SRF 2013 Tutorial

CAEN, FRANCE

# BEYOND NIOBIUM

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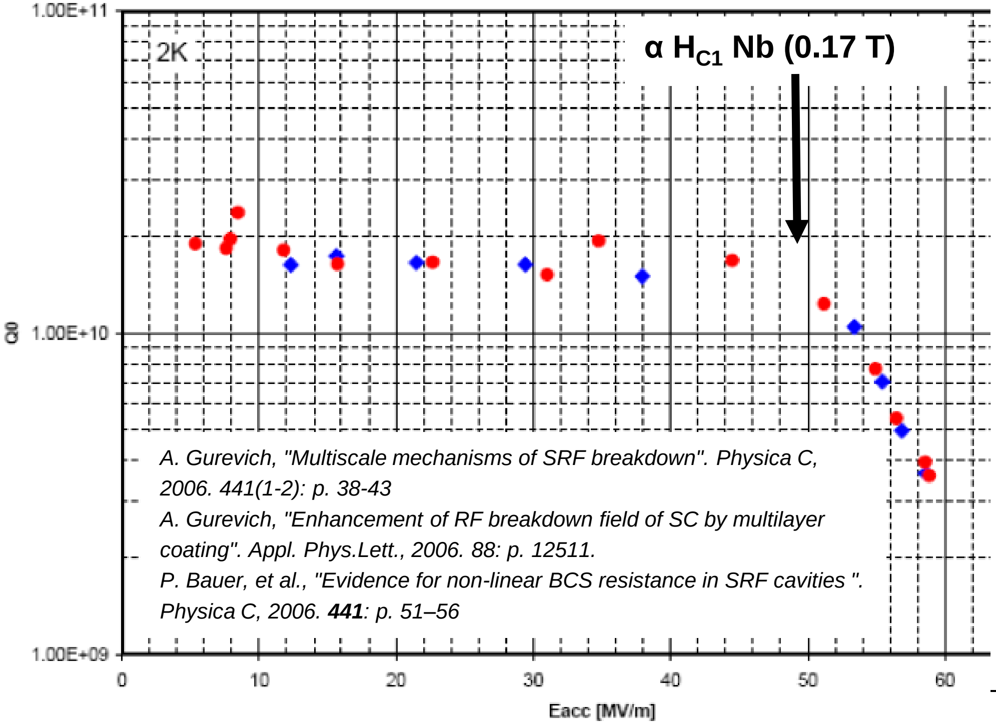
# Outline

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

# Why looking beyond Nb?

**Nb has the highest critical temperature $T_c$ (=9.25k) and the highest lower critical magnetic field $H_{c1}$(≈180 mT) of any elemental superconductor**

Cornell 60 mm aperture re-entrant cavity LR1-3 March 14, 2007

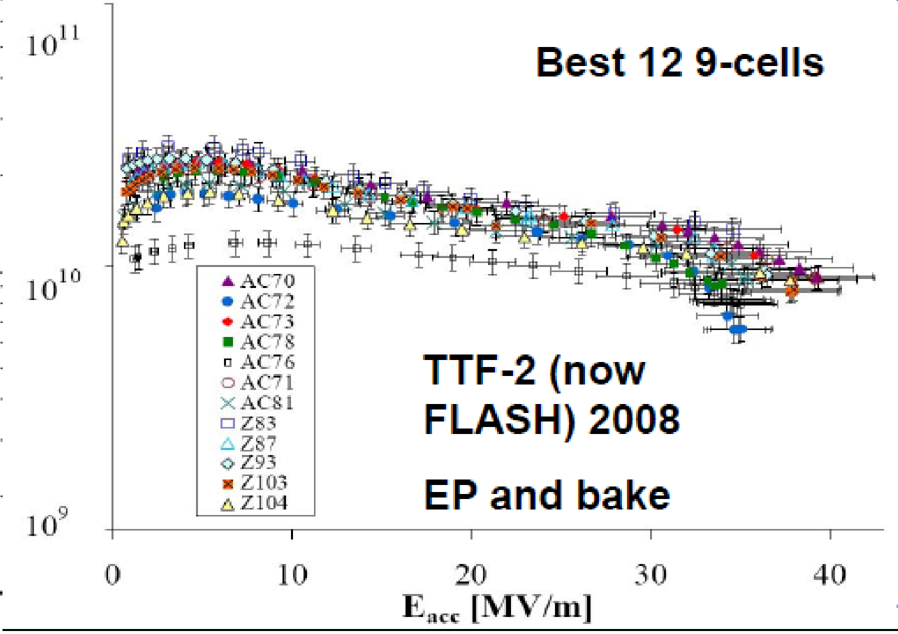


*A. Gurevich, "Multiscale mechanisms of SRF breakdown". Physica C, 2006. 441(1-2): p. 38-43*

*A. Gurevich, "Enhancement of RF breakdown field of SC by multilayer coating". Appl. Phys.Lett., 2006. 88: p. 12511.*

*P. Bauer, et al., "Evidence for non-linear BCS resistance in SRF cavities ". Physica C, 2006. **441**: p. 51–56*

Data from the Jlab, KEK, Cornell and other groups



**Breakdown fields close to the de-pairing limit of 50 MV/m for Nb have been achieved**

**Best Nb cavities approaching their intrinsic limit at $H_{max} = H_C$**

**For further improved cavity RF performance, innovation needed**

**Possibilities to use higher performance superconductors other than Nb?**

# Looking beyond Nb – Potential Benefits

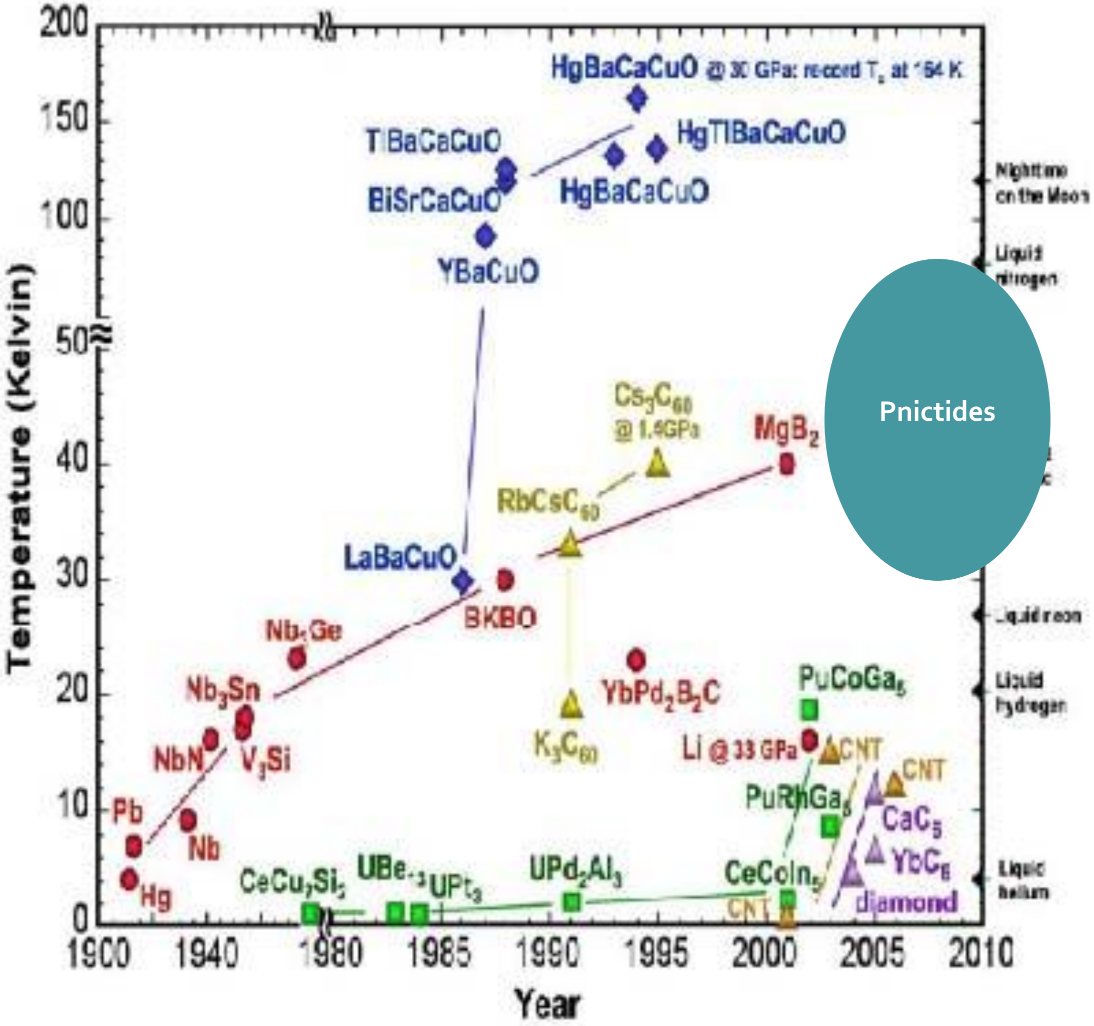
- Reduced material costs
    - Use of inexpensive, highly formable materials with higher thermal conductivity such as Cu or Al
- Simplified engineering, fabrication and assembly
    - Separation of cavity structure from superconducting surface
    - Maximum flexibility & largest variety of options in design of integrated cavity/cryostat structures
- Higher gradients

    Increasing gradients reduces capital expense of cryomodules – potentially several $100M savings & minimize conventional facilities
- Lower RF losses

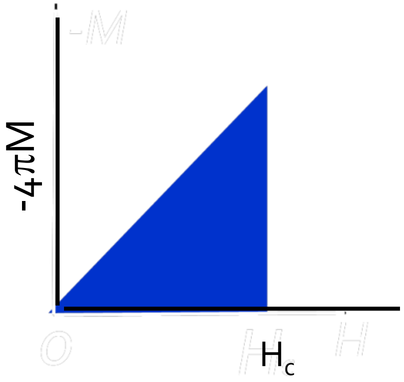
    Low loss (high Q) cavities reduce He costs, >$10M potential capital savings, and several $M/year in operating costs
- Potentially higher operating temperatures (>4.2K)

# Which materials are suitable for SRF cavities?

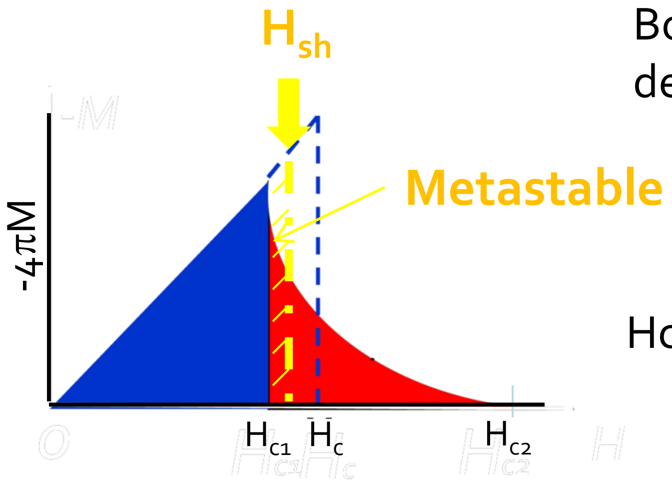
Highest Tc=164K (under GPa)



# Critical Field



**Type-I**



**Type-II**

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

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

Hc is the thermodynamic critical field

&

$H_c = H_{c_2}/\sqrt{2}\kappa$

(for type-II superconductors).

- Meissner state at $0 < H < H_{c1}$
- Mixed vortex state at $H_{c1} < H < H_{c2}$
- Exponentially small $R_s$ at $H < H_{c1}$ ($Q = 10^{10}$-$10^{11}$)
- Drastic Q drop due to vortex dissipation at $H > H_{c1}$

**The superheating field $H_{sh}$ is the field up to which the Meissner state metastably persists above Hc1**

**For type-II superconductors, at T = 0 in the clean limit with a Gindzburg-Landau parameter $\kappa=\lambda/\xi \gg 1$, $H_{sh}$ has been calculated to be ~ $0.75H_c$.**

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

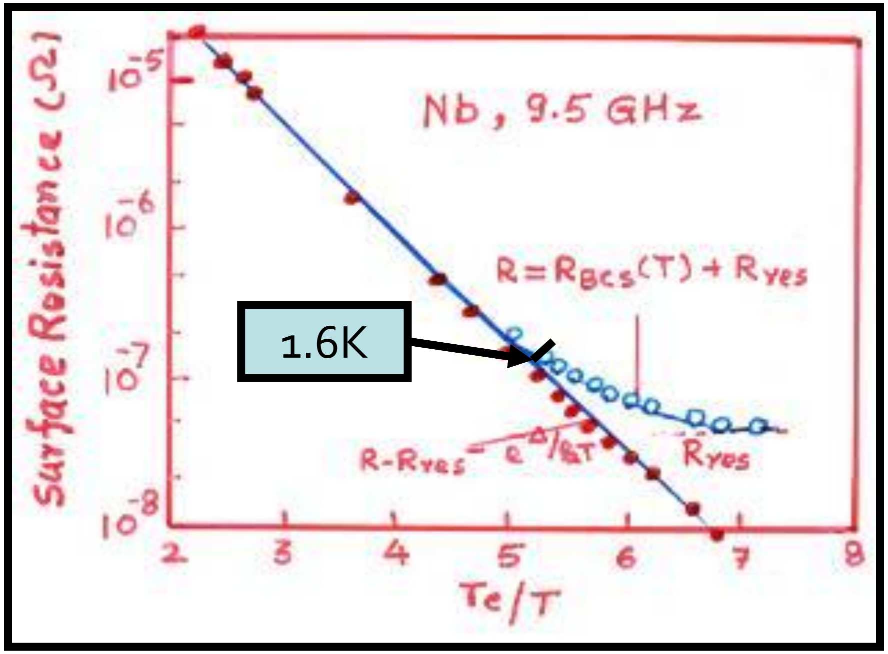
# Surface Resistance

The power dissipated per unit area of SC in RF regime $P = R_S \cdot \frac{H^2}{2}$

and

## 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"

# BCS Surface Resistance $R_{BCS}$

**If T < $T_c$ / 2, for dirty limit supeconductors**

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

A constant weakly dependent on material
$\omega$ = RF frequency
$\rho_n$ = Normal State conductivity
$\Delta$ = Superconducting gap
$T_c$ = Transition Temperature

dependence on $\rho_n$ and $T_c$ represents an immediate criterion for selecting the most favorable candidates for cavities

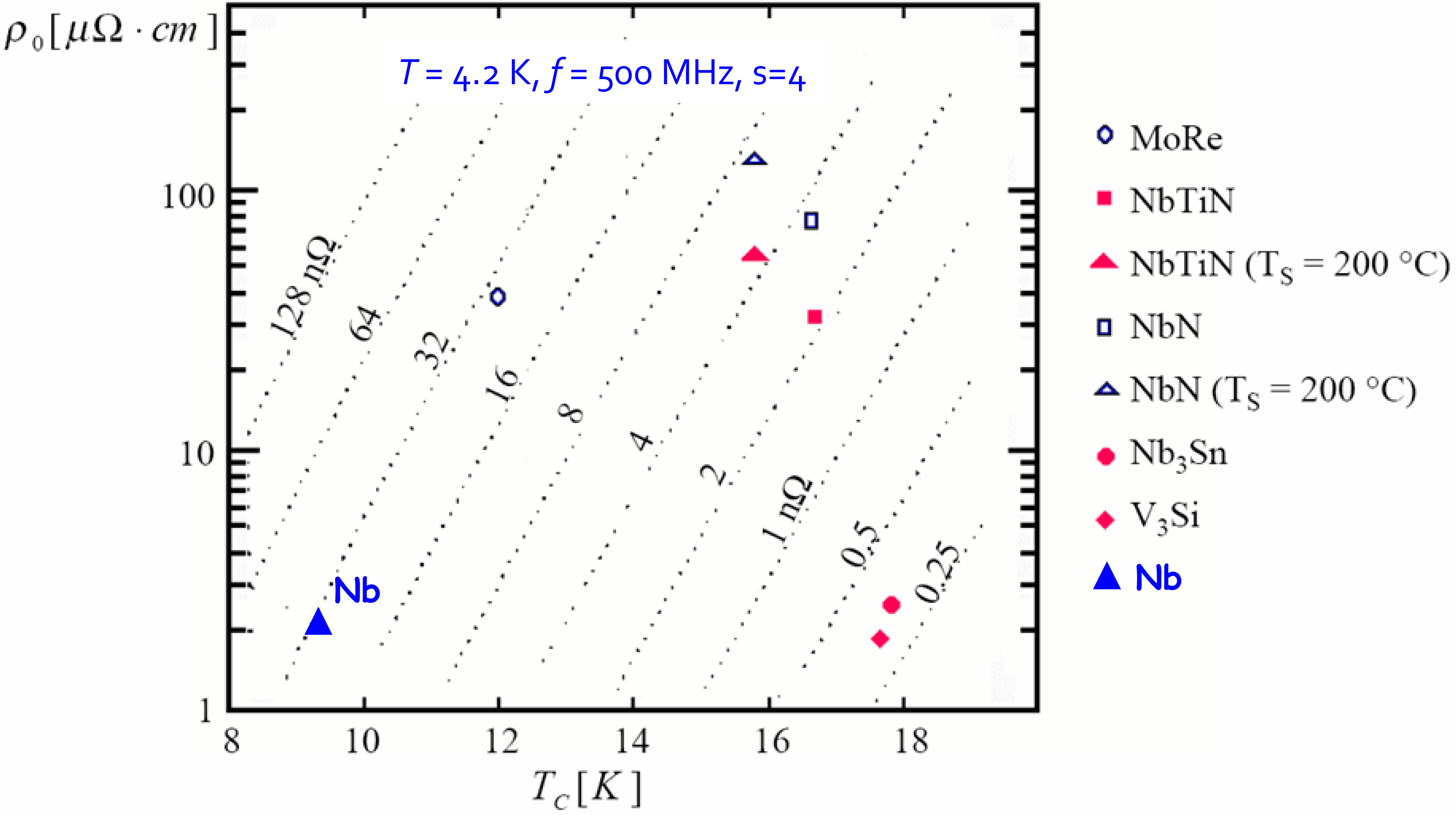
**The higher Tc (= 0.57Δ), the smaller the BCS surface resistance**

**Material with high normal state conductivity and high Tc (high superconducting gap Δ)should be selected**

# Other materials than niobium

**$R_{BCS}$ versus $\rho_0$, $T_c$**

Vaglio, *Particle Accelerators* 61, 391 (1998)



# Residual Resistance $R_{res}$

Temperature independent

**Contributions to residual losses:**

**Intrinsic:**

**Inhomogeneity, Metallic Inclusions within l, 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 $\sqrt{\rho_n}$**

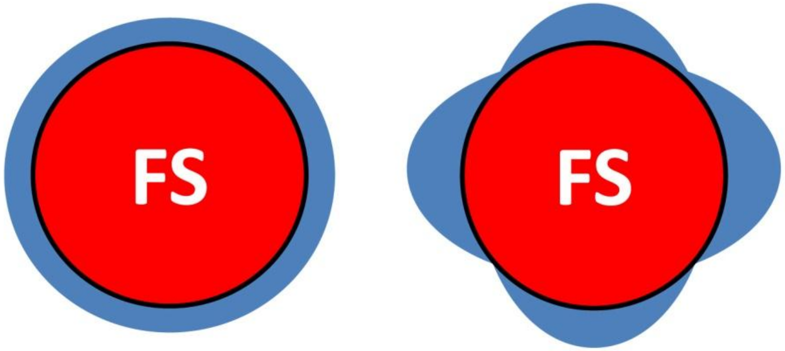
For two materials with the same $R_{BCS}$ and different $T_c$ and $\mathbf{r}_n$,
the one with the smallest $\rho_n$ should have the smallest $R_{res}$

**Metallic behaviour is favored**

# The gap symmetry is important

- The high Q required by SRF cavities results from the exponentially small BCS surface resistance

$$R_s = \frac{A\omega^2}{T}\exp\left(-\frac{\Delta}{T}\right) + R_{res}$$



**s-wave**: all conventional BCS uperconductors, ferropnictides

**d-wave**: high-$T_c$ cuprates, heavy fermions, borocarbides ferropnictides

- All high-$T_c$ cuprates are d-wave SC with nodes in the gap
- Power-law $R_s$ and gap suppression by nonmagnetic impurities:

$$R_s \propto T^{\alpha}, \qquad \alpha \cong 2-3$$

**d - wave cuprates, or heavy fermions cannot compete with s-wave LTS at low T**

# 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 $\rho_n$**

For high gradients → **High $H_{sh}$, $H_c$; small $\kappa$**

# Possible Choices among Superconducting Materials

| Material | Critical Temp. $T_c$ [K] | Normal-state resistivity $\rho_n(\mu\Omega cm)$ | Critical Field $H_c(0)$ [T] | Lower Critical field $H_{c1}(0)$ [T] | Upper Critical field $H_{c2}(0)$ [T] | Penetration depth $\lambda(0)$ [nm] | Type |
|---|---|---|---|---|---|---|---|
| Nb | 9.22 | 2 | 0.2 | 0.18 | 0.28 | 40 | II |
| Pb | 7.2 | | 0.08 | N/A | N/A | 48 | I |
| NbN | 17 | 70 | 0.23 | 0.02 | 15 | 200 | II, B1 comp. |
| NbTiN | 17.5 | 35 | | 0.03 | | 151 | II, B1 comp. |
| $Nb_3Sn$ | 18.3 | 20 | 0.54 | 0.05 | 30 | 85 | II, A15 |
| $V_3Si$ | 17 | | | | 24.5 | 179 | II, A15 |
| $Mo_3Re$ | 15 | | 0.43 | 0.03 | 3.5 | 140 | II, A15 |
| $MgB_2$ | 40 | | 0.43 | 0.03 | 3.5 | 140 | II- 2 gaps |
| YBCO | 93 | | 1.4 | 0.01 | 100 | 150 | d-wave |

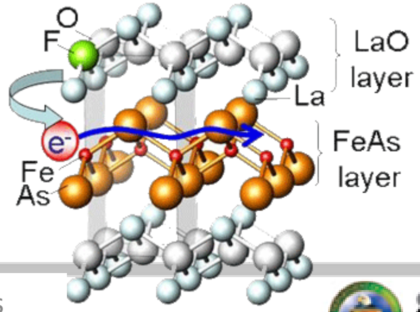
## A new family of superconductors: Oxypnictides ReOMPn

–M = Fe, Co, Ni/Pn = As or P/ Re = La, Nd, Sm, Pr

Layered as HTS –superconducting AsFe layers and $T_c$ from <10K to 55K

**$\Delta^{oxy}$ = 5-10 meV > $\Delta^{Nb3Sn}$ = 3 meV**

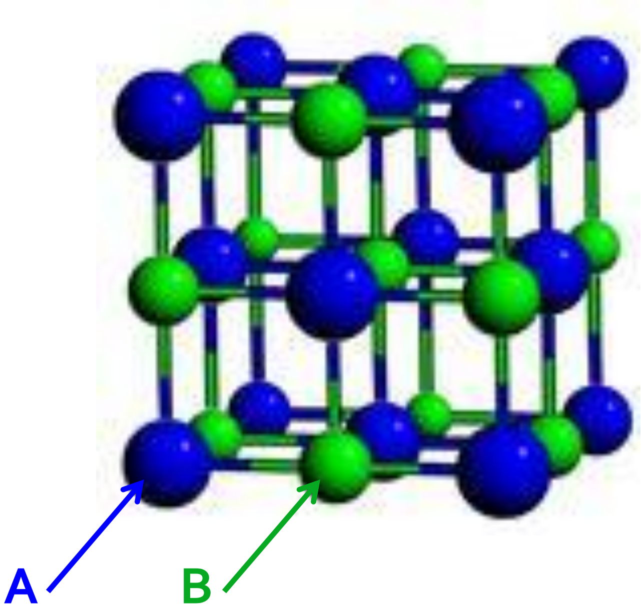
**High $\rho_n$~1mΩcm ~10$\rho_n^{MgB_2}$, big $\lambda$= 180-250**



# Nb Compounds

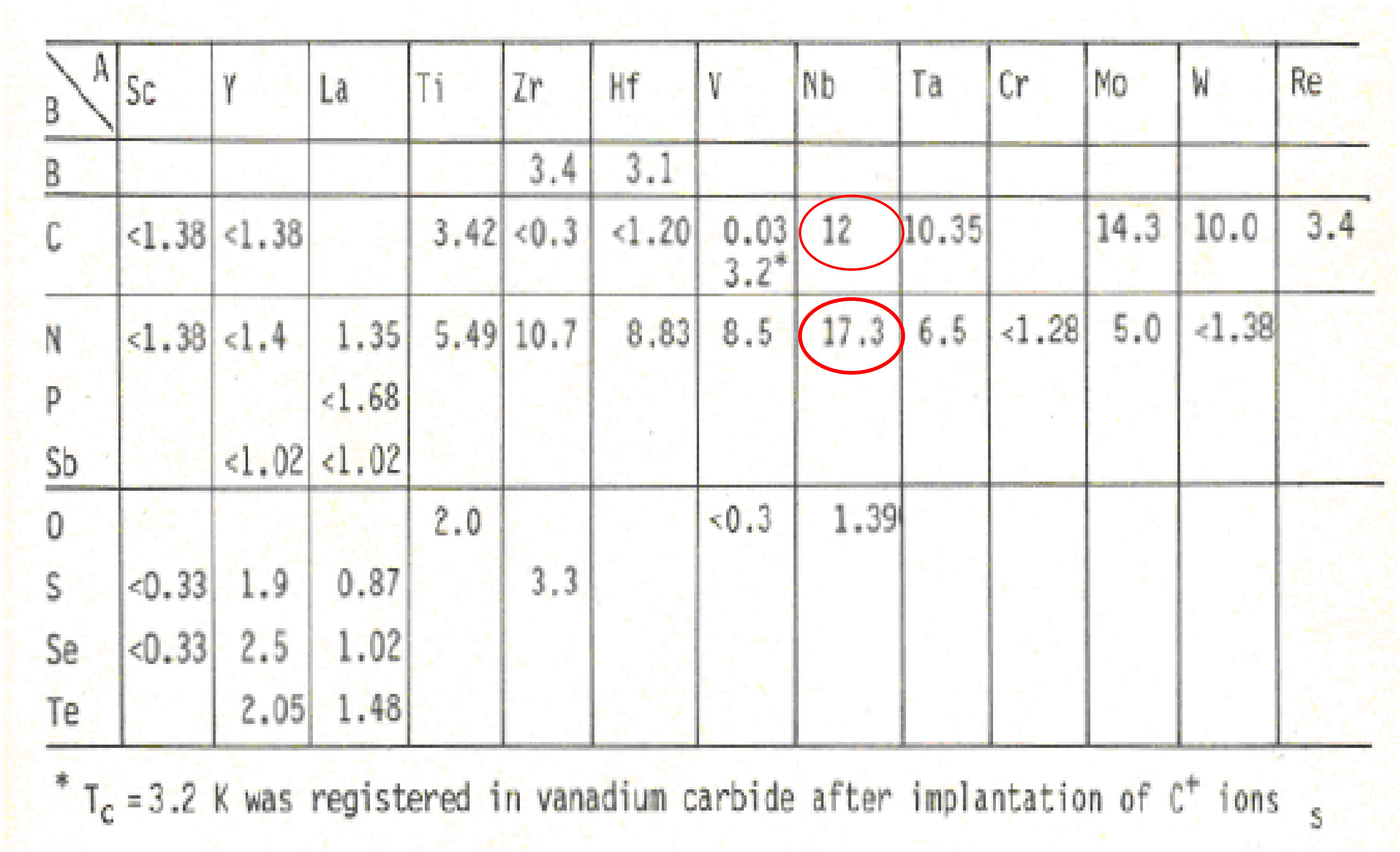
## B1 compounds – NaCl structure

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.**



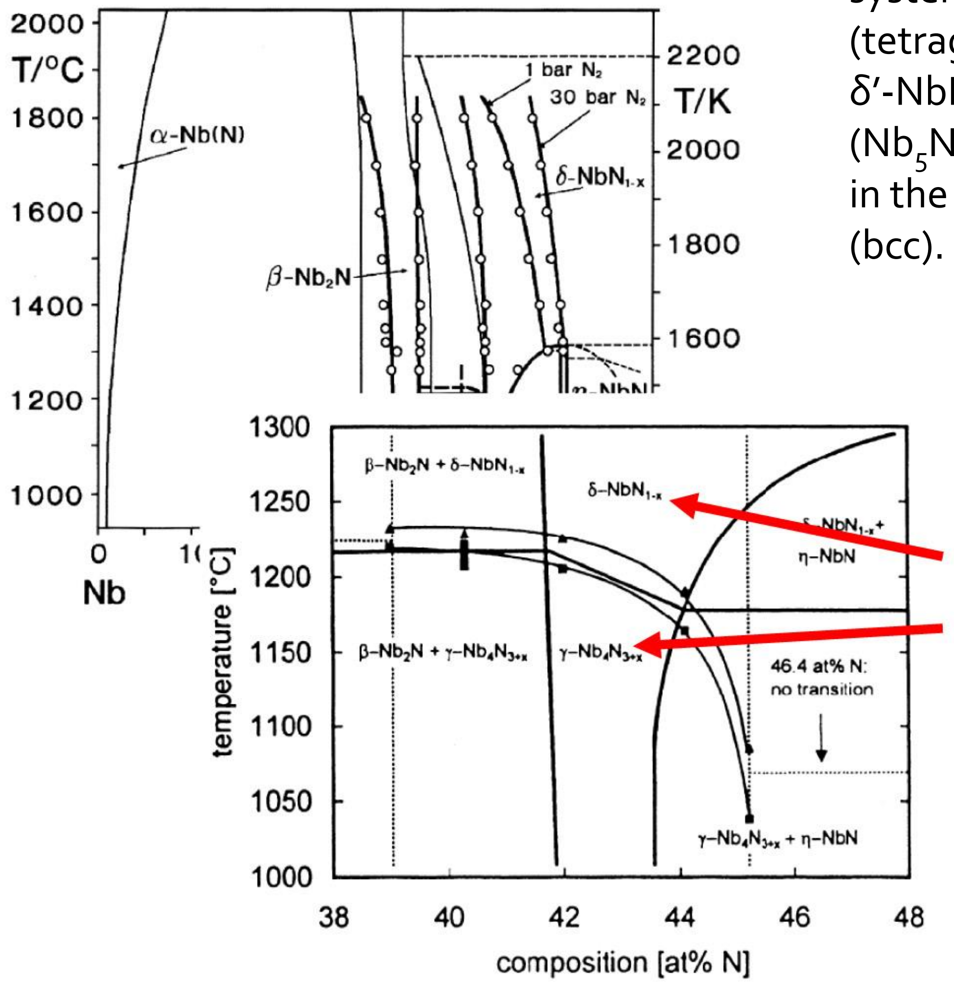
| A<br>B | Sc | Y | La | Ti | Zr | Hf | V | Nb | Ta | Cr | Mo | W | Re |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B | | | | | 3.4 | 3.1 | | | | | | | |
| C | <1.38 | <1.38 | | 3.42 | <0.3 | <1.20 | 0.03<br>3.2* | 12 | 10.35 | | 14.3 | 10.0 | 3.4 |
| N | <1.38 | <1.4 | 1.35 | 5.49 | 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 s

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

# NbN phase diagram

Different nitrides are present in the Nb–N system: β-$Nb_2N$ (hexagonal), γ-$Nb_4N_{3\pm x}$ (tetragonal), δ-$NbN_{1-x}$ (fcc), η-NbN (hexagonal), δ′-NbN (hexagonal) and other N-rich phases ($Nb_5N_6$, $Nb_4N_5$). In addition, nitrogen dissolves in the metal forming α-Nb(N) solid solution (bcc).



$$\delta - \text{NbN} \rightarrow T_c \sim 15 - 17.3\ \text{K}$$

$$\gamma - \text{NbN} \rightarrow T_c \sim 12 - 15\ \text{K}$$

RF cavity studies mostly focus on δ phase

# 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, $P_{N_2}$=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

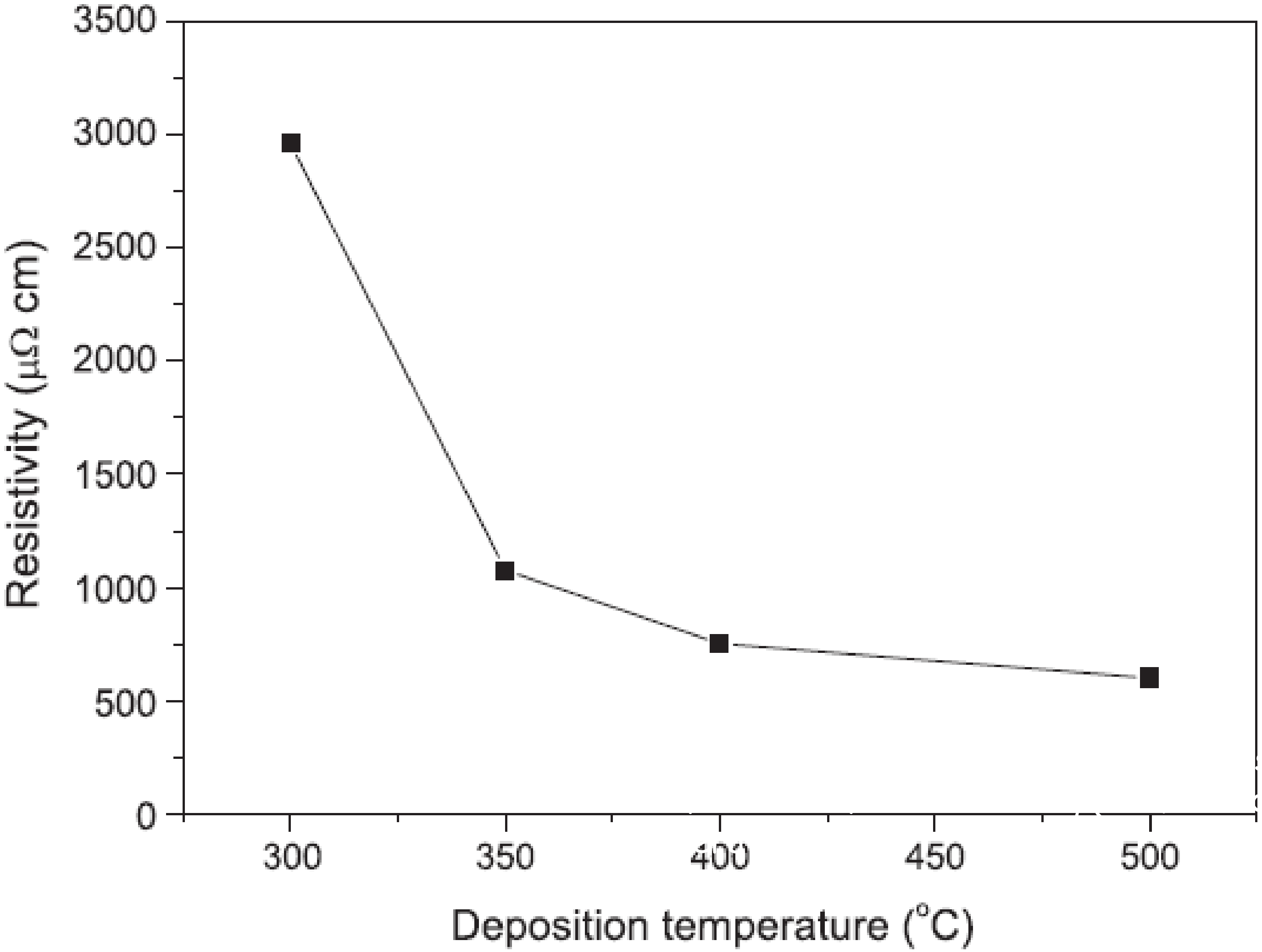
The right B1-NbN superconducting phase is the so-called d-phase

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

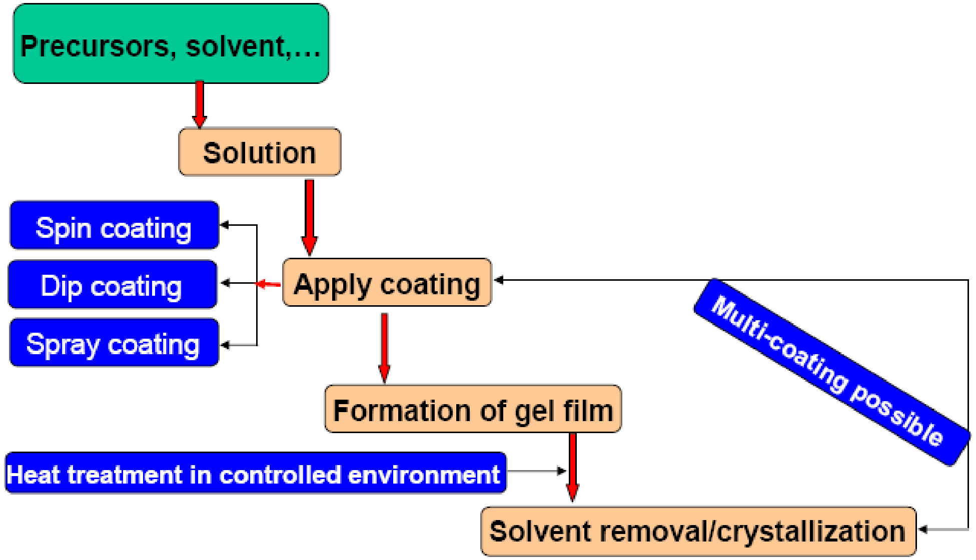


P. Alen, M. Ritala, K. Arstila, J. Keinonen, and M. Leskelae, Thin Solid Films 491:235 (2005).

# Polymer Assisted Deposition (PAD) at LANL (Q. Jia et al.)

- A chemical solution technique to deposit films of nearly any metal-oxide using aqueous solution by mixing metal precursors with water-soluble polymers
- Polymer plays a critical role in metal-oxide films

**Typical chemical solution deposition process flowchart**



Precursors, solvent,…

Solution

Spin coating

Dip coating

Spray coating

Apply coating

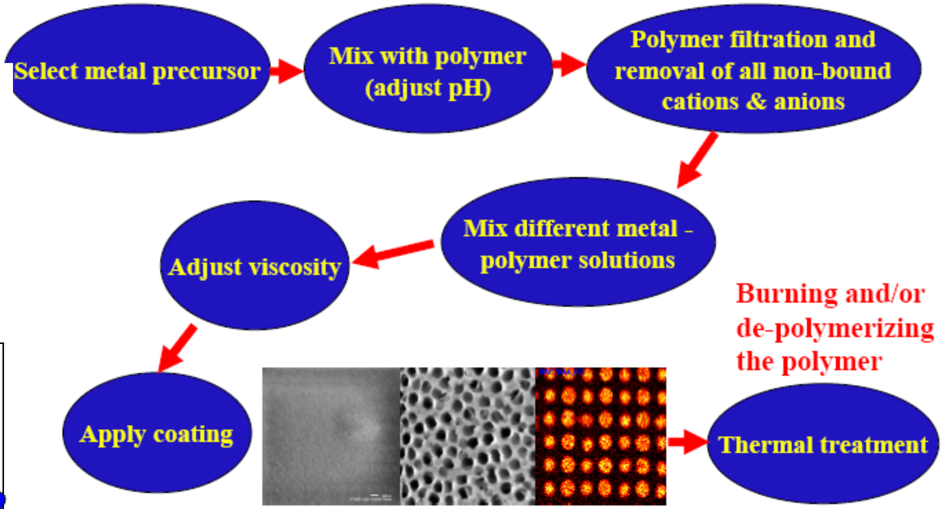
Multi-coating possible

Formation of gel film

Heat treatment in controlled environment

Solvent removal/crystallization

- Process



Select metal precursor

Mix with polymer (adjust pH)

Polymer filtration and removal of all non-bound cations & anions

Mix different metal - polymer solutions

Adjust viscosity

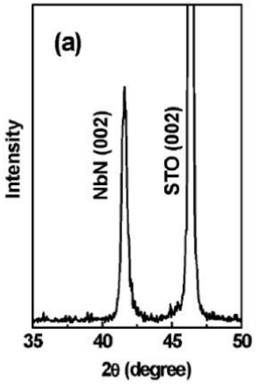
Apply coating

Burning and/or de-polymerizing the polymer

Thermal treatment

# NbN grown by Polymer Assisted Deposition

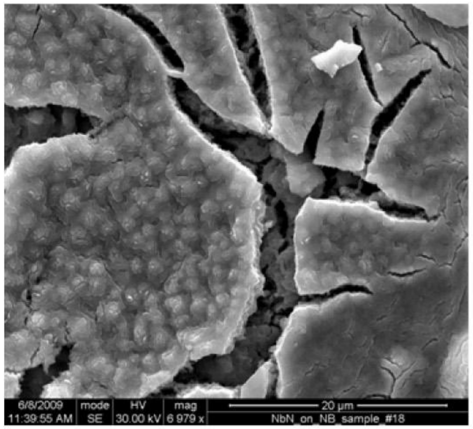
High-quality epitaxial films grown by PAD: an aqueous solution of niobium ion bound to polymer spin coated on substrate, and then annealed at 900 °C for 5 hours in gaseous ammonium.

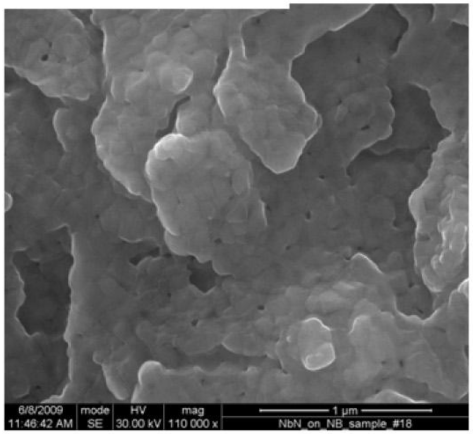


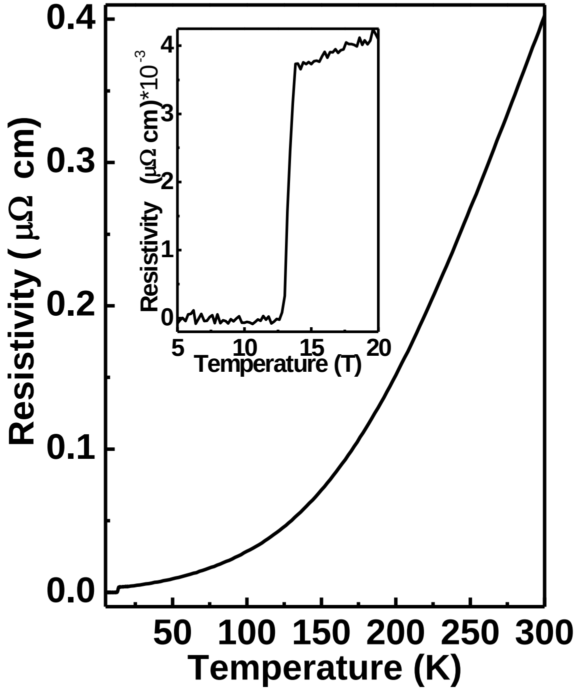
Unusually high RRR = 98.4 and low $\rho_{20} \approx 0.4\ \mu\Omega$ cm

$T_c \approx 14$ K ($\gamma$ – NbN)

LANL: First attempts to deposit on polycrystalline niobium – unsuccessful, working with single-crystal Nb now







# 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 d-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

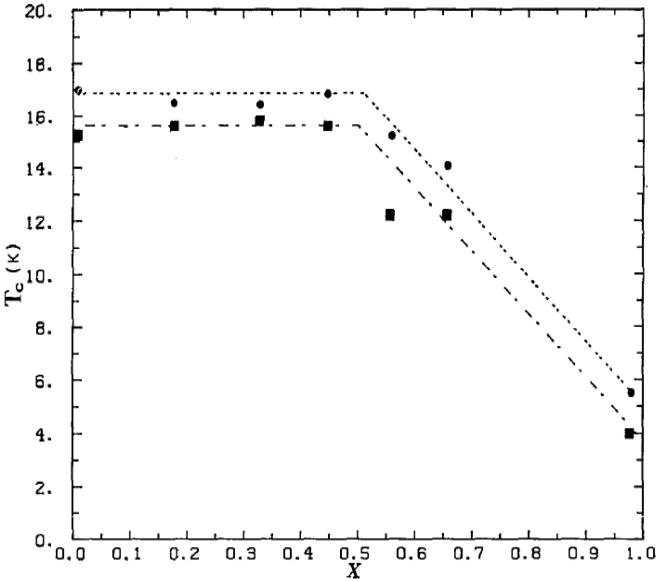


Fig. 1. Superconducting critical temperature $T_c$ as a function of the titanium composition ($x$) for the ($Nb_{1-x}Ti_x$)N films deposited at $T_s = 600°C$ (circles) and at $T_s = 200°C$ (squares).

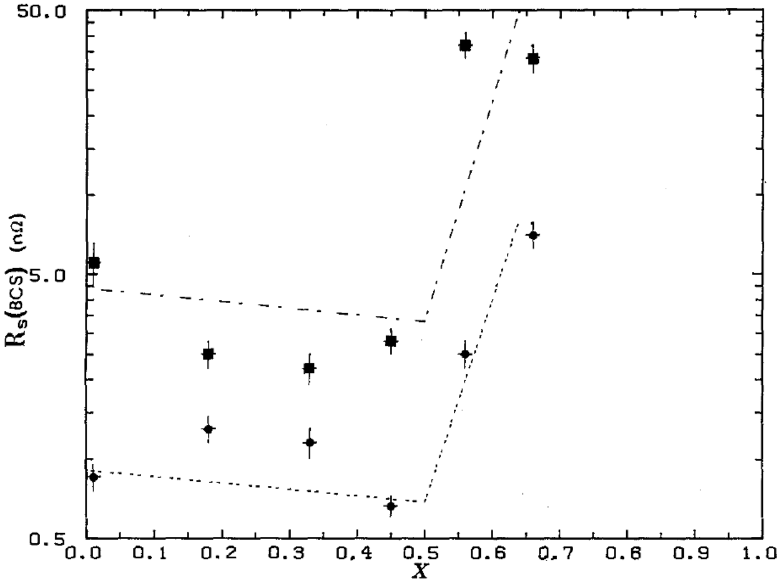


Fig. 3. Calculated BCS surface impedance $R_s$(BCS) as a function of the titanium composition ($x$) for the ($Nb_{1-x}Ti_x$)N films deposited at $T_s = 600°C$ (circles) and at $T_s = 200°C$ (squares). The continuous lines correspond to the values of the lines through the data in Figs. 1 and 2.

# Nb Compounds - NbTiN

**Reactive Magnetron Sputtering:**

**CEA Saclay :**

NbTiN films deposited on 12 cm copper disks by magnetron sputtering and tested in a cylindrical $TE_{oll}$ 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.

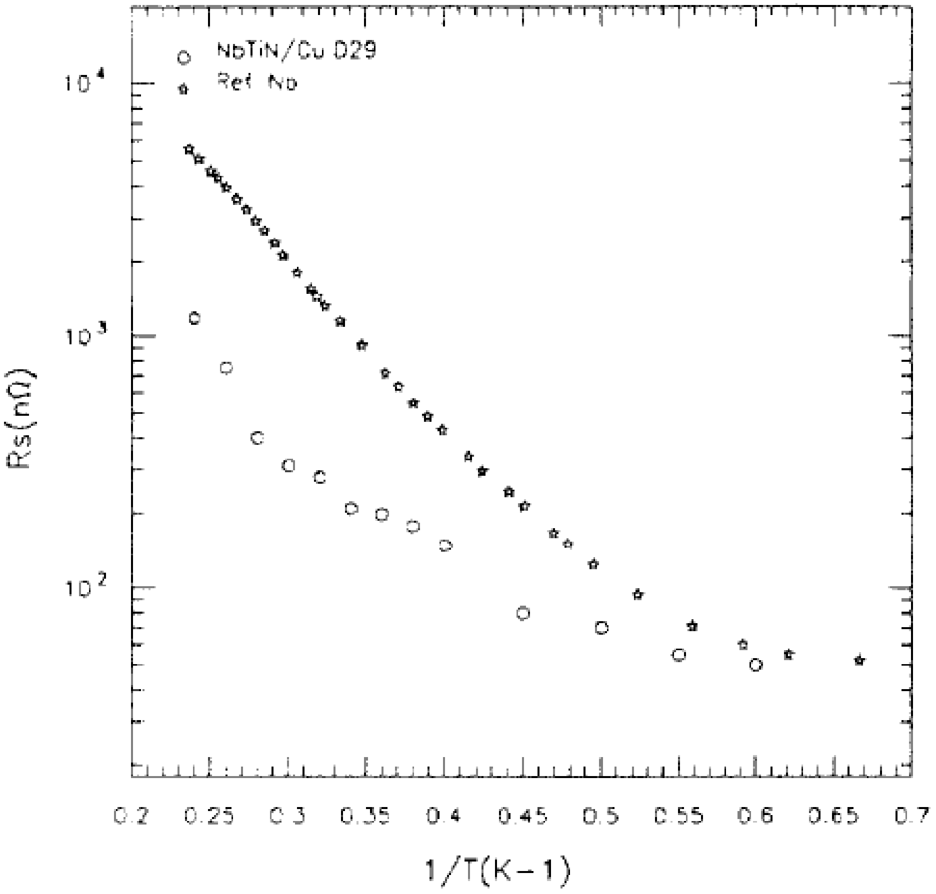


Figure 3 Surface resistance vs temperature for a NbTiN sample, at 4 GHz.

# 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*

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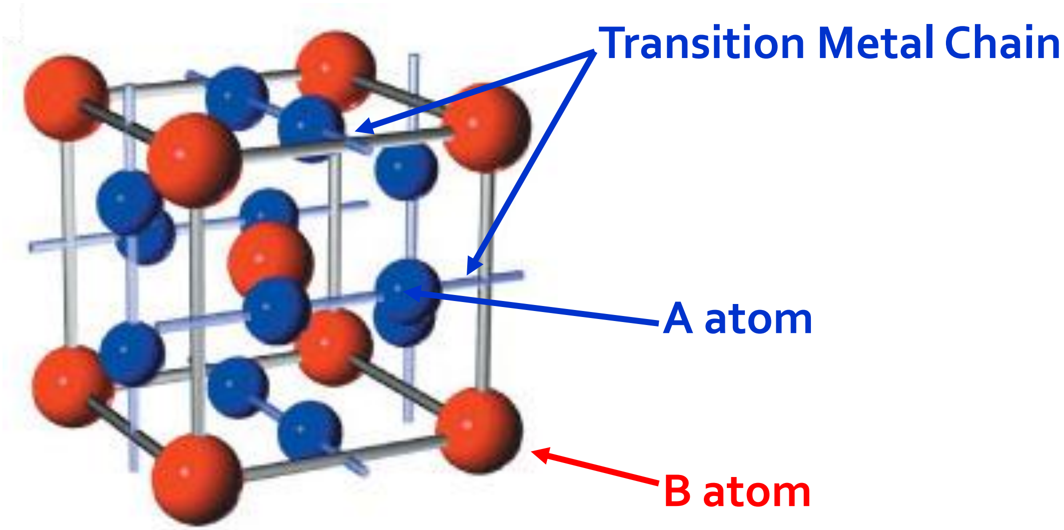
# A15 Compounds - Structure

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 (long-range order required)

# 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
$\lambda_L$ (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

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

## Diffusion Reaction

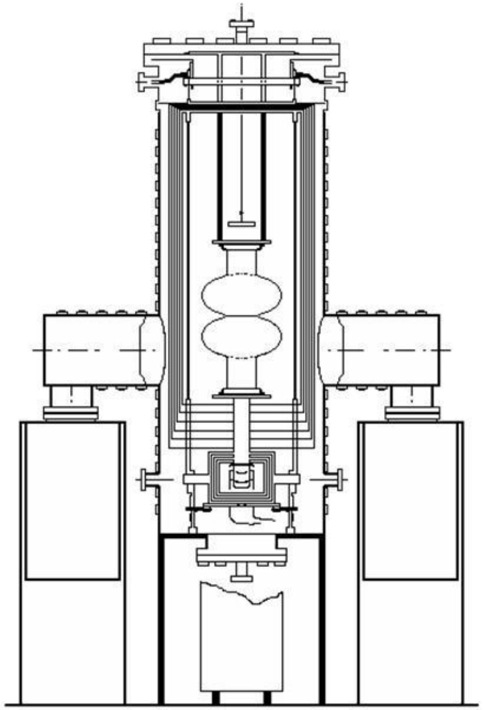
Technique proved successful for magnet conductor application

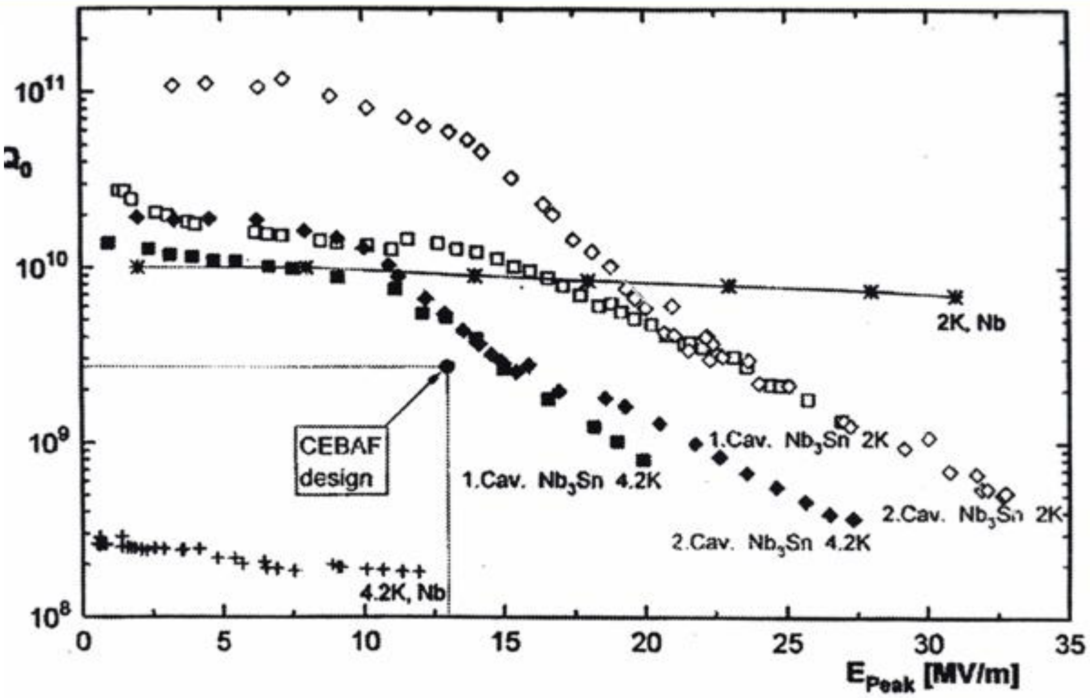
Simple equipment compared to sputtering and CVD

# 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: $Q_0 \sim 10^9$, $E_{acc}$=7MV/m with $Q=8.10^8$**

*G. Müller et al.,*
*M. Peiniger & H. Piel , IEEETrans. On Nucl. Sc. Vol NS-32, n°5, Oct. 1985*

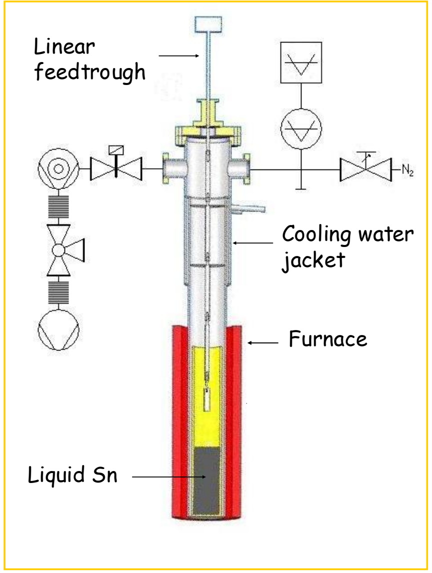
# A15 Compounds – $Nb_3Sn$ through liquid diffusion

*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*

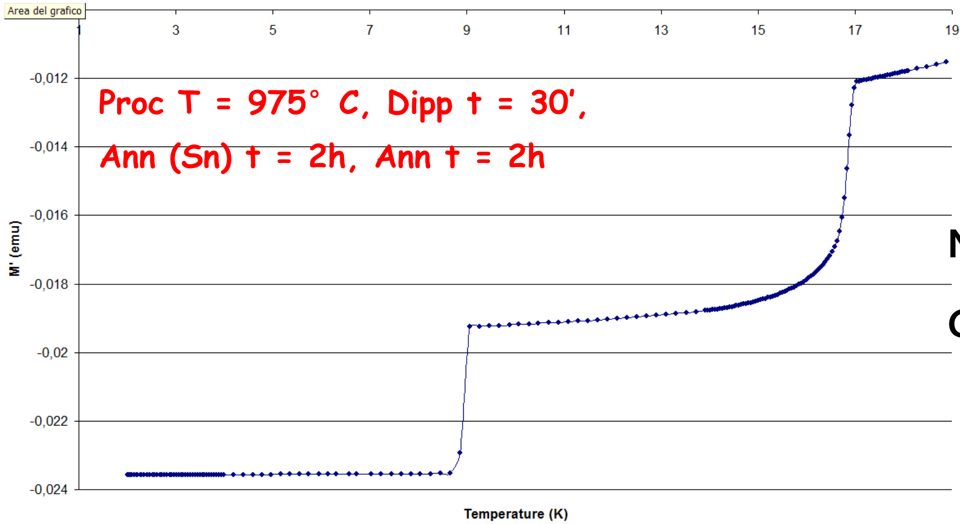
## $Nb_3Sn$ coatings on Nb by liquid diffusion method at INFN Legnaro

**"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



$Nb_3Sn$ 42 1: 975°C x 30' + 2h; 975°C x 2h


Proc T = 975° C, Dipp t = 30',
Ann (Sn) t = 2h, Ann t = 2h

**No Residual Sn traces on the sample surface**

**Good $Nb_3Sn$ film superconductive properties**

**$T_c$ = 16.8 K, $DT_c$ = 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 liquid diffusion

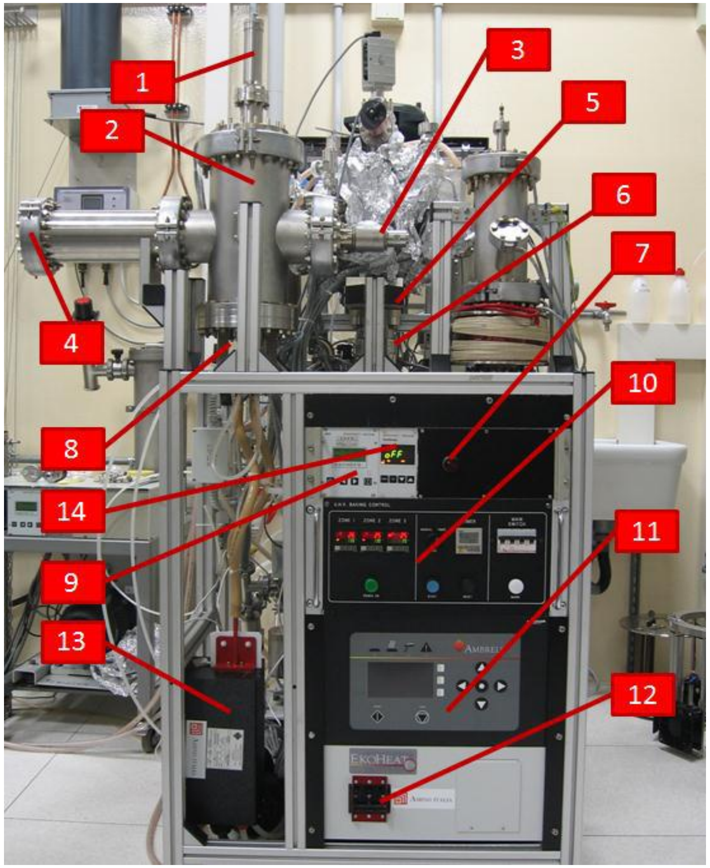
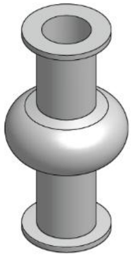
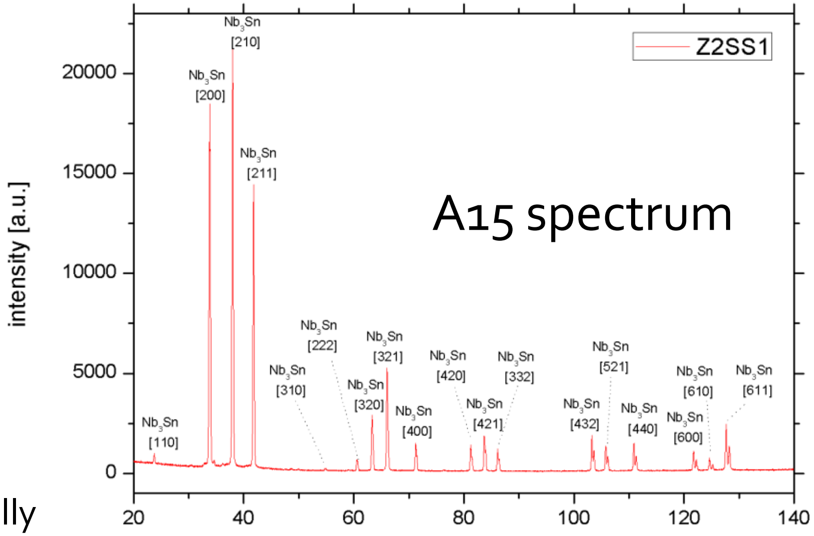


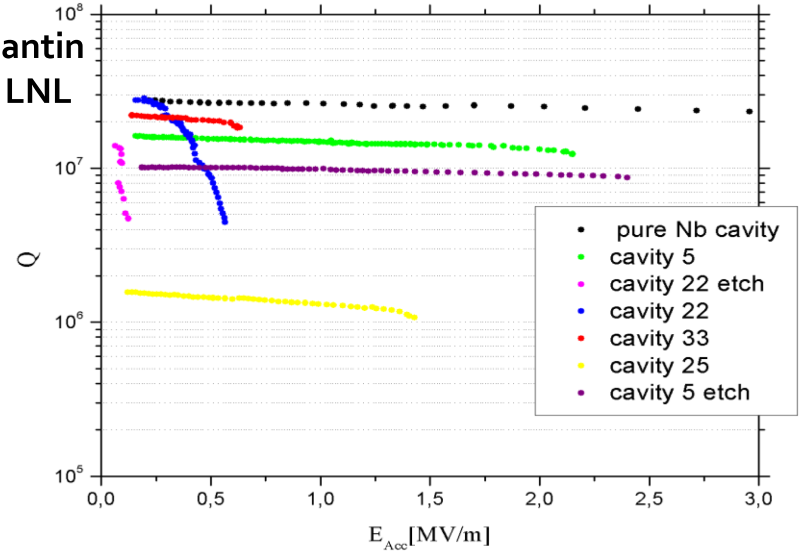
*Figure 7.3.* Inductive annealing stand

*1-manipulator; 2-vacuum chamber; 3-whole metal valve; 4-window flange; 5-pneumatic gauge; 6-turbomolecular pump; 7-gauge switcher; 8-inlet of work coil; 9-pump controller; 10-baking control unit; 11-induction heater controlling and inverter block; 12-inductor main*



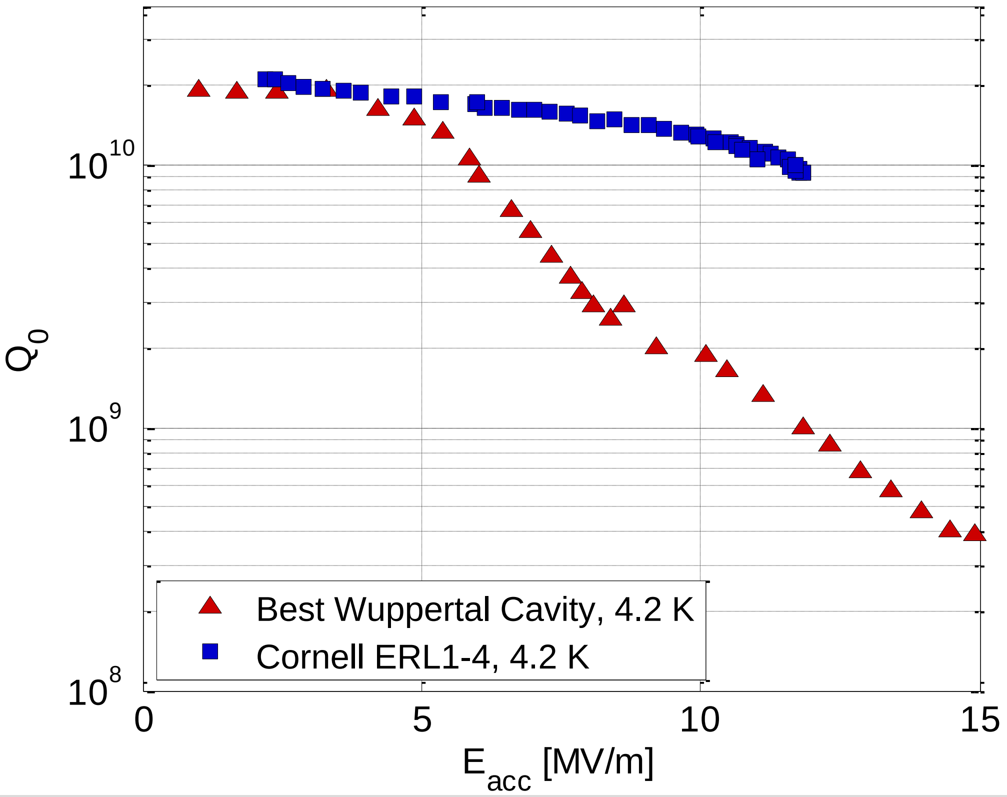


High temperature annealing for thermally diffused Nb3Sn ,
**Atroshchenko Konstantin**
**Master Thesis, INFN LNL**



# Nb3Sn @ Cornell University – Vapor diffusion

- New cavity fabricated, coated with $Nb_3Sn$, and tested at Cornell U. by Sam Posen and Matthias Liepe
- First ever accelerator cavity made with an alternative superconductor to far outperform Nb at useable gradients



# Nb3Sn @ Jefferson Lab– Vapor diffusion

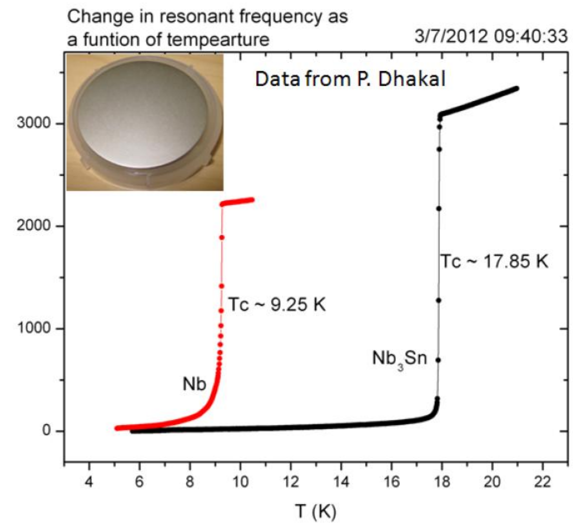
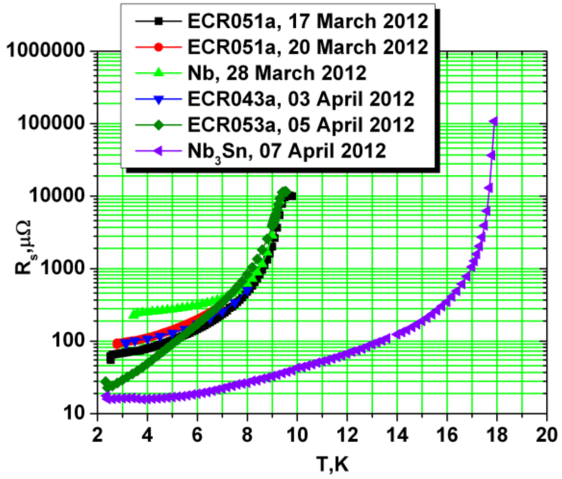


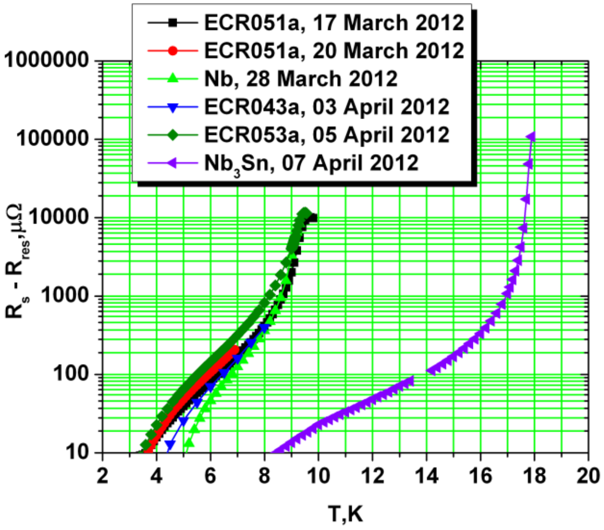
Figure 4: Test results on the coaxial sample. The data shows that the transition temperature of the coaxial sample was 17.95 K. In the top left corner the surface of the best sample is shown.



B. P. Xiao, G. V. Eremeev, M. J. Kelley, H. L. Phillips, C. E. Reece, LINAC'12

Measurement of coated Nb3Sn sample as well as some Nb and thin film niobium samples

Same results with the residual resistance subtracted. Note resistance measurement error is estimated to be about 20%.

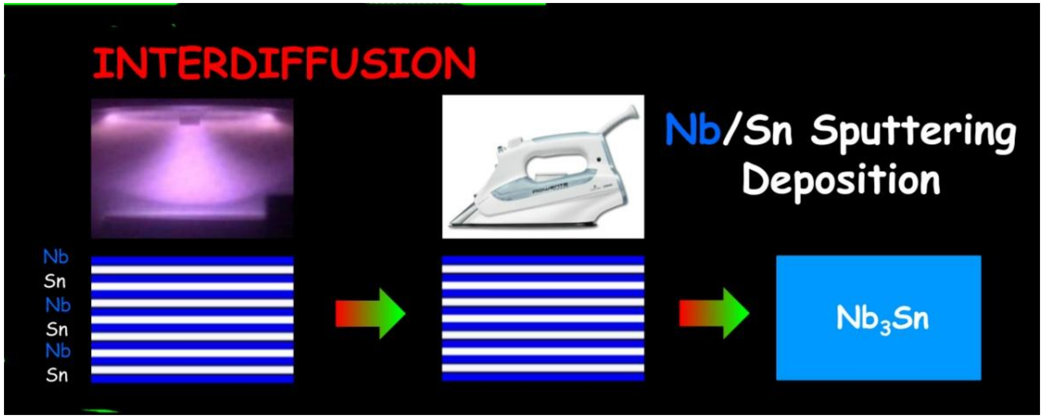


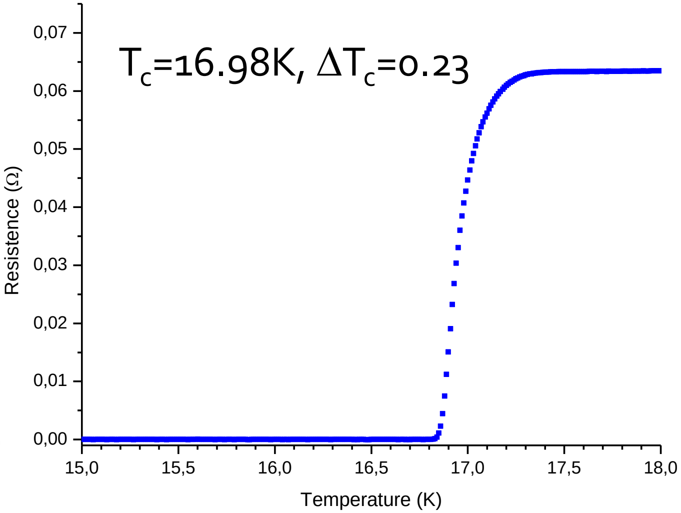
# A15 Compounds -$Nb_3Sn$ through Multilayer Coating

*Deambrosis, Keppel, LNL/INFN, International Workshop on Thin Films and New Ideas for Pushing The Limits Of RF Superconductivity, LNL-INFN , Oct.2006* & SRF 2009

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

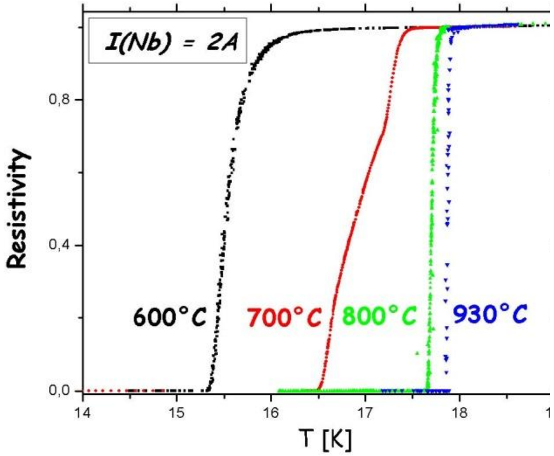
Preliminary results: a sharp transition and a $T_c$ of 17 K has been obtained

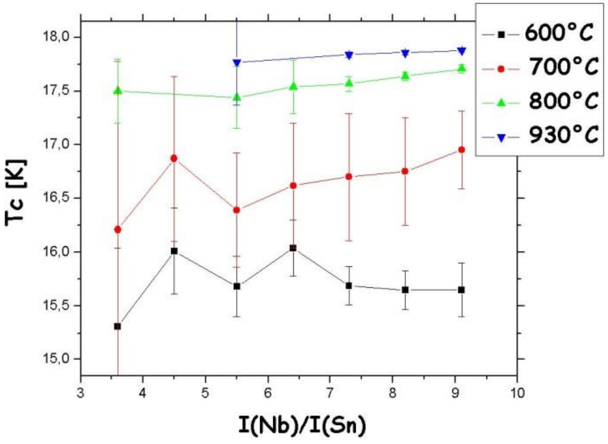




Thickness Nb = 4.5 xThickness Sn

Annealed after sputtering for 3 hours at 975 °C



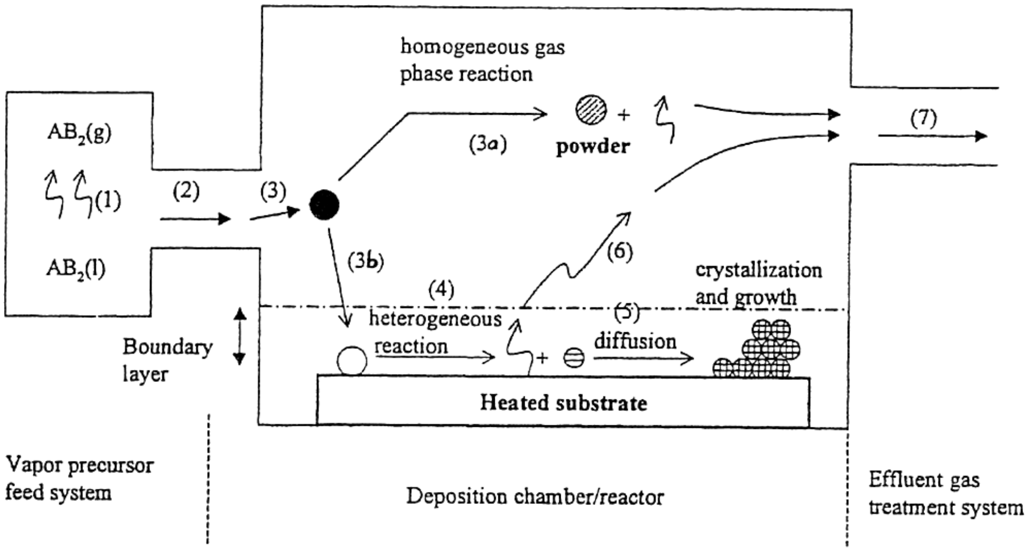


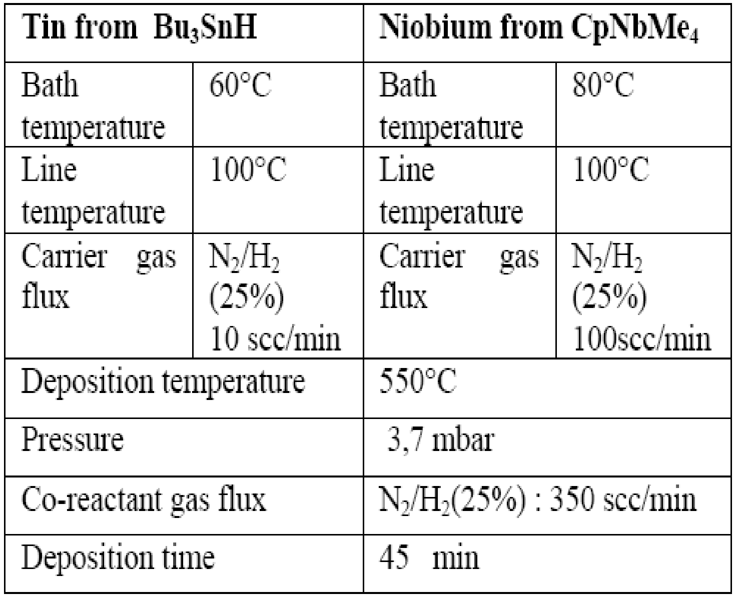
| Sputtering Target | Voltage (V) | Current (A) | Power (W) |
|---|---|---|---|
| **Sn** | 613 | 0.18 | 108 |
| **Nb** | 407 | 1.99 | 800 |

# 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%)<br>10 scc/min | Carrier gas flux | $N_2/H_2$ (25%)<br>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.

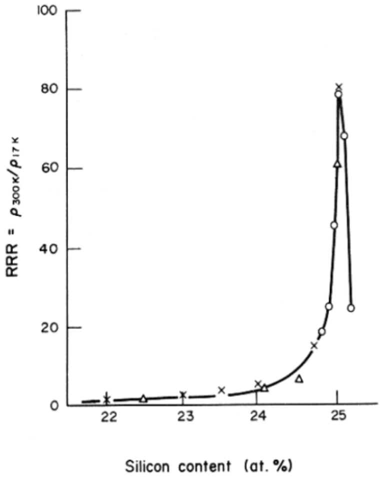
**Problems:**

**great oxophilic character of Nb**

# A15 Compounds – $V_3Si$

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

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



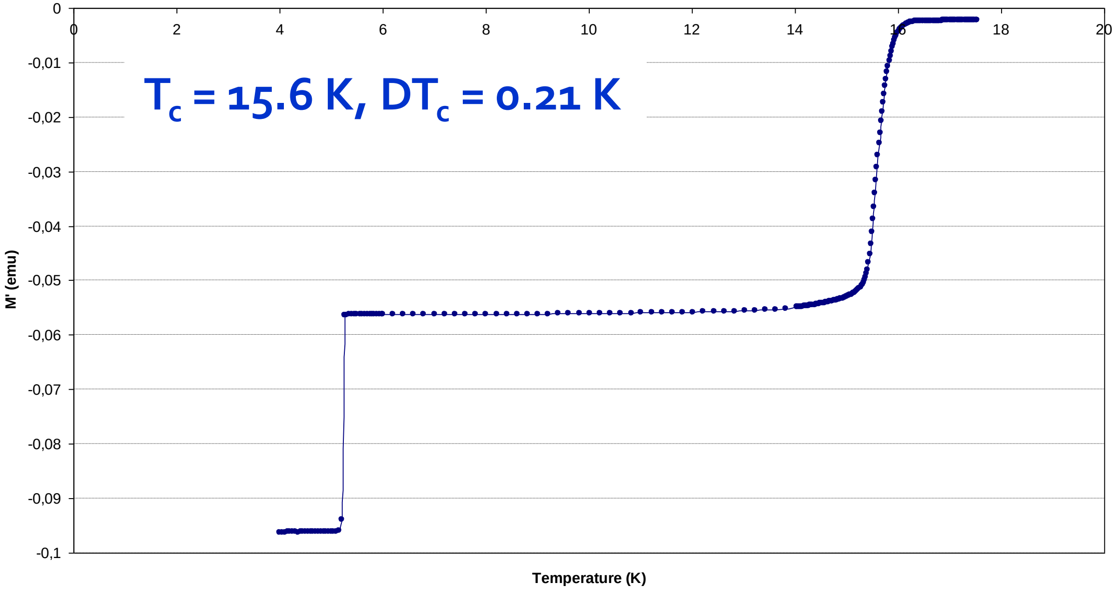
**$V_3Si$ layers by silanization of V substrate and Thermal Diffusion**

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**



**$T_c$ = 15.6 K, $DT_c$ = 0.21 K**

* 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° 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

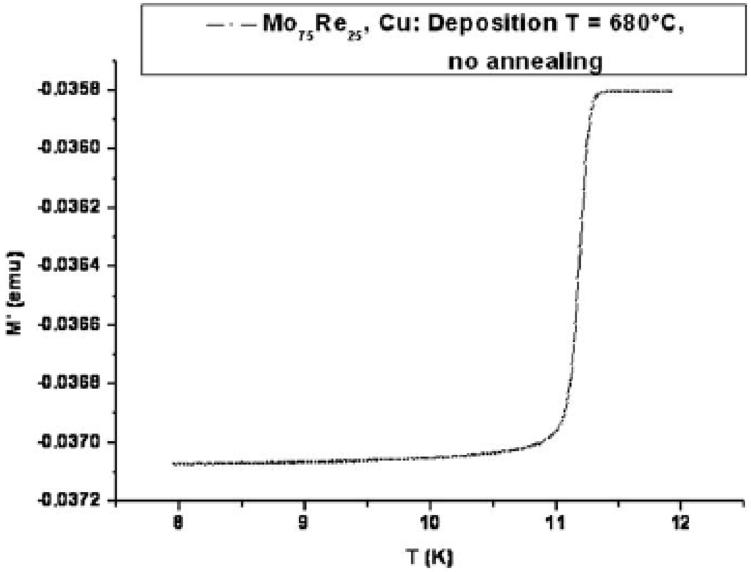
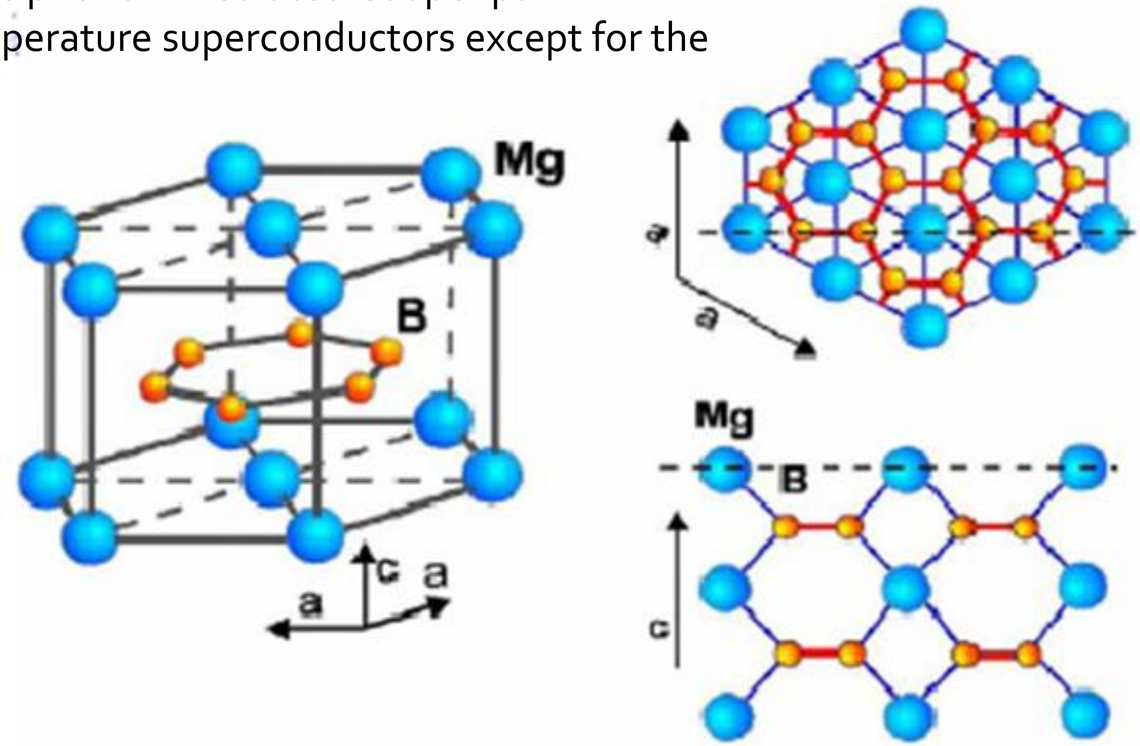


Fig. 4. A $Mo_{75}Re_{25}$ film deposited on Cu transition curve: deposition $T = 680\,°C$, $T_c = 11.18$, $\Delta T_c = 0.08$ K.

# 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:**

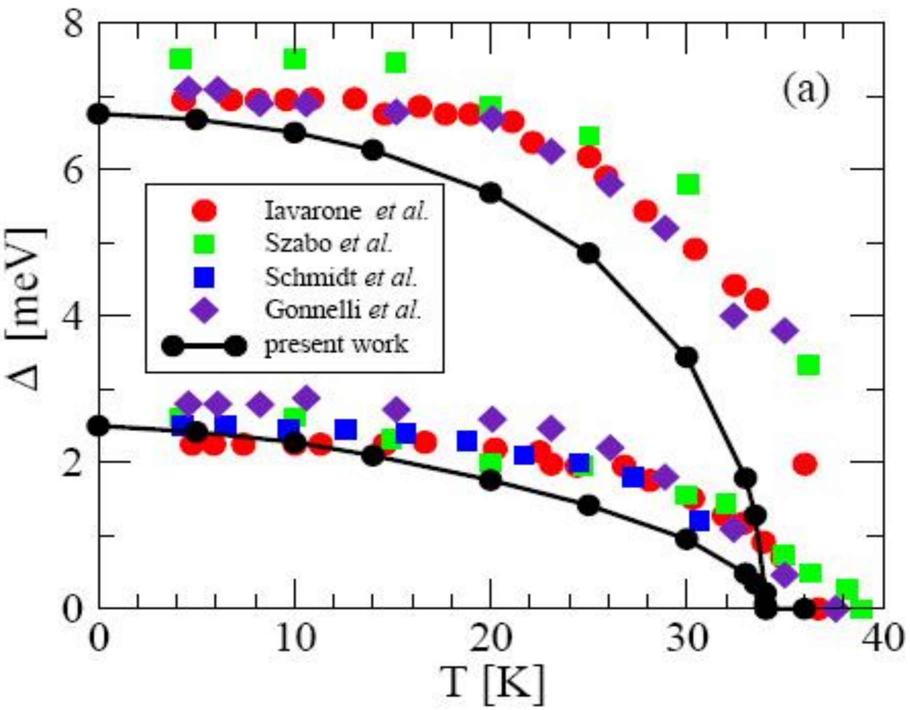
- **Cheaper**
- **Lower anisotropy**
- **Larger coherence length**
- **Transparency of grain boundaries to current flows**

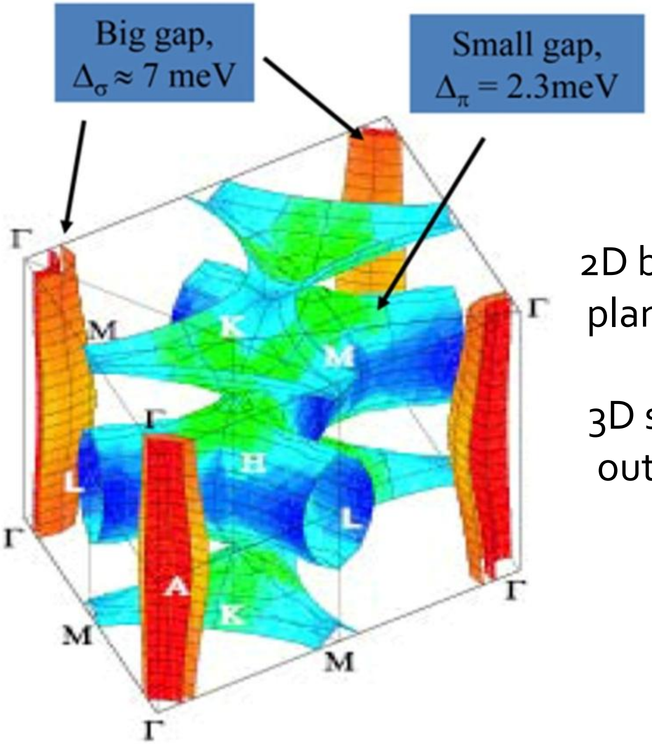
→ **attractive for RF applications.**

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*





Big gap, $\Delta_\sigma \approx 7$ meV

Small gap, $\Delta_\pi = 2.3$meV

Liu, Mazin and Kortus (2002);
Choi et al, (2002)

2D big gap for in-plane σ-orbital s
&
3D small gap for out-of-plane π-orbitals

**$R_s$ is dominated by the smaller gap, so $MgB_2$ may not be better than $Nb_3Sn$ because $\Delta_\pi^{MgB_2} = 2.3$ meV < $\Delta^{Nb_3Sn} = 3.1$ meV, but better than Nb ($\Delta^{Nb} = 1.5$ meV)**

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

# 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 |
| $\rho_o$ (mΩcm) | 0.1-10 | 0.05 |
| RRR | 3-30 | 300 |
| $\Delta_{p,s}$ (meV) | 2, 7 | 1.2 |
| 2 $\Delta_{p,s}/K_BT_c$ (meV) | 1.6, 4 | 3.9 |
| $x_{p,s}$ (nm) | 50,12 | 40 |
| l (nm) | 85 | 80 |
| $m_oH_{c2}$ (T) | 6-50 | 0.2 |
| $R_{BCS}$ @ 4K, 500MHz (nΩ) | $2.5/2.3\times10^{-5}$ | 69 |

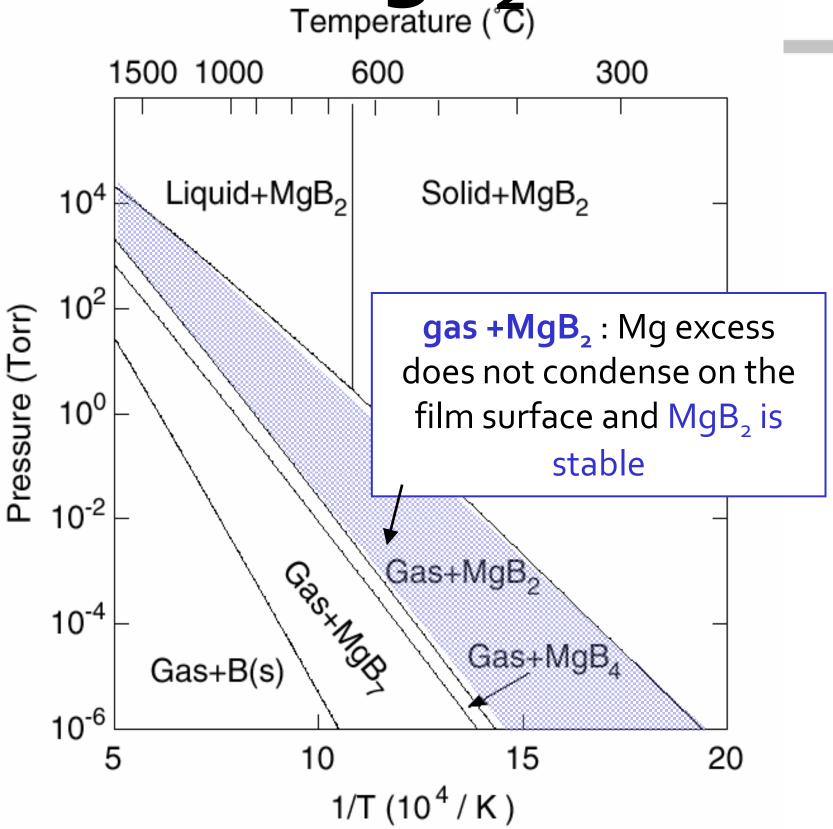
↓

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



**gas +$MgB_2$** : Mg excess does not condense on the film surface and $MgB_2$ is stable

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

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

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

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

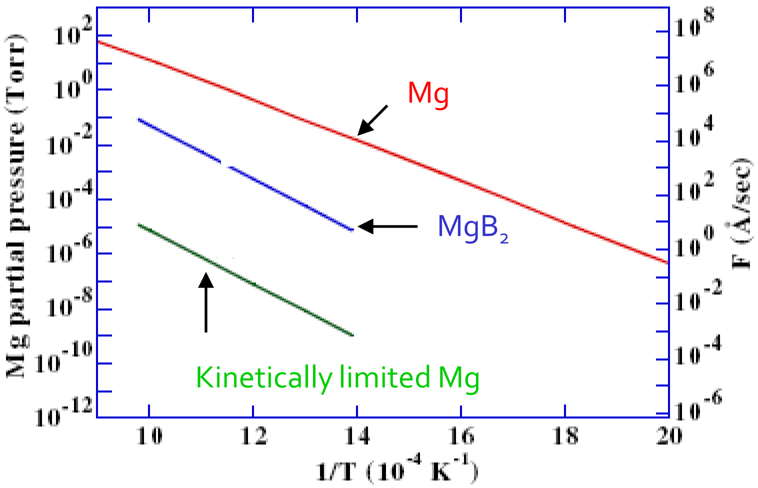
*Too high for UHV deposition techniques (PLD, MBE…)*

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

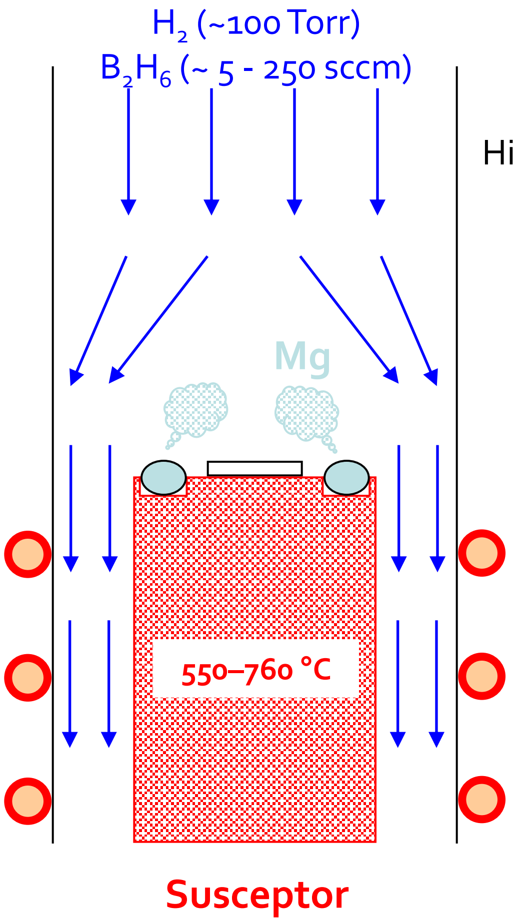


*M. Naito and K. Ueda, SUST 17 (2004) R1*

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



## 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**

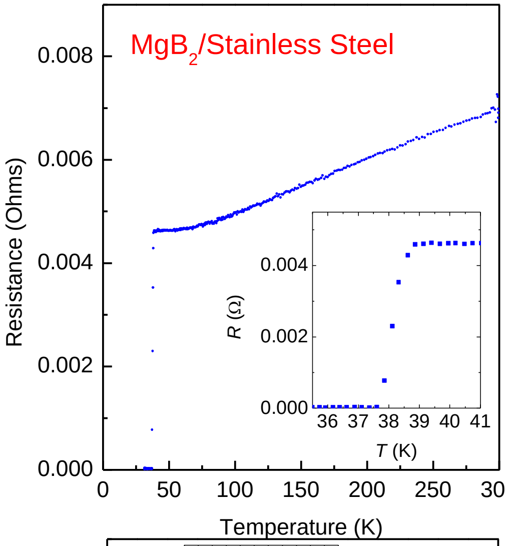
- **high *Tc* ~ 42 K (due to tensile strain), high *Jc* (10% depairing current)**
- **low surface resistance, short penetration depth**
- **smooth surface (RMS roughness < 10 Å with N$_2$ addition)**
- **good thermal conductivity (free from dendritic magnetic instability)**

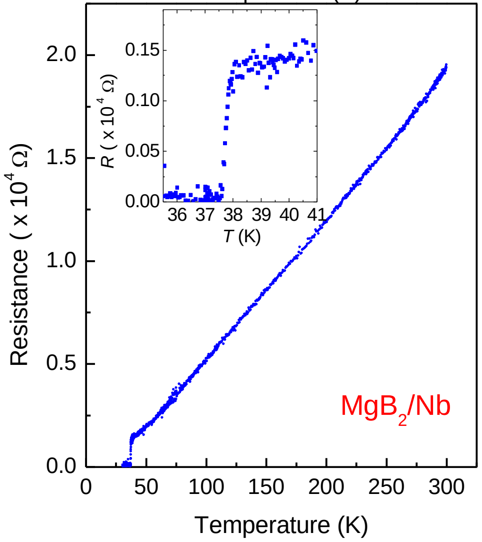
## Critical engineering considerations:

**generate high Mg pressure at substrate (cold surface is Mg trap)**

**deliver di-borane to the substrate (the first hot surface di-borane sees should be the substrate)**

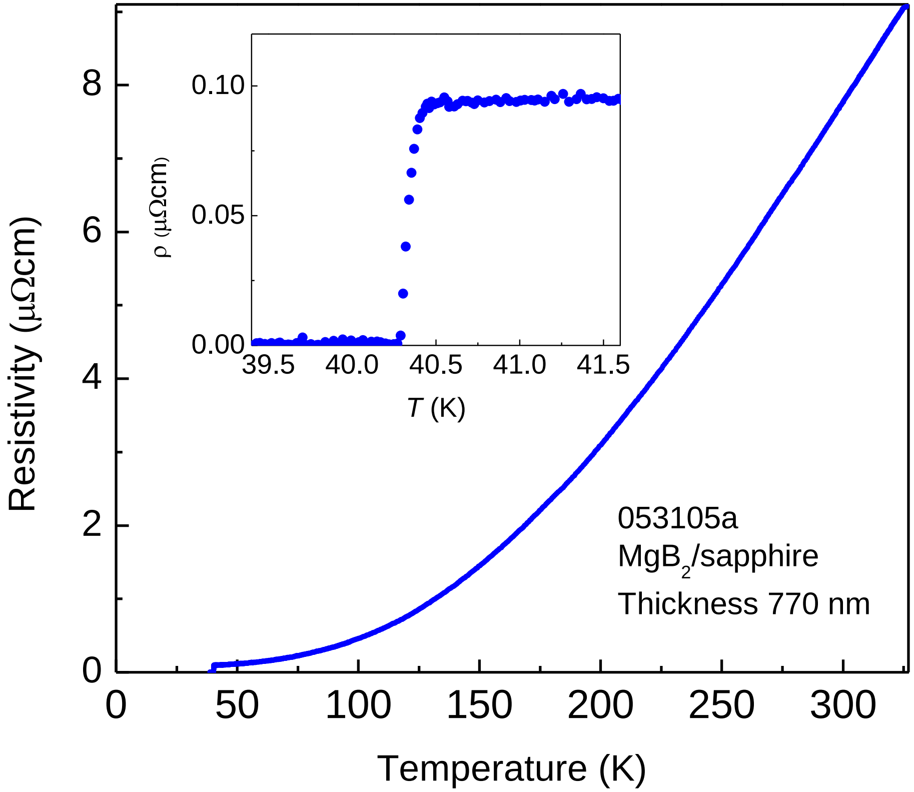
*X. Xi- TempleUniversity*

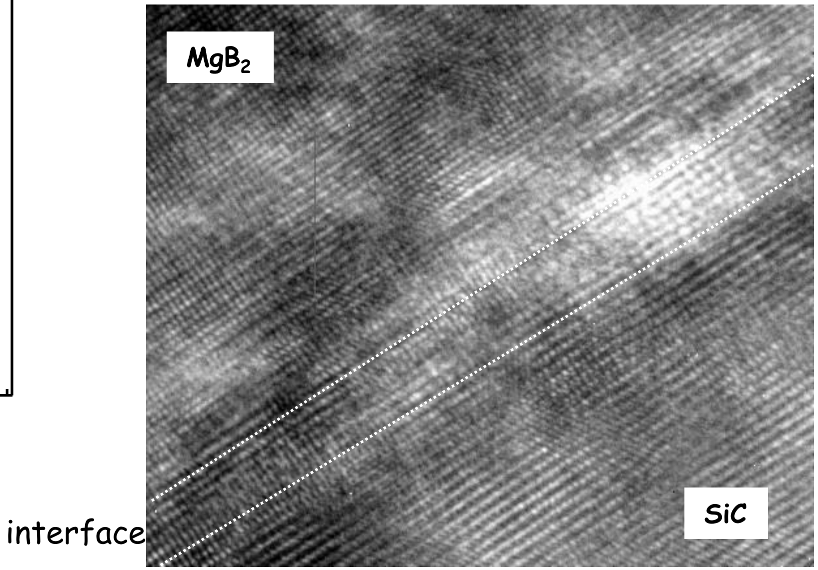




# HPCVD at Temple Uni. (X. Xi et al.)

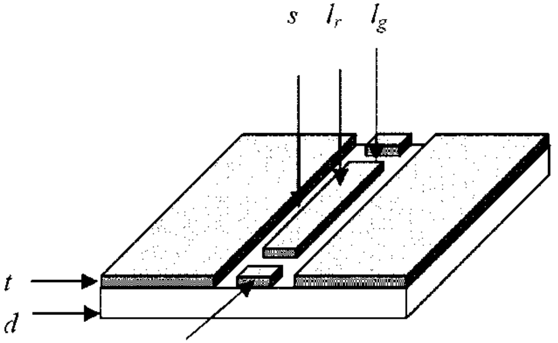
- Example of epitaxial MgB2 Films by HPCVD: *RRR* > 80

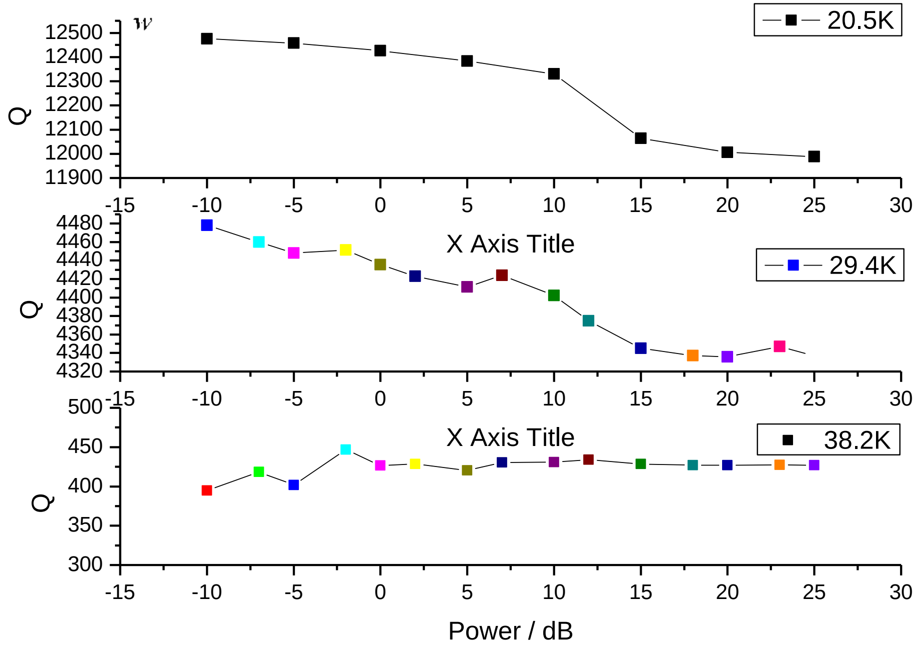




# MgB$_2$ – Microwave Performance on HPCVD Films

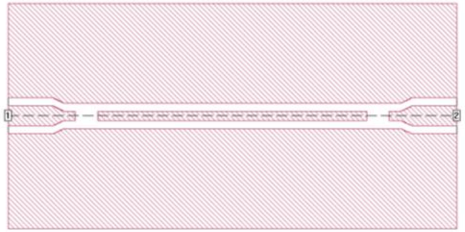
*X. Xi , private communication*

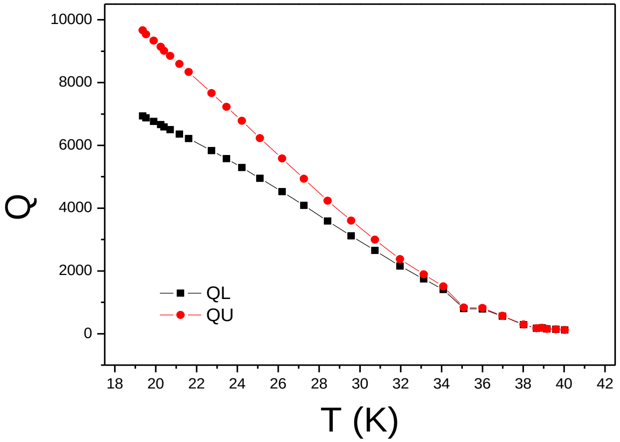


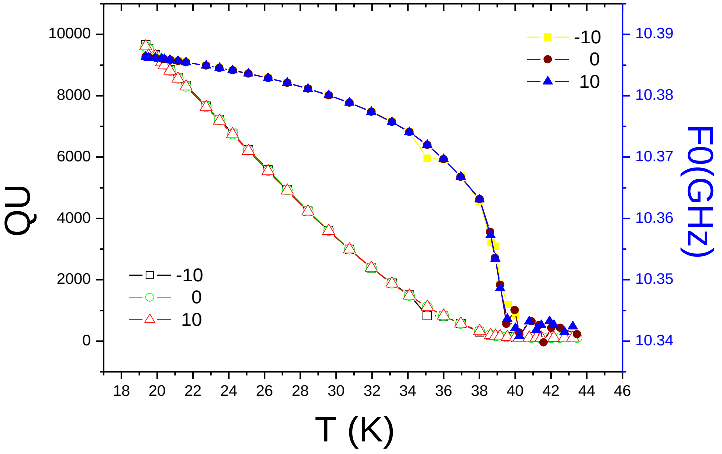


*C. Zhuang et al. Peking University*

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



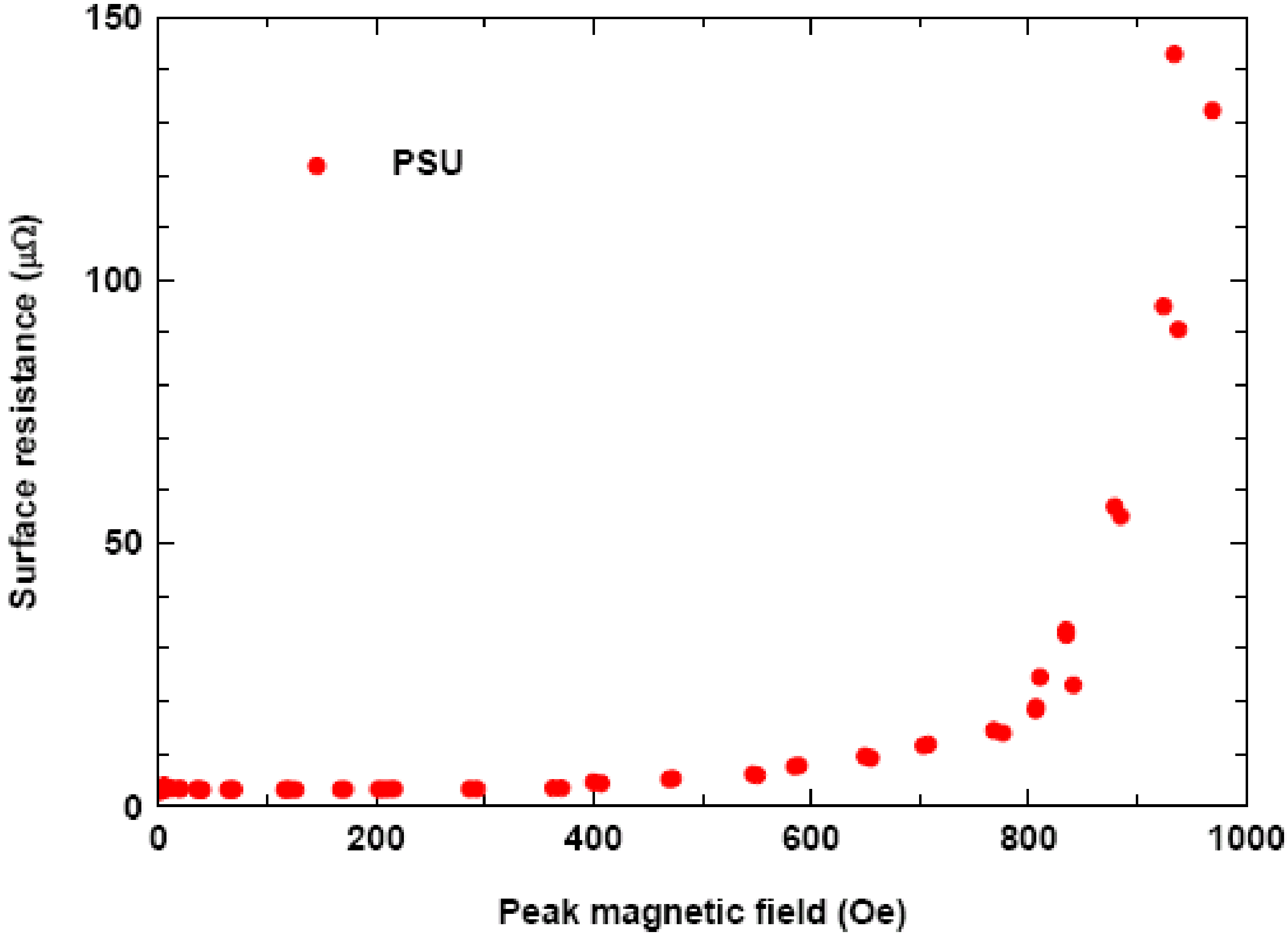




**High Q value ~10000 at 20K, sharp transition in Fo-T curve around the critical temperature, no power dependence in QU-T and Fo-T**

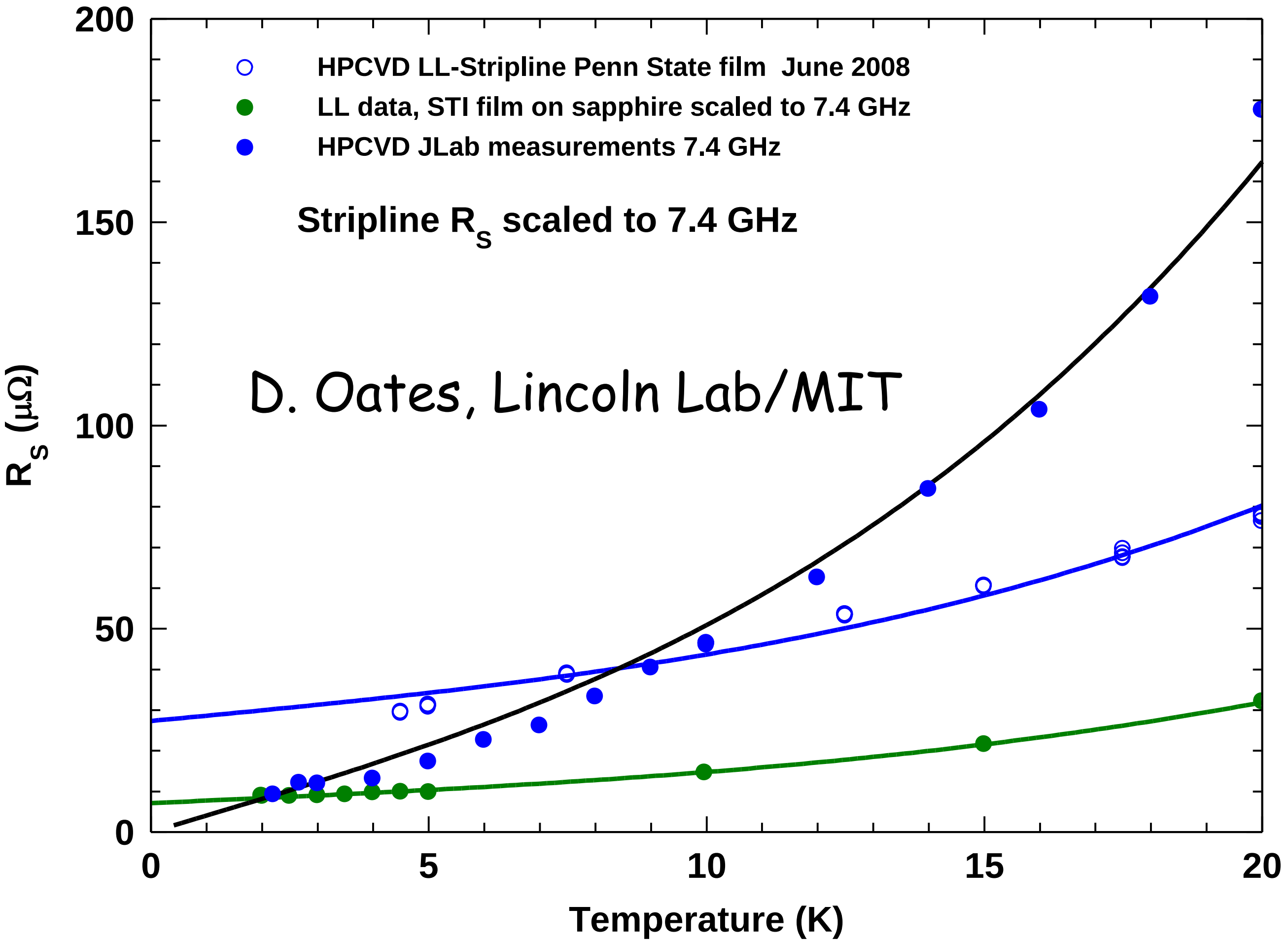
# $R_s$ for $MgB_2$

The achieved field with little RF loss is increasing! (Now ~800 Oe or higher considering the field enhancement effect at the edges) (Xiaoxing Xi at Temple Uni.)



Test at MIT
scaled to 1.5 GHz

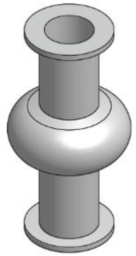
# Low-Power Surface Resistance of $MgB_2$



**Fits**

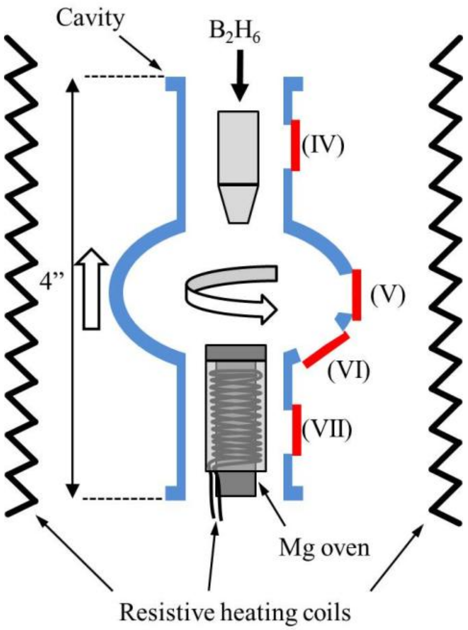
$$R_S(T) = a\left(\frac{1}{\bar{\beta}} + \left(\frac{15}{8}\right)\frac{1}{\bar{\beta}^3}\right) + c \quad , \bar{\beta} = \frac{\Delta_\pi(0)}{k_B T}, \Delta_\pi = 2.3\ \mathrm{meV}$$

# MgB2 @ Temple University – cavity coating

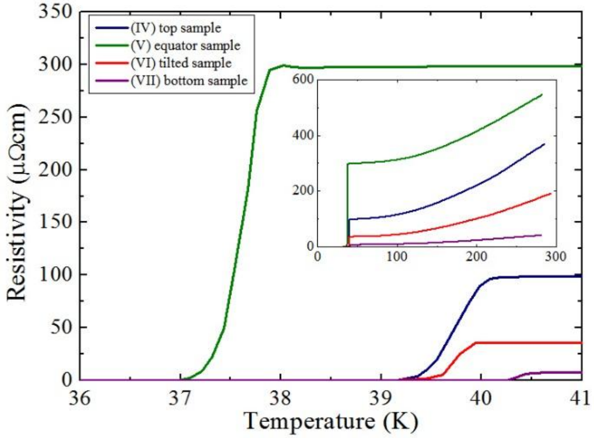


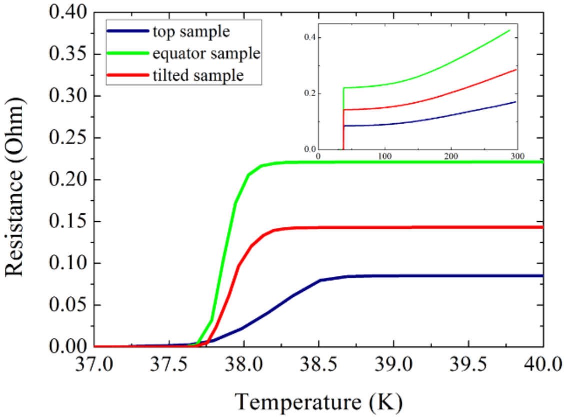
***<u>In-situ depositions on dummy cavity</u>***

- A stainless steel dummy cavity was fabricated to resemble actual cavity.
- $MgB_2$ films were deposited, through openings at different locations of the dummy cavity, on *c*-cut sapphire mounted on the outside.



- The films exhibit residual resistivity between 7.4 and 267 μΩcm and RRR between 2 and 6.
- $T_c(0)$ ranges between 36.9 K and 40.2 K.

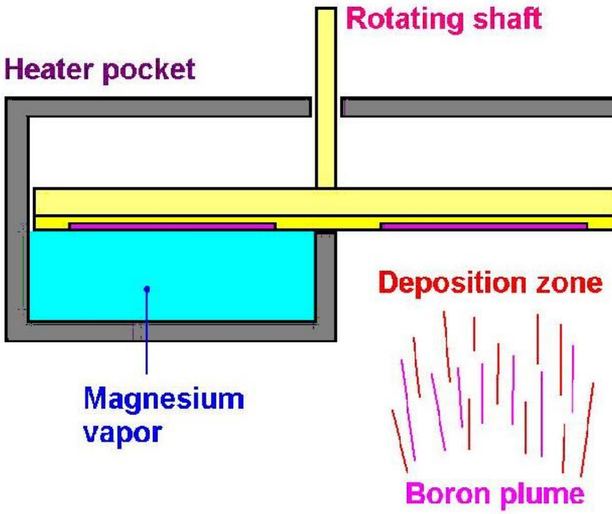




***<u>Different sequences of deposition steps on dummy cavity</u>***

# $MgB_2$ - Reactive Evaporation

*SuperconductingTechnologies Inc.*



*T. Tajima, LANL*

*In-situ* reactive evaporation @ 550˚C

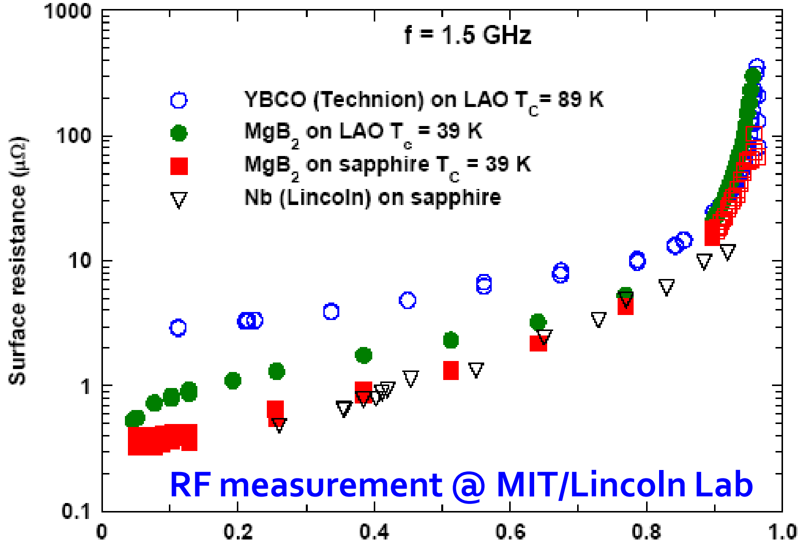
**Compared to Nb:**

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

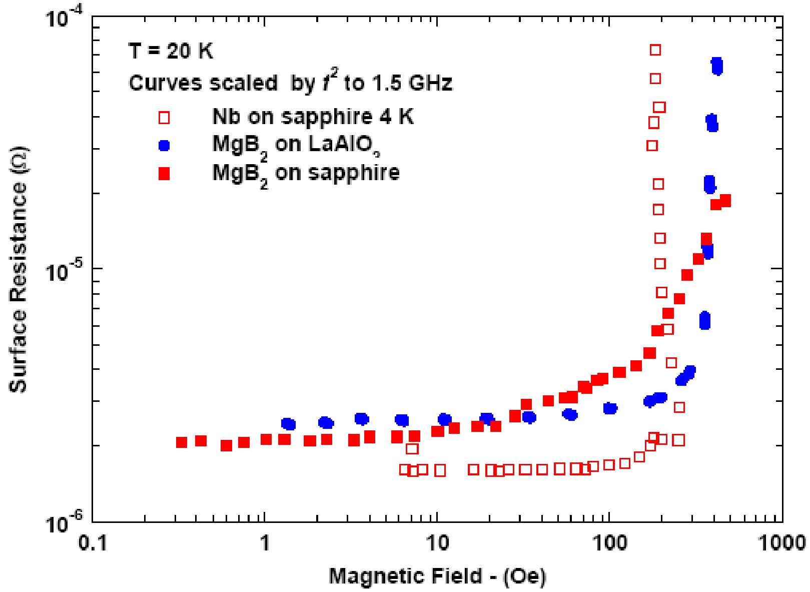
*B.H. Moeckly et al., IEEE Trans. Appl. Supercond. 15 (2005) 3308.*
*T. Tajima et al, Proc. PAC05.*

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

*Oates, Agassi, and Moeckly, ASC 2006 Proceeding*



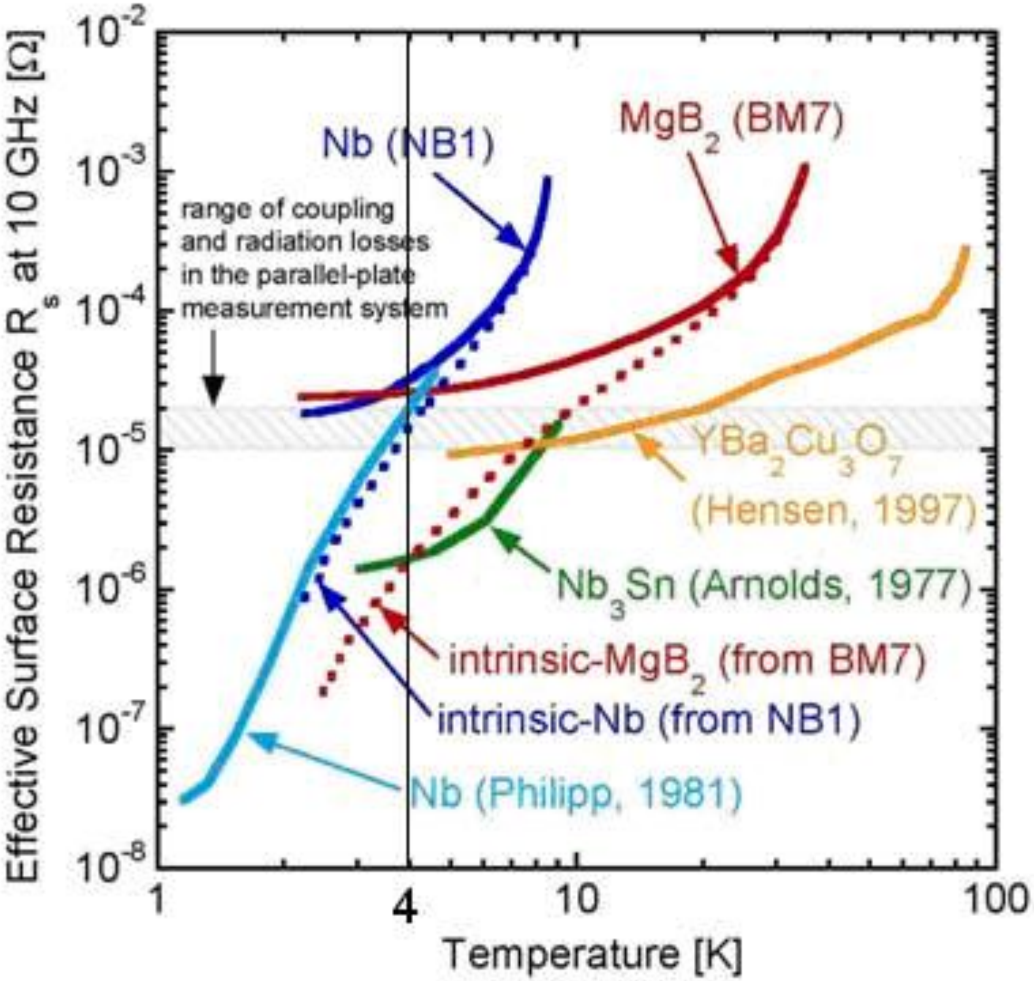
RF measurement @ MIT/Lincoln Lab



# RF Surface Resistance ($R_s$) at 10 GHz: LANL measurements compared to the data from other references, and prediction

- Dotted line is the predicted BCS resistance by subtracting the residual resistance (temperature independent)
- $R_s$ lower than Nb at 4K
- Still residual resistance dominates at low temperatures

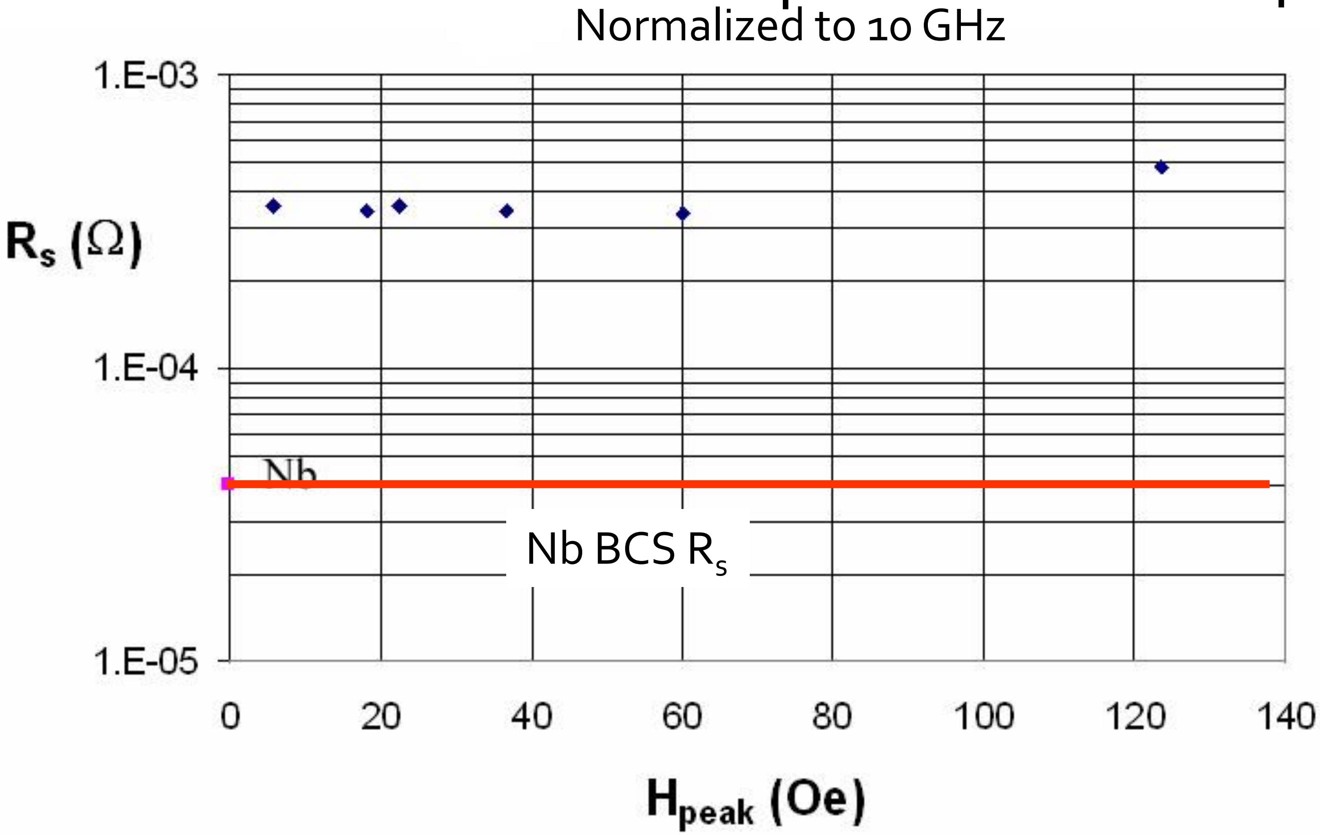
Generally, $R_s \propto f^2$ at $T<T_c/2$

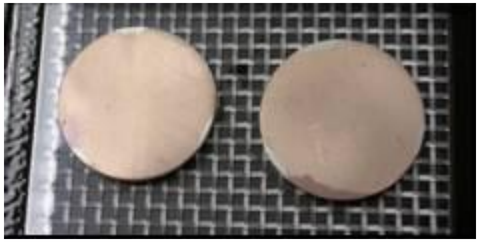


- A.T. Findikoglu et al., NSF/DOE Workshop on RF Superconductivity, Bethesda, MD, Aug. 29, 2003.
- B.H. Moeckly et al., IEEE Trans. Appl. Supercond. 15 (2005) 3308.

# $R_s$ for $MgB_2$

**$R_s$ Power Dependence Test of the sample coated on a rough Nb disk at STI with reactive evaporation method in 2004**





First attempt to coat on a Nb substrate (1.5 cm disk). $R_s$ was higher than Nb due to the rough ($R_a$~400nm) substrate.

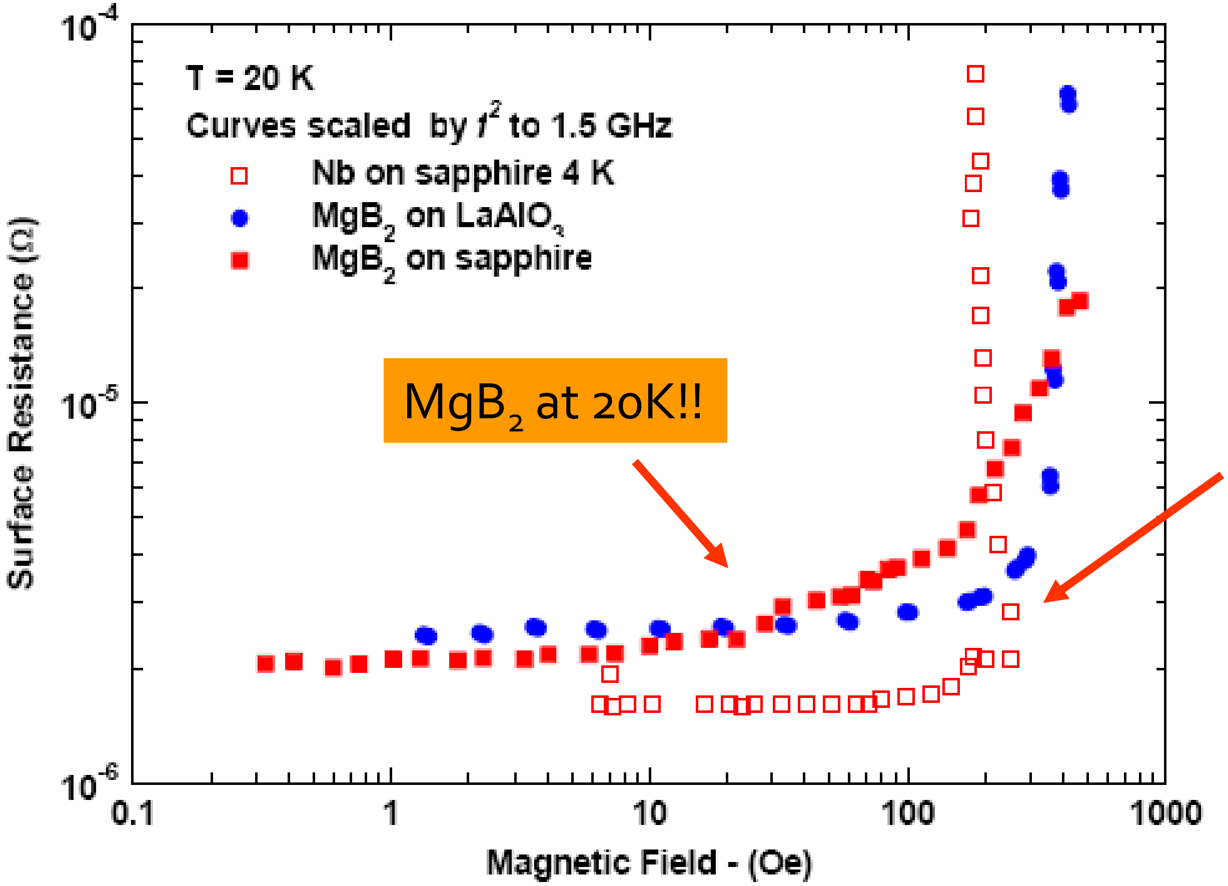
Test at Cornell with $TE_{011}$ Nb cavity at 4.2 K.

T. Tajima et al., Proc. PAC2005, p. 4215

**$R_s$ Power Dependence Test showed little increase up to ~120 Oe!**

# $R_s$ for $MgB_2$

**Results at MIT in 2006 showed $R_s$ comparable to Nb even at 20 K! and the field at which the Rs start to increase rapidly was higher than Nb!!**



$MgB_2$ at 20K!!

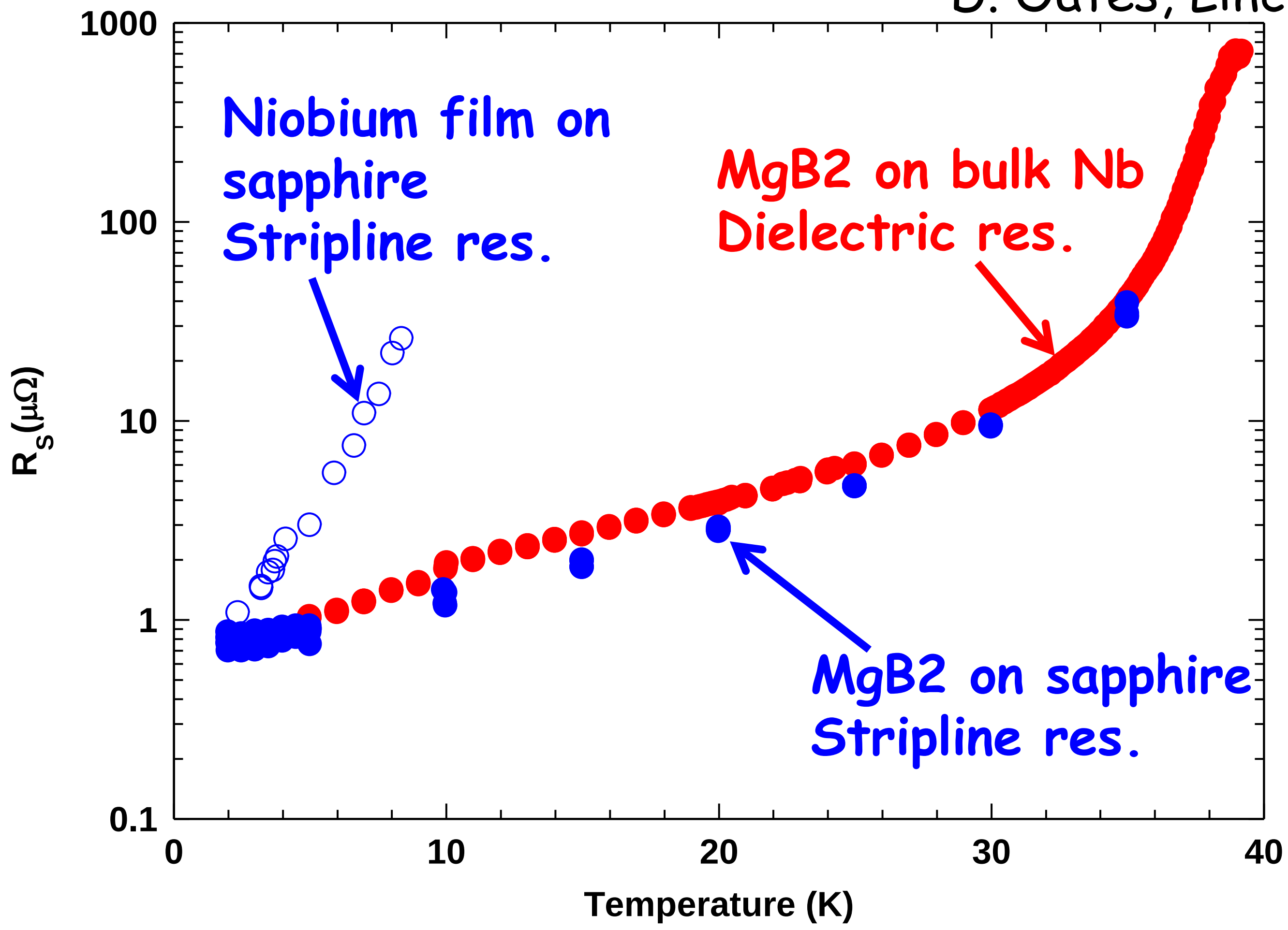
Coated at STI with reactive evaporation
Thickness: 500 nm

Nb at 4.2 K, Enhanced field at the edges may have caused this take off at low gradient.

Oates et al., IEEE Trans. Appl. Supercond. 17 (2007) 2871.

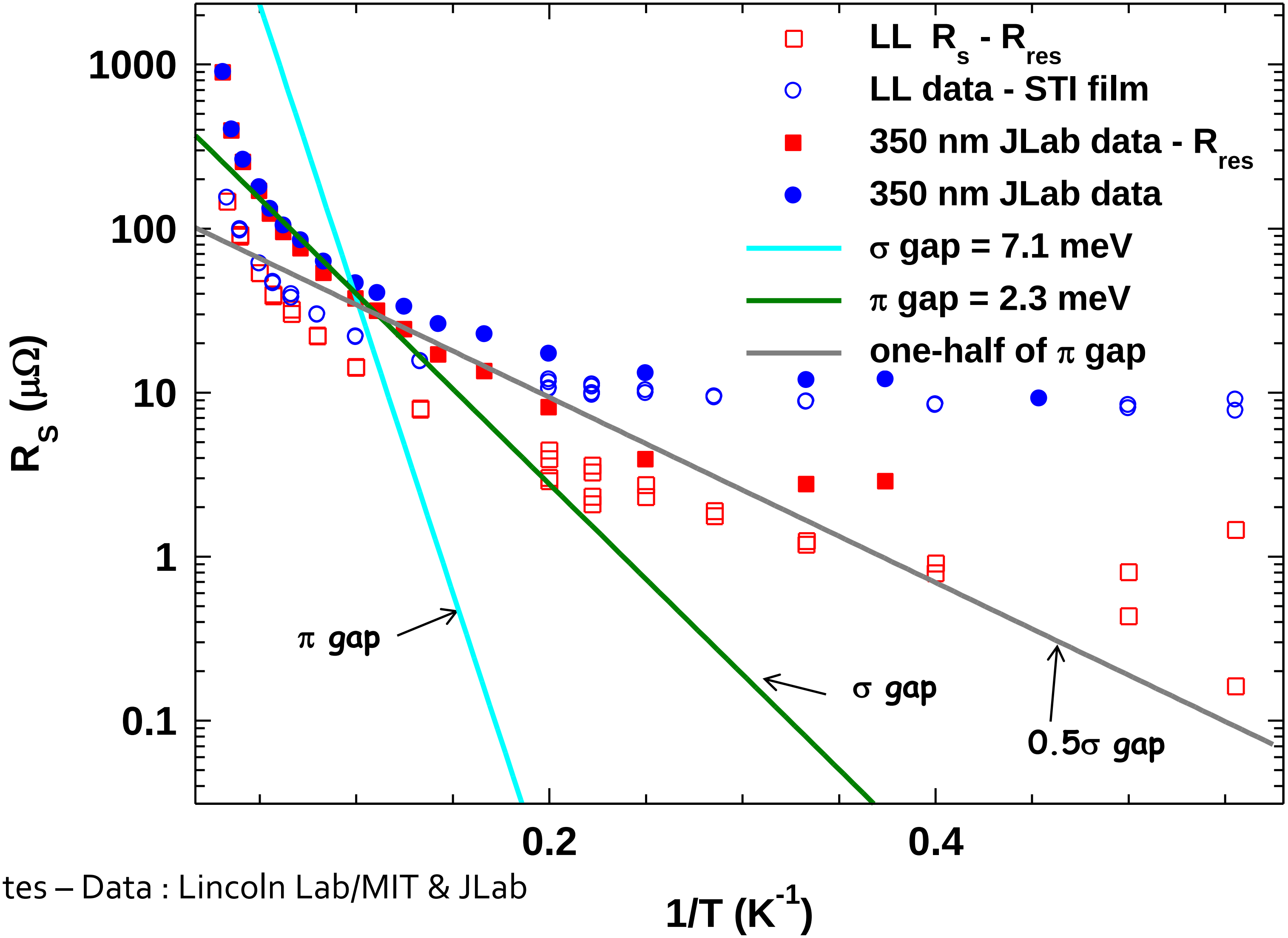
# Low-Power $R_S(T)$: $MgB_2$ and Nb

D. Oates, Lincoln Lab/MIT



$R_S$ extrapolated to 2.2 GHz by $f^{\,2}$ for the dielectric-resonator data

# $R_S$ vs 1/T Semi-log Plot



D. Oates – Data : Lincoln Lab/MIT & JLab

# $MgB_2$ – 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

# A new superconducting family

Oxypnictide base

$ReOMP_n$
    - M = Fe, Co, Ni
    - Pn = As or P
    - Re = La, Nd, Sm, Pr

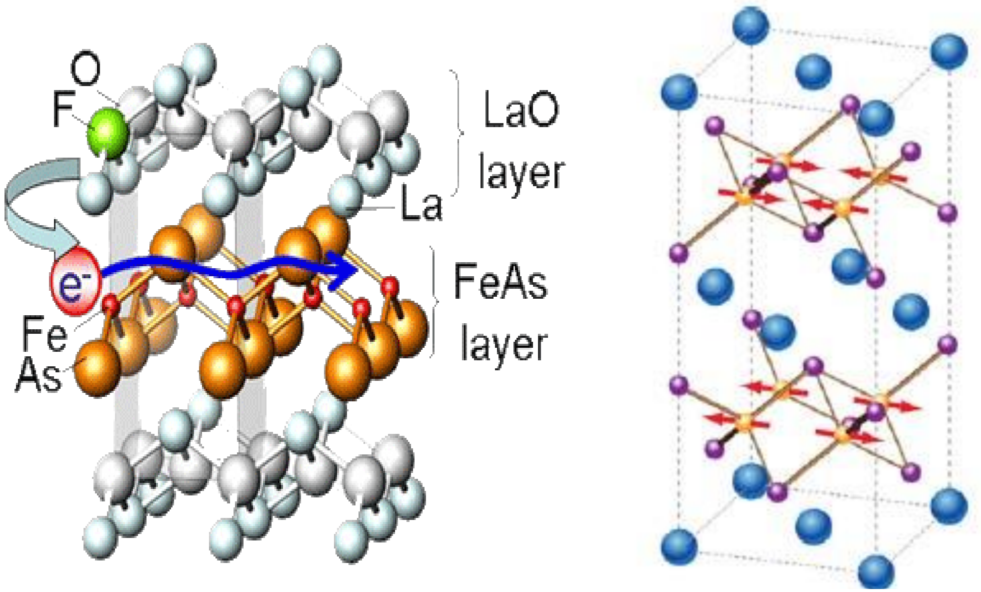
Layered as HTS –superconducting AsFe layers and $T_c$ from <10K to 55K

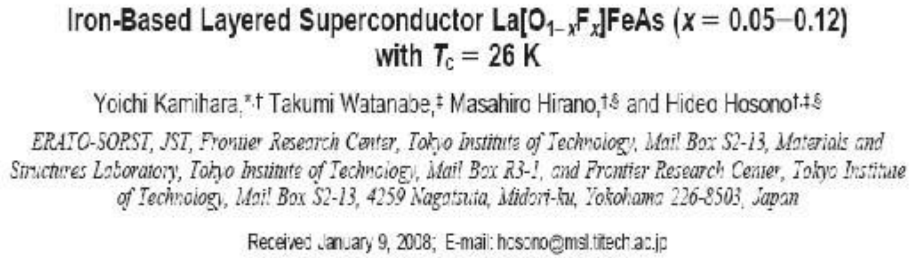
Superconductivity occurs on the FeAs layer with magnetic pair-breaking $Fe^{2+}$ions

Another families: $Ba_{1-x}K_xFe_2As_2$

Up to a few thousand compounds

Materials usually brittle




**Iron-Based Layered Superconductor $La[O_{1-x}F_x]FeAs$ ($x = 0.05–0.12$) with $T_c = 26$ K**

Yoichi Kamihara,*† Takumi Watanabe,‡ Masahiro Hirano,†§ and Hideo Hosono†‡§

*ERATO-SORST, JST, Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, Materials and Structures Laboratory, Tokyo Institute of Technology, Mail Box R3-1, and Frontier Research Center, Tokyo Institute of Technology, Mail Box S2-13, 4259 Nagatsuta, Midori-ku, Yokohama 226-8503, Japan*

Received January 9, 2008; E-mail: hosono@msl.titech.ac.jp

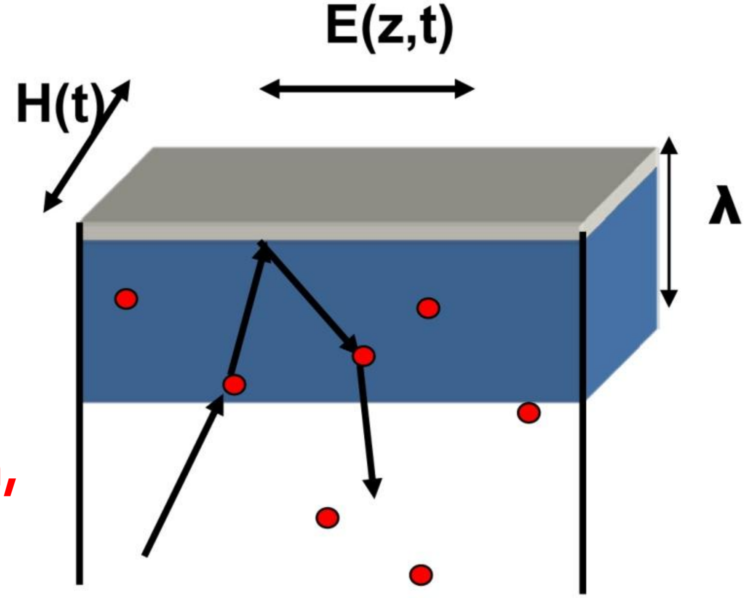
Tests in magnetic fields up to 45 T suggest the $H_{c2}$ of $LaFeAsO_{0.89}F_{0.11}$ may be ~64 T.
A different La-based material ($La_{0.8}K_{0.2}FeAsO_{0.8}F_{0.2}$) tested at 6 K predicts $H_{c2}$ ~122 T.

# Can pnictides be useful for TFSRF?

For s-wave members of the pnictide family, one can expect a much lower $R_s$ at 2K because

$\Delta_{oxy}$ = 5-10 meV > $\Delta_{Nb3Sn}$ = 3 meV

Normal skin effect( l << λ): multiple impurity scattering in the λ-belt:



$Rs \sim (\mu_o^2 \omega^2 \lambda^3 \sigma_n \Delta/T) \exp(-\Delta/T)$

Anomalous skin effect ( l >> λ)in the clean limit:

Effective $\sigma_{eff} \sim e^2 n\lambda/p_F$

High $\rho_n \sim 1 m\Omega cm \sim 10 \rho_n MgB_2$, bigλ= 180-250 nm, low $H_{c1} \sim 10$ mT

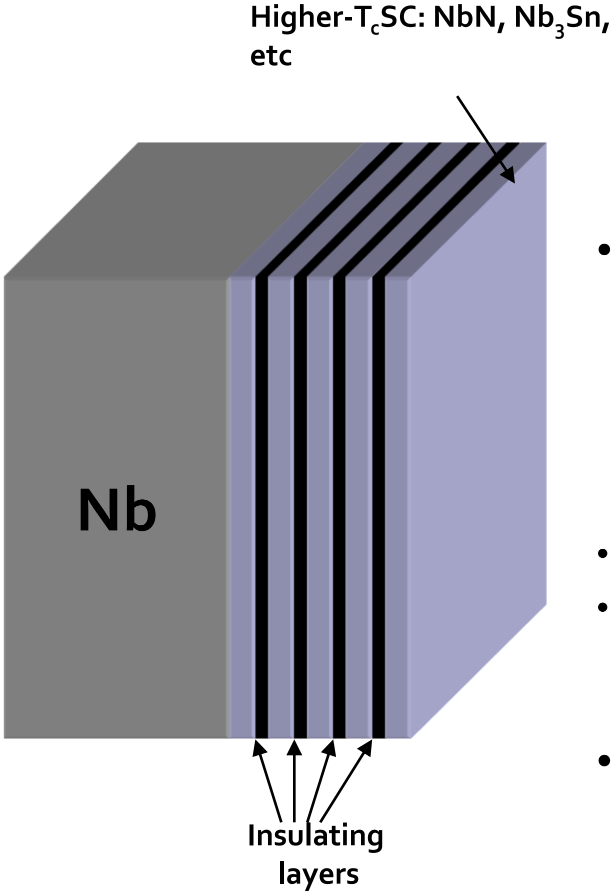
$R_s$ can be much lower than $R_s$ of $Nb_3Sn$, but TF multilayer coating is necessary

High quality epitaxial films have been grown – MBE - C.-B. Eom (UW)

# SIS Multilayers

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

**Taking advantage of the high –Tc superconductors with much higher $H_c$ without being penalized by their lower Hc1…**



Multilayer coating of SC cavities:
alternating SC and insulating layers with $d < \lambda$
Higher $T_c$ thin layers provide magnetic screening of the Nb SC cavity (bulk or thick film) 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
  - 540 mT for Nb3Sn or 1T for pnictides
    - -high HC1 => no transition, no vortex in the layer
    - -applied field is damped by each layer
- insulating layer prevents Josephson coupling between layers
- applied field, i.e. accelerating field can be increased without vortex nucleation

- Strong reduction of BCS resistance because of using SC layers with higher $\Delta$ ($Nb_3Sn$, NbN, etc)

=> low $R_{BCS}$ at low field => higher $Q_o$

**=>Opportunity to move operation from 2K to 4.2K**

# 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, …

# NbN/MgO Multilayer @ CEA Saclay/IPN-Orsay/CNRS Grenoble

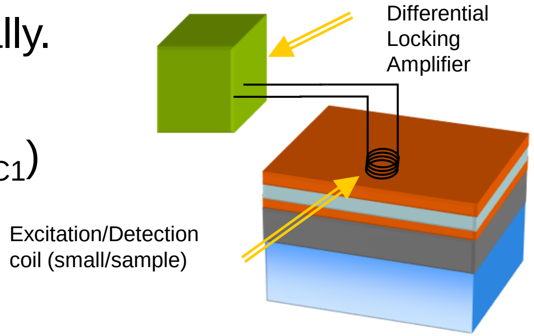
## Local magnetometry

- 3rd harmonic measurement, coll. INFM Napoli

*M. Aurino, et al., Journal of Applied Physics, 2005.* ***98: p. 123901.***

Perpendicular field : field distribution can be determined analytically.

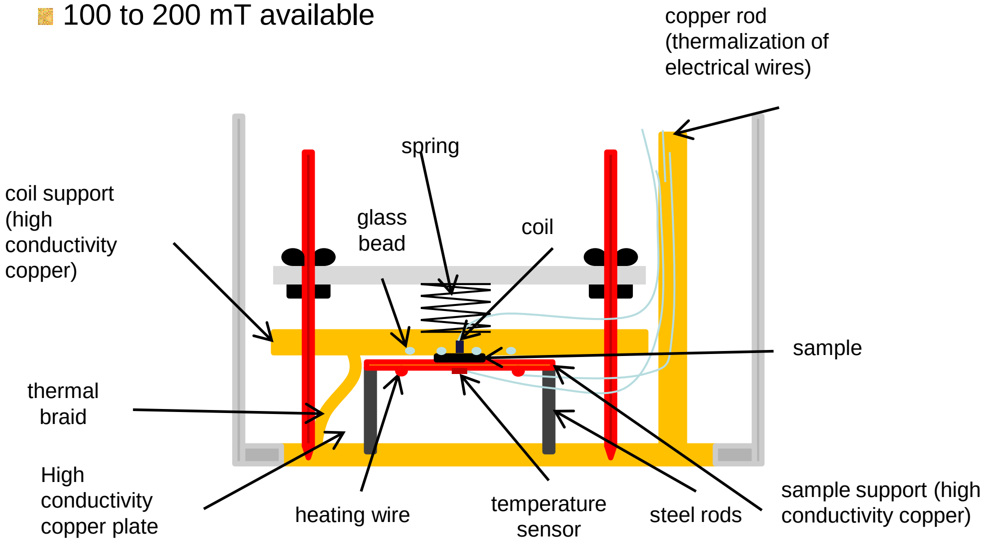
- If $r_{sample} > 4\ r_{coil}$ : Sample ≡ infinite plate approximation
- Applied field : perpendicular, induction (B ) // surface (below $B_{C1}$)

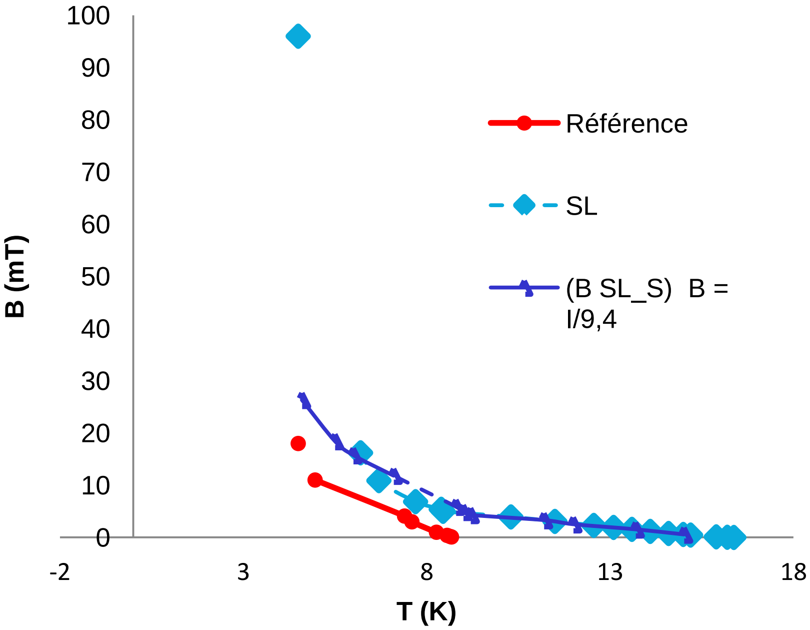


- thermal regulation

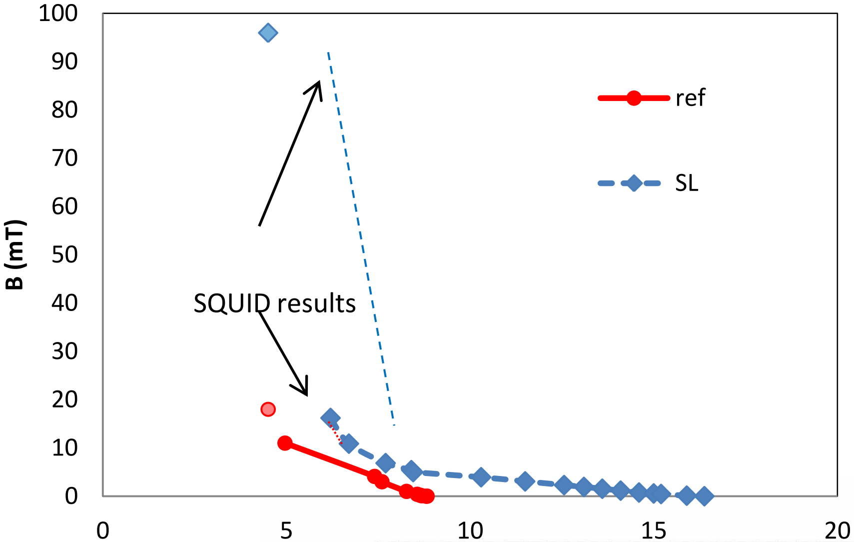
1.6 K <Tp°< 40K, automated

- 100 to 200 mT available

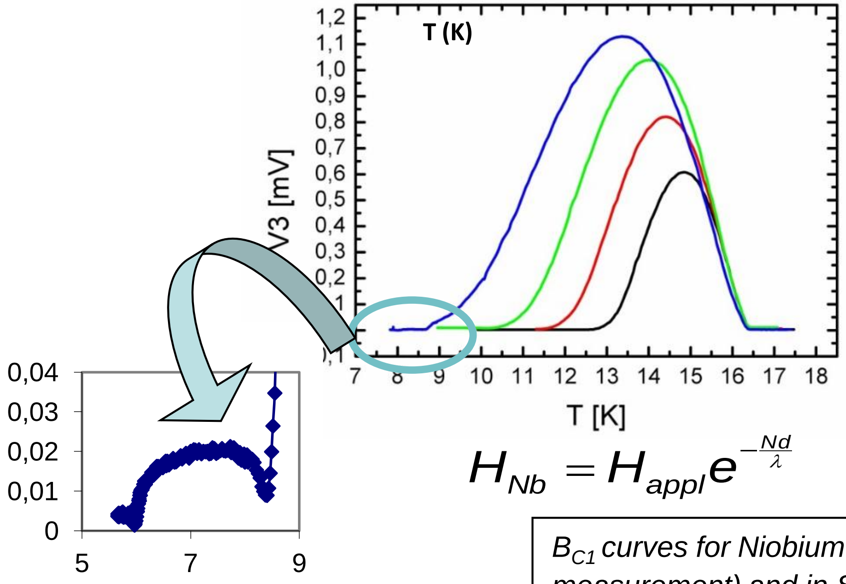




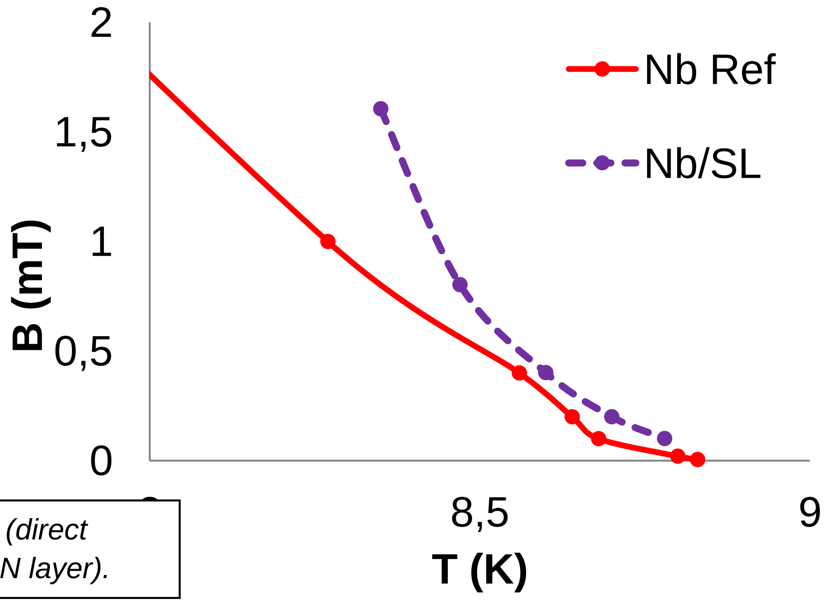
# NbN/MgO Multilayer @ CEA Saclay/IPN-Orsay/CNRS Grenoble



- **SL sample :** 250 nm Nb + 14 nm MgO + 25 nm NbN
- Tp°< 8.90K, i.e. when Nb substrate is SC , **=> $B_{C1}^{SL} >> B_{C1}^{Nb}$**
- Sample SL : small Nb signal @ ~$Tc^{Nb}$ : Nb is sensed through the NbN layer !
- Since the Nb layer feels a field attenuated by the NbN layer, the apparent transition field is higher.
- This curve provides a direct measurement of the attenuation of the field due to the NbN layer
- **Need to extend measure @ higher field and lower temperature**



$$H_{Nb} = H_{appl} e^{-\frac{Nd}{\lambda}}$$



*$B_{C1}$ curves for Niobium in the reference (direct measurement) and in SL (under the NbN layer).*

# NbN, NbTIN based ML -JLAB/W&M Collaboration

**SIS Multilayer Structures:**

✓Nucleation studies of NbTiN, NbN on dielectrics like MgO, $Al_2O_3$ and reciprocately.

✓Creation and characterization of a set of NbTiN , NbN.../insulator/Nb samples by UHV multi-target energetic ion deposition with well-controlled, incremented thickness. The variation of rf field properties with temperature as a function of thickness of the superconducting overlayer will provide a direct test of the Gurevich delayed flux entry model.

## Study of growth modes of Superconductor/ Insulator & Insulator/superconductor

**Substrates :**

Single crystal Nb
Poly crystalline Nb
thick Nb/Cu films

**Alternative Materials:**

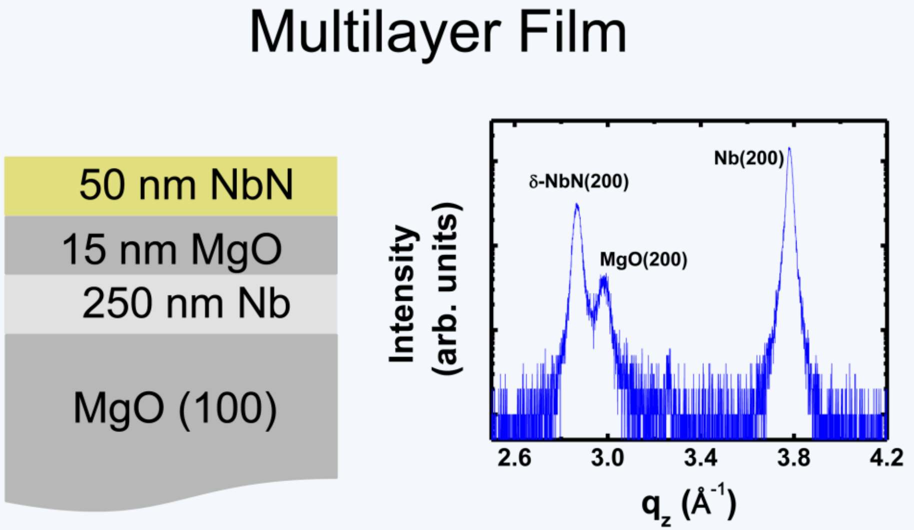
NbTiN, NbN
Nb3Sn, V3Si, Mo3Re

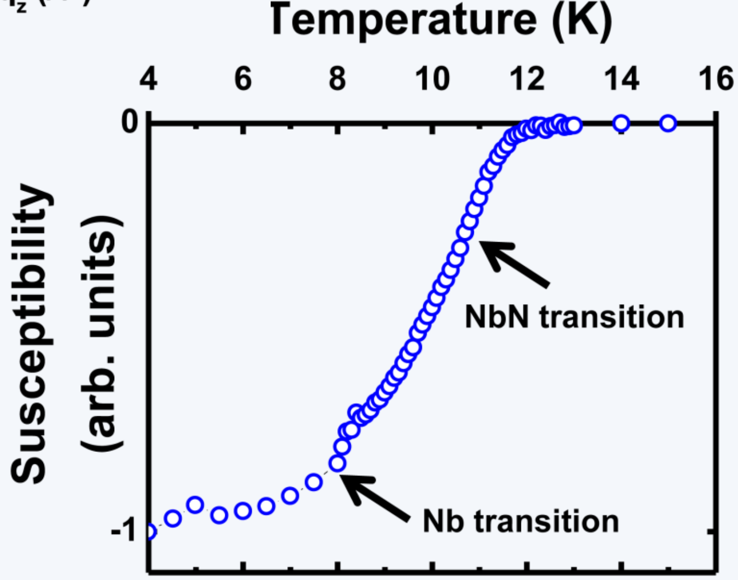
**Insulator:**

Al2O3, MgO, AlN
according to
lattice mismatch
between
I and S materials

## Multilayer: S/I/Nb and S/I/S/I/.../S/I/Nb

# NbN/MgO Multilayer @ College William & Mary





- Further optimization
  - Surface modification (ion gun)
  - Alternative insulators (AlN)

# NbTiN/AlN Multilayer @ Jefferson Lab (DC-MS, HiPIMS)

NbTiN deposited with various thicknesses by reactive DC sputtering at 600°C on MgO substrates

NbTiN, NbN, $Mo_3Re$, $V_3Si$ coatings with Reactive Sputtering and High Power Pulse Magnetron Sputtering & MgO coating with RF sputtering

**NbTiN/MgO (100)**

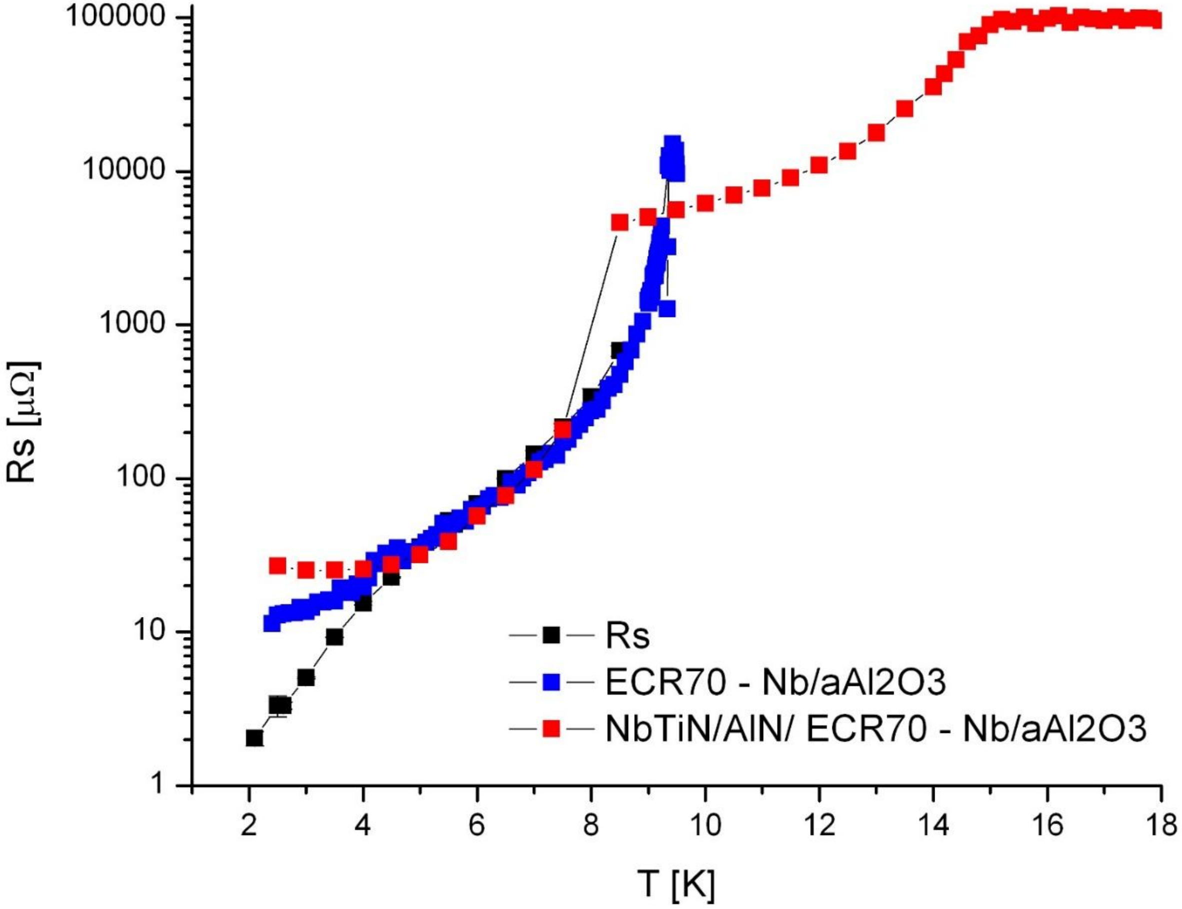
| Thickness [nm] | $T_c$ [K] | $\Delta T_c$ [K] | $a_o$ [Å] |
|---|---|---|---|
| 10 | 12.11 | 0.91 | 4.3487 |
| 35 | 16 | 0.39 | |
| 50 | 15.97 | 0.16 | 4.3644 |
| 100 | 16.57 | 0.21 | 4.3657 |
| 1625 | 16.95 | 0.06 | 4.3618 |

NbTiN layers have been coated at various temperatures on MgO (100) and AlN ceramic substrates.

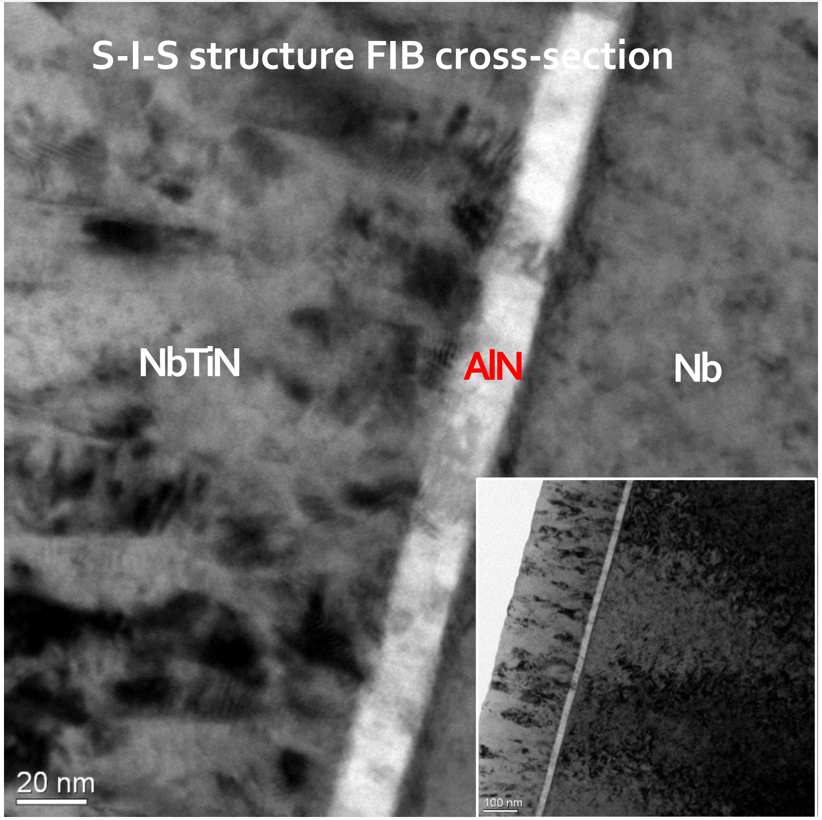
The NbTiN films exhibit the cubic d-phase and $T_c$ above 16K for thicknesses larger than 30-50 nm and coating temperatures of 450˚C or higher.

# NbTiN/AlN Multilayer @ Jefferson Lab (DC-MS, HiPIMS)

The SIS structure coated on the ECR Nb/(11-20)$Al_2O_3$ film exhibits a suppressed Tc for the Nb film compared to the measurement prior to the SIS coating. This is most likely due to the Nb oxide reduction and oxygen diffusion during the bake at 600˚C. The NbTiN has a Tc of about 15K.

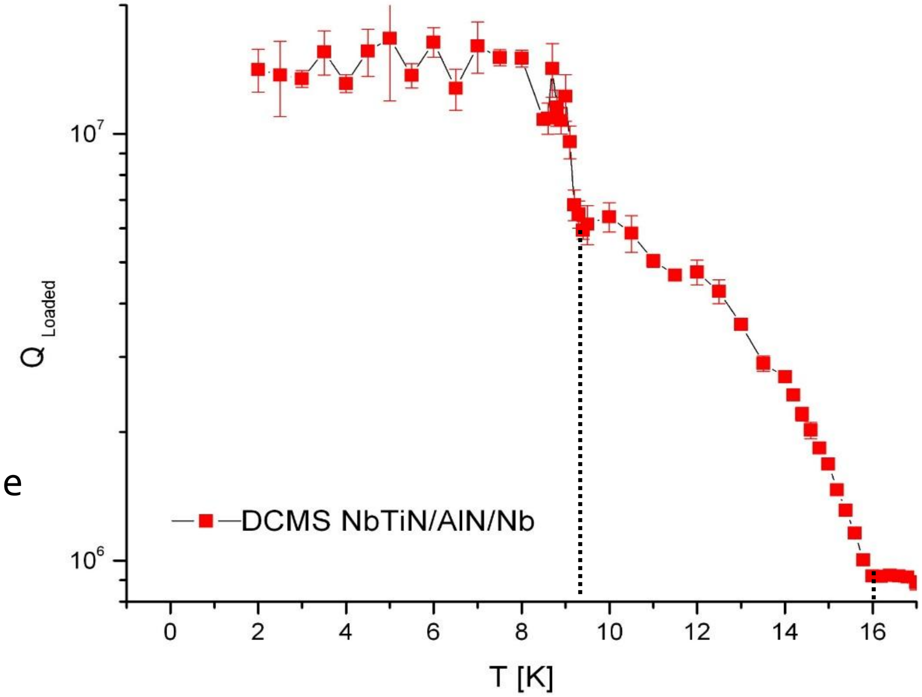


# NbTiN/AlN Multilayer @ Jefferson Lab (DC-MS, HiPIMS)



NbTiN/AlN/Nb SIS structure coated at 450°C in-situ after a 24h-bake at 600°C. Annealing at 450°C for 4 hours.

XRD measurements ($\theta$-2$\theta$) reveal lattice parameters of respectively 3.301Å, 4.041Å and 4.330 Å for the Nb substrate, AlN and NbTiN layers.

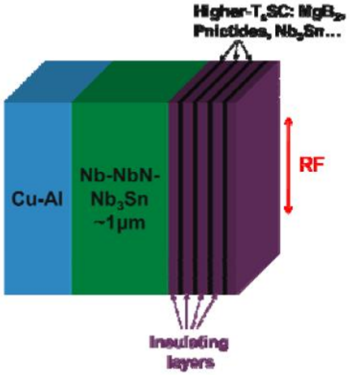


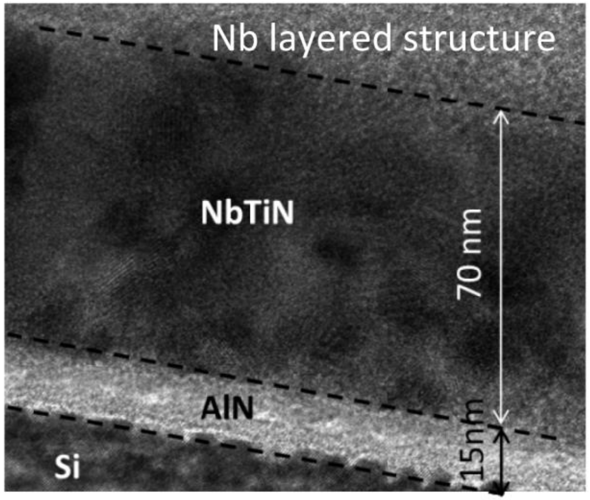
The SIS structure coated on the Nb exhibits a $T_c$ for the NbTiN of 16K . RF measurements are in going.

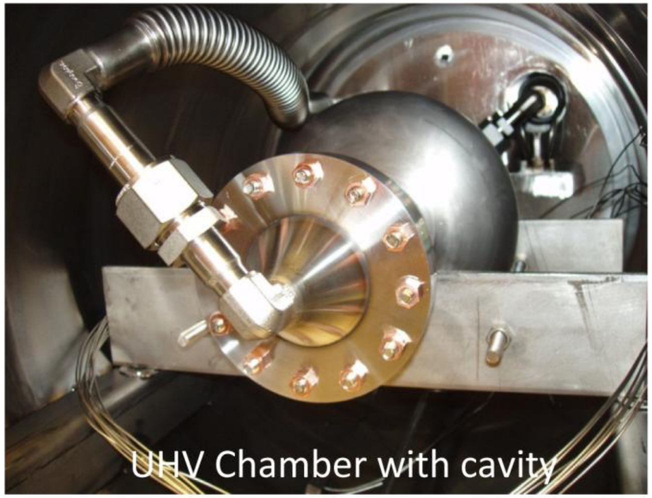
# NbTiN/AlN Multilayer @ ANL (Atomic Layer Deposition -ALD)

- Able to synthesize better superconductors than Niobium:
  - NbTiN with new ALD chemistry is very pure (<0.05%)
  - NbTiN  Tc= 14K for 60 nm thick film (bulk=16K)

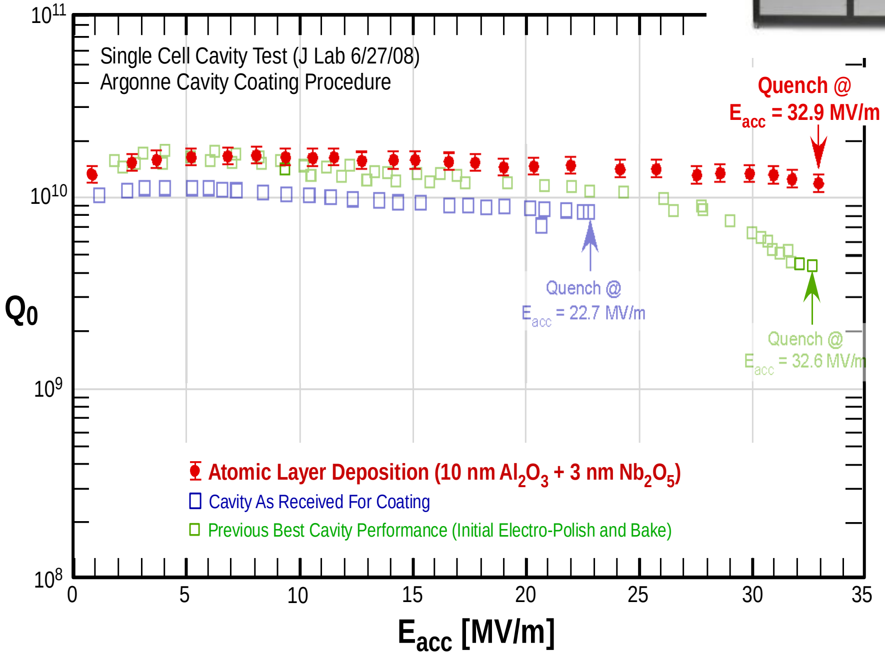
- Multilayer structure:
  Aluminum Nitride (AlN) + NbTiN
  works perfectly:
  (15 nm AlN/ 70 nm NbTiN) x n



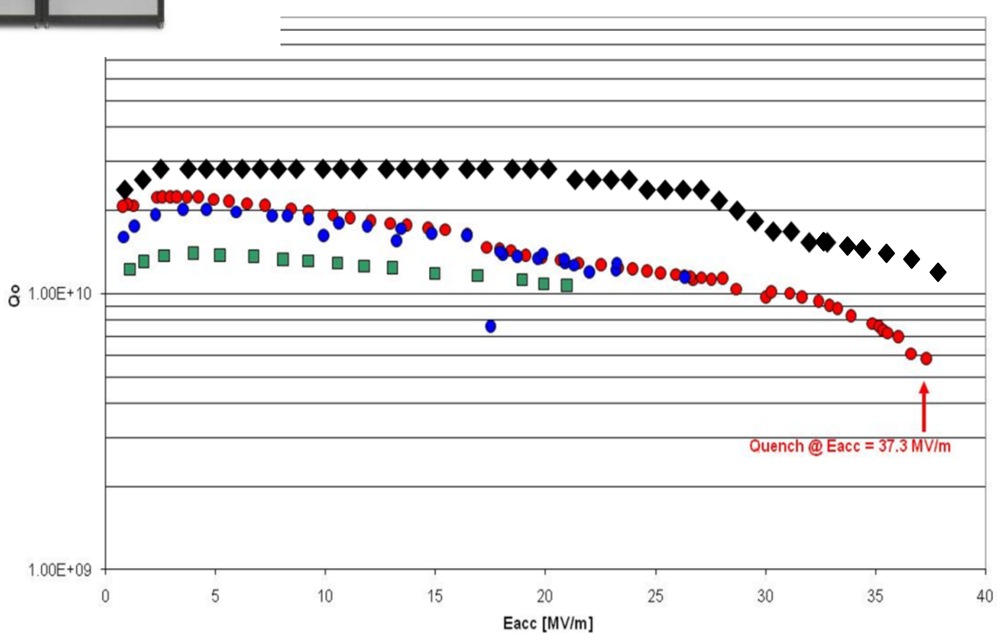




# NbTiN/AlN Multilayer @ ANL (ALD)



ALD dielectric layer compatible with high E or B

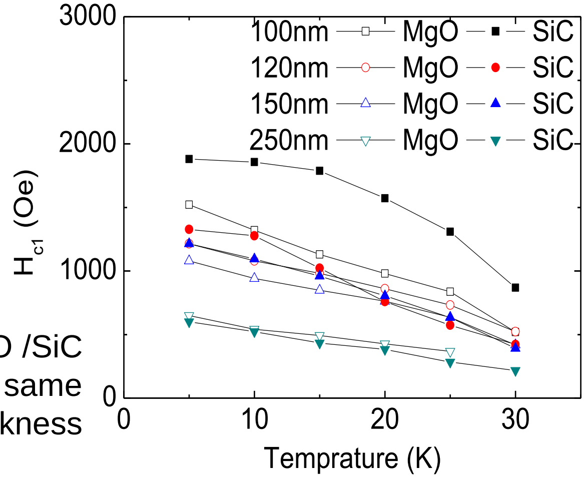


ALD + annealing improves the Q & Q-slope

# MgB2 based Multilayer @ Temple University

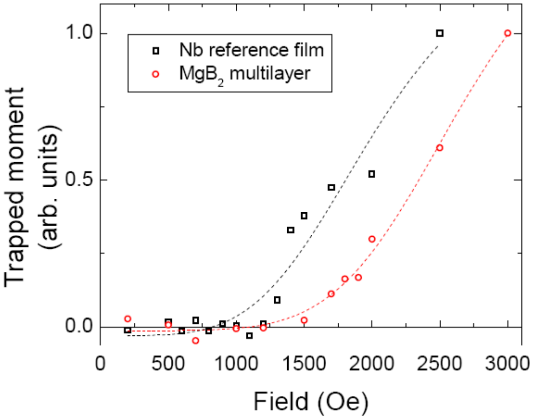
## ***Enhancement of $H_{c1}$ in thin $MgB_2$ films***

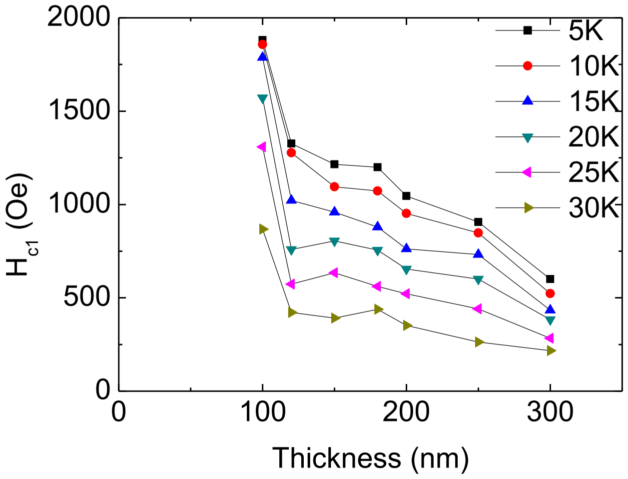
- 2 group of samples were studied:
  - Single crystalline thin films on SiC(0001) substrate
  - Polycrystalline thin films on amorphous MgO layer on SiC(0001)
- $H_{c1}$(5K) is enhanced when the film thickness decreases, for films on both single crystal SiC substrate and polycrystalline MgO films.
- $H_{c1}$(5K) ~ 2000 Oe in 100nm-thick $MgB_2$ film.



films on MgO /SiC with the same thickness

- Results show that $MgB_2$ thin films with $d > \lambda$ also have enhanced $H_{c1}$, which makes it possible to use single layer coating to increase $H_{c1}$ of cavities.
- Films grown on MgO buffer layers with thicknesses of 100-250 nm have the same enhanced $H_{c1}$ as thin films grown on bare SiC substrates.





films on bare SiC substrates

Samples: Temple University/$H_{c1}$ Measurements: William&Mary

# Oxypnictides based Multilayer structures@ ODU

A project on the development of
SIS structures based on
oxypnictides
is starting at
Old Dominion University
(A. Gurevich)
in collaboration with University
Wisconsin-Madison

oxypnictides

| Material | $T_c$ (K) |
|---|---|
| $LaO_{0.89}F_{0.11}FeAs$ | 26[9] |
| $LaO_{0.9}F_{0.2}FeAs$ | 28.5[10] |
| $CeFeAsO_{0.84}F_{0.16}$ | 41[9] |
| $SmFeAsO_{0.9}F_{0.1}$ | 43[9] |
| $La_{0.5}Y_{0.5}FeAsO_{0.6}$ | 43.1[11] |
| $NdFeAsO_{0.89}F_{0.11}$ | 52[9] |
| $PrFeAsO_{0.89}F_{0.11}$ | 52[12] |
| $GdFeAsO_{0.85}$ | 53.5[13] |
| $SmFeAsO_{\sim 0.85}$ | 55[14] |

F. Hunte, J. Jaroszynski, A. Gurevich, D. C. Larbalestier, R. Jin, A. S. Sefat, M. A. McGuire, B. C. Sales, D. K. Christen & D. Mandrus (2008). "Two-band superconductivity in LaFeAsO0.89F0.11 at very high magnetic fields". *Nature* **453** (7197): 903–905.

# 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 penalty of lower field onset for vortex penetration and increase the accelerating gradient and Q.

✓Strong reduction of the BCS resistance for superconducting layers with higher Δ(Nb3Sn, MgB2, BKBO, NbN … s-wave, fully gapped superconductors)

✓New non-magnetic members of the oxypnictide family with 15K < Tc< 55K or BaO0.6K0.4BiO3 with Tc≈30K: a possibility to greatly increase Q if TF coating can be developed.

# CONCLUDING REMARKS cont.

✓Possibility to move from 2K to 4.2K would mean huge cost saving on refrigeration in LINACS

✓Higher –$T_c$ s-wave materials are often multi-gap superconductors, which do not always have better SRF performance despite higher $H_c$ and $T_c$

✓First experimental evidence of field enhancement with NbN/MgO/…/Nb samples with SQUID measurement with H // sample plane. Field penetration delayed for NbN layered samples compared to Nb sample. Limitation of method: edge effect due to sample size comparable to measurement setup size (C. Antoine et al, CEA Saclay)

✓Many long-standing problems of condensed matter physics and non-equilibrium superconductivity will have to be addressed to understand nonlinear surface resistance under strong rf fields

✓Multi-parameter materials optimization is required to revel the full SRF performance potential.

✓The effort for new materials research for SRF cavities is gaining amplitude. But there is still a lot of work ahead!