Tutorial

SRF Materials other than Niobium

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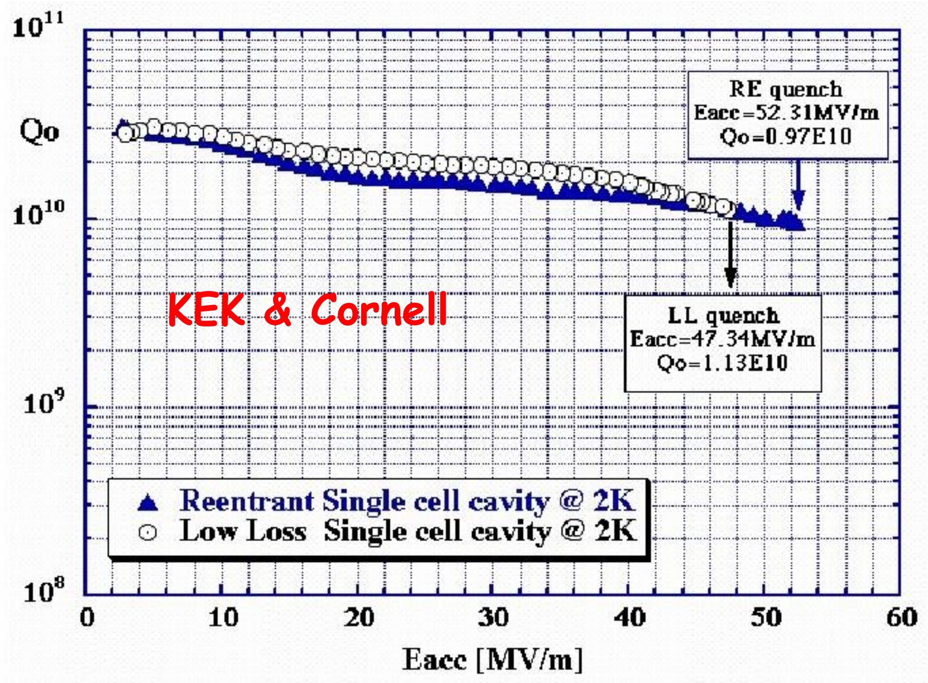
Outline

- Motivation
- Which Superconductors for SRF Cavities?
- Nb compounds: NbN, NbTiN
- A15 Compounds: Nb_3Sn, V_3Si, …
- MgB_2
- SIS Multilayer Structures
- Concluding Remarks

Why looking beyond Nb?

Nb has the highest T_c for a pure metal and the highest lower magnetic field H_{c1}

- Nb cavities performance have reached close to its theoretical limit **(H ≈ Hc = 200 mT)**



- For further improved cavity RF performance, innovation needed

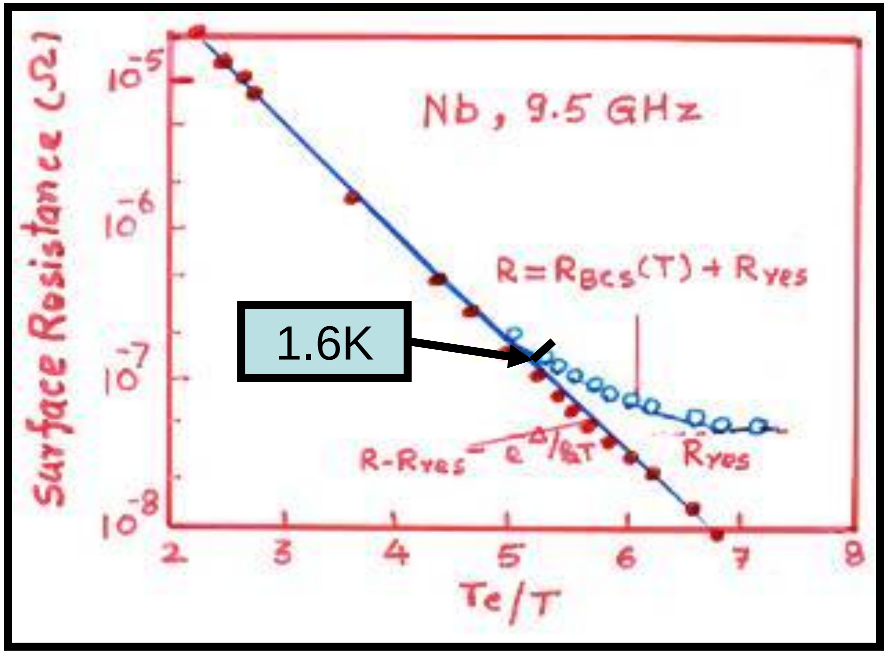
Looking beyond Nb – Potential Benefits

- Higher Tc
- potentially higher Hc
- Substrates with higher thermal conductivity
- Potentially cryogenics cost reduction if cavity operation temperature at 4.2K or higher

Which superconductors are suitable for SRF applications?

Surface Resistance

$$R_S = R_{BCS}(T) + R_{res}$$



V. Palmieri, 10th Workshop on RF Superconductivity Proceedings, Tsukuba 2001 (Noguchi)
"New materials for superconducting radiofrequency cavities"

R_{BCS}

If $T < T_c / 2$

$$R_{BCS} \cong \frac{R_n}{\sqrt{2}}\left(\frac{\eta\omega}{\pi\Delta}\right)^{\frac{3}{2}}\frac{\sigma_1}{\sigma_n} = A\sqrt{\rho_n}\; e^{-\frac{\Delta}{K_B T}}\left(1+O(\Delta,\omega,T)\right)$$

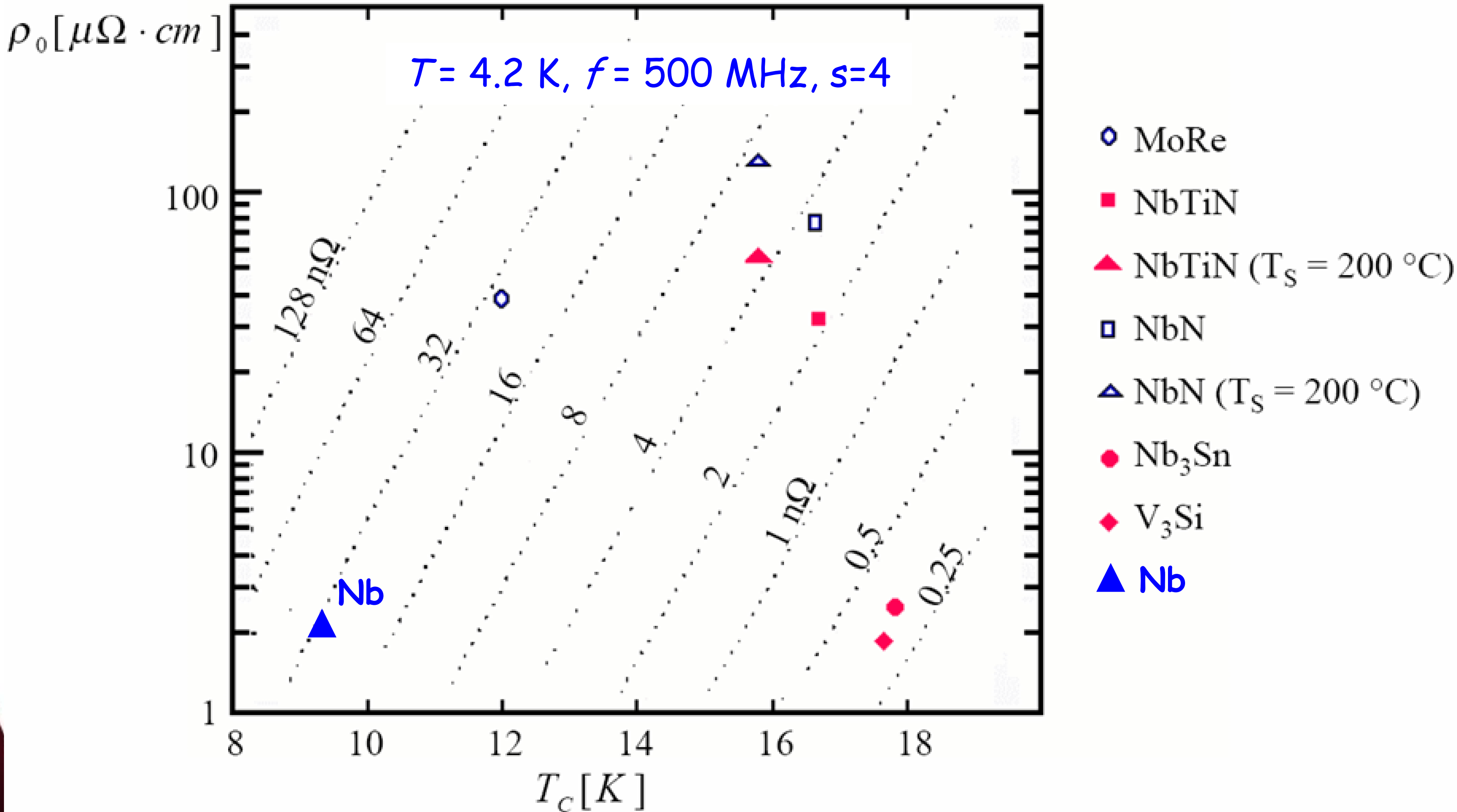
A & B constants weakly dependent on material
ω = RF frequency
ρn = Normal State conductivity
λ = Penetration depth
Tc = Transition Temperature

dependence on ρ_n and T_c represents an immediate criterion for selecting the most favorable candidates for cavities

Material with high normal state conductivity and high Tc should be selected

Other materials than niobium

R_{BCS} versus ρ_0, T_c Vaglio, *Particle Accelerators* 61, 391 (1998)



Residual Resistance R_{res}

Temperature independent

Contributions to residual losses:

Intrinsic:

Inhomogeneties, Metallic Inclusions within λ, Grain Boundaries, Oxides

Extrinsic:

Trapped Flux during cooling (can be avoided)

Variety of phenomena involved ➡ Not one formula predicting R_{res}

From literature

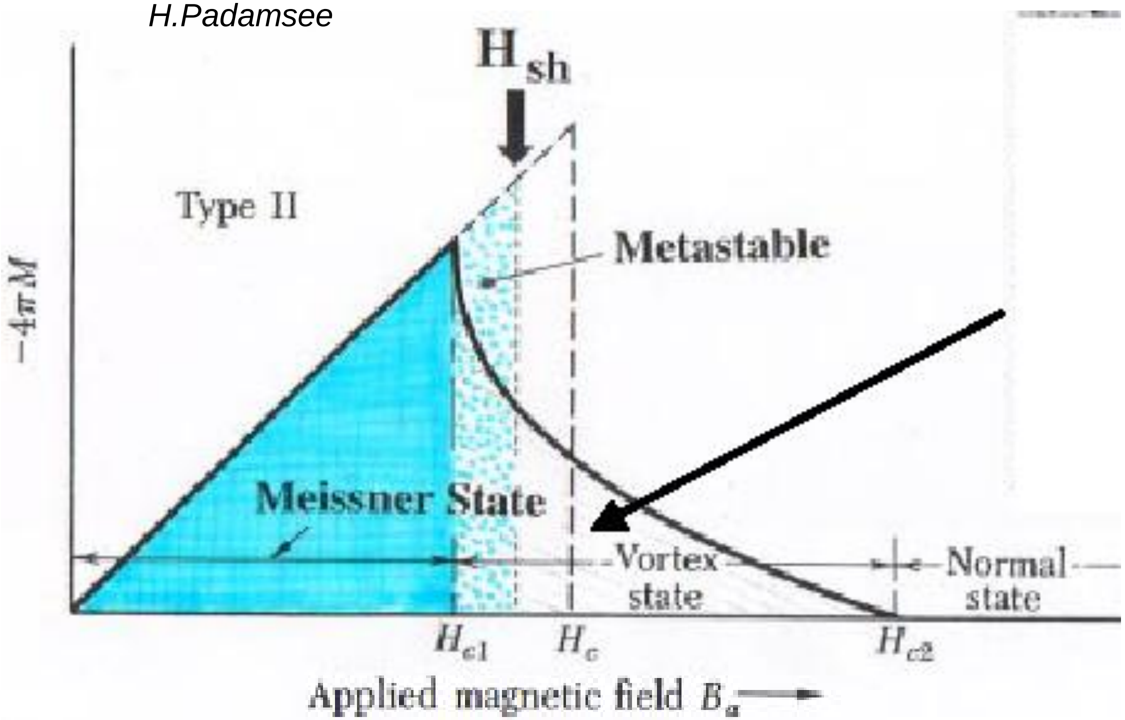
Empirically, R_{res} found proportional to at least $\sqrt{\rho_n}$

For two materials with the same R_{BCS} and different T_c and ρ_n, the one with the smallest ρ_n should have the smallest R_{res}

Metallic behaviour is favored

Critical Field

H.Padamsee



Boundary between Type I and Type II determined by the Ginzburg-Landau parameter

$$\kappa = \lambda/\xi$$

Ginzburg-Landau theory relates H_{c1}, H_{c2} and H_c to κ, over a restricted range of κ.

H_{sh} is the maximum permissible value of the applied field, which satisfies Ginzburg Landau equations.

$$H_{c1} = \frac{\phi_0}{4\pi\lambda^2}\left(\ln\frac{\lambda}{\xi} + 0.5\right)$$

SC fully in Meissner state up to H_{c1}

For Type – II superconductors, the Meissner state can persist metastably above H_{c1} but only up to H_{sh}

$$H_{RFcrit} \approx H_{sh}$$

Criteria of choice

THERE IS NO IDEAL SUPERCONDUCTOR FOR CAVITY

CHOICE IS BASED ON COMPROMISE

For low RF losses → **high T_c**

Metallic behavior in the normal state , small ρ_n

For high gradients → **High H_{SH},H_c;small κ**

Possible Choices among Superconducting Materials

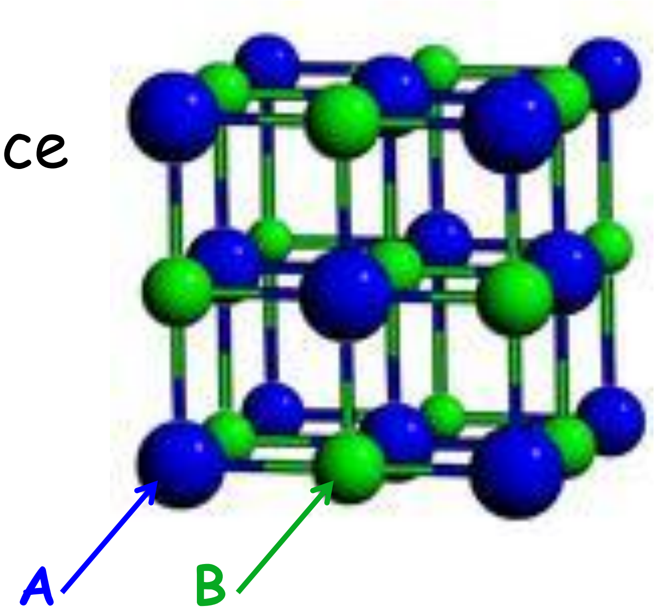
- Nb compounds
- A15 compounds
- MgB2

Material	T_c (K)	ρ_n($\mu\Omega$cm)	$H_c(0)$ [T]	$H_{c1}(0)$ [T]	$H_{c2}(0)$ [T]	$\lambda(0)$ [nm]
Nb	9.2	2	0.2	0.17	0.4	40
NbN	16.2	70	0.23	0.02	15	200
NbTiN	17.5	35		0.03		151
Nb_3Sn	18.3	20	0.54	0.05	30	85
V_3Si	17					
Mo_3Re	15		0.43	0.03	3.5	140
MgB_2	40		0.43	0.03	3.5	140

Nb Compounds

B1 compounds – NaCl structure

Metallic atoms A form an fcc lattice
and
non-metallic atoms B occupy
all the octahedral interstices.



Nb Compounds

Only few Nitrides and Carbides of the IV, V and VI group Transition Metals have critical temperatures higher than Niobium.

B \ A	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

Superconductivity of Transition Metals, their Alloys and Compounds,
S.V Vonsovsky, Y.A. Izyumov, E.Z. Kurmaev, Springer-Verlag, 1982

Nb Compounds - NbN

The only B1 simple compound that has widely tested for accelerating cavities

Mainly two different techniques have been investigated for this application:

- **Thermal diffusion of N into Nb followed by rapid quench cooling**
- **Reactive Sputtering on metallic or ceramic substrates to Nb cavities**

Thermal Diffusion:

Bulk Nb (RRR 300) annealed @ 1550°C for 2h

+

reacted in N_2 vapor(150mbar) @ 1400°C for 4h

Rs=1.3 10^{-6} @ 4.2K and 4 10^{-9} @1.8K @7.9GHz

G.Gemme et al., J.Appl.Phys. 77**(1)**, Jan. 1995

Reactive Sputtering:

Sputtering from high purity Nb target in Ar+ N_2 in DC triode magnetron sputtering system

Highest Tc for substrate temp. > 500°C, P_{Ar}=8.10^{-3}mbar, P_{N2}=1.10^{-3}mbar

A. Nigro et al., Physica Scripta Vol. 38, 483-485, 1988

Nb Compounds - NbN

Good SC properties, even if deposited at low temperature
Low secondary emission coefficient
Very stable surface properties

The right B1-NbN superconducting phase is the so-called δ-phase

Tc= 17.2 K for δ-phase (lattice parameter = 4.388 Å)
T_C very sensitive to Nitrogen stoichiometry

. In sputtered films, the δ -phase can be found mixed to some other low T_C phases

Even if no grain boundaries are present and δ-phase single crystal is considered the single grain resistivity is not so low.

Anomalously high resistivity of NbN in the normal state, often higher than 100 μΩcm
due to both metallic and gaseous vacancies randomly distributed in both sublattices
Equiatomic composition is $Nb_{0.987}N_{0.987}$ not $Nb_{1.0}N_{1.0}$
Common problem for B1 compounds

Nb Compounds - NbTiN

Ternary Nitride $Nb_{1-x}Ti_xN$

Presence of Ti found to reduce significantly the resistivity
And facilitate formation of a pure cubic structure.
The δ-phase remains thermodynamically stable even at RT.
T_c as high as for good quality NbN, for Nb fraction $(1-x)>0.5$

extreme hardness, excellent adherence on various substrates, very good corrosion and erosion resistance, high-sublimation temperature, and relative inertness

More metallic nature and better surface properties than NbN should result in better RF performance

Nb Compounds - NbTiN

INFN : reactive sputtering with Ar/N_2 in DC Triode Magnetron Sputtering @ 600°C and 200°C

$(Nb_{1-x}Ti_x)N$ films with 1-x<0.5 present a lower calculated surface impedance, lower critical fields and better surface properties than NbN, especially when deposited at low temperatures.

R. Di Leo et al. J. of Low Temp. Phys, vol 78, n1/2, pp41-50, 1990

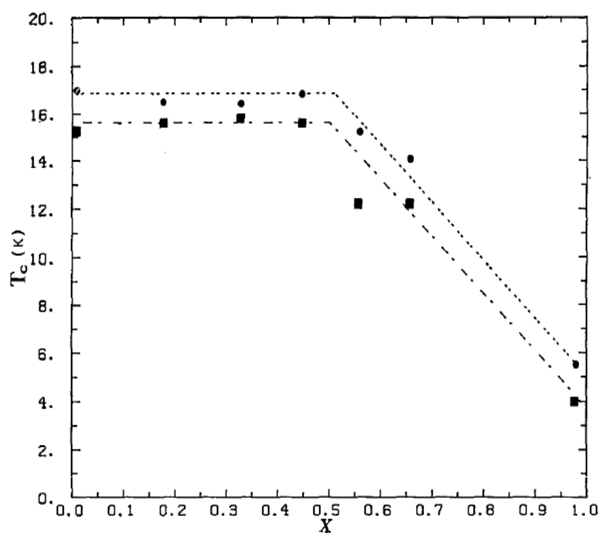


Fig. 1. Superconducting critical temperature T_c as a function of the titanium composition (x) for the $(Nb_{1-x}Ti_x)N$ films deposited at $T_s = 600°C$ (circles) and at $T_s = 200°C$ (squares).

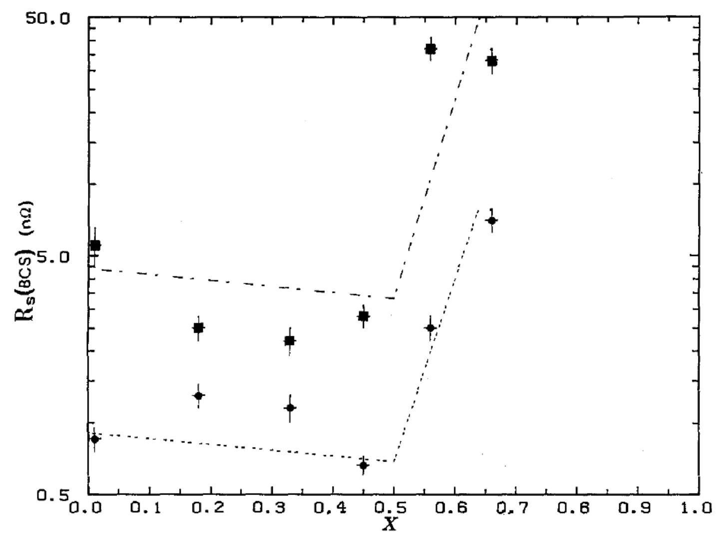


Fig. 3. Calculated BCS surface impedance R_s(BCS) as a function of the titanium composition (x) for the $(Nb_{1-x}Ti_x)N$ films deposited at $T_s = 600°C$ (circles) and at $T_s = 200°C$ (squares). The continuous lines correspond to the values of the lines through the data in Figs. 1 and 2.

Nb Compounds - NbTiN

Reactive Magnetron Sputtering:

CEA Saclay :

NbTiN films deposited on 12 cm copper disks by magnetron sputtering and tested in a cylindrical TE_{011} cavity

reached RF field levels of 35 mT

low residual surface resistance (< 100 nΩ at 4 GHz) with a very small BCS resistance

4 cavities deposited but no RF measurement due to film blistering on large area of the cavity.

Rs slope significantly decreased when coating with bias ranging from -50V to -100V

P. Bosland et al.

S. Cantacuzène et al.

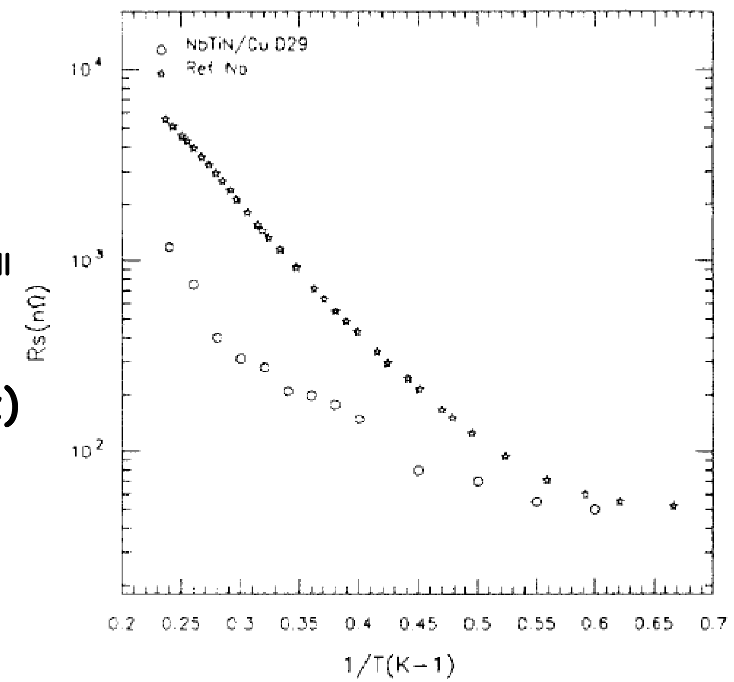


Figure 3 Surface resistance vs temperature for a NbTiN sample, at 4 GHz.

Nb Compounds - NbTiN

CERN:

Samples and six 1.5 GHz Cu cavities coated by reactive cylindrical magnetron sputtering

Best cavity result for thicker film (4.3µm) and lower deposition temperature (265°C)

Rs = 330nΩ @ 4.2K

Q_0 at zero field is higher than the Q-value of Niobium cavities but Eacc limited under 10 MV/m

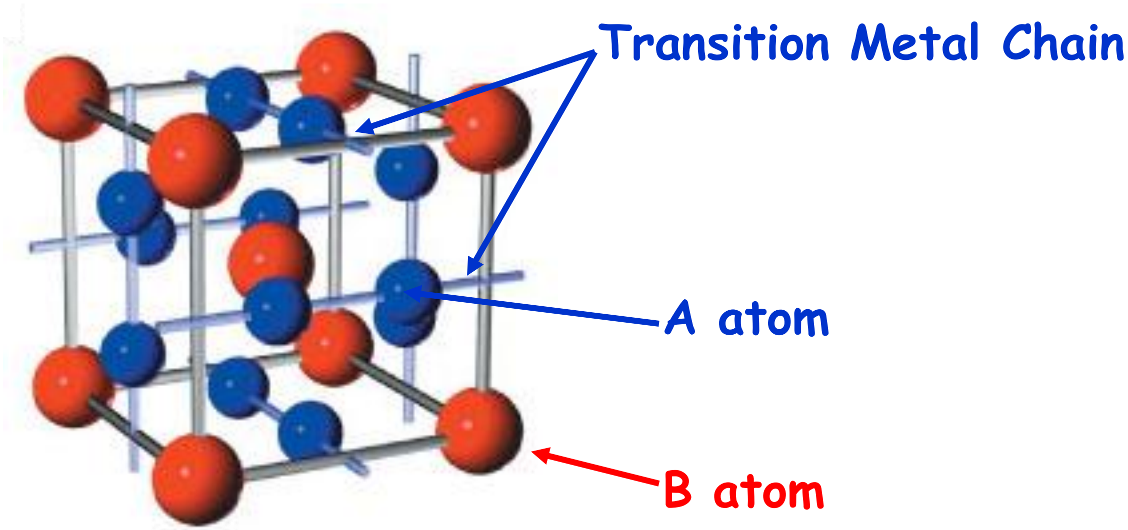
As for NbN, N stoichiometry critical to obtain the right SC phase

M. Marino, Proceedings of the 8th Workshop on RF Superconductivity, October 1997, Abano Terme (Padua), (Rep) 133/98, vol.IV, p.1076

A15 Compounds - Structure

A atoms = Transition elements of group IV, V or VI
B atoms = Non transition or transition elements

A_3B



B atoms occupy corners and centre of BCC structure
A atoms form orthogonal chains bisecting the faces of the BCC unit cell.
Linear Chain Integrity is crucial for Tc

A15 Compounds – Potential candidates for RF Cavities

Nb_3Sn, Nb_3Al, Nb_3Ge, Nb_3Ga, V_3Si, Mo_3Re

- Among the Nb and V based high Tc (15 – 20 K)
- Nb_3Ga and Nb_3Ge do not exist as stable bulk materials at 3:1 stoichiometry
- Nb_3Al exists only at high temperature causing excessive atomic disorder
- Production of above materials need non equilibrium processes
- V_3Ga, V_3Si & Nb_3Sn are stable bulk material and have high T_c
- Another A-15 compound holding promise is Mo_3Re (Tc=15K)

Sharma, International Workshop on Thin Films and New Ideas for Pushing The Limits Of RF Superconductivity, LNL-INFN , Oct.2006

A15 Compounds – Preparation Methods I

Extreme brittleness so A-15 bulk structure cannot be formed

The A-15 should be produced as thin layer on the interior of the already formed structure

Such a layer need to be only 1 or 2 microns thick
λ_L (Nb3Sn) = 65 nm

Thin film route ideal

A15 Compounds – Preparation Methods II

Co-Sputtering

- Considerable success achieved in synthesizing difficult materials like Nb_3Ge with highest Tc(~23k) or V_3Si
- Typically two constituents are sputtered simultaneously onto a temperature controlled substrate
- Stoichiometry dependent on relative positions of target and substrate (can be manipulated to get perfect stoichiometry)
- Stoichiometry control difficult over large areas like accelerating system and if stoichiometry range for A-15 phase is narrow.

Sputtering

To sputter from a single target of correct stoichiometry (prepared by powder sintering)
Stoichiometry, Substrate Temperature, Deposition Rate, Deposition Thickness Can be varied independently

A15 Compounds – Preparation Methods III

Chemical Vapor Deposition (CVD)

MOCVD (*Metal Organic Chemical Vapour Deposition)* is a particular case of CVD in which the precursor is a metallorganic compound

Process in which one or more precursors, present in vapor phase, chemically react on an appropriate warm substrate, giving rise to a solid film

Deposition rate and structure of the film depend upon temperature and reagent concentration

⇒ Uniformity of temperature and flow of gaseous over entire cavity surface may be difficult with complex geometry

Diffusion Reaction

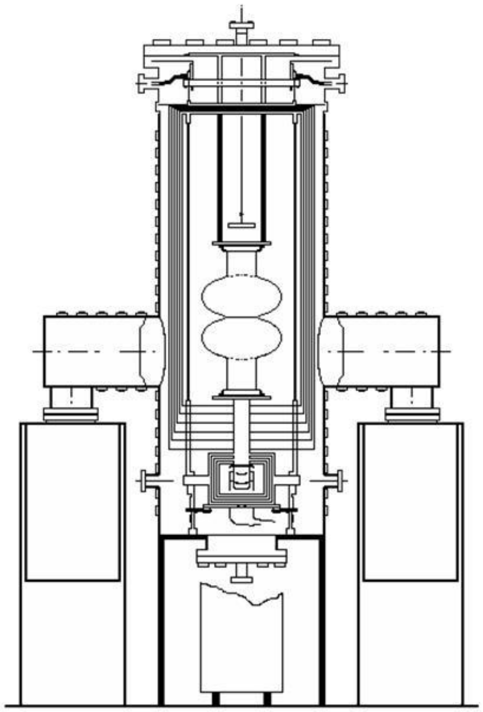
Technique proved successful for magnet conductor application

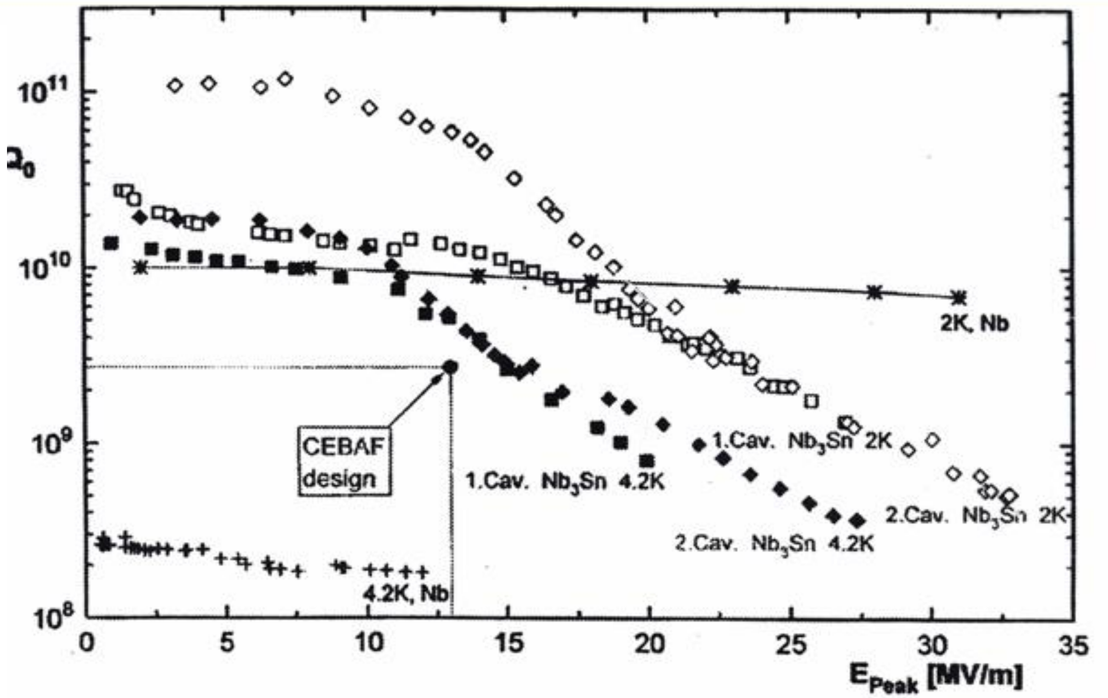
Simple equipment compared to sputtering and CVD

A15 Compounds – Nb_3Sn

Wuppertal, end '80s :

Nb3Sn cavity (1.5 GHz) obtained trough Sn vapour phase diffusion @ 1200°C





Q vs. E_{peak} of the 1st two Nb_3Sn-coated 1.5GHZ single cell cavities in comparison to pure Nb at 4.2K and 2K from CEBAF

5-cell 1.5GHz cavity also coated: Q_o~10^9, E_{acc}=7MV/m with Q=8.10^8

G. Müller et al.,
M. Peiniger & H. Piel , IEEETrans. On Nucl. Sc. Vol NS-32, nº5, Oct. 1985

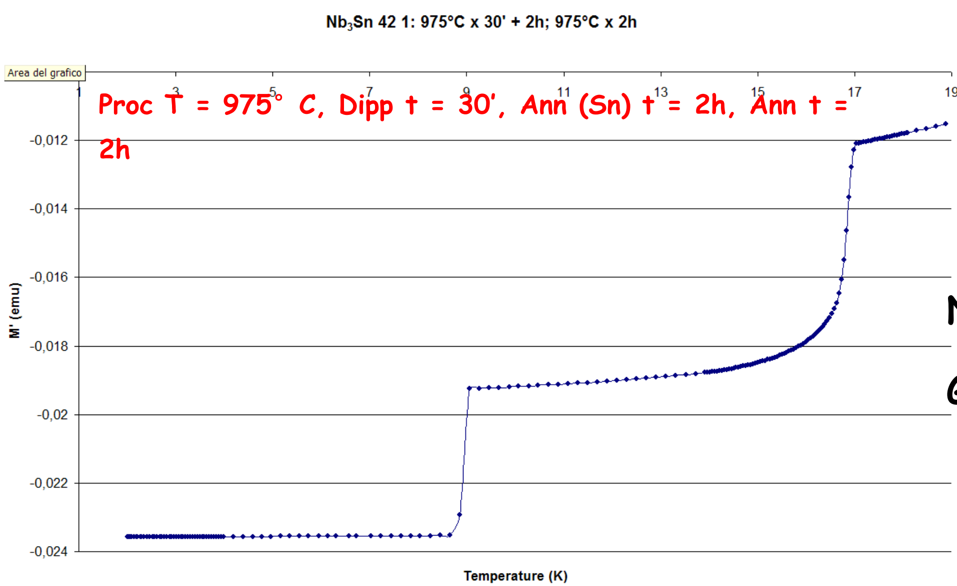
A15 Compounds – Nb_3Sn through liquid diffusion

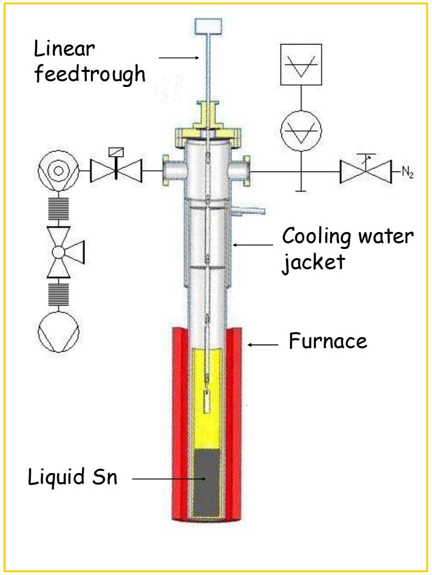
S. Deambrosis, Sharma, International Workshop on Thin Films and New Ideas for Pushing The Limits Of RF Superconductivity, LNL-INFN , Oct.2006
S. Deambrosis et al., Physica C 441 (2006) 108-113

Nb_3Sn coatings on Nb by liquid diffusion method at INFN Legnaro

"Hybrid" Process"

- Substrate thermalization (30 min - 1 h)
- Dipping (few min - 2 h)
- Sample annealing with Sn vapor for a few hours
- Sample annealing without Sn vapor for a few hours





No Residual Sn traces on the sample surface

Good Nb_3Sn film superconductive properties

T_c = 16.8 K, ΔT_c = 0.16 K

No Sn rich Phases

Diffusion temperature to be kept above 930°C to avoid formation of low Tc phases like Nb_6Sn_5 (2.6 K) and NbSn2 (2.1 K)
Diffusion time optimize to obtain desired Nb3Sn thickness
Post diffusion heat reaction important to get rid of the outer Sn layer
Post diffusion annealing to have enlarged grains and perfect ordering

A15 Compounds -Nb_3Sn through Multilayer Coating

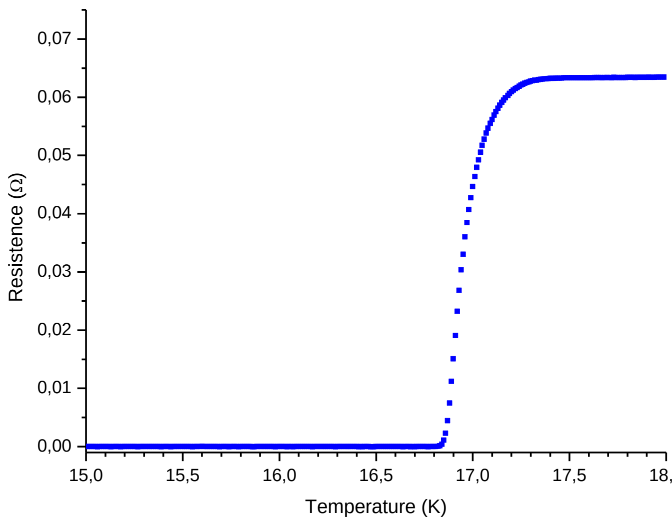
Deambrosis, Keppel, LNL/INFN, International Workshop on Thin Films and New Ideas for Pushing The Limits Of RF Superconductivity, LNL-INFN , Oct.2006

Coat alternate layers of Nb and Sn and subject to diffusion reaction

Preliminary results: a sharp transition and a T_c of 17 K has been obtained

Sputtering Target	Voltage (V)	Current (A)	Power (W)
Sn	613	0.18	108
Nb	407	1.99	800

T_c=16.98K, ΔT_c=0.23



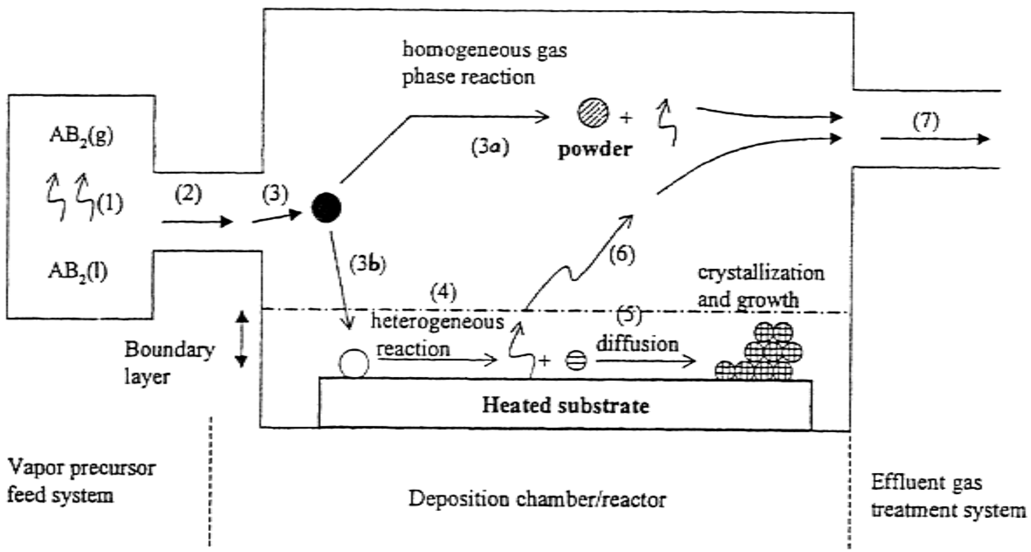
Thickness Nb = 4.5 Thickness Sn

Annealed after sputtering for 3 hours at 975 °C

A15 Compounds - Nb_3Sn through MOCVD process

G. Carta et al. *International Workshop on Thin Films and New Ideas for Pushing The Limits Of RF Superconductivity, LNL-INFN , Oct.2006*

MOCVD technique using bis(cyclopentadienil)niobium borohydride, (cyclopentadienil)niobium tetramethyl and tributyltin hydride as Nb and Sn precursors respectively.



Tin from Bu_3SnH		Niobium from $CpNbMe_4$	
Bath temperature	60°C	Bath temperature	80°C
Line temperature	100°C	Line temperature	100°C
Carrier gas flux	N_2/H_2 (25%) 10 scc/min	Carrier gas flux	N_2/H_2 (25%) 100scc/min
Deposition temperature		550°C	
Pressure		3,7 mbar	
Co-reactant gas flux		N_2/H_2(25%) : 350 scc/min	
Deposition time		45 min	

Sample characterization by XRD, SEM and RBS analyses: presence of niobium (I, II, V) and tin (II) oxides on the surface.

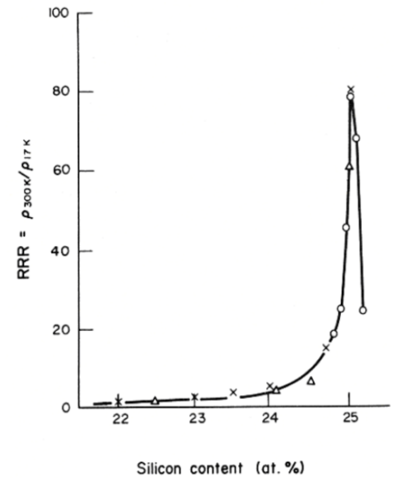
Problems:

great oxophylic character of Nb

A15 Compounds – V_3Si

S. Deambrosis et al., Physica C 441 (2006) 108-113

Highly ordered compound, RRR~80 achievable, m,ax Tc (17.1K) when stoichiometric composition (25at.% Si)



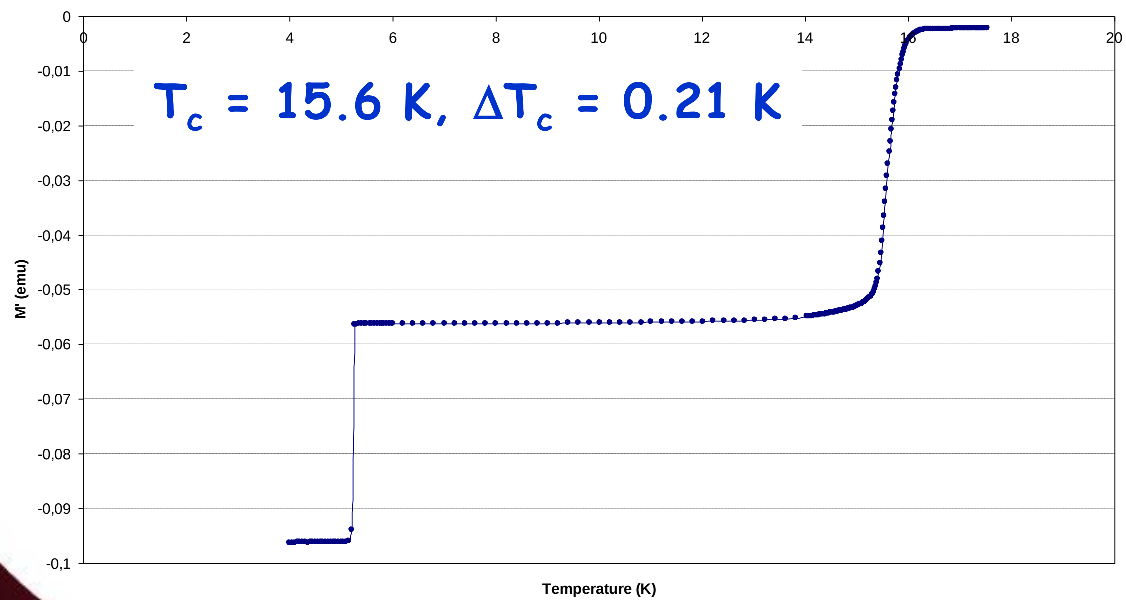
V_3Si layers by silanization of V substrate and Thermal Diffusion

V substrate heated to get SiH_4 decomposition and Silicon diffusion

Film grown by silanization with p (SiH_4) ~ 10^{-3}-10^{-4} mbar

Annealing in vacuum to get rid of hydrogen

825°C, 4h+8h



* Diffusion parameters and silane flow rate have been optimized

* Tc ~ 16 K is routinely obtained

* RF measurement on 6 GHz V-cavities will be available soon

A15 Compounds – Mo_3Re

Mo_3Re thin films by DC magnetron deposition: $Mo_{75}Re_{25}$, $Mo_{60}Re_{40}$ …

Solid solution , free of bulk and surface inhomogeneities, low intersticials solubility compared to Nb, low κ, high H_{c1} (500G)

Bulk in σ phase, tetragonal low T_c (6K)

but T_c up to 18K reported in literature with bcc structure

S.M. Deambrosis et al., Physica C 441(2006) 108-113

* Deposition on Sapphire, Cu and Nb substrates
*Substrate temperature up to 950^0 C
*Post-annealing to increase crystallinity and transition sharpness
* Tc = 12K obtained for composition $Mo_{60}Re_{40}$

Higher deposition temperature, longer annealing time

➡ Higher Tc

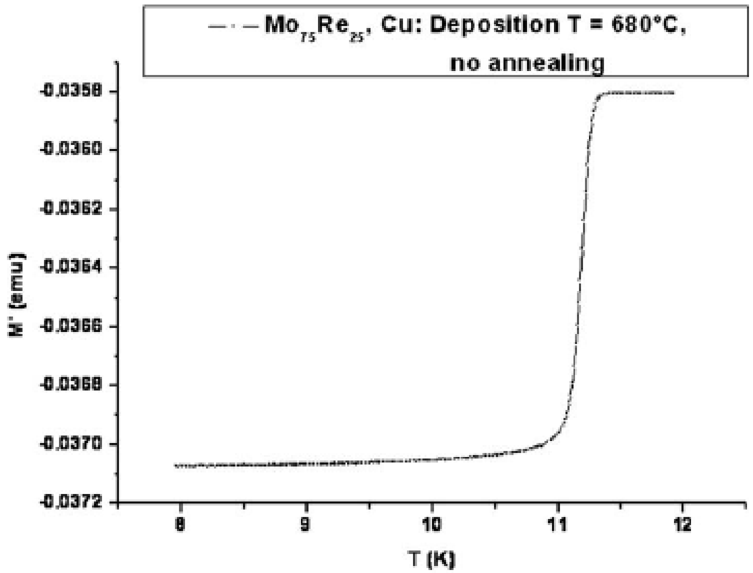


Fig. 4. A $Mo_{75}Re_{25}$ film deposited on Cu transition curve: deposition $T = 680$ °C, $T_c = 11.18$, $\Delta T_c = 0.08$ K.

A15 Compounds – Results on cavities?

Cf. WE203:The progress at LNL on Nb_3Sn and V_3Si, Silvia Deambrosis (INFN-LNL, Padua University)

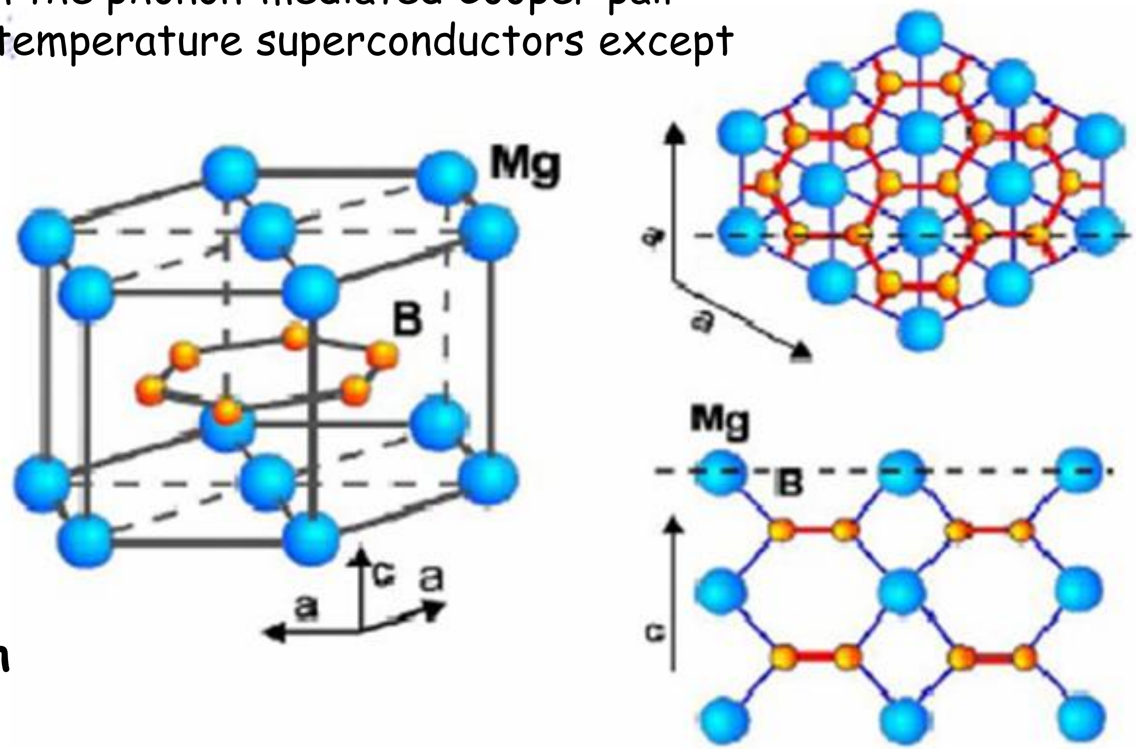
6 GHz Nb cavities for RF properties systematic testing for V_3Si, Nb_3Sn

Magnesium Diboride (MgB_2)

Graphite-type boron layers separated by hexagonal close-packed layers of magnesium

Superconductivity comes from the phonon-mediated Cooper pair production similar to the low-temperature superconductors except for the **two-gap nature**.

T_c ~ 40 K



Compared to cuprates:

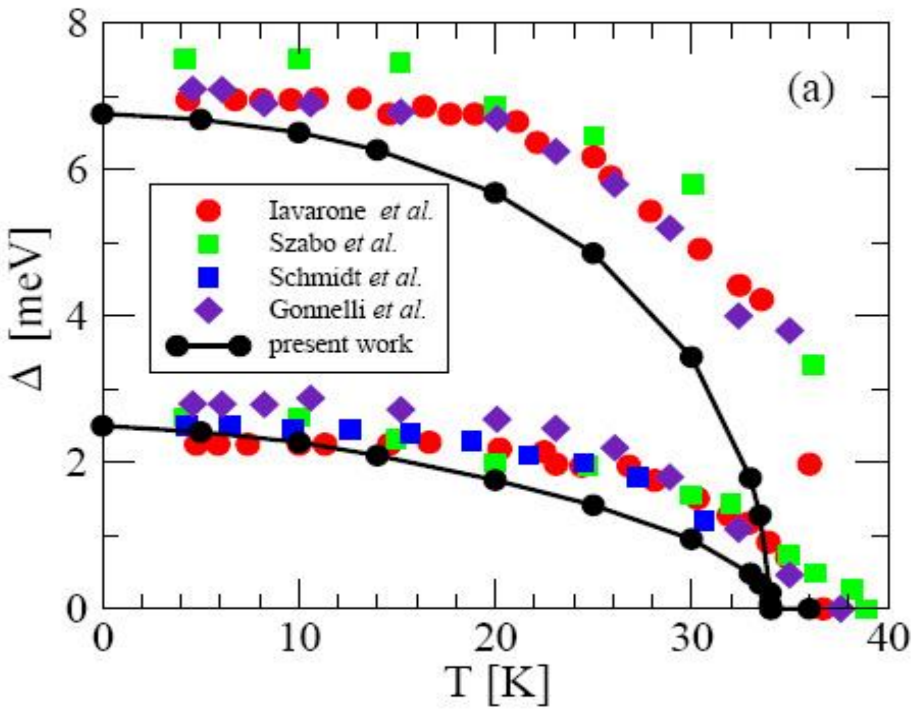
- **Cheaper**
- **Lower anisotropy**
- **Larger coherence length**
- **Transparency of grain boundaries to current flows**

➡ **attractive for RF applications.**

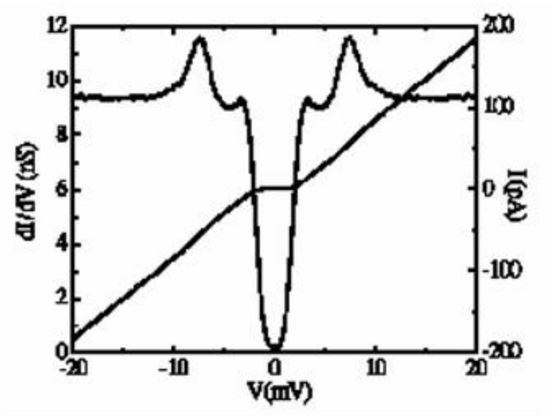
C. Buzea and T. Yamashita, Superconductor Sci. Technol. 14 (2001) R115.

MgB_2: Two Energy Gaps

A. Floris et al., cond-mat/0408688v1 31 Aug 2004



Δ_p=2.6meV, Δ_s=6.7meV



RF response has shown lower energy gap behavior. This must be compared to $\Delta \approx$ 1.5 mV for Nb. There is room for better performance than niobium, since the resistivity can also be made quite low (best values are $\leq$1 $\mu\Omega$cm).

MgB_2 - Potential Low BCS *Rs* for RF Cavity

X. Xi, Penn State Uni., SRF Materials Workshop, Fermilab 2007

BCS R_s for MgB_2 presented in the same coordinates as in the figure.

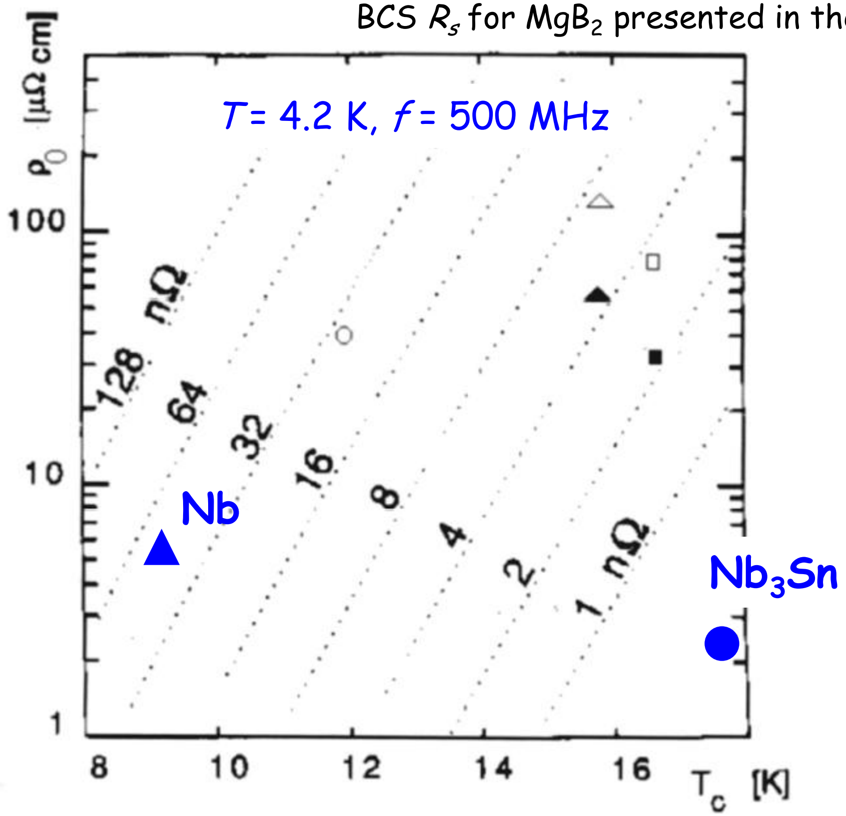
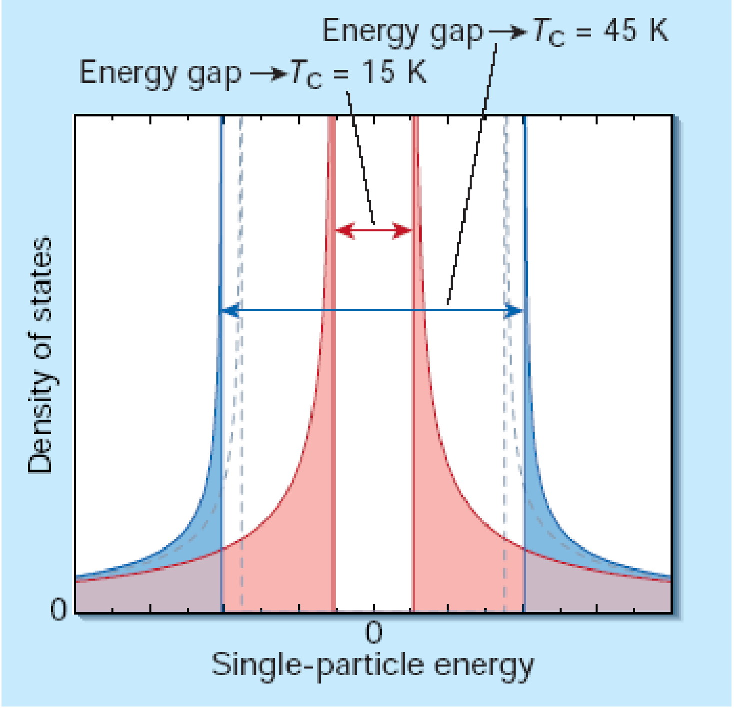


FIGURE 1 Lines of equal R_{BCS} in the (ρ_0, T_c) plane at $T = 4.2$ K and $f = 0.5$ GHz. (○) MoRe, (■) (NbTi)N, ((▲) (NbTi)N $T_s = 200$°C), (□) NbN, ((△) NbN $T_s = 200$°C), (●) Nb_3Sn; for Nb $R_{BCS} = 55$ nΩ.



Pickett, *Nature* 418, 733 (2002)

R_s from π Gap

R_s from σ Gap

MgB2 - A comparison with conventional SC for RF applications

X. Xi, International SRF Thin Films Workshop, Padua, Italy, 2006

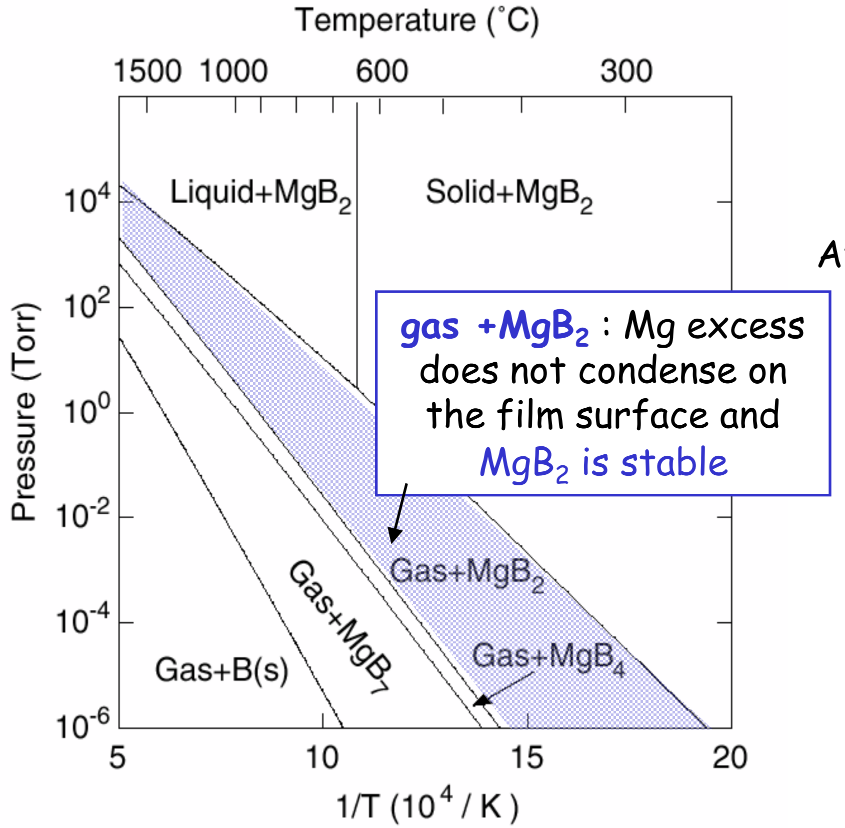
	MgB_2	Nb
T_c (K)	39	9.2
ρ_0 (mΩcm)	0.1-10	0.05
RRR	3-30	300
$\Delta_{p,s}$ (meV)	2, 7	1.2
2 $\Delta_{p,s}$ /$K_B T_c$ (meV)	1.6, 4	3.9
x $_{p,s}$ (nm)	50,12	40
λ (nm)	85	80
$m_0 H_{c2}$ (T)	6-50	0.2
R_{BCS} @ 4K, 500MHz (nΩ)	$2.5/2.3\times10^{-5}$	69

↓

from $$R_{BCS}(n\Omega) = \left(\frac{1}{T}\right) 10^5 \nu_{GHz}^2 e^{(-\Delta/KT_c)}$$

F.Collings et al. SUST 17 (2004)

MgB_2-Thin films growth



Z.-K. Liu et al., APL 78(2001) 3678.

optimal T for epitaxial growth ~ $T_{melt}/2$

For MgB_2 , 540° C → it requires P_{Mg} ~11 Torr

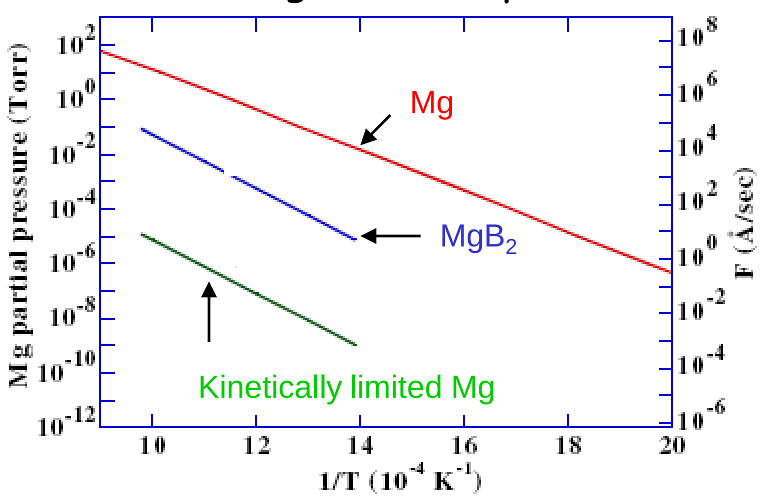
Too high for UHV deposition techniques (PLD, MBE…)

At $P_{Mg} = 10^{-4}$-10^{-6} Torr, compatible with MBE, Tsub ~ 400° C

MgB_2 is stable, but no MgB_2 formation:

Mg atoms re-evaporate before reacting with B

Kinetic of Mg is also important



M. Naito and K. Ueda, SUST 17 (2004) R1

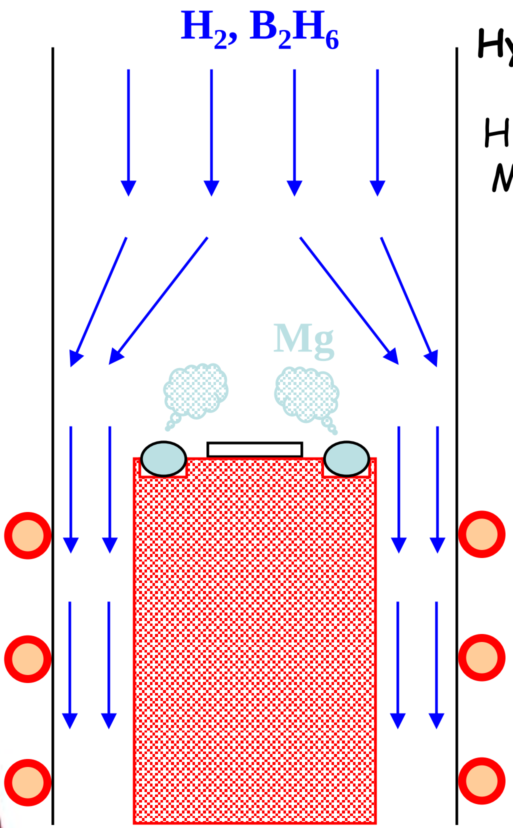
evaporation Mg pressure from MgB_2 < decomposition curve of MgB_2 < Mg vapor pressure

At $P=10^{-6}$ Torr and T> 250°C no accumulation of Mg will take place on the substrate and the growth of the superconducting phase is very slow due to a large kinetic energy barrier.

At low Mg pressure only extremely low deposition temperatures can be used

MgB_2 – HPCVD on metal substrates

X. Xi- Penn State University



Hybrid Physical Chemical Vapor Deposition

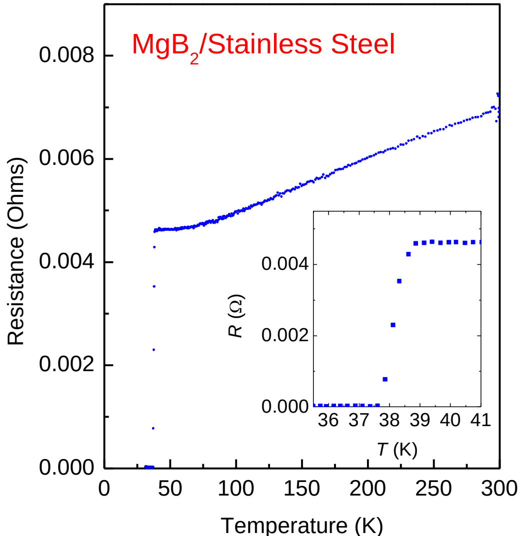
High T_c has been obtained in polycrystalline MgB_2 films on stainless steel, Nb, TiN, and other substrates.

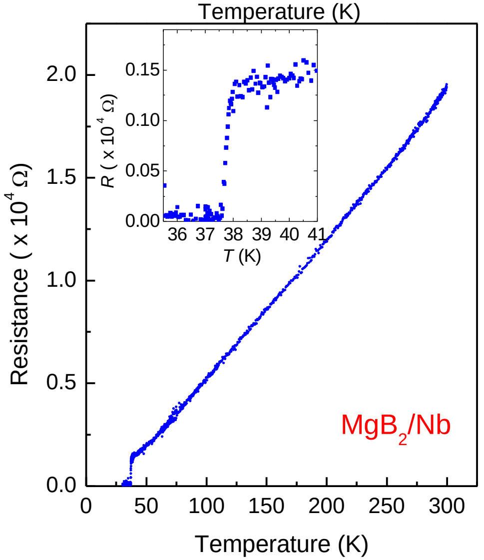
Clean HPCVD MgB2 thin films with excellent properties:

- RRR>80
low resistivity (<0.1 μΩ) and long mean free path
- high Tc ~ 42 K (due to tensile strain), high Jc (10% depairing current)
- low surface resistance, short penetration depth
- smooth surface (RMS roughness < 10 Å with N_2 addition)
- good thermal conductivity (free from dendritic magnetic instability)

Critical engineering considerations:

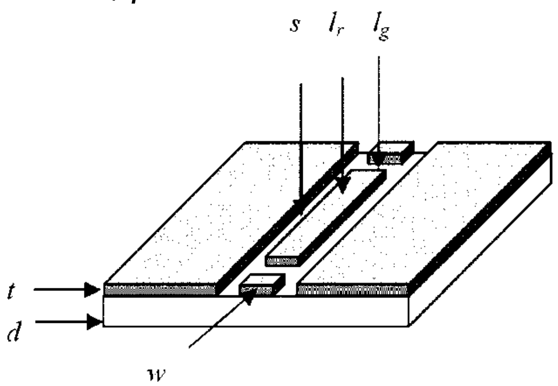
generate high Mg pressure at substrate (cold surface is Mg trap)
deliver diborane to the substrate (the first hot surface diborane sees should be the substrate)





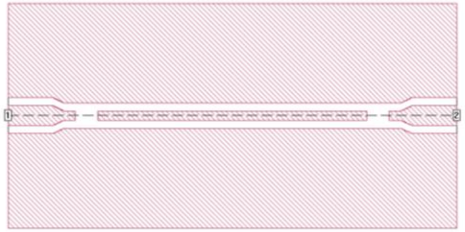
MgB_2 – Microwave Performance on HPCVD Films

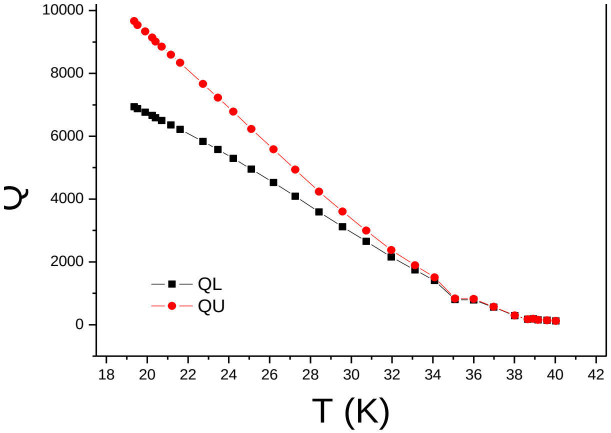
X. Xi , private communication

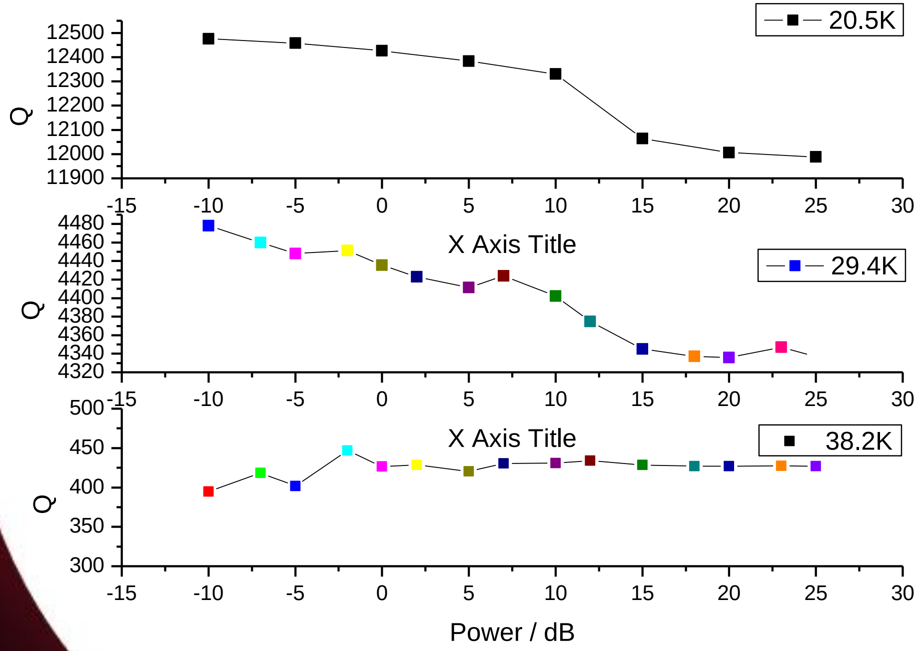


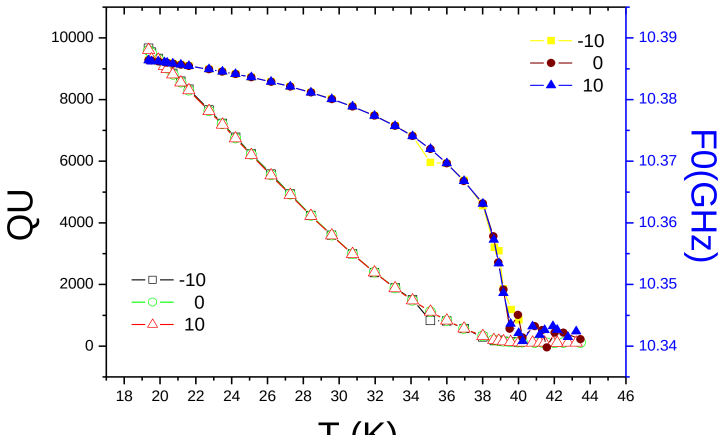
C. Zhuang et al. Peking University

Yusheng He et al. Institute of Physics of Chinese Academy of Sciences







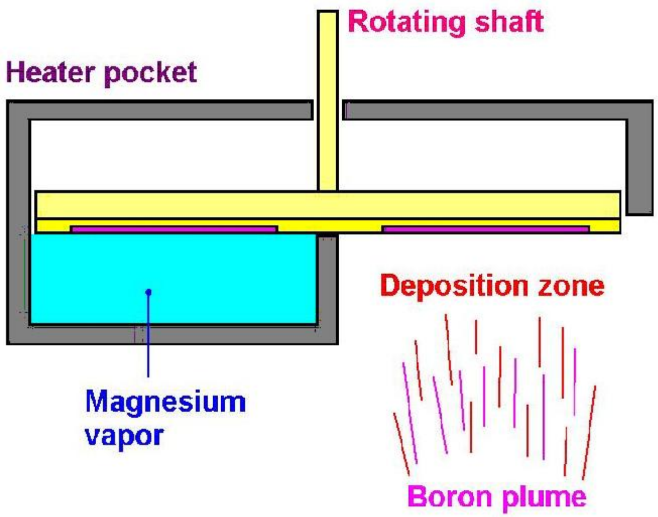


High Q value ~10000 at 20K, sharp transition in F0-T curve around the critical temperature, no power dependence in QU-T and F0-T

MgB_2 - Reactive Evaporation

T. Tajima, LANL

SuperconductingTechnologies Inc.



In-situ reactive evaporation @ 550°C

Compared to Nb:

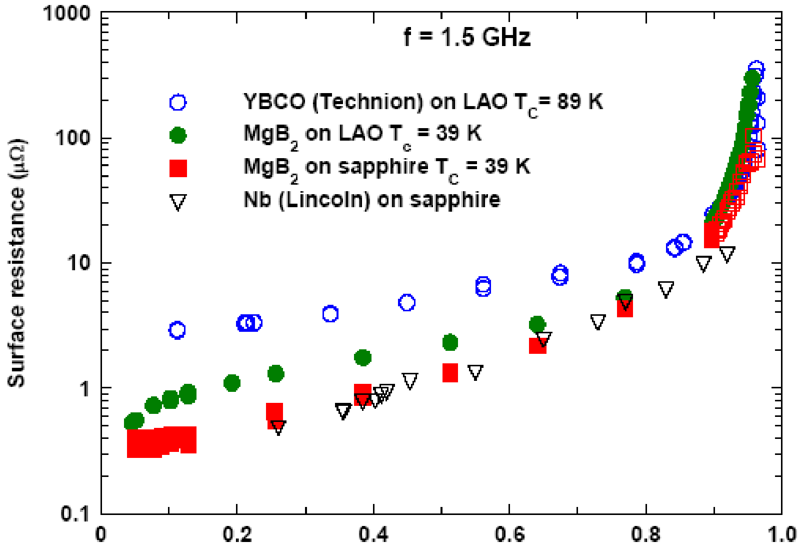
- **Higher T_c**
- **low resistivity**
- **larger gap**
- **higher critical field**

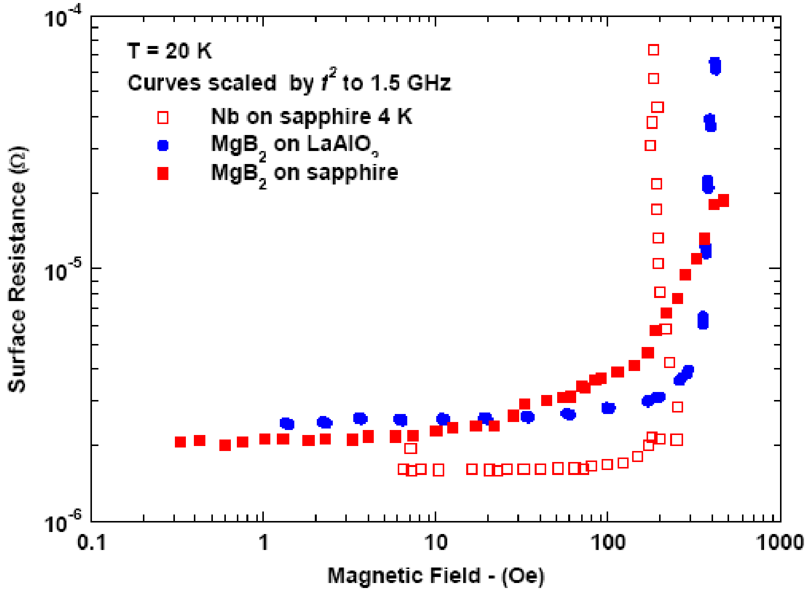
B.H. Moeckly et al., IEEE Trans. Appl. Supercond. 15 (2005) 3308.
T. Tajima et al, Proc. PAC05.

B.H. Moeckly, ONR Superconducting Electronics Program Review
Red Bank, NJ, February 8, 2005

Oates, Agassi, and Moeckly, ASC 2006 Proceeding

RF measurement @ MIT/Lincoln Lab

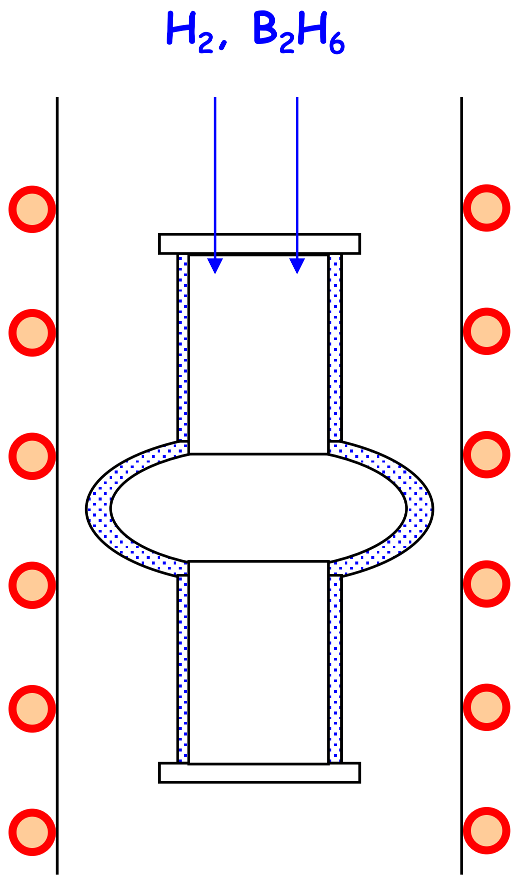




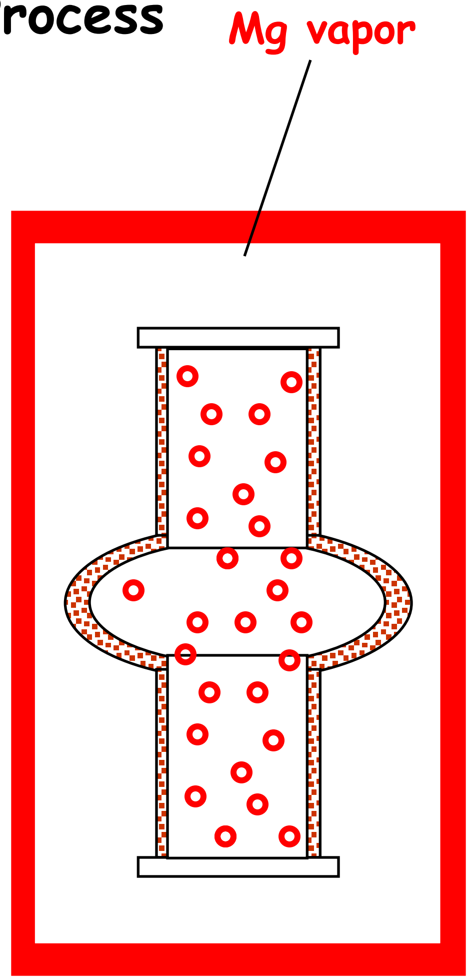
MgB_2 – An Idea for SRF Cavity Coating

X. Xi, Penn State Univ.

Coating SRF Cavity with a Two-Step Process



Coating cavity with B layer at ~400-500° C using CVD



Reacting with Mg to form MgB_2 at ~ 850-900 ° C in Mg vapor

MgB_2 – Challenges

Keys to high quality MgB2 thin films:

- High Mg pressure for thermodynamic stability of MgB_2
- oxygen-free or reducing environment
- clean Mg and B sources

Challenges

Film properties degrade with exposure to moisture: resistance goes up, T_c goes down

Clean cavity surface leads to degradation in water and moisture … need of a cap layer?

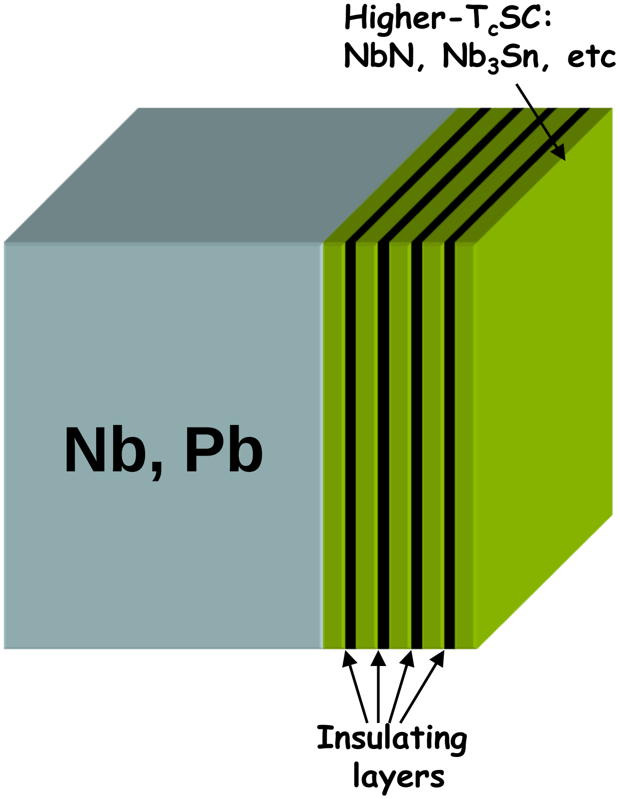
Safety … procedures for use of diborane

Cf.TU203 Prospects for higher Tc-Superconductors for SRf Applications, Xiaoxing Xi (Penn State University)

SIS Multilayers

Alex Gurevich, Appl. Phys. Lett. 88, 012511 (2006)

Taking advantage of the high –Tc superconductors without being penalized by their lower Hc1…

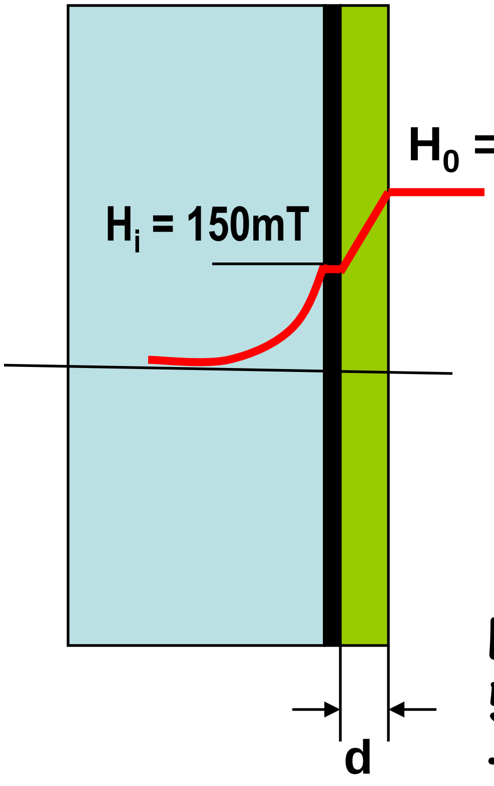


Multilayer coating of SC cavities: alternating SC and insulating layers with d < λ

Higher T_c thin layers provide magnetic screening of the bulk SC cavity (Nb, Pb) without vortex penetration

- Strong increase of H_{c1} in films allows using RF fields > H_c of Nb, but lower than those at which flux penetration in grain boundaries may become a problem
- Strong reduction of BCS resistance because of using SC layers with higher Δ (Nb_3Sn, NbN, etc)

SIS Multilayers - A minimalistic solution with Nb_3Sn



A Nb cavity coated with an insulator and a single 50 nm thick Nb_3Sn layer

- If the Nb cavity can withstand Hi = 150mT, then the external field can be as high as 324mT

$$H_0 = H_i \exp(d/\lambda_0) = 150 \exp(50/65) = 323.7 mT$$

Lower critical field for the Nb_3Sn layer with d = 50 nm and ξ = 3nm: H_{c1} = 1.4T is much higher than H_0

A single layer coating more than doubles the breakdown field with no vortex penetration, enabling E_{acc}~ 100 MV/m
Potential to increase Q for bulk Nb of 2 orders of magnitude above Nb values

SIS Multilayers: Experiments in progress

- JLab

  $NbN/Al_2O_3/Nb$ and $NbTiN/Al_2O_3/Nb$ coated in UHV multi-techniques and ECR deposition systems under preparation (combining magnetron sputtering, IBAD, ECR, …)
- INFN Legnaro

  Multilayers with Nb_3Sn
- INFN Naples

  Multilayers with NbN, NbTiN by Sputtering
- Argonne National Lab

  Atomic Layer Deposition (ALD): alternating, saturating reactions between gaseous precursor molecules and a substrate to deposit films layer by layer. Films from a wide variety of elements, compounds and alloys with a thickness from a few atomic monolayers to microns

  cf.TUP64
- Penn State University, Los Alamos National Lab,…

  MgB_2 as a top layer with HPCVD
- KEK

  MgB_2 by PLD cf. WEP69

SIS Multilayers – The Benefits

- Multilayer S-I-S-I-S coating could make it possible to take advantage of superconductors with much higher H_c, than those for Nb without the penalty of lower H_{c1}
- Strong increase of H_{c1} in films allows using rf fields > H_c of Nb, but lower than those at which flux penetration in grain boundaries may become a problem
- Strong reduction of BCS resistance because of using SC layers with higher Δ(Nb_3Sn, NbN, …)
- The significant performance gain may justify the extra cost.

… but …

Technical challenges, influence of composition on Hc1 and Hc, influence of the morphology and composition at grain boundaries, …

CONCLUDING REMARKS

Over the years, some attempts have been made to study alternative materials to Nb for applications to SRF cavities.

Most of the sample/cavities using alternative materials have been produced by reactive magnetron sputtering or thermal diffusion. Use of Energetic Condensation Techniques like Vacuum Arc Deposition, ECR, or ALD? (production of very dense films with nm-scale roughness…Some trials with Vacuum Arc @ INFN-Rome, non conclusive)

The multilayer approach opens the door to further potential improvement for SRF cavities, taking benefits from the advantages of higher T_c superconductors without the limitation of H_{c1}.

The effort for new materials research for SRF cavities application has been very limited so far… There is still a lot of work ahead!

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