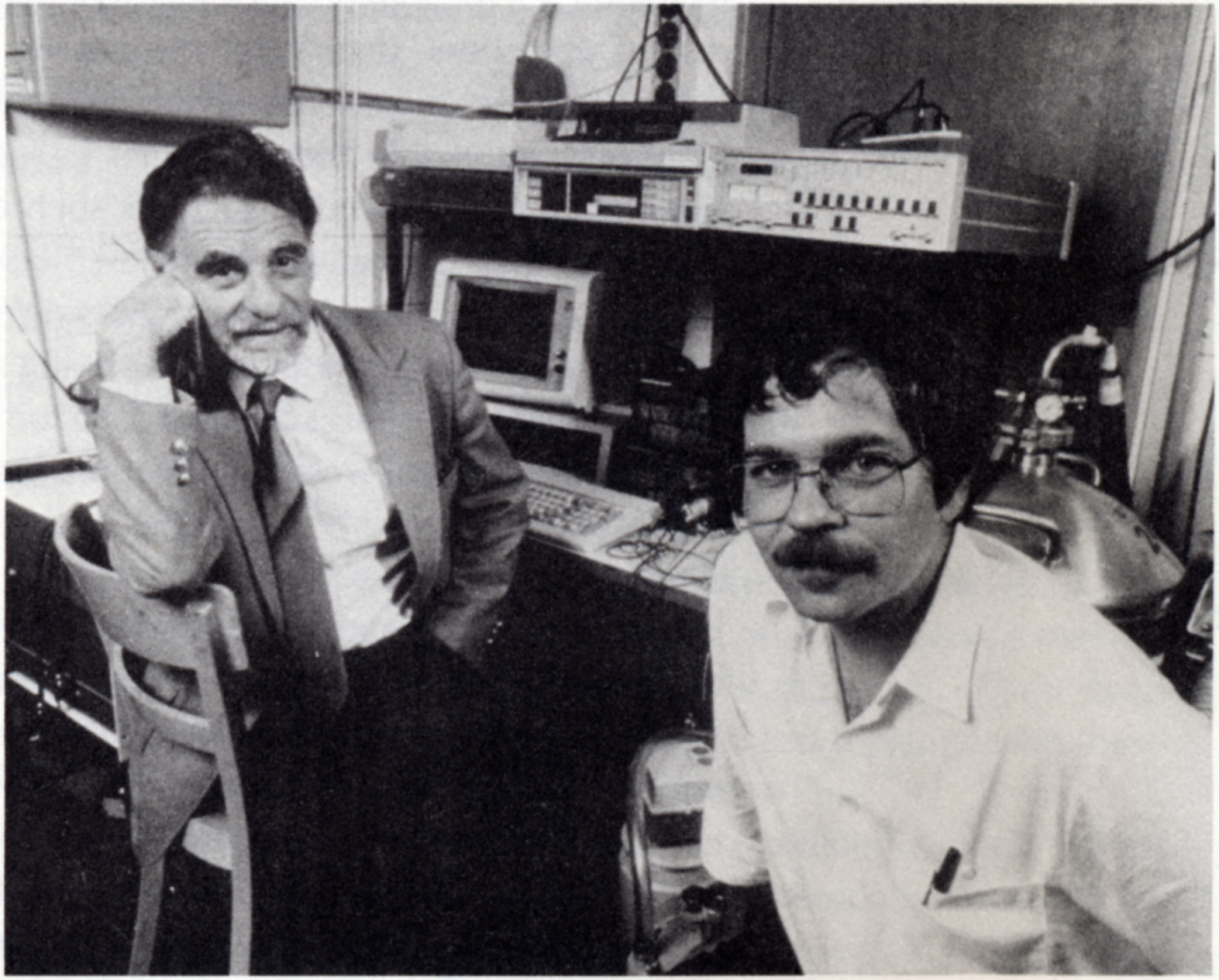
Magnetic Superconductors

Struttura cristallina di composti **Er-Rh_4B_4**



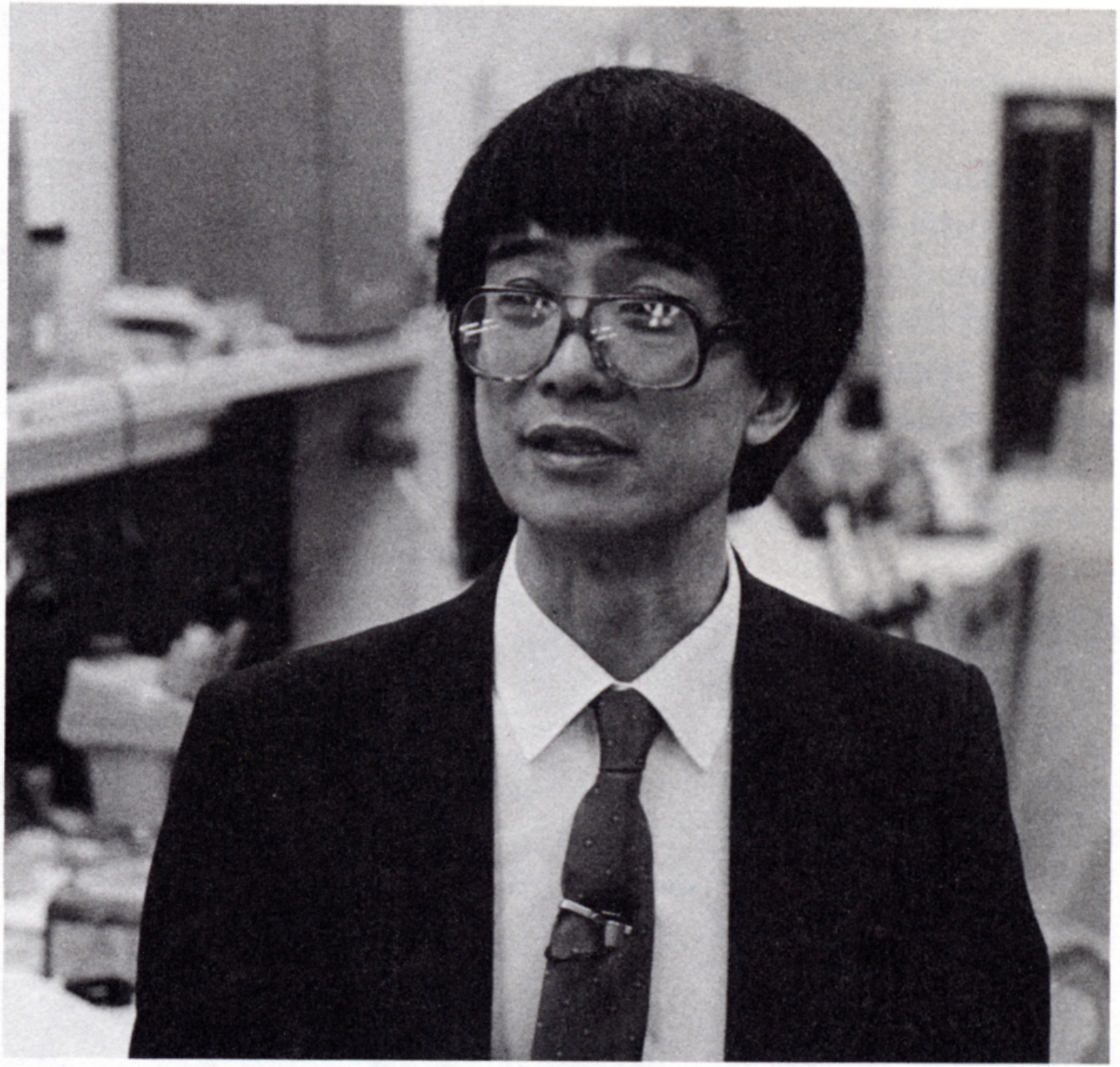
Er-Rh_4B_4





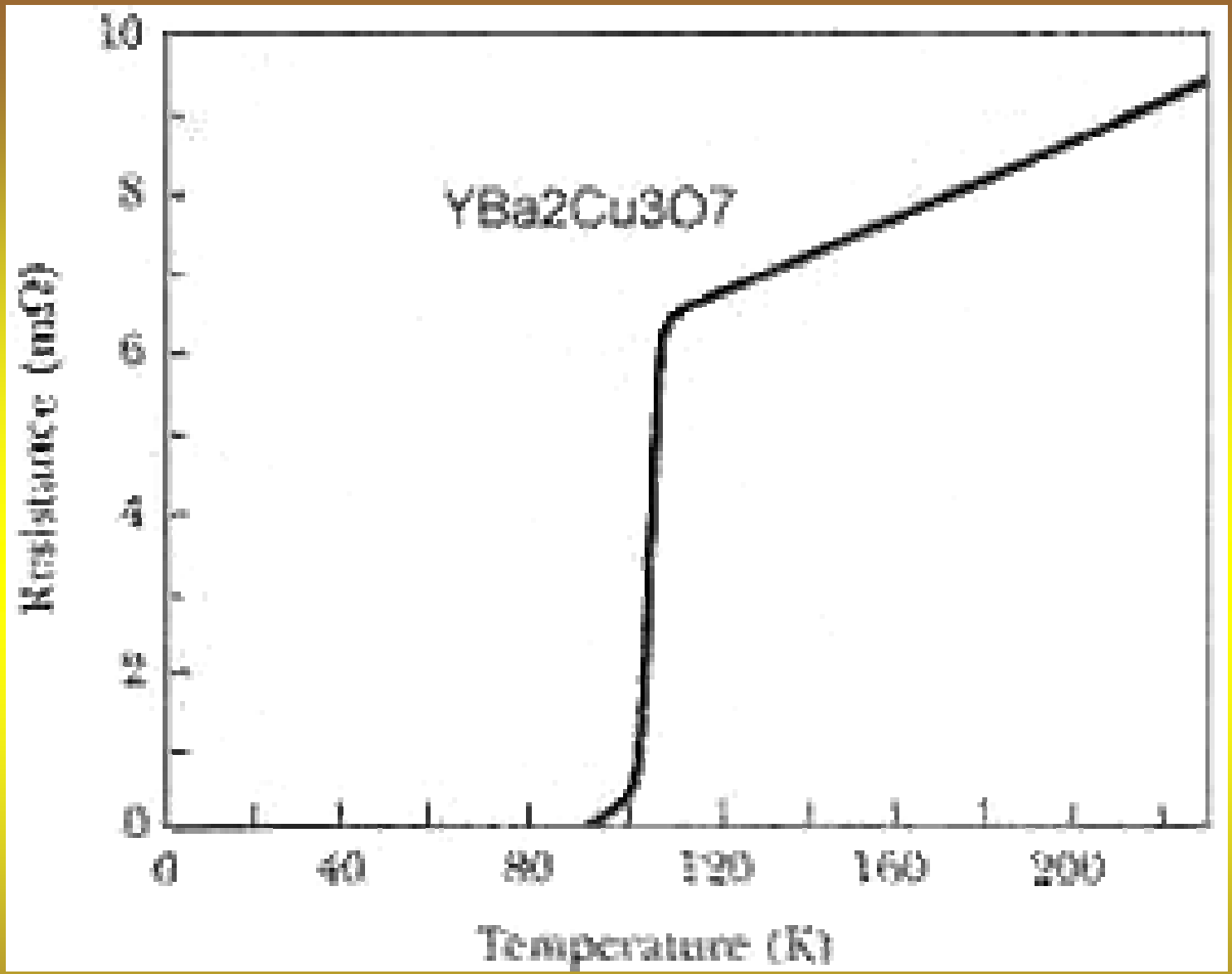
(Photograph courtesy of IBM Research Division.)

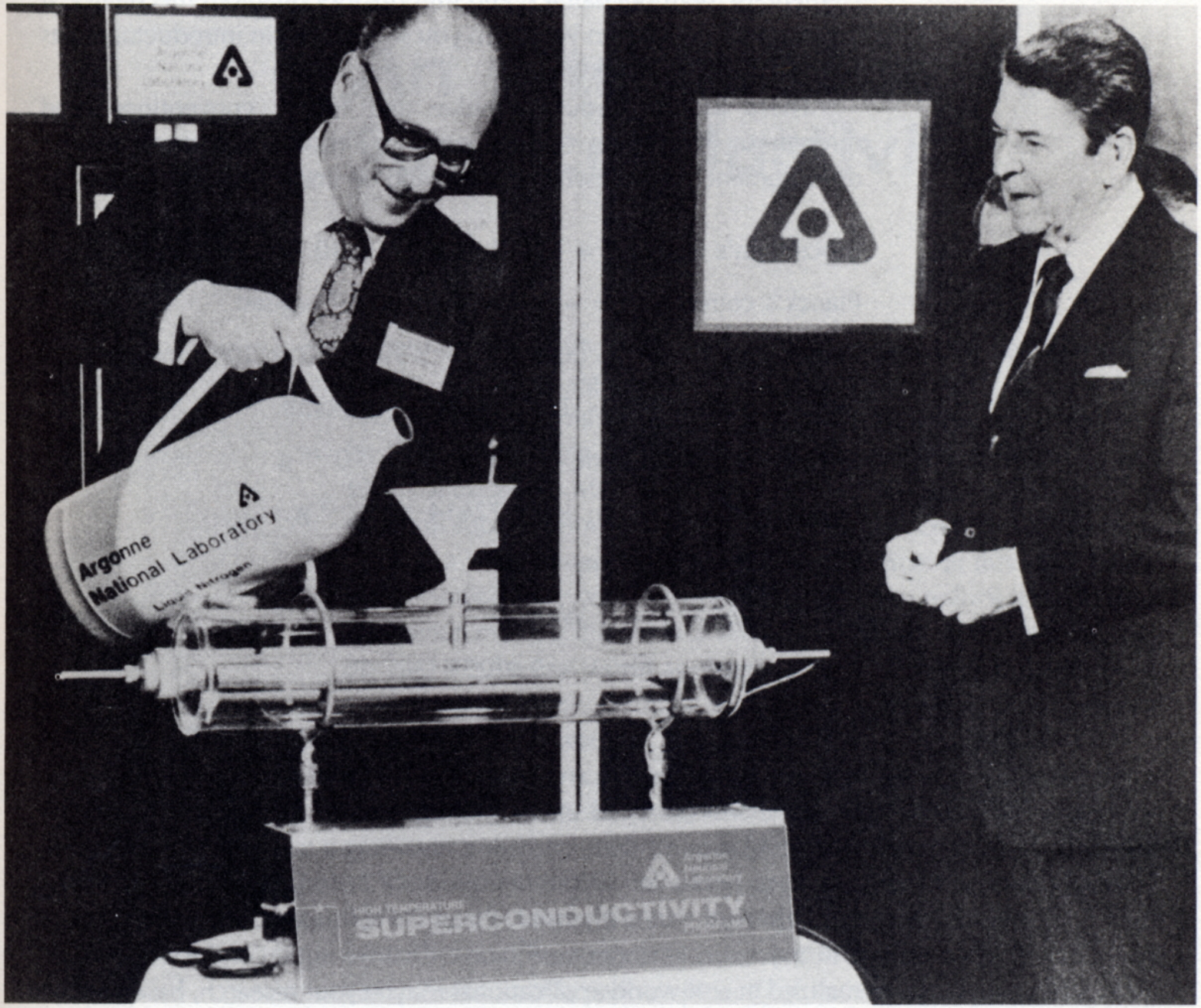
Fig. 1-1. J. Georg Bednorz and K. Alex Müller at IBM's Zurich Research Laboratory.



(Photograph courtesy of Jonathan E. Jereb, University of Houston.)

Fig. 1-2. Dr. Paul Chu, T.L.L. Temple Chair in Science, University of Houston.


YBa2Cu3O7
Resistance (mΩ)
Temperature (K)
0
40
80
120
160
200



(Photograph courtesy of Argonne National Laboratory.)

Fig. C. President Ronald Reagan receives a lesson in superconductivity from Alan Schriesheim, the director of Argonne National Laboratory (left).

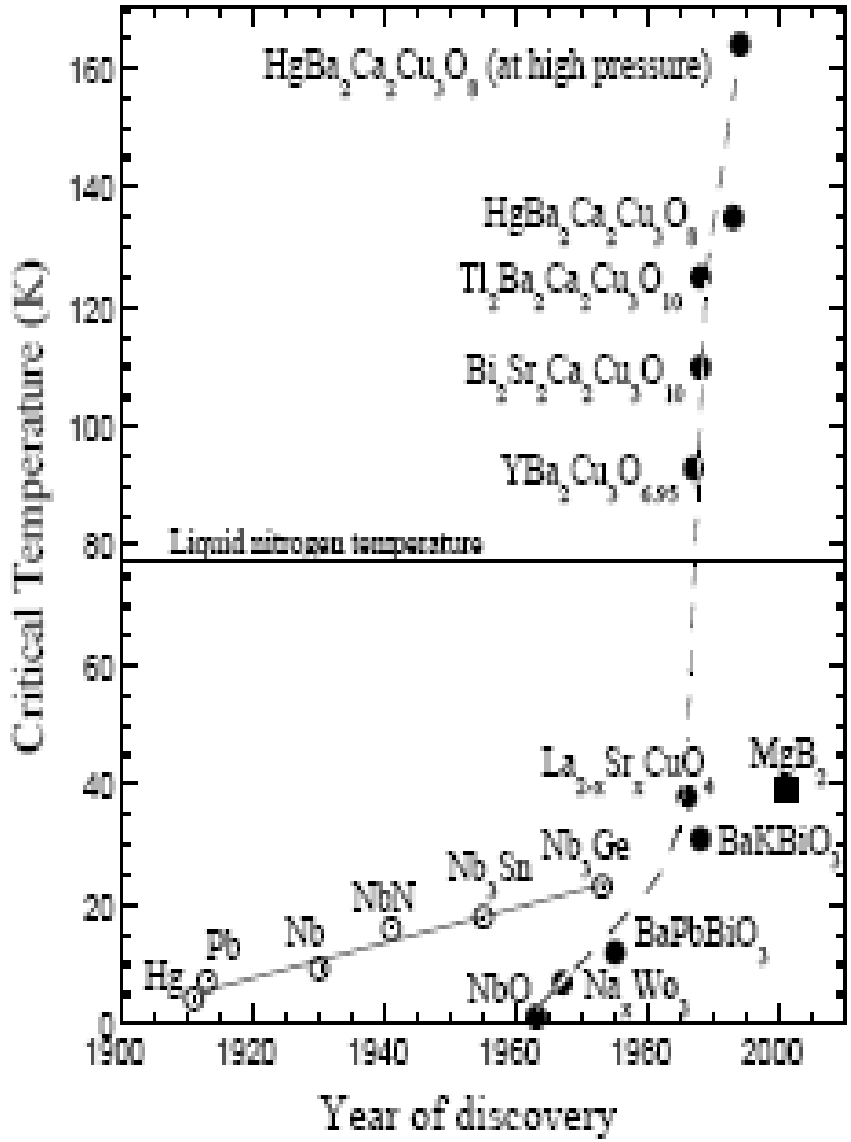


Figure 1.2. The time evolution of the superconducting critical temperature since the discovery of superconductivity in 1911. The solid line shows the T_c evolution of metallic superconductors, and the dashed line marks the T_c evolution of superconducting oxides.

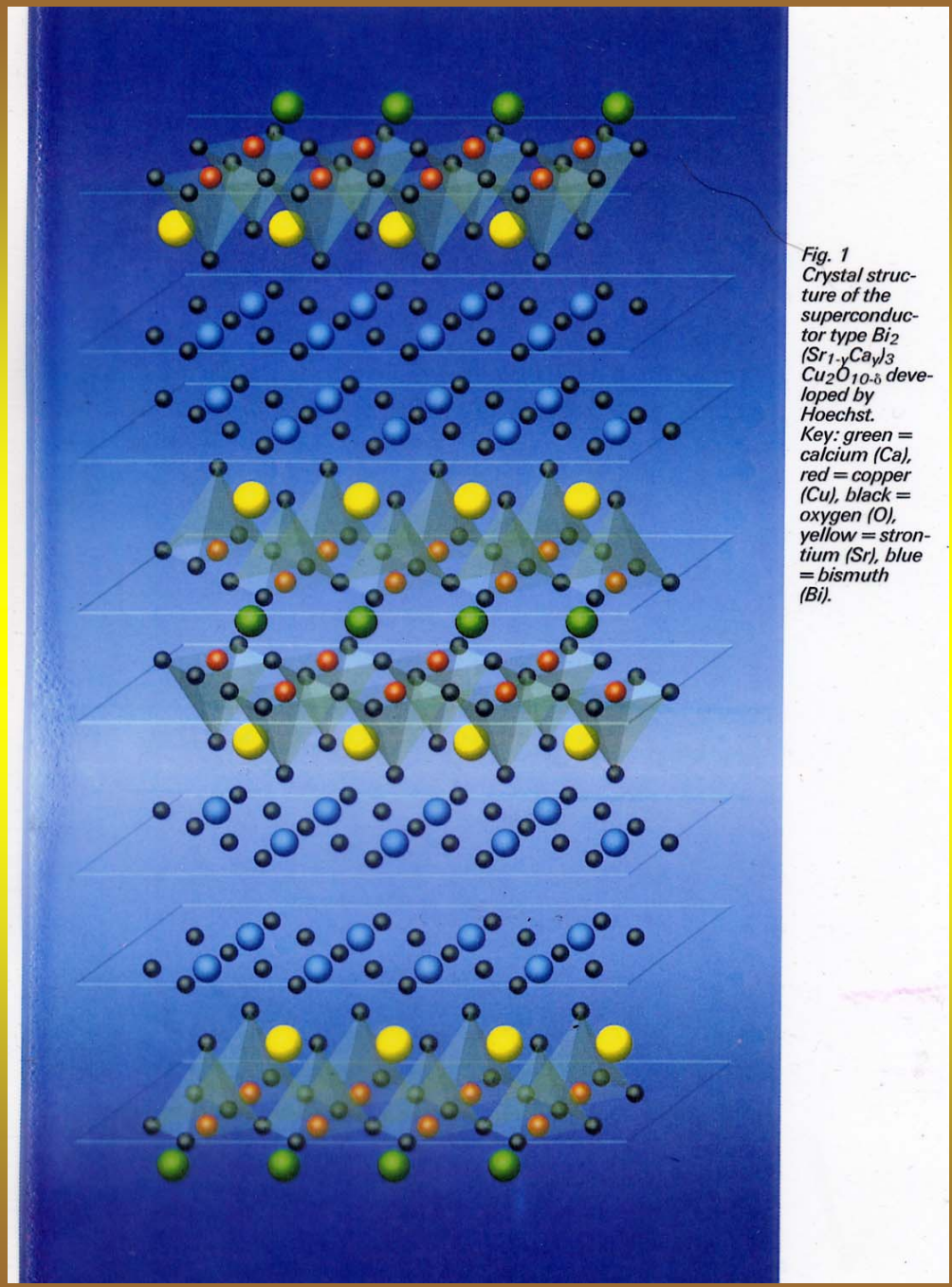


Fig. 1
Crystal structure of the superconductor type $Bi_2(Sr_{1-y}Ca_y)_3Cu_2O_{10-\delta}$ developed by Hoechst.
Key: green = calcium (Ca), red = copper (Cu), black = oxygen (O), yellow = strontium (Sr), blue = bismuth (Bi).

$InSnBa_4Tm_4Cu_6O_{18+}$ *(As a 1234/1212 intergrowth.)*	~150 K (Patent Pending)
$(Hg_{0.8}Tl_{0.2})Ba_2Ca_2Cu_3O_{8.33}$	138 K*
$HgBa_2Ca_2Cu_3O_8$	133-135 K
$HgBa_2Ca_3Cu_4O_{10+}$	125-126 K
$HgBa_2(Ca_{1-x}Sr_x)Cu_2O_{6+}$	123-125 K
$HgBa_2CuO_4$+	94-98 K
$Tl_2Ba_2Ca_2Cu_3O_{10}$	127-128 K
$(Tl_{1.6}Hg_{0.4})Ba_2Ca_2Cu_3O_{10+}$	126 K
$TlBa_2Ca_2Cu_3O_{9+}$	123 K
$(Tl_{0.5}Pb_{0.5})Sr_2Ca_2Cu_3O_9$	118-120 K
$Tl_2Ba_2CaCu_2O_6$	118 K
$(Tl_{0.5}Sn_{0.5})Ba_2(Ca_{0.5}Tm_{0.5})Cu_2O_x$	~115 K (Superconductors.ORG - 2005)
$TlBa_2Ca_3Cu_4O_{11}$	112 K
$TlBa_2CaCu_2O_{7+}$	103 K
$Tl_2Ba_2CuO_6$	95 K
$Sn_2Ba_2(Ca_{0.5}Tm_{0.5})Cu_3O_x$	~115 K (Superconductors.ORG - 2005)
$SnInBa_4Tm_3Cu_5O_x$	~113 K (Superconductors.ORG - 2005)
$Sn_3Ba_8Ca_4Cu_{11}O_x$	109 K (One-of-a-Kind Resonant)
$Sn_4Ba_4Tm_3Cu_7O_x$	~98 K (Superconductors.ORG - 2006)
$Sn_3Ba_4Y_2Cu_5O_x$	~91 K (Superconductors.ORG - 2006)
$SnInBa_4Tm_4Cu_6O_x$	87 K (Superconductors.ORG - 2005)
$Sn_2Ba_2(Sr_{0.5}Y_{0.5})Cu_3O_8$	86 K (Aleksandrov, et al - 1989)
$Sn_4Ba_4Y_3Cu_7O_x$	~80 K (Superconductors.ORG - 2005)
$Bi_{1.6}Pb_{0.6}Sr_2Ca_2Sb_{0.1}Cu_3O_y$	115 K (thick film on MgO substrate)
$Bi_2Sr_2Ca_2Cu_3O_{10}$***	110 K
$Bi_2Sr_2CaCu_2O_9$***	110 K
$Bi_2Sr_2(Ca_{0.8}Y_{0.2})Cu_2O_8$	95-96K
$Bi_2Sr_2CaCu_2O_8$	91-92K

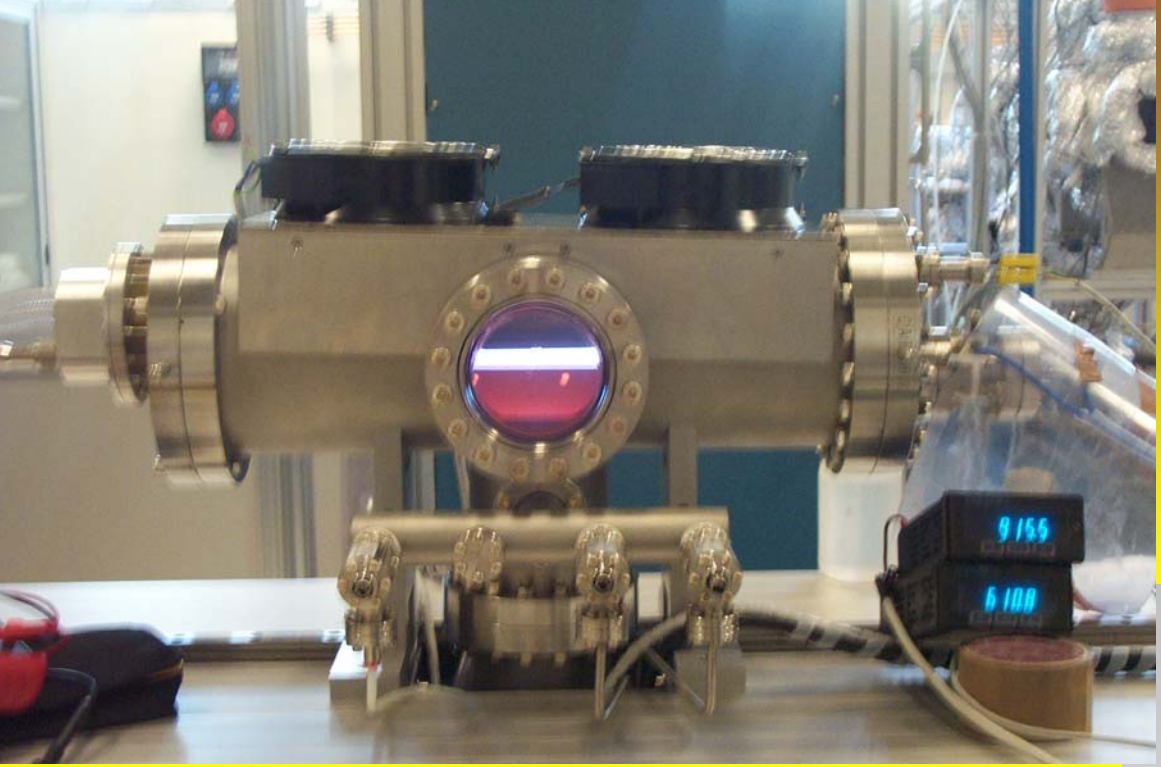
$(Ca_{1-x}Sr_x)CuO_2$ **110 K** (Highest Tc quaternary compound)

$NaWO_3$ Tungsten-bronze with Tetragonal Lattice

(The First Non-Cuprate High-temperature Superconductor)

A recent preprint by S. Reich and Y. Tsabba (Weizmann Institute) reported experimental evidence suggesting the possibility of superconductivity with Tc ~ 91 K in WO3 crystals with a surface composition of Na0.05WO3

As of October, 2000, Shimon Reich reports that the 91K Tc has been confirmed, but is localized in small islands about 100nm across and 10nm in height on the surface of the material. He also states that, as yet, no other tungsten-bronze compounds have exhibited this kind of high-temperature 2D superconductivity. Rb and Cs surface-doped WO3 only exhibit Tc's ~6K.



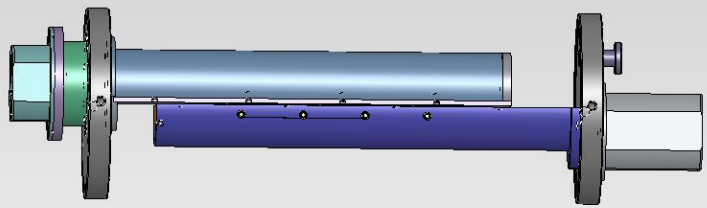
YBCO thin films on large area substrates

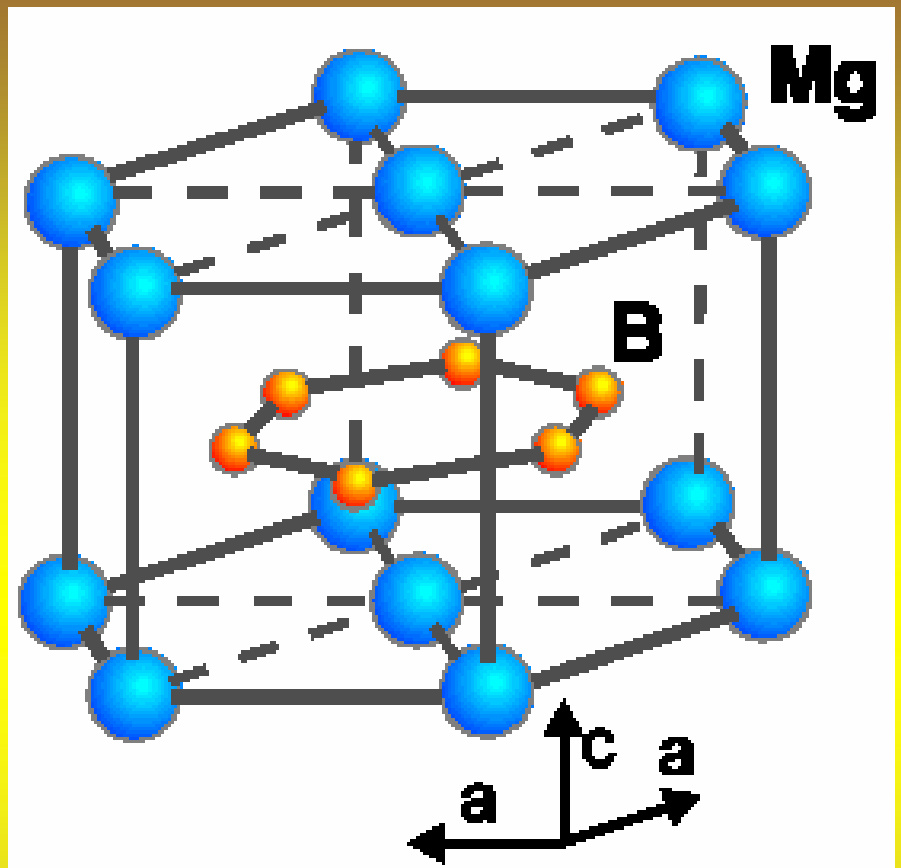
P.Romano, A. Vecchione,
G. Keppel and V. Palmieri

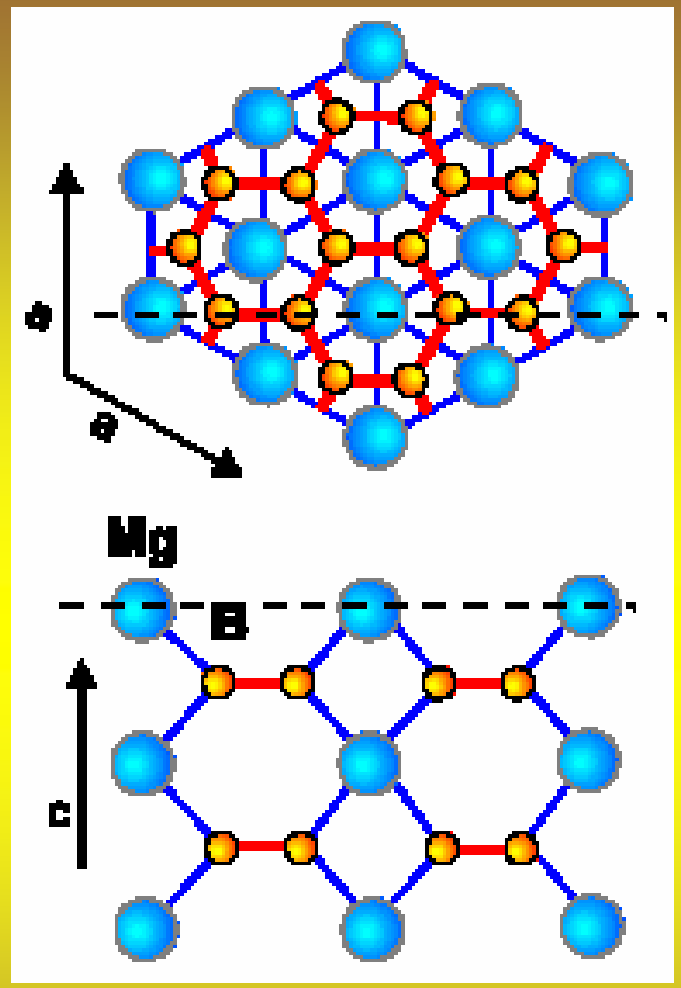
DIODE Sputtering at **950 C at 1 mbar**

onto sapphire, and SrTiO3

Distance cathode substrate = 10 mm



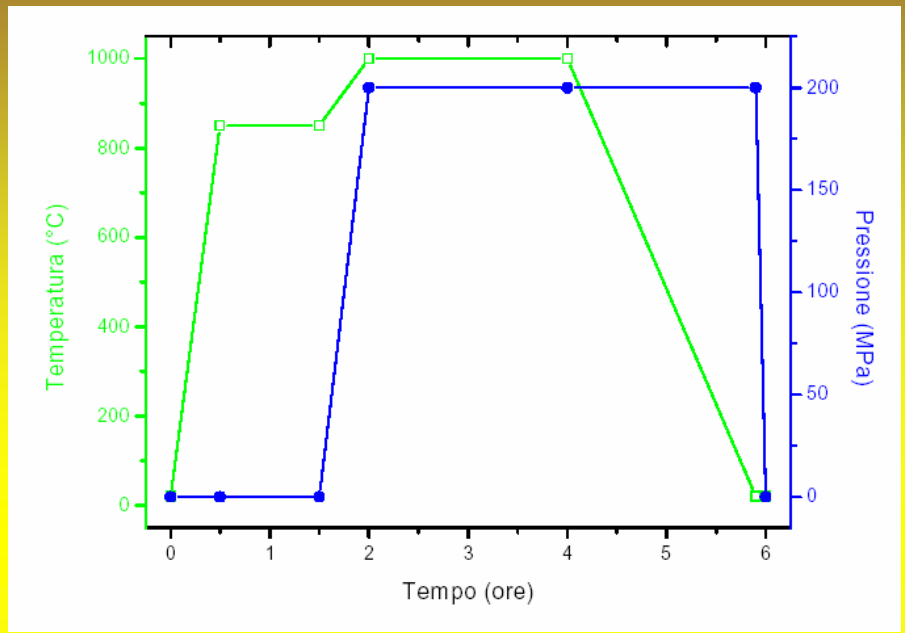


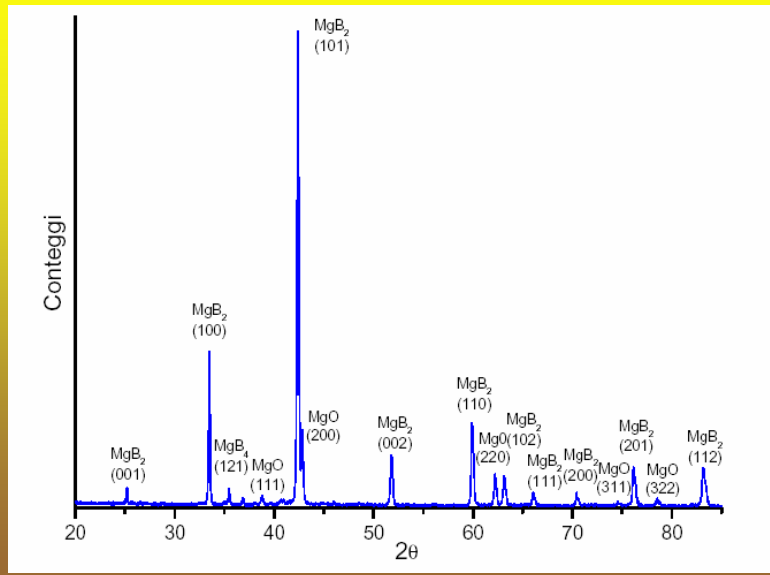


Structure of MgB_2 containing graphite-type B layers separated by hexagonal close-packed layers of Mg

(After Buzea and Yamashita)

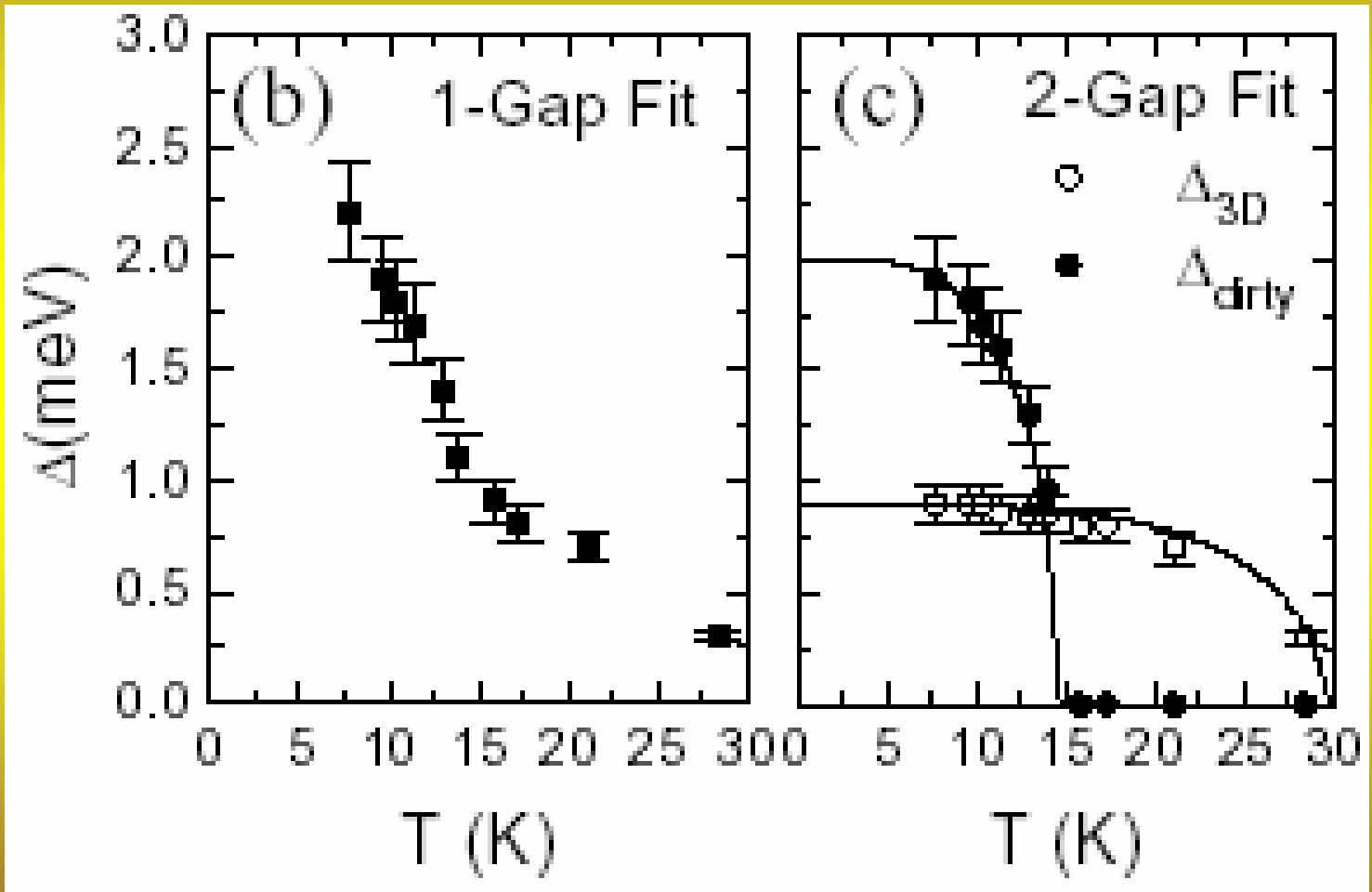
Giorgio Keppel, Thesis 2004, Material Science Dept, Padua University





T-dependence of the order parameter from fit with the one-gap model.Δ_{dirty}(T) and Δ_{3D}(T) from fit with the two-gap model. Fit to BCS curves

T-dependence of the order parameter from fit with the one-gap model.Δ_{dirty}(T) and Δ_{3D}(T) from fit with the two-gap model. Fit to BCS curves



(after G. Carapella, N. Martucciello, G. Costabile, C. Ferdeghini, V. Ferrando, and G. Grassano)

Gap parameters

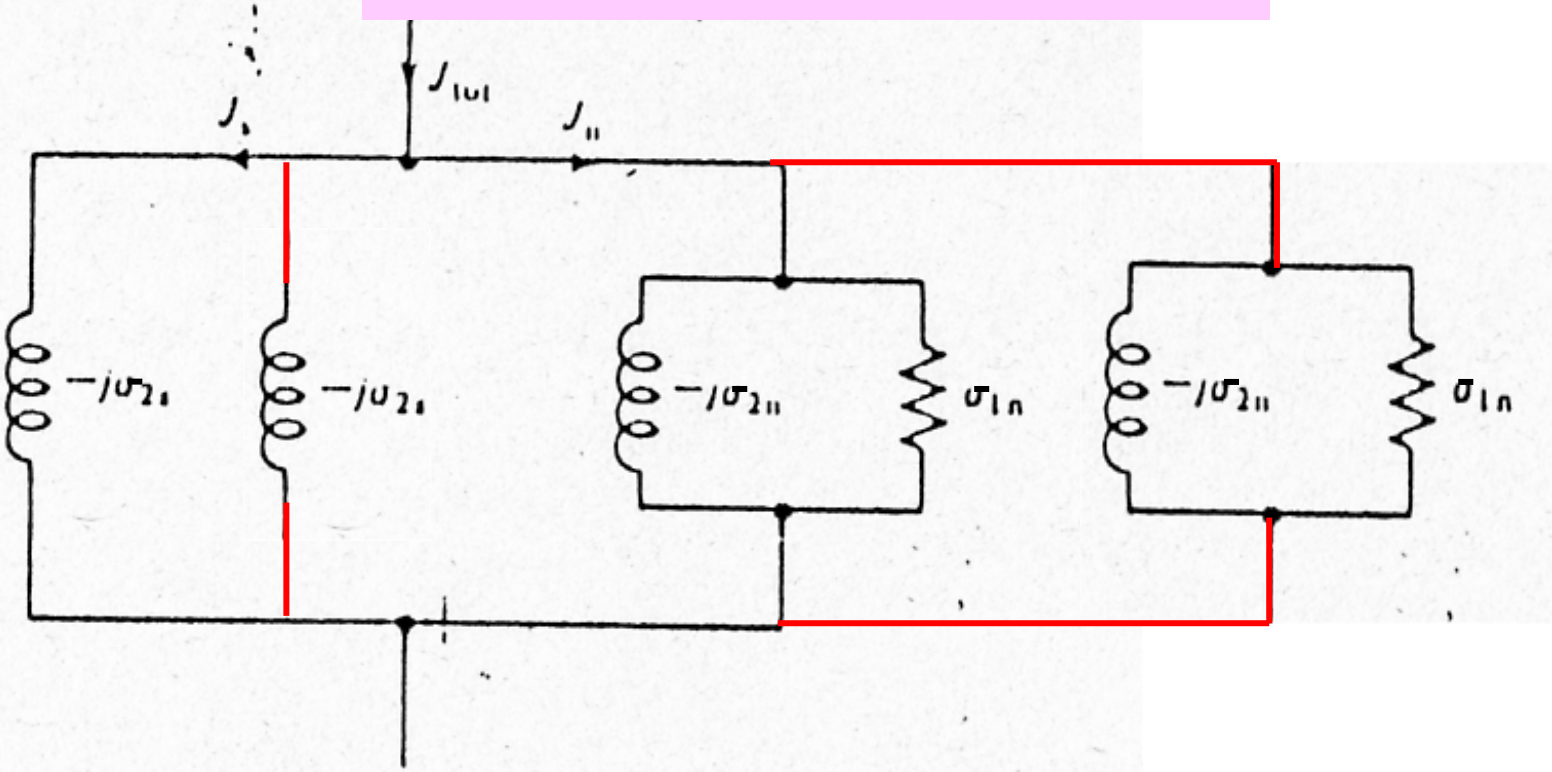
from specific heat and spectroscopic experiments:

Technique	$2\Delta_1(0)/k_BT_c$	$2\Delta_2(0)/k_BT_c$	$\gamma_1 : \gamma_2$
specific heat	3.8	1.3	0.5:0.5
specific heat	3.9	1.3	0.5:0.5
specific heat	4.4	1.2	0.55:0.45
penetration depth	4.6	1.6	0.60:0.40
tunneling	4.5	1.9	
Raman	3.7	1.6	
point-contact	4.1	1.7	
photoemission	3.6	1.1	
band structure	4	1.3	0.53:0.47

(After A. Junod, Y. Wang, .F. Bouquet, P. Toulemonde)

Two fluid model

Three fluid model



Equivalent circuit for the admittance of a unit cube of superconductor

High Purity MgB_2 Thin Films

Xiaoxing Xi

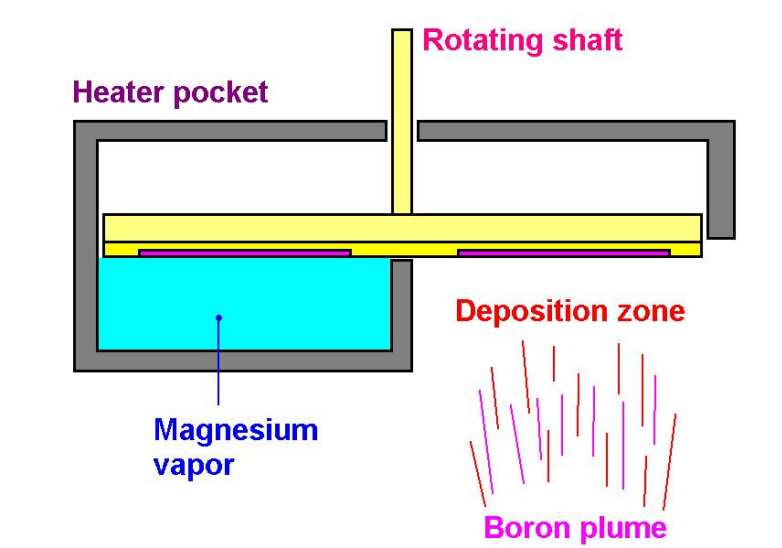
Department of Physics and
Department of Materials Science and Engineering
Penn State University, University Park, PA

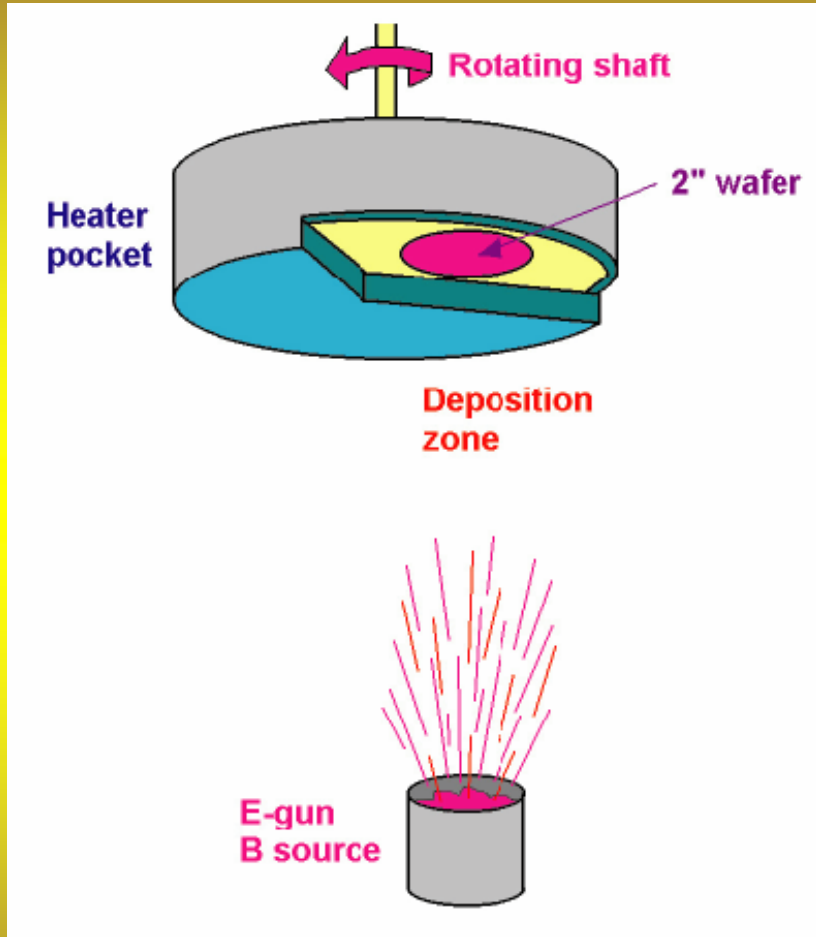
October 10, 2006
Thin Film RF Workshop
Padua, Italy

Supported by ONR, NSF

PENNSTATE
1855

Reactive Co-Evaporation





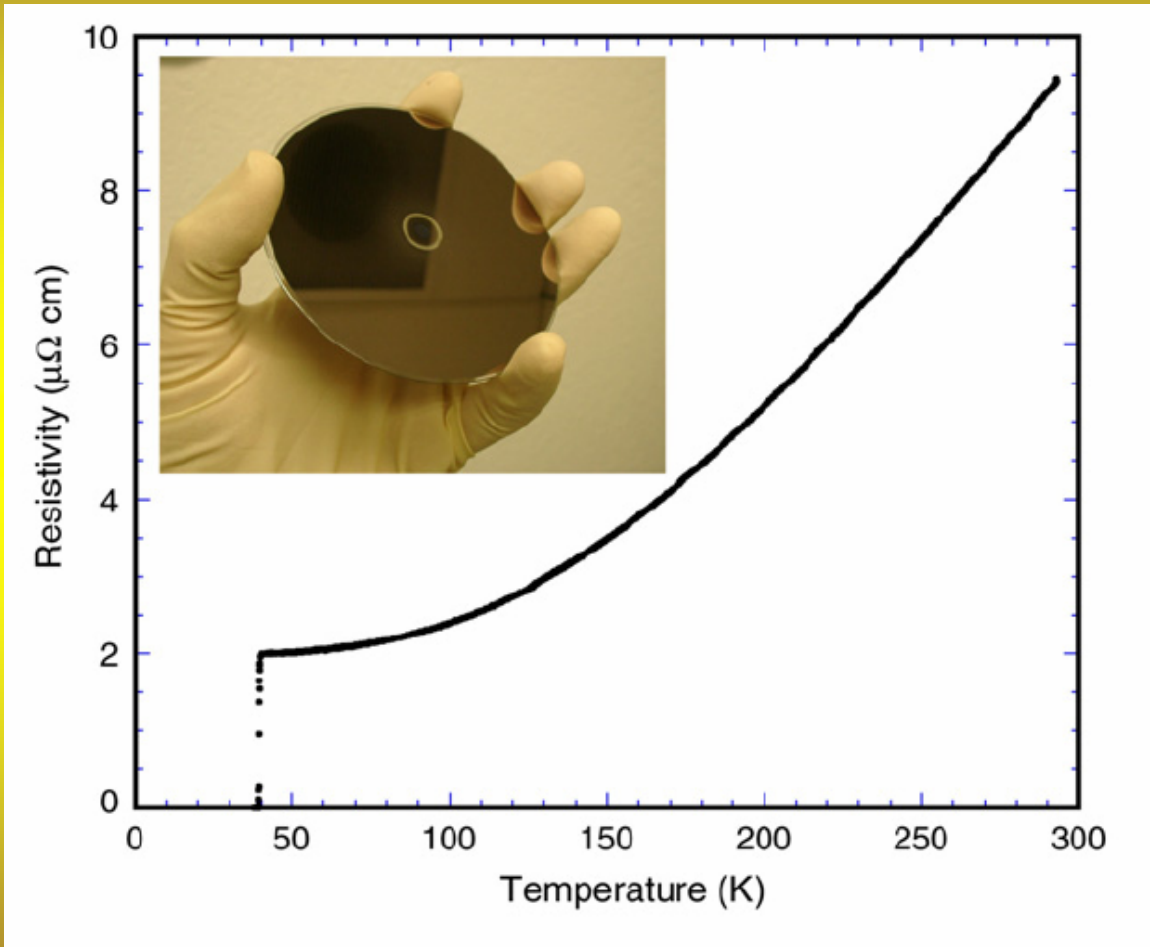
— Deposition temperature 550°C
— Good superconducting properties
— Large area and double sided films
— Films stable to moisture
— On various substrates: *r*-plane, *c*-plane, and *m*-plane sapphire, 4H-SiC, MgO, $LaAlO_3$, $NdGaO_3$, $LaGaO_3$, LSAT, $SrTiO_3$, YSZ, etc.

SUPERCONDUCTOR TECHNOLOGIES

(Moeckly & Ruby, SC Sci Tech 19, L21 (2006))

MgB_2 Films by Reactive Co-Evaporation

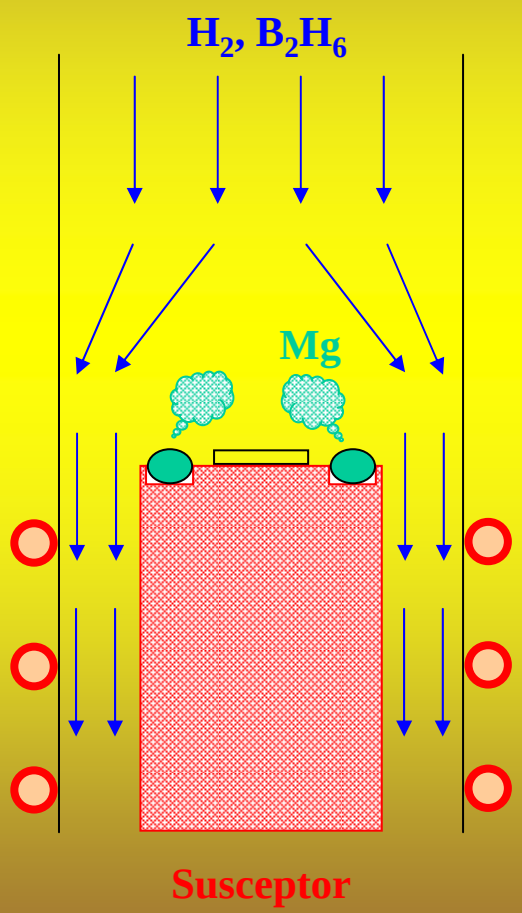
4” MgB_2 film on polycrystalline alumina



(Moeckly & Ruby, SC Sci Tech 19, L21 (2006))

Hybrid Physical-Chemical Vapor Deposition

Schematic View



Deposition procedure and parameters:

- Purge with N_2, H_2
- Carrier gas: H_2
- P_{total} = 100 Torr.
- Inductively heating susceptor, AND Mg, to 550–760 °C. P_{Mg} = ? (44 mTorr is needed at 750 °C according to thermodynamics)
- Start flow of B_2H_6 mixture (1000 ppm in H_2): 25 - 250 sccm. Film starts to grow.
- Total flow: 400 sccm - 1 slm
- Deposition rate: 3 - 57 Å/sec
- Switch off B_2H_6 flow, turn off heater.

rid of oxygen prevent oxidation

make high Mg pressure possible

generate high Mg pressure

high enough *T* For epitaxy

pure source of B

control growth rate

low Mg sticking no Mg deposit

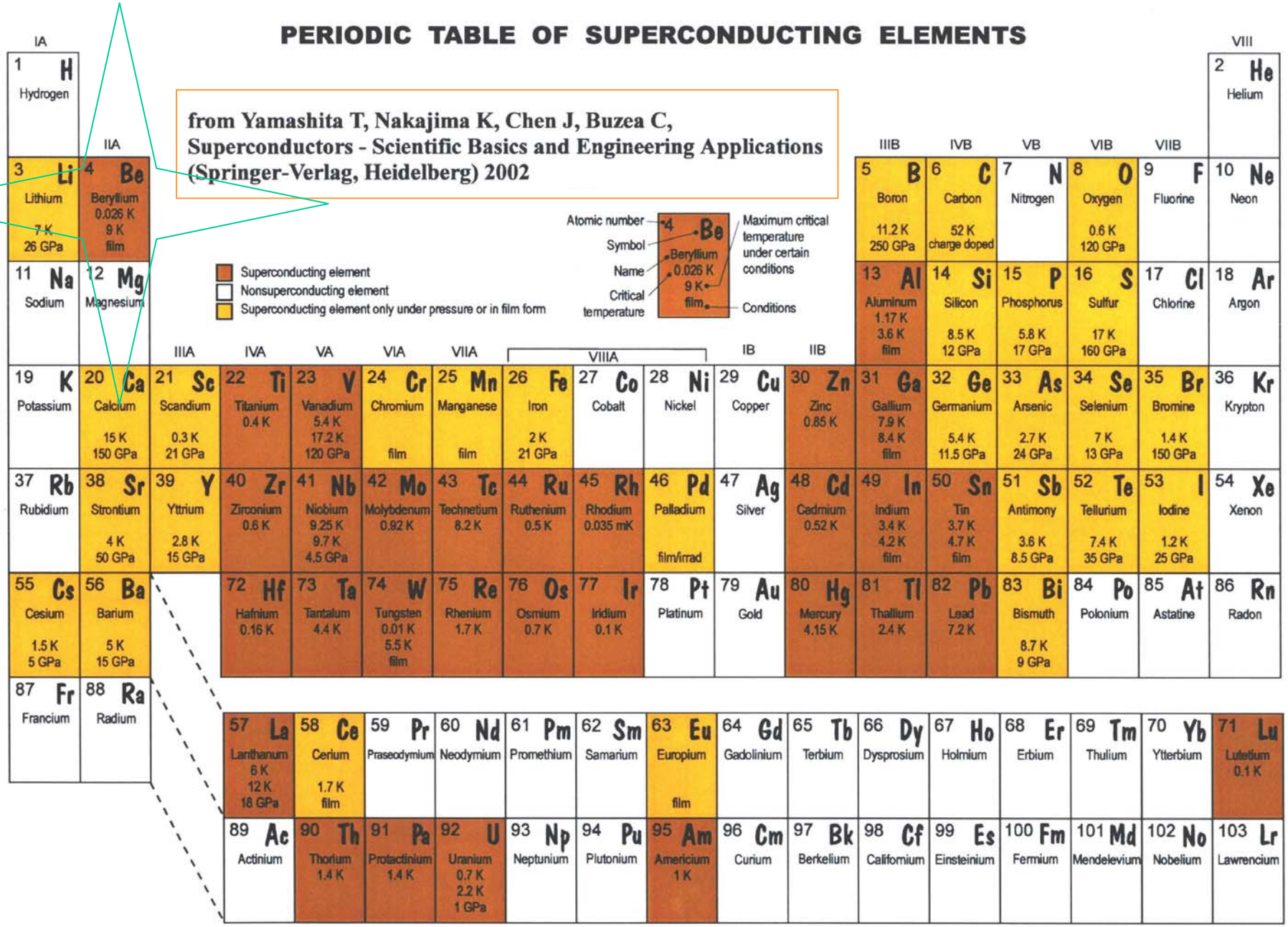


Figure 4. Periodic Table of elements with critical temperature at normal pressure, and maximum critical temperature attained under certain conditions (pressure, film form or charge injected) [Yamashita].

Physicists in Japan have shown that "entirely end-bonded" multi-walled carbon nanotubes can superconduct at temperatures as high as 12 K, which is 30 times greater than for single-walled carbon nanotubes. The discovery has been made by a team led by Junji Haruyama of Aoyama Gakuin University in Kanagawa. The superconducting nanotubes could be used to study fundamental 1D quantum effects and also find practical applications in molecular quantum computing (*Phys. Rev. Lett.* 96 057001).

Ping Sheng and co-workers at Hong Kong University of Science and Technology have found that the nanotubes exhibit superconducting behaviour below 20 kelvin, confirming that resistance-free current can flow through pure carbon (Z K Tang *et al* 2001 *Science* 292 2462).

Superconductivity in diamond

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Diamond is an electrical insulator well known for its exceptional hardness. It also conducts heat even more effectively than copper, and can withstand very high electric fields[1]. With these physical properties, diamond is attractive for electronic applications[2], particularly when charge carriers are introduced (by chemical doping) into the system. Boron has one less electron than carbon and, because of its small atomic radius, boron is relatively easily incorporated into diamond[3]; as boron acts as a charge acceptor, the resulting diamond is effectively hole-doped. Here we report the discovery of superconductivity in boron-doped diamond synthesized at high pressure (nearly 100,000 atmospheres) and temperature (2,500–2,800 K). Electrical resistivity, magnetic susceptibility, specific heat and field-dependent resistance measurements show that boron-doped diamond is a bulk, type-II superconductor below the superconducting transition temperature $T_c \approx 4$ K; superconductivity survives in a magnetic field up to $H_{c2}(0) \geq 3.5$ T. The discovery of superconductivity in diamond-structured carbon suggests that Si and Ge, which also form in the diamond structure, may similarly exhibit superconductivity under the appropriate conditions.

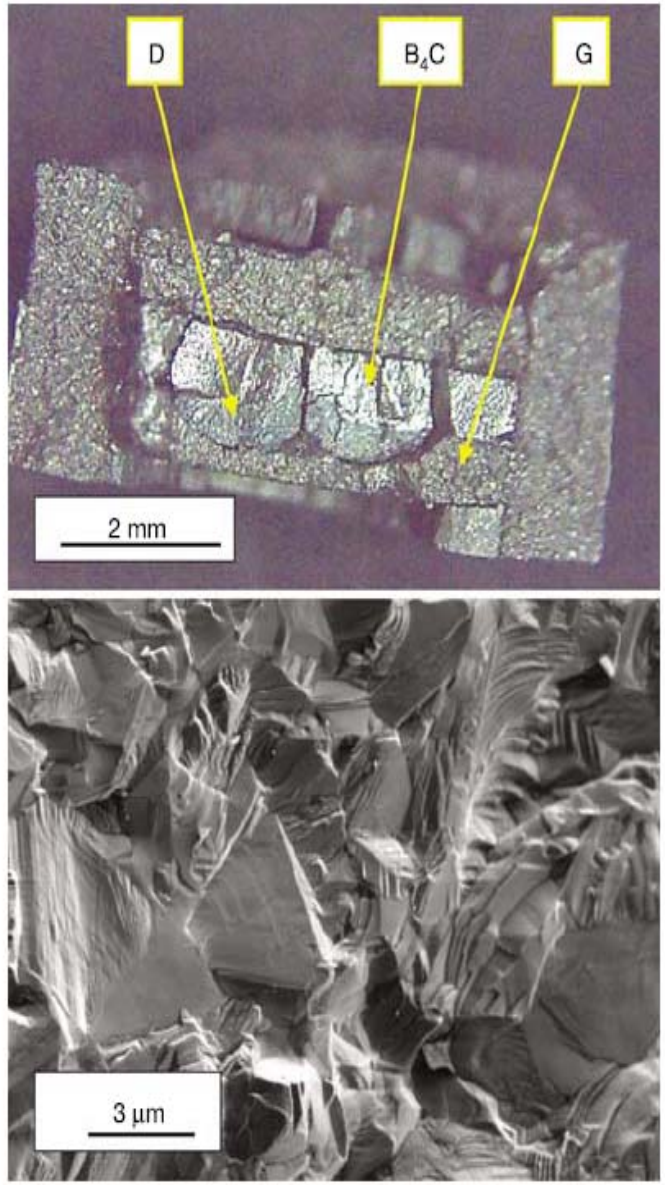

Figure 1 Optical and scanning electron microscopy images of the material. Top, central part of the high-pressure synthesis cell after subjecting graphite and B_4C to high-pressure, high-temperature conditions. D, diamond; G, graphite. Bottom, SEM image of B-doped diamond synthesized at high pressures and temperatures.

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The superconductivity in boron-doped polycrystalline diamond thick films

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Abstract

Boron-doped polycrystalline diamond thick film was prepared by a hot filament chemical vapor deposition (HFCVD) method. The morphology and structure of the diamond were evaluated by scanning electron microscopy (SEM), X-ray diffraction (XRD) and micro-Raman spectroscopy. The carrier concentration of the boron-doped diamond was 7.3×10^{20} cm^{-3}, determined by a Hall measurement system. The transport measurements show that the boron-doped diamond thick film is superconductive and the superconducting transition temperatures are 10 K for T_c onset and 8.3 K for zero resistance, and there is a strong diamagnetic response in the alternating current (AC) magnetic susceptibility of the boron-doped diamond sample below 8.9 K. Such a high T_c value can be attributed to the higher efficiency of doping, contraction of the reconstructed bonds and two-dimensional nature of the surface states for diamond thick films, all together inducing a stronger electron–phonon coupling.

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