Prospects for Higher T_c Superconductors for SRF Application

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Aknowledgements

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October 16, 2007
SRF 2007
Beijing, China

Supported by ONR, NSF, PRF, 973 Proj.

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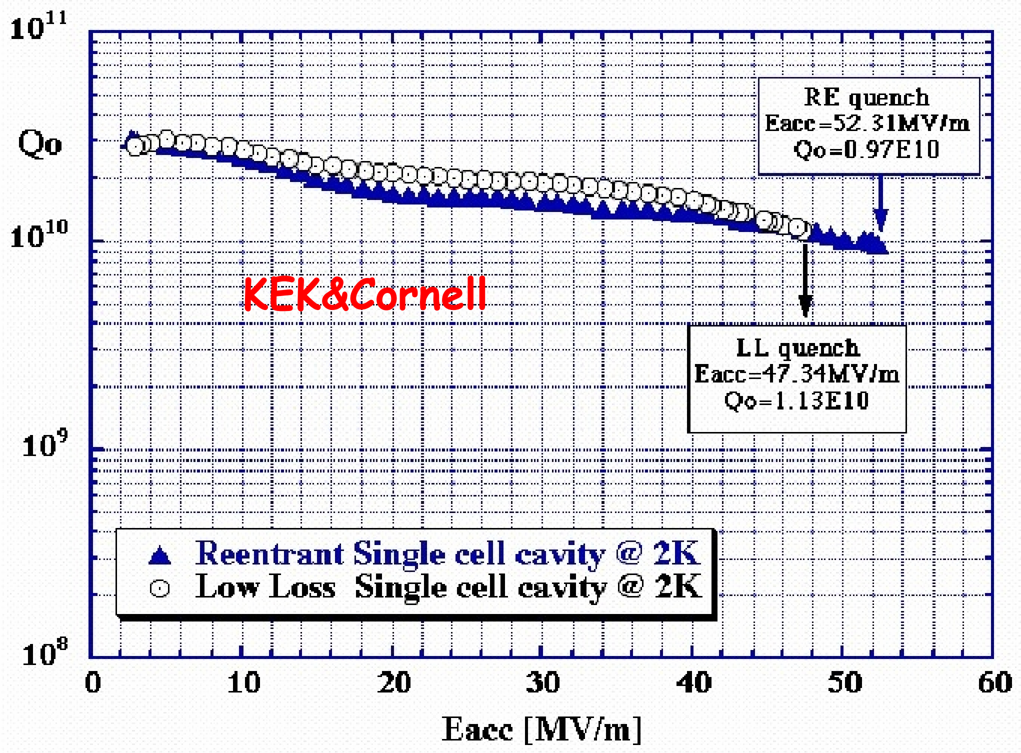
Outline

- **Introduction**
- **B1 compounds and A15 compounds**
- **High-temperature superconductors (HTS)**
  - **Short coherence length**
  - ***d*-wave gap symmetry**
- **MgB_2**
  - **Potential for low R_s and high ultimate critical field**
  - **Properties at RF**
  - **Processing issues**
- **Conclusions**

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 **($H \approx H_c$ = 200 mT)**



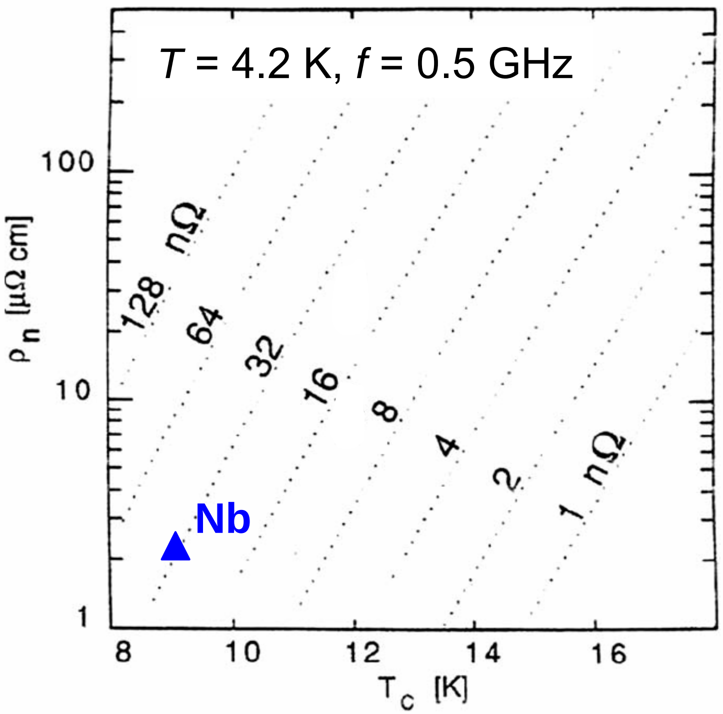
- For further improved cavity RF performance, innovation needed
- Higher T_c , potentially higher H_c
- Substrates with higher thermal conductivity
- Potentially cryogenics cost reduction if cavity operation temperature at 4.2K or higher

(Slide from Anne-Marie Valente-Feliciano)

Search for Higher T_c Materials for RF Cavities

Low BCS Surface Resistance R_{BCS}

$$R_{BCS} \cong A\sqrt{\rho_n}\, e^{-\frac{\Delta}{K_B T}} \left(1 + O(\Delta, \omega, T)\right)$$



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

- Large superconducting energy gap, or high T_c (BCS: $2\Delta / k_B T_c = 3.52$).
- Low residual resistivity

High *RF* Critical Field

$$H_c = \frac{H_{c2}}{\sqrt{2}\kappa}$$

$$H_{sh} \approx 0.75 H_c \text{ for } \kappa >> 1 \quad (?)$$

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

- Large thermodynamic critical field H_c or superheating field H_{sh}
- Small κ
- Balance among smal penetration length λ, large coherence length ξ, and high upper critical field H_{c2}

Small *Q*-Slope

- Weak field dependence (low microwave nonlinearity)

Properties of Various Superconductors

Material	Crystal structure	Anisotropy	T_c (K)	H_{c2}	In-plane coherence length $\xi(0)$ (nm)	In-plane penetration depth $\lambda(0)$ (nm)	$\rho(T_c)$ ($\mu\Omega$ cm)
Nb47wt%Ti	Body-centred cubic	Negligible	9	12 T (4 K)	4	240	60
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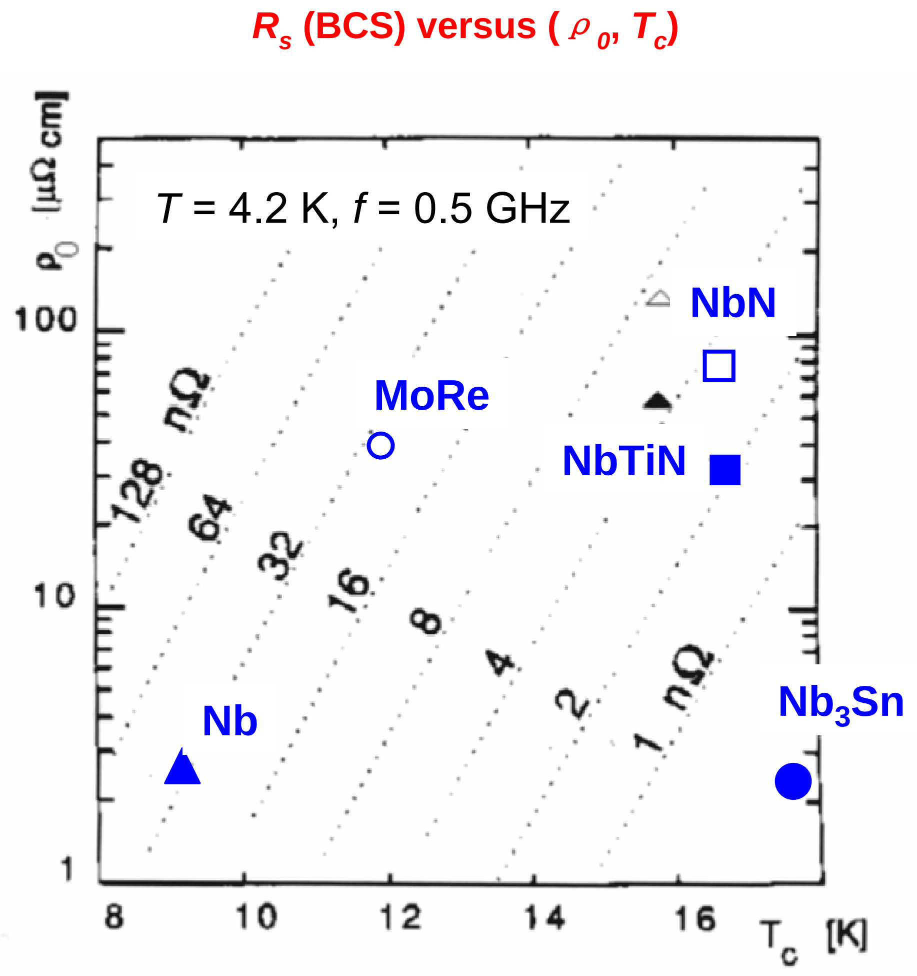
Bi-2223	Tetragonal layered perovskite	~50–100	108	>100 T (4 K)	1.5	150	~150–800
Nb			9.2	0.4	22	40	2
NbN			16.2	15	3.6	200	70

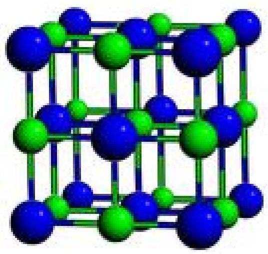
Larbalestier *et al*., Nature 414, 368 (2001)

B1 compounds and A15 compounds

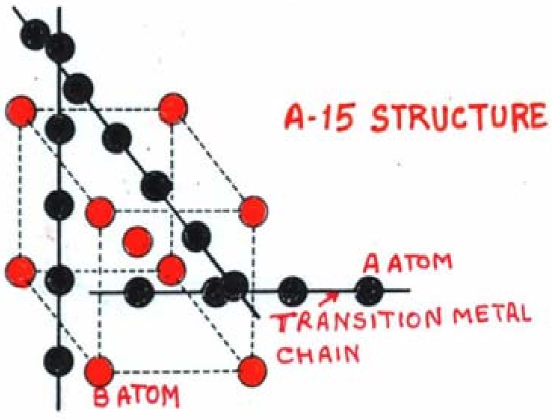


Vaglio, *Particle Accelerators* 61, 391 (1998)

— B1 compounds: NbN, NbTiN, etc.
High resistivity.



— A15 compounds: Nb_3Sn, V_3Si, Mo_3Re, etc.



1.5 GHz Nb_3Sn Cavity by Sn Thermal Diffusion

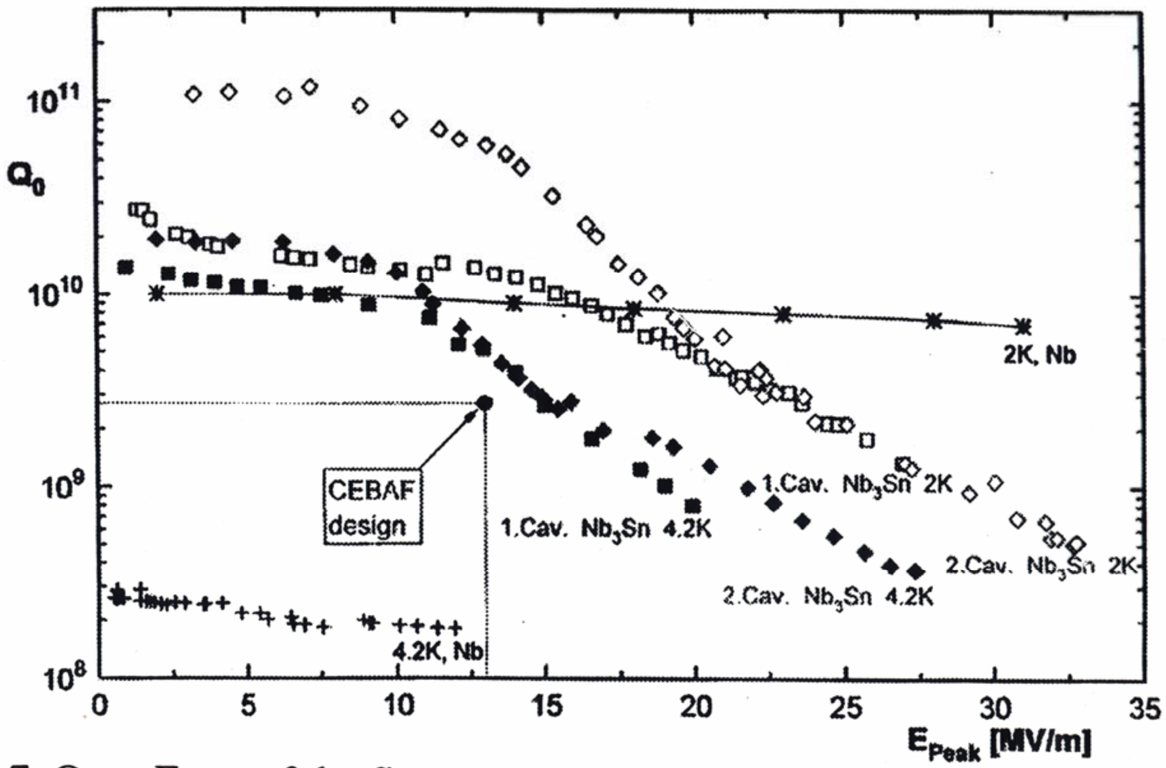


Fig. 7 Q vs. Epeak of the first two Nb3SN-coated 1.5 GHz single-cell cavites in comparison to pure Nb at 4.2 K and 2 K from CEBAF.

G. Müller *et al.*, 1985

— Effort at Wuppertal ended in the ’80s

— Nb_3Sn cavities actively investigated at LNL-INFN

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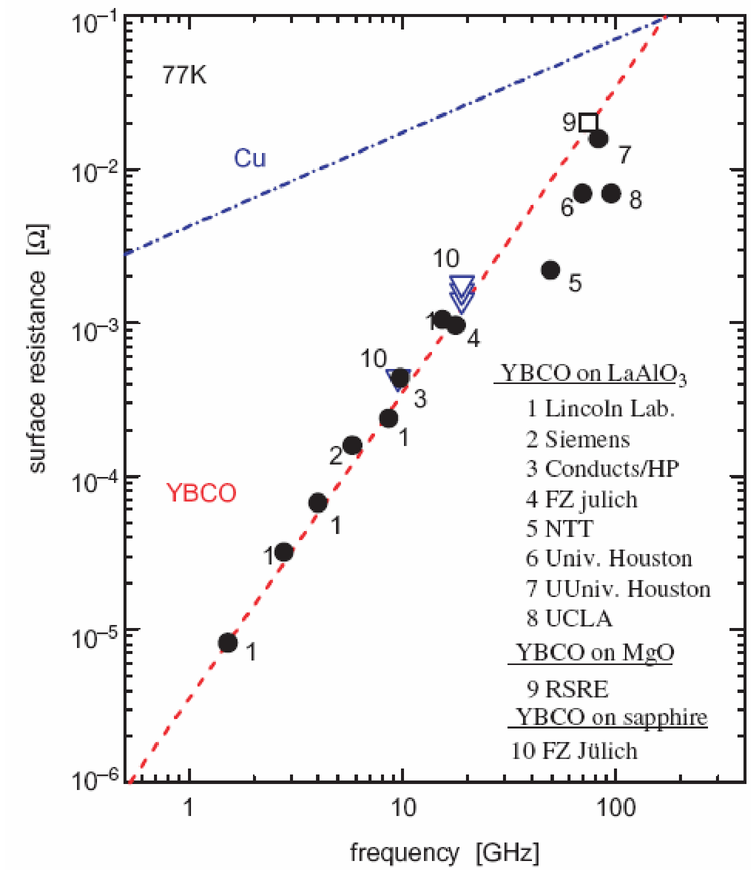
Larbalestier *et al*., Nature 414, 368 (2001)

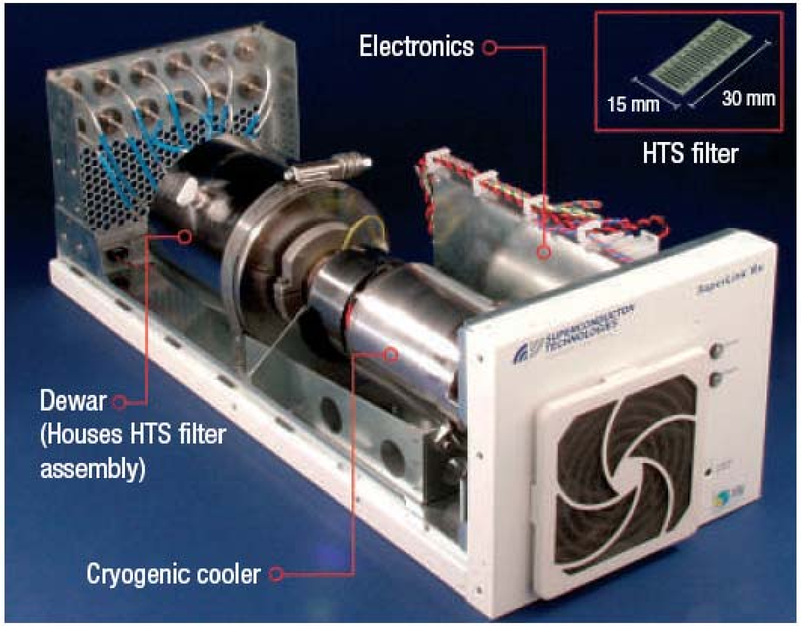
HTS for Passive Microwave Devices

Surface Resistance of HTS



Klein, Rep. Prog. Phys. 65, 1387 (2002)

HTS Filter System for Cell-Phone Base Station

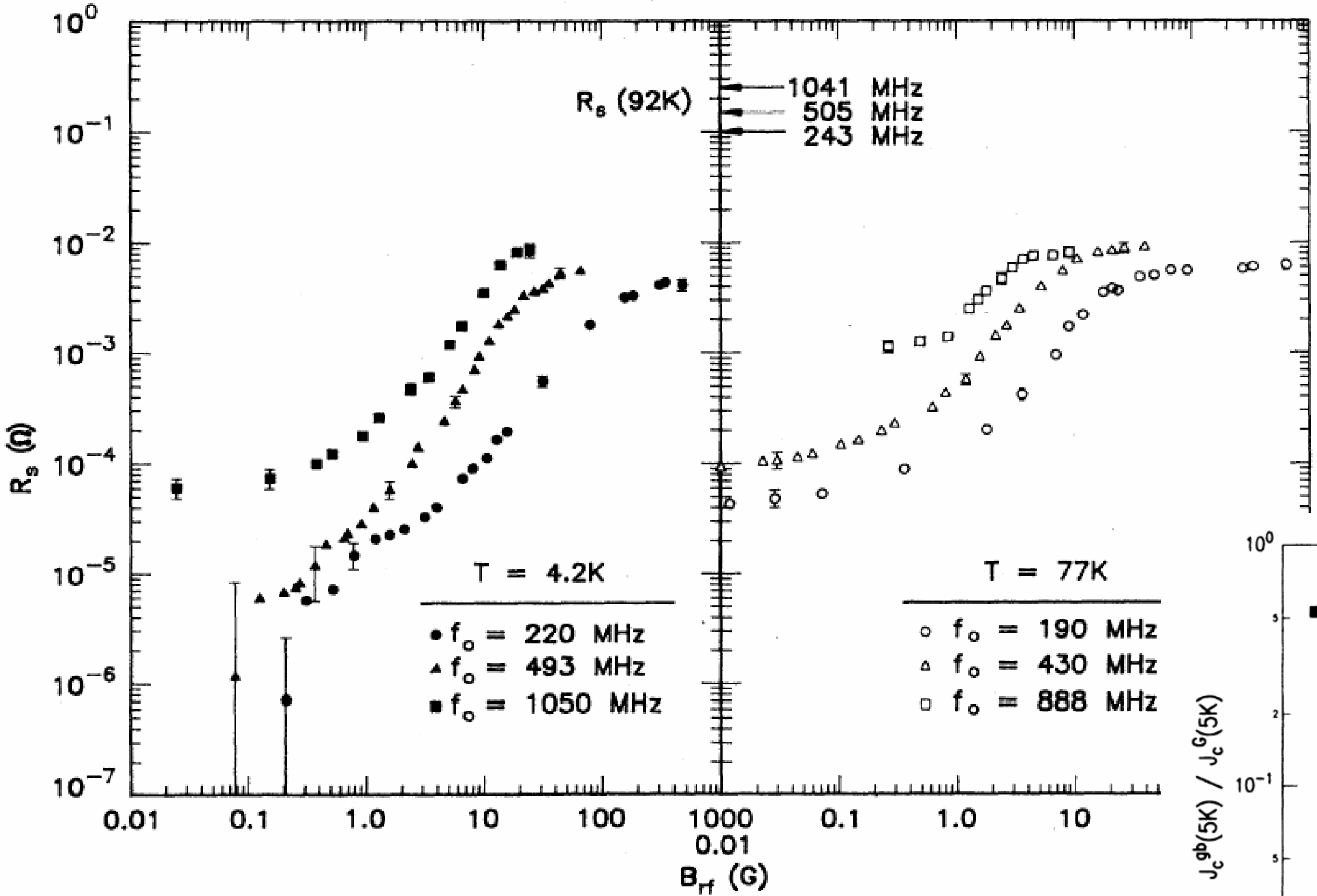


Clarke & Larbalestier, Nature Phys. 2, 794 (2006)

Low microwave surface resistance of superconductors allows for microwave devices with high performance and low loss.

Strong Power Dependence in Polycrystalline HTS

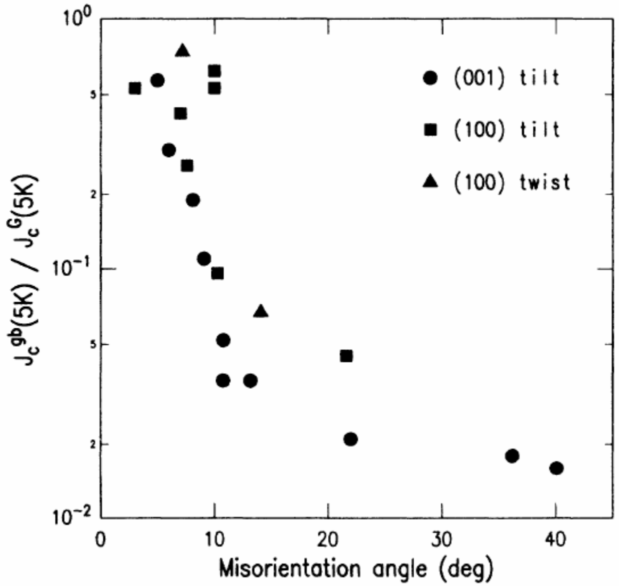
Bulk Polycrystalline $YBa_2Cu_3O_{7-x}$



Grain boundaries are weak links in HTS.

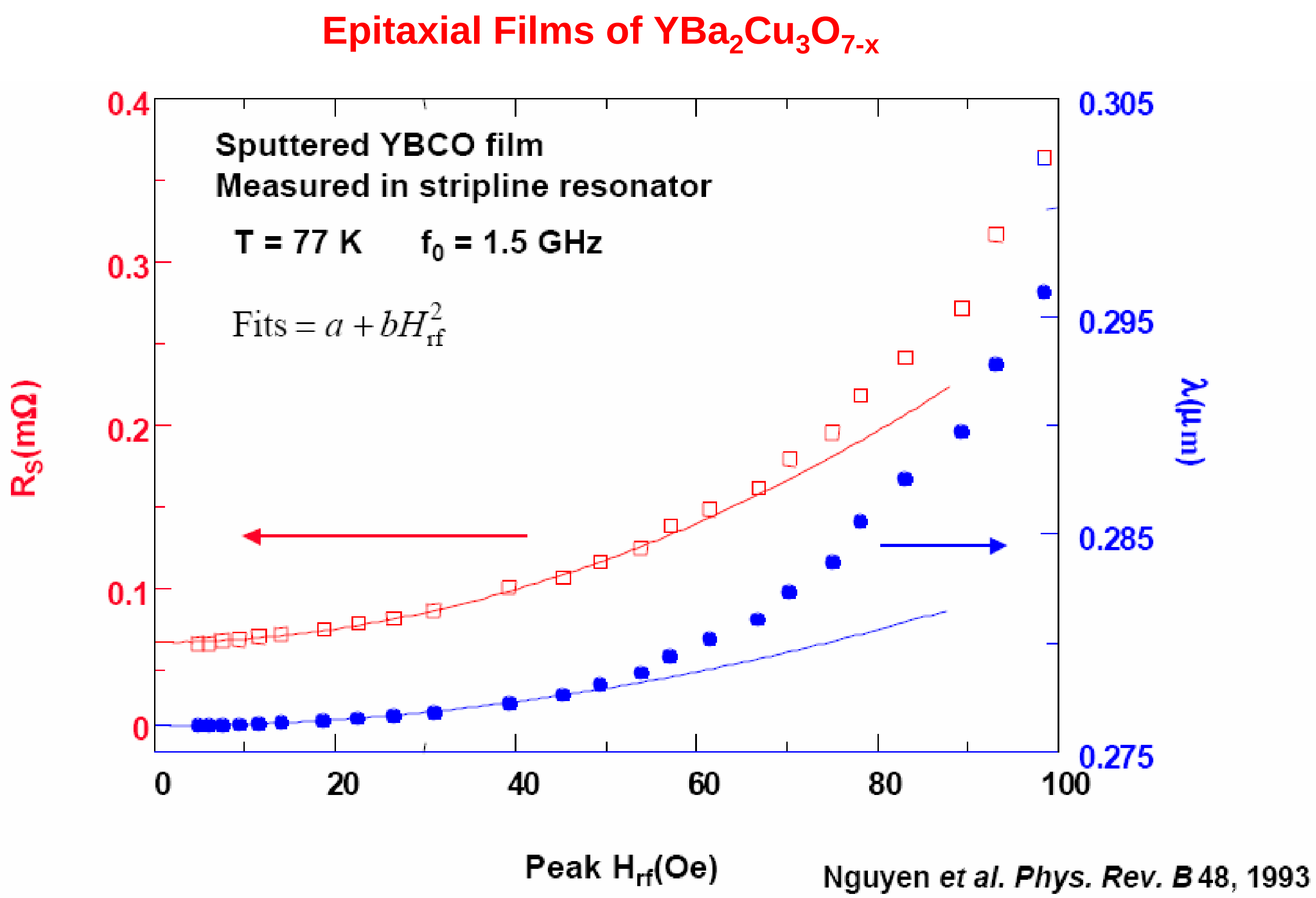
Delayen and Bohn, PRB 40, 5151 (1989).

J_c vs. GB angle in $YBa_2Cu_3O_{7-x}$



Dimos *et al.*, PRB 41, 4038 (1990).

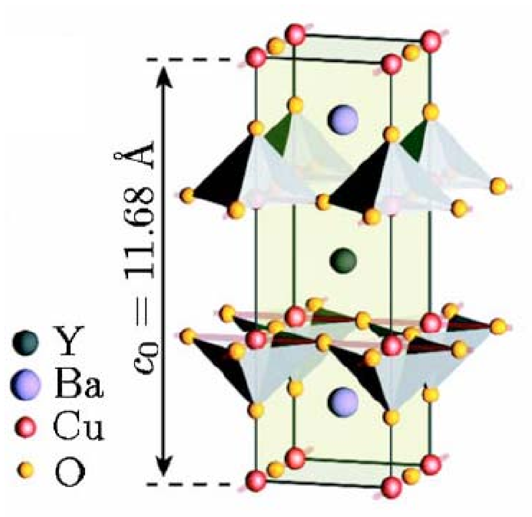
Weaker Power Dependence in Epitaxial HTS Films

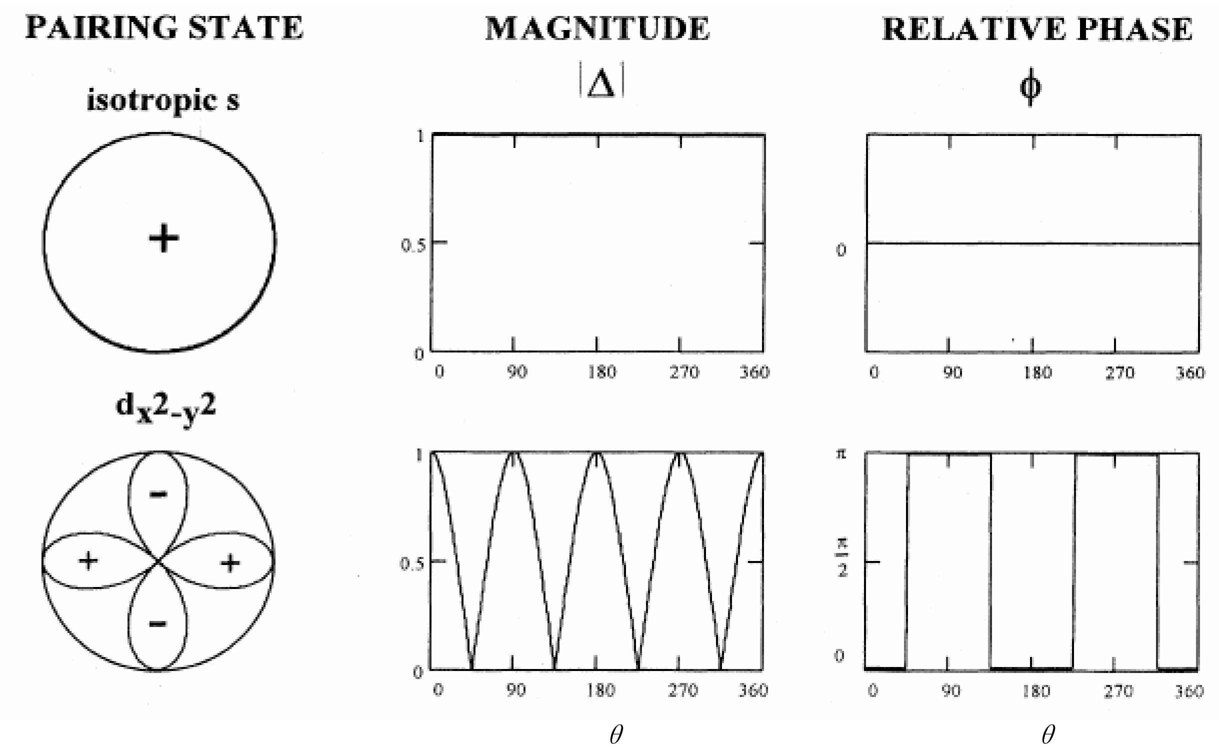


Single-crystallinity is important for the properties of HTS, including microwave properties such as *Q* and nonlinearity.

Symmetry of Gap in Superconductors

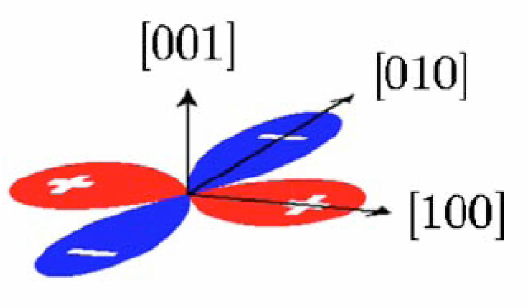
$YBa_2Cu_3O_{7-x}$





Van Harlingen, Rev. Mod. Phys. 67, 515 (1995)

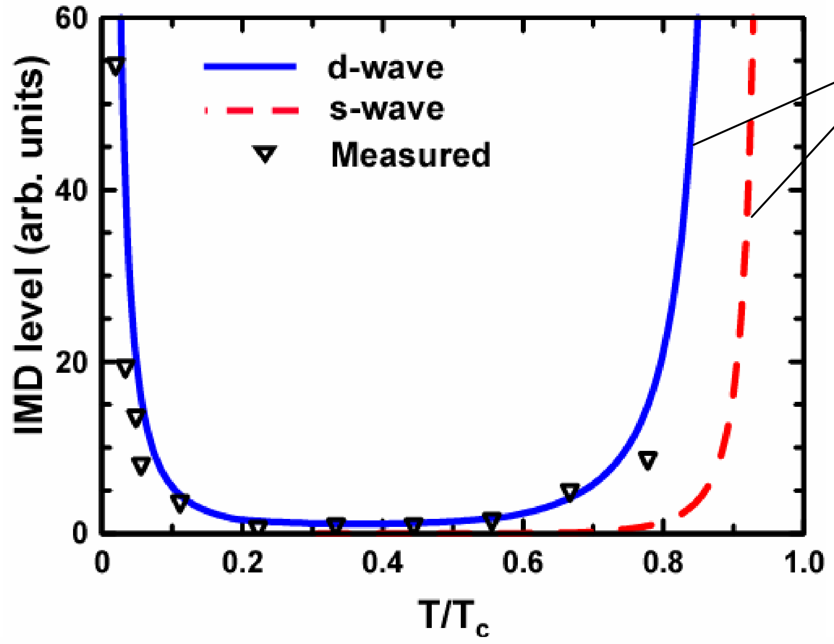
***d*-wave Gap Symmetry**



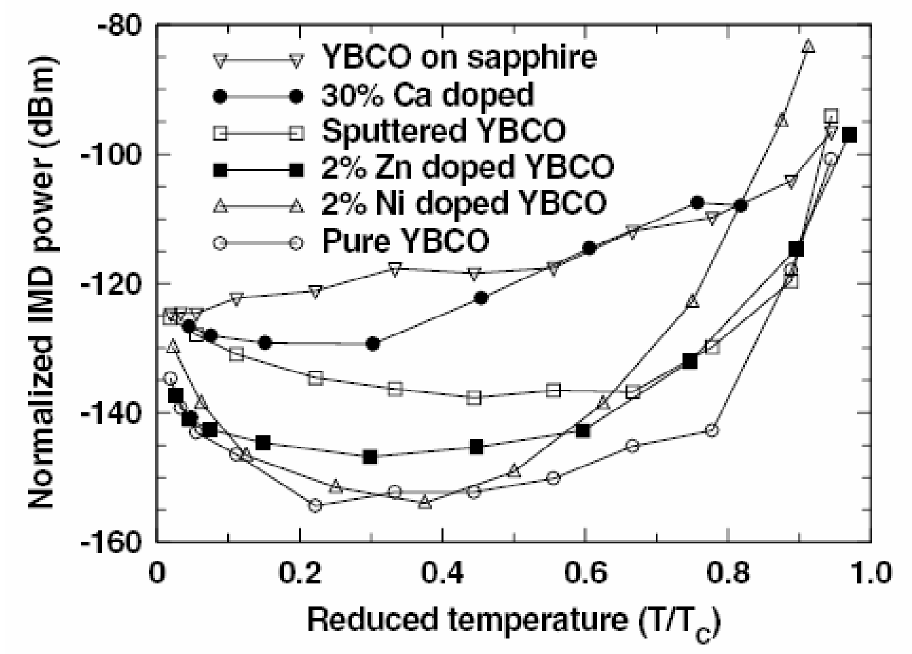
Fischer et al., Rev. Mod. Phys. 79, 353 (2007)

While conventional superconductors such as Nb are *s*-wave, high temperature cuprate superconductors are *d*-wave, having nodes in the gap.

Effect of *d*-Wave Symmetry on RF Nonlinearity



Dahm & Scalapino, PRB 60, 13125 (1999)



The *d*-wave symmetry of gap leads to nonlinear Meissner effect, characterized by an increase in intermodulation distortion (IMD).

Improvement of film quality does not help at low temperature.

Oates *et al*., PRL 93, 197001 (2004)

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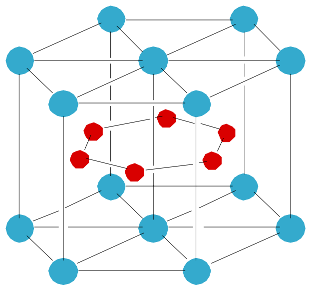
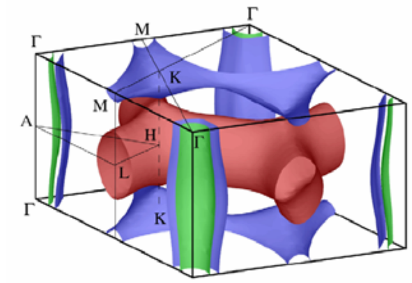
Larbalestier *et al*., Nature 414, 368 (2001)

MgB_2: An Exciting Superconductor

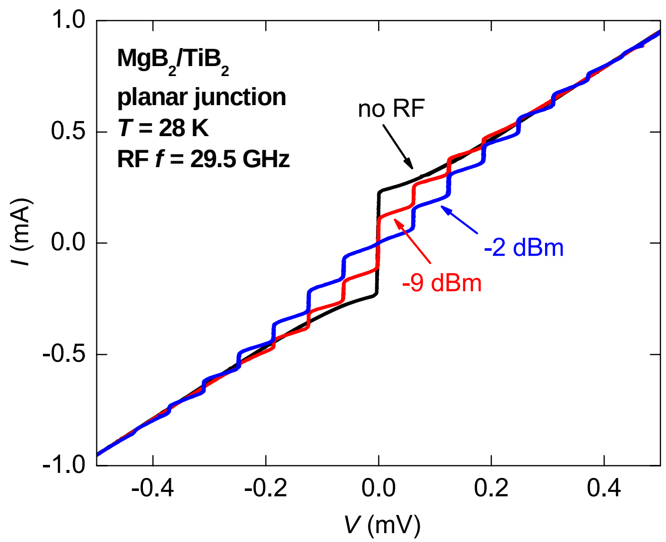




SCIENCE

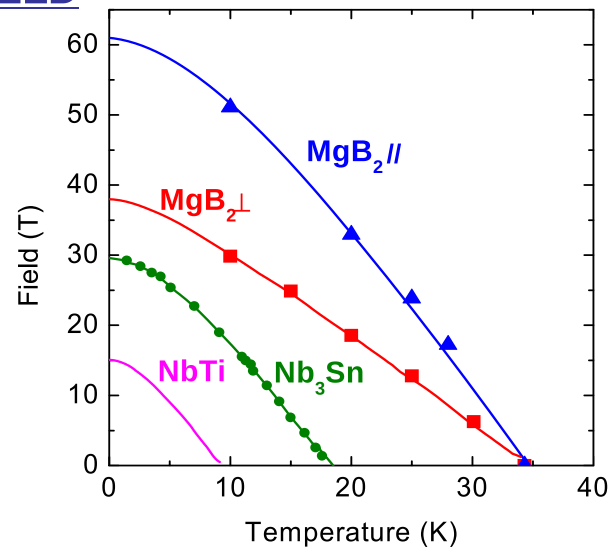
— BCS, T_c = 40 K
— Two bands with weak inter-band scattering: σ band and π band
— Two gaps: A superconductor with two order parameters

ELECTRONICS



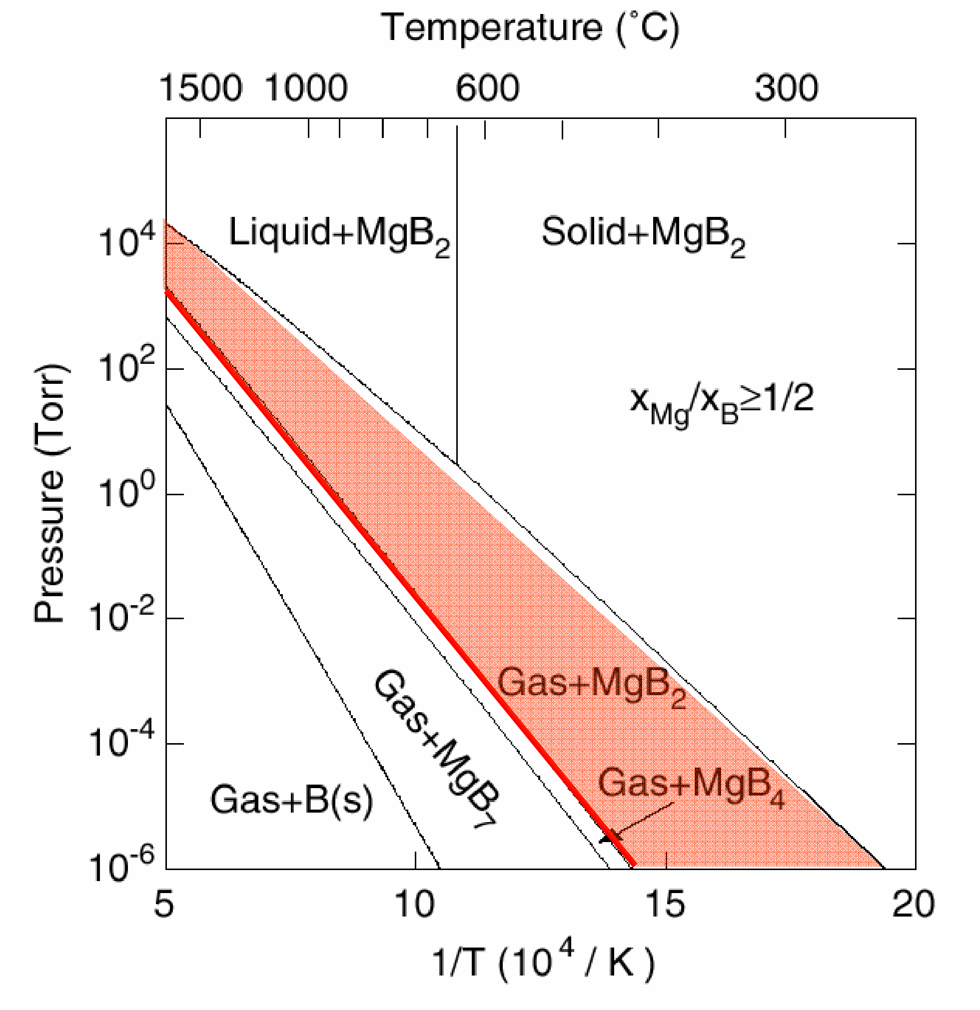
— No reproducible, uniform HTS Josephson junctions yet, may be easier for MgB_2
— 25 K operation, much less cryogenic requirement than LTS Josephson junctions
— Superconducting digital circuits

HIGH FIELD



— Low material cost, easy manufacturing
— High performance in field (H_{c2} over 60 T)
—Cryogen free, mobile MRI, high field magnets, etc.
— Filter Inductors and Transformers

Challenges in Growth of MgB_2 Films



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

PHASE STABILITY

— Mg pressure for the process window is very high for high temperature growth

For example, at 600° C Mg vapor pressure of 0.9 mTorr or Mg flux of 500 Å/s is needed

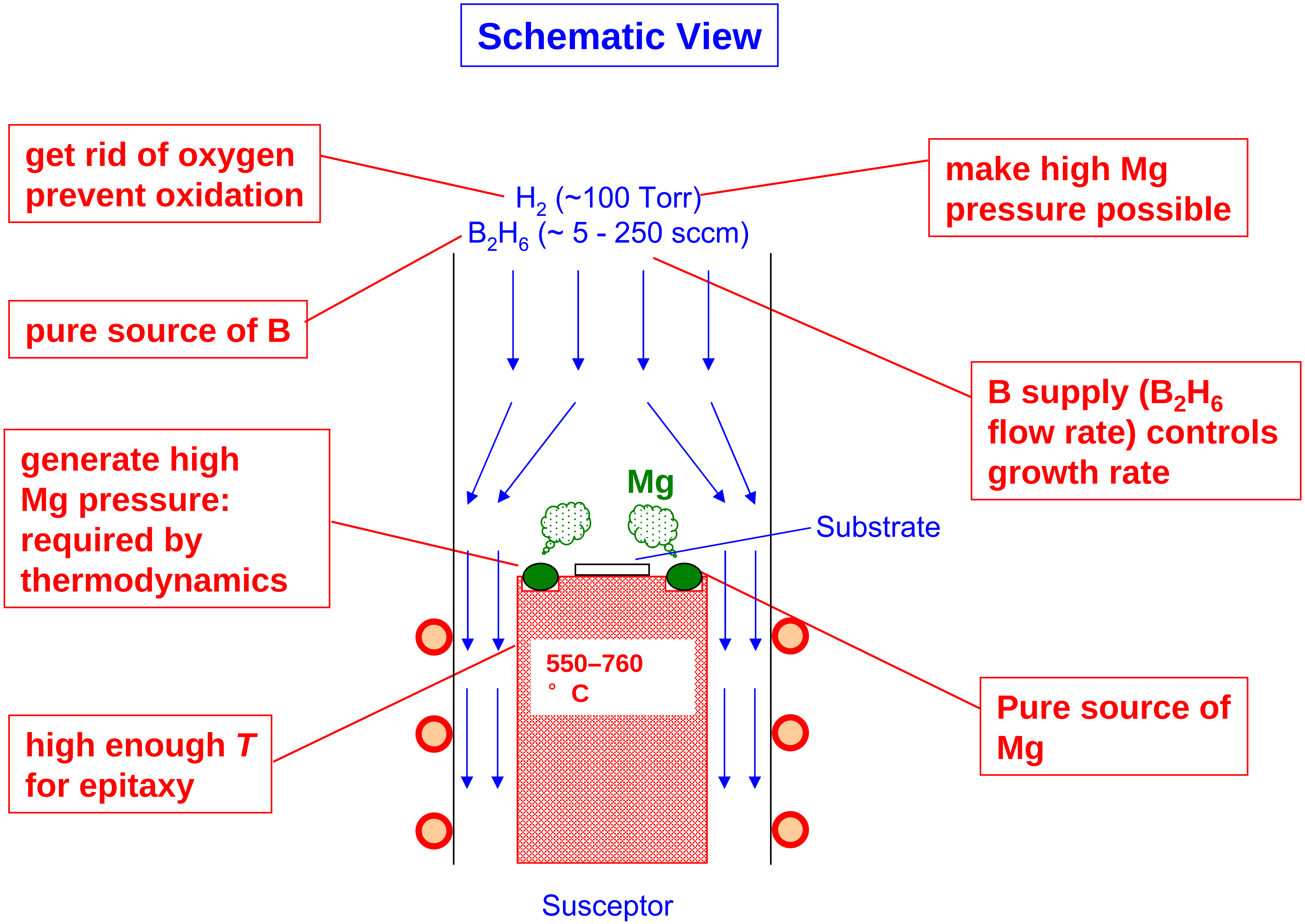
— Automatic composition control for all Mg:B ratio above 1:2.

CONTAMINATIONS

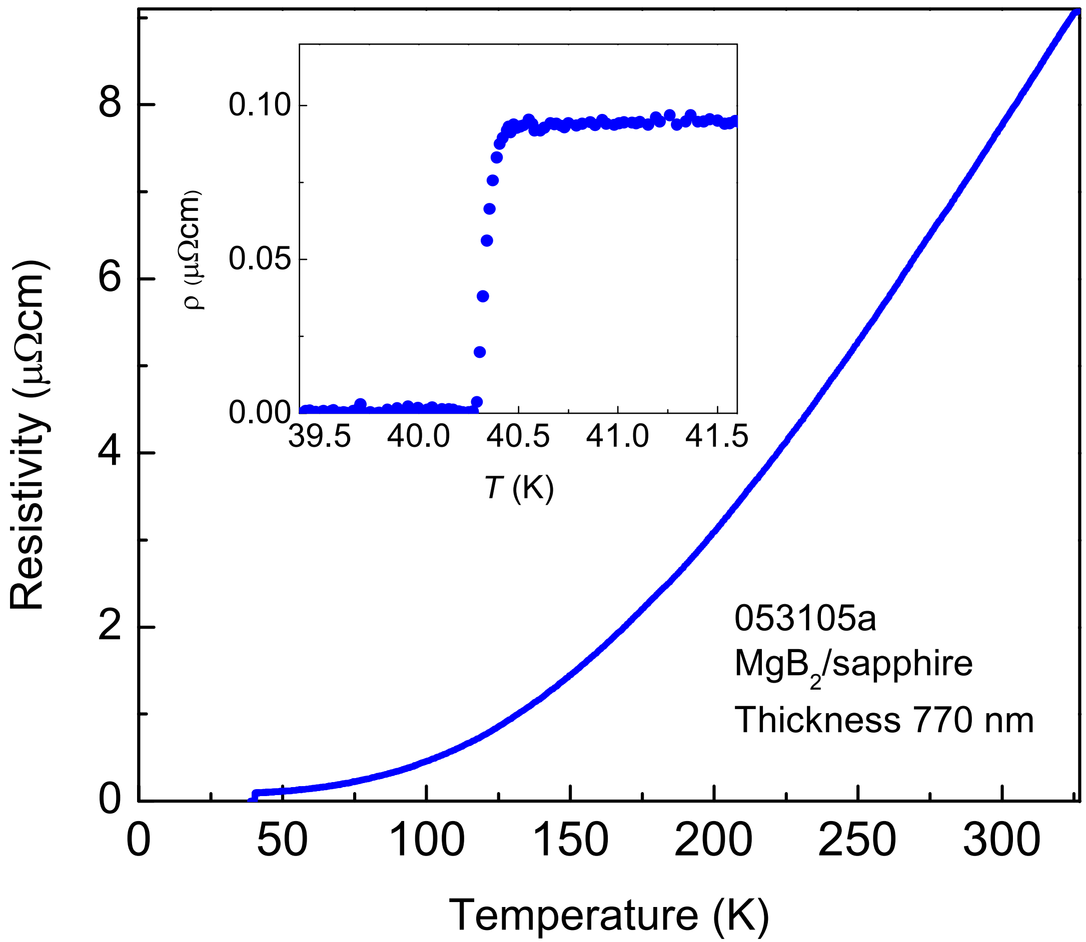
— Mg reacts strongly with ***oxygen***: forms MgO, reduces Mg vapor pressure. Requires UHV.

— ***Carbon*** doping: reduces T_c. Source materials should be carbon-free.

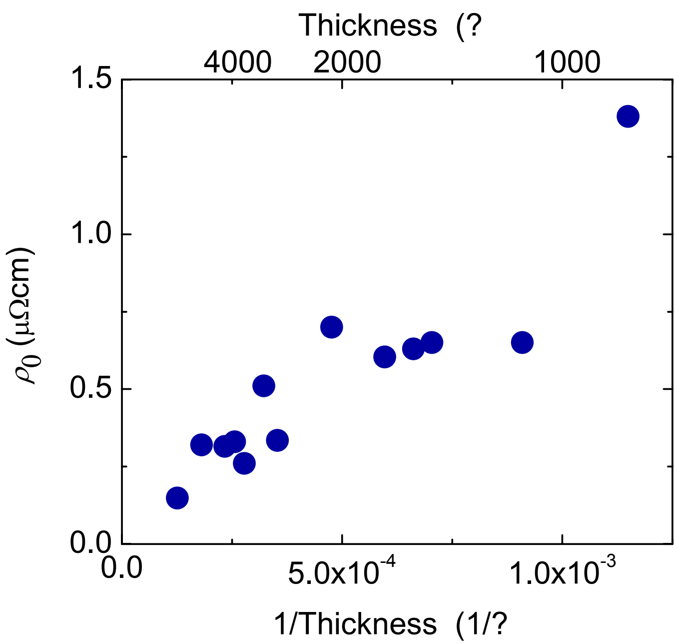
Hybrid Physical-Chemical Vapor Deposition



Very Clean HPCVD MgB_2 Films: *RRR* > 80



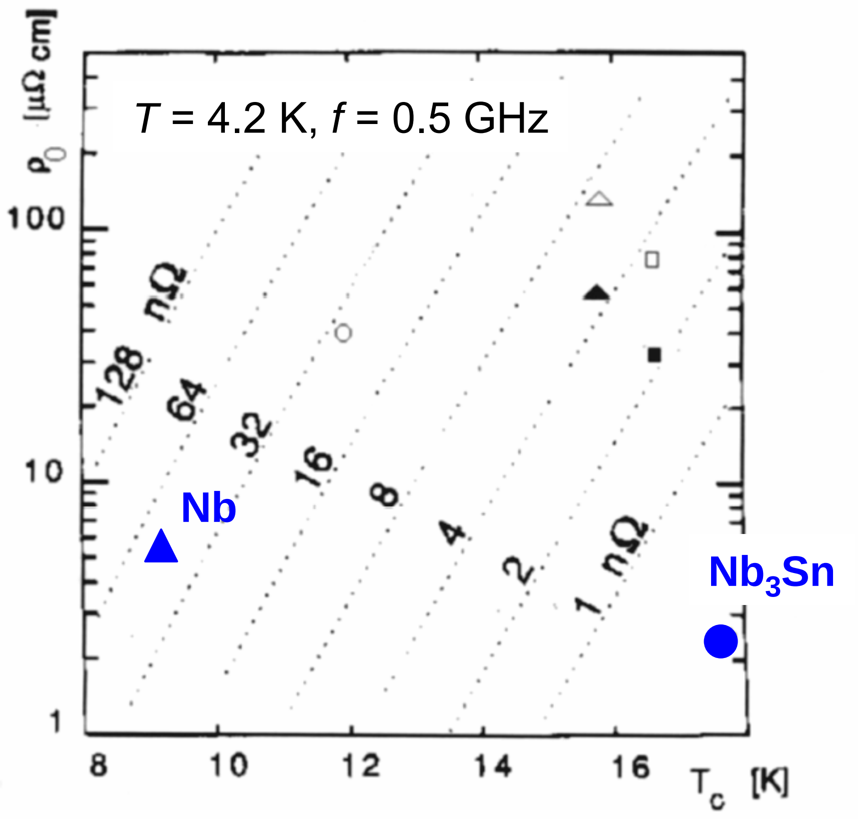
Mean free length is limited by the film thickness.



Xi *et al*, Physica C 456, 22 (2007)

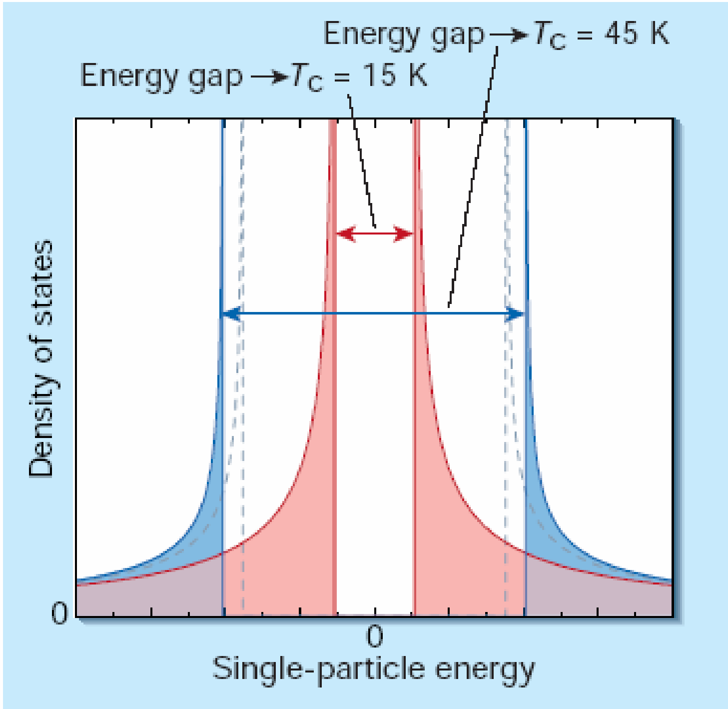
Potential Low BCS R_s for MgB_2 RF Cavity

R_s (BCS) versus (ρ_0, T_c)



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

Two Energy Gaps in MgB_2



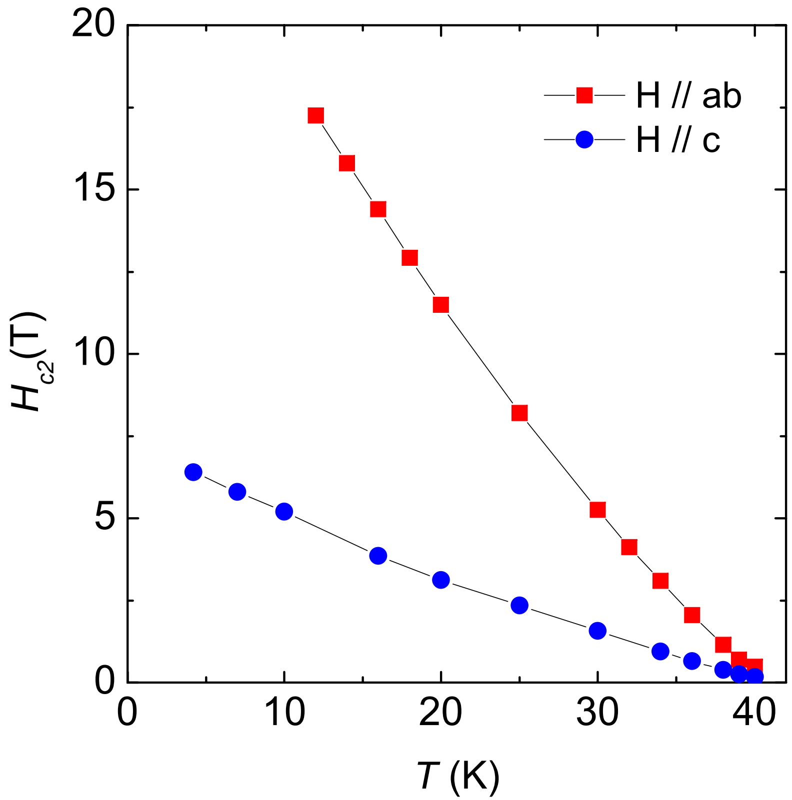
Pickett, *Nature* 418, 733 (2002)

R_s from π Gap **R_s from σ Gap**

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

Long ξ and Short λ in HPCVD MgB_2 Films

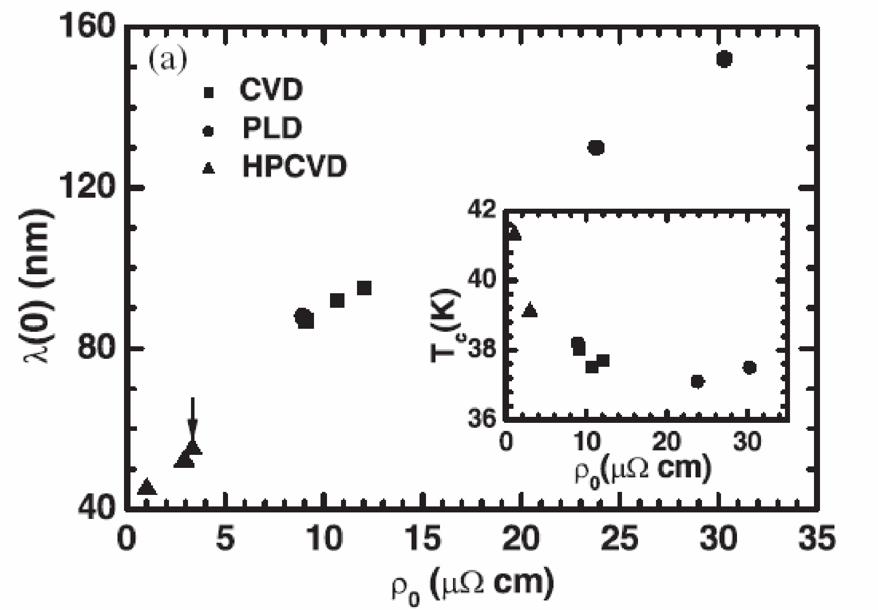
Upper Critical Field



$$H_{c2}(0) = \Phi_0/2\pi\xi_{ab}(0)^2$$

$$\xi_{ab}(0) \approx 7 \text{ nm}$$

Penetration Depth



Microwave measurement: sapphire resonator technique at 18 GHz.

$$\kappa = \lambda/\xi \approx 6$$

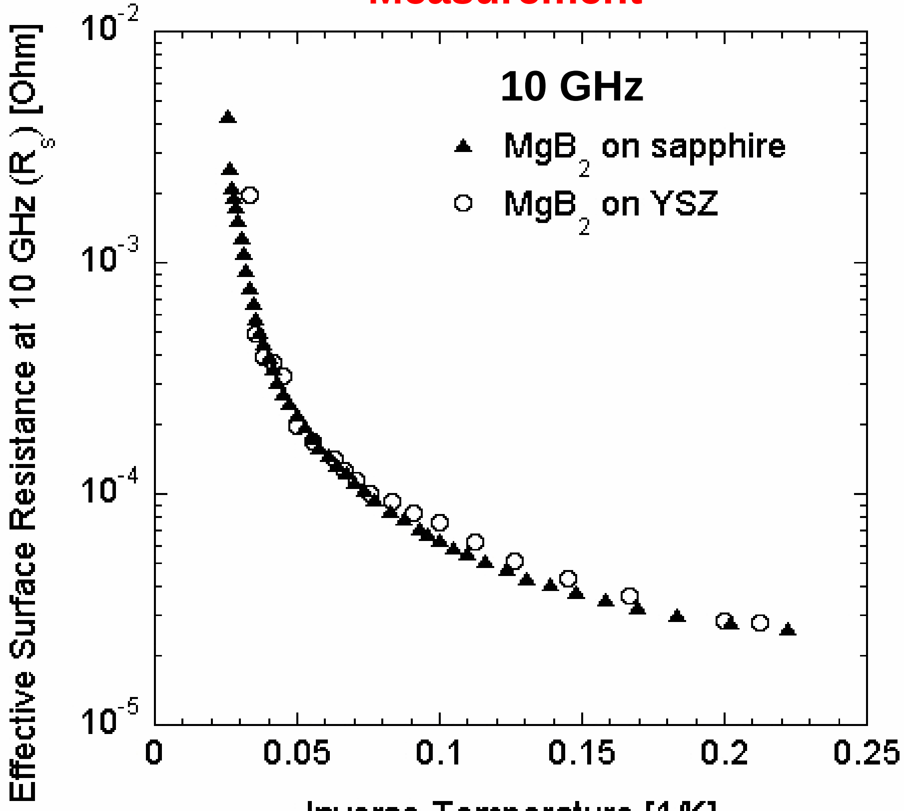
$$H_c = H_{c2}/\sqrt{2}\kappa \approx 820 \text{ mT}$$

$$H_{sh} \approx 0.75\, H_c \approx 620 \text{ mT}$$

Jin *et al*, SC Sci. Tech. 18, L1 (2005)

Polycrystalline HPCVD MgB_2 Films on YSZ

Parallel Plate Resonator Measurement

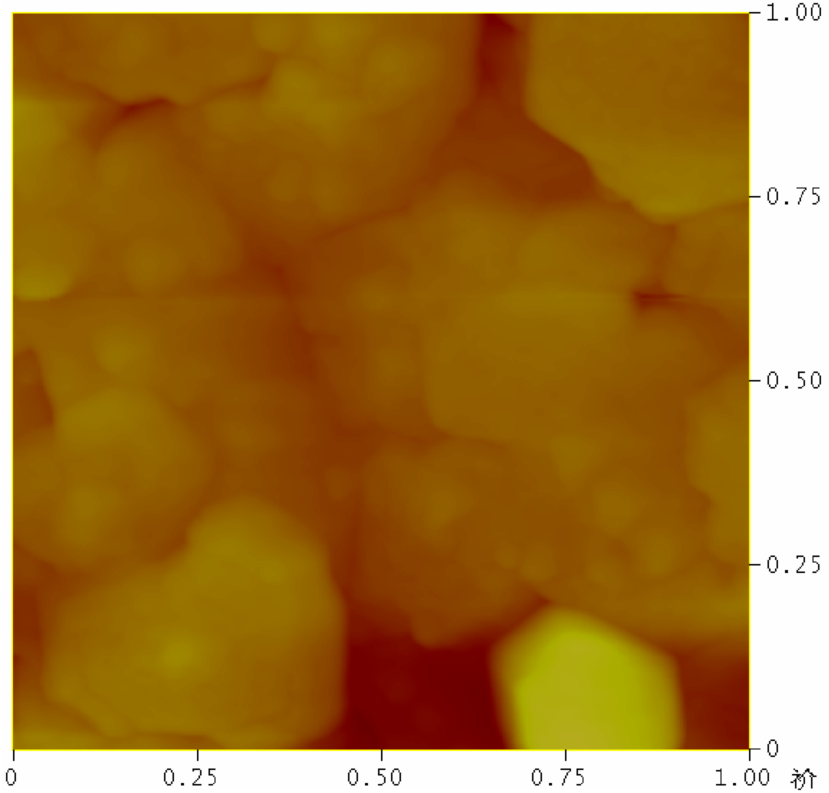


Polycrystalline MgB_2 films on YSZ grown by HPCVD show similar low R_s to epitaxial films on sapphire substrate.

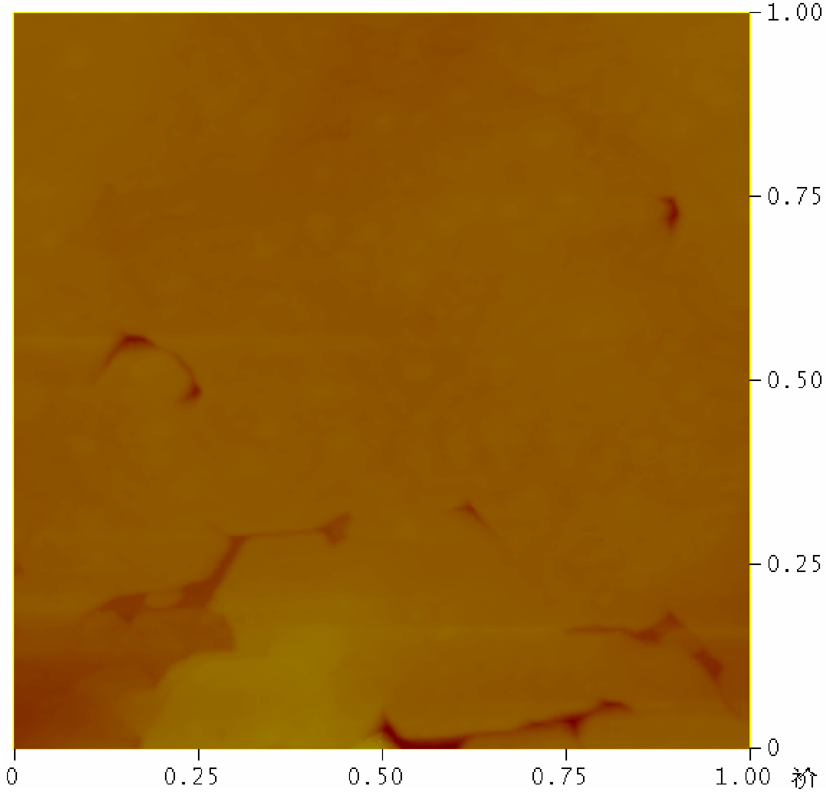
Pogrebnyakov *et al*, IEEE Trans. Appl. Supercond. 17, 2854 (2007)

Smooth Surface of HPCVD Films

Pure MgB_2



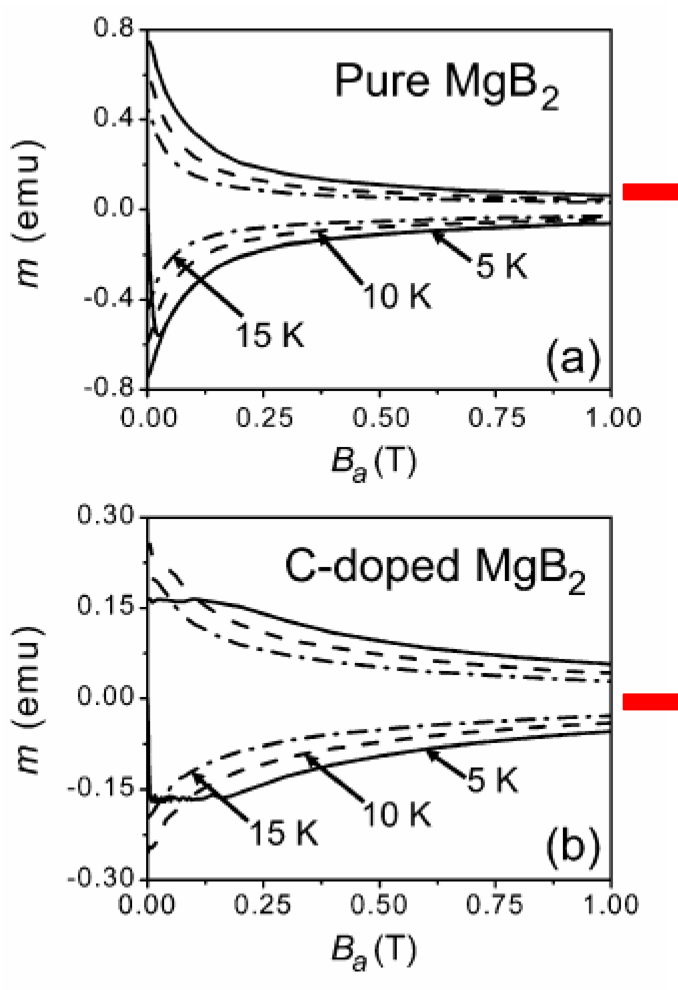
Small amount of N_2 added in the deposition atmosphere



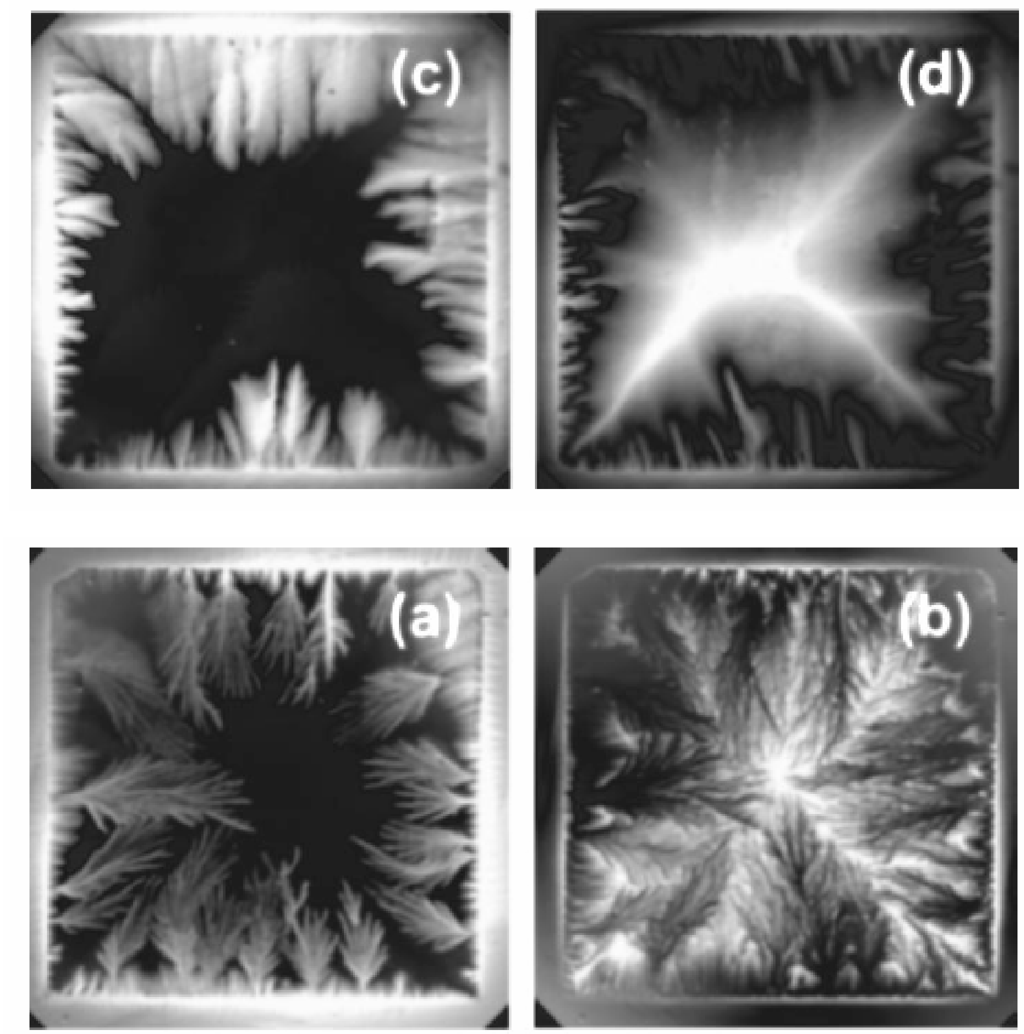
RMS Roughness = 3.64 nm

RMS Roughness = 0.96 nm

Absence of Dendritic Magnetic Instability in Clean HPCVD Films



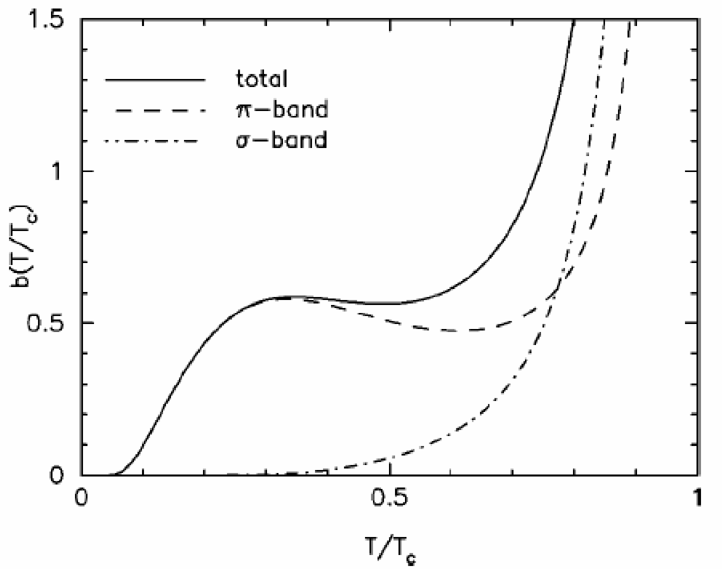
Flux Entry **Remnant State**



(Ye *et al. APL* 85, 5285 (2004))

Effects of Two Gaps on Microwave Nonlinearity

Nonlinear Coefficient of MgB_2

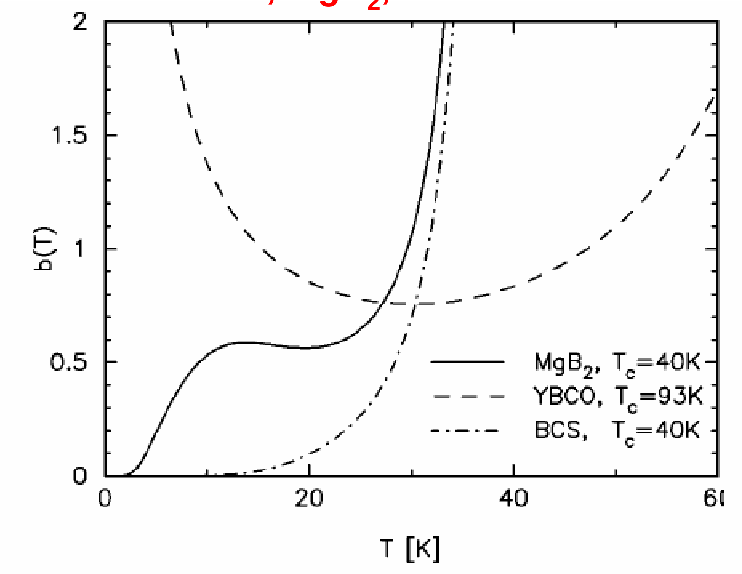


— It has been predicted theoretically that

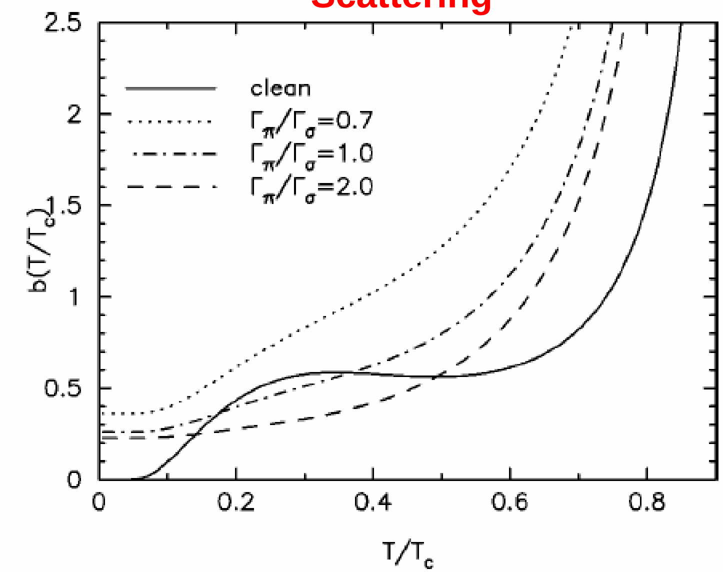
- nonlinearity in MgB_2 is larger than 40 K BCS superconductor due to existence of two bands.
- compares favorably with HTS at low temperature

— Manipulation of interband and intraband scattering could improve nonlinearity.

YBCO, MgB_2, & 40-K BCS SC

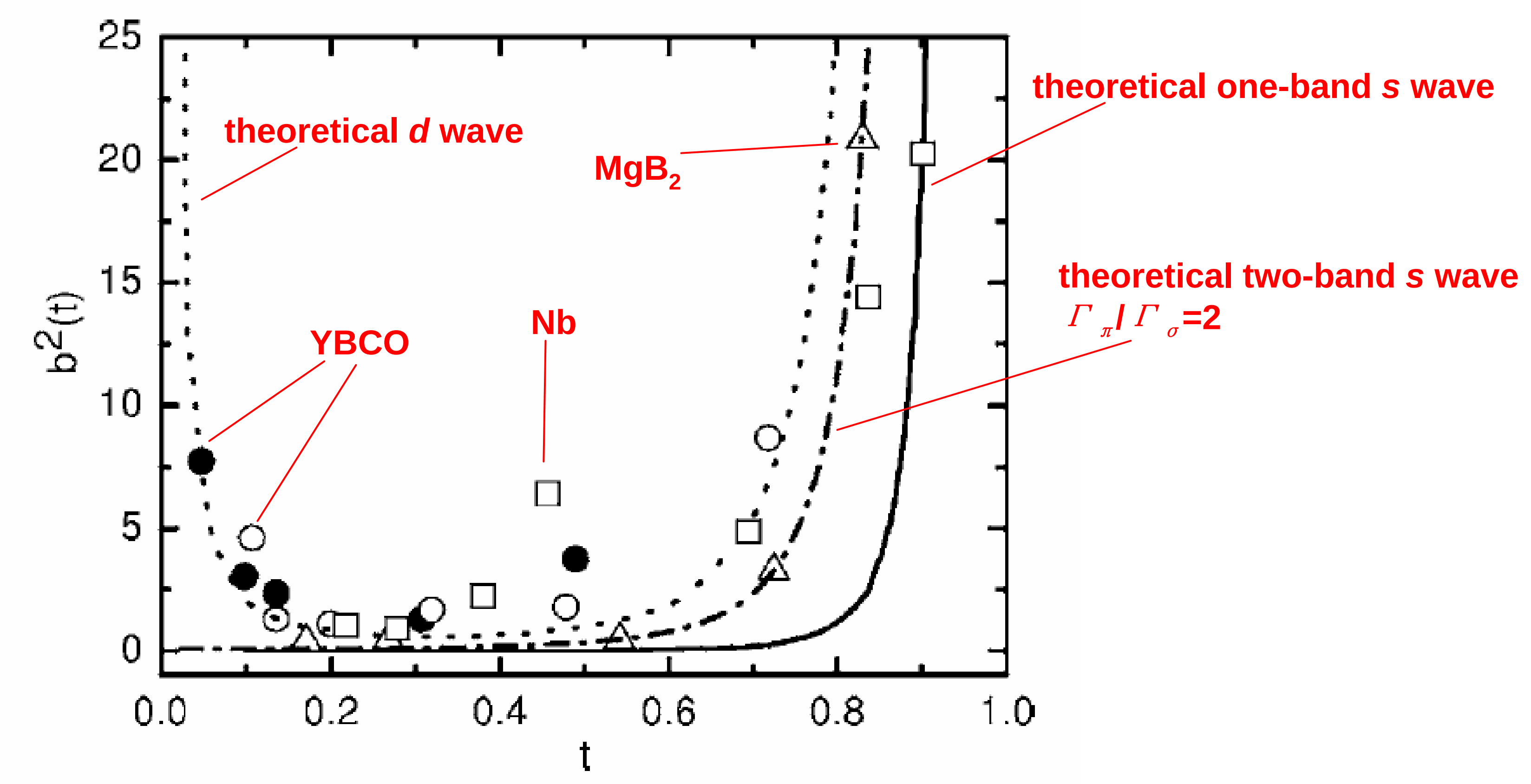


MgB_2 of Different Intraband Scattering



Dahm & Scalapino, APL 85, 4436 (2004)

Microwave Nonlinearity of HPCVD MgB_2 Films



— Result in agreement with Dahm – Scalapino prediction.

— Modification of interband and intraband scattering key to low nonlinearity.

Cifariello *et al*, APL 88, 142510 (2006)

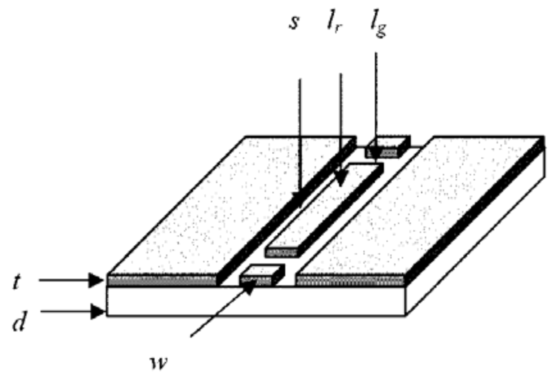
HPCVD System at Peking University

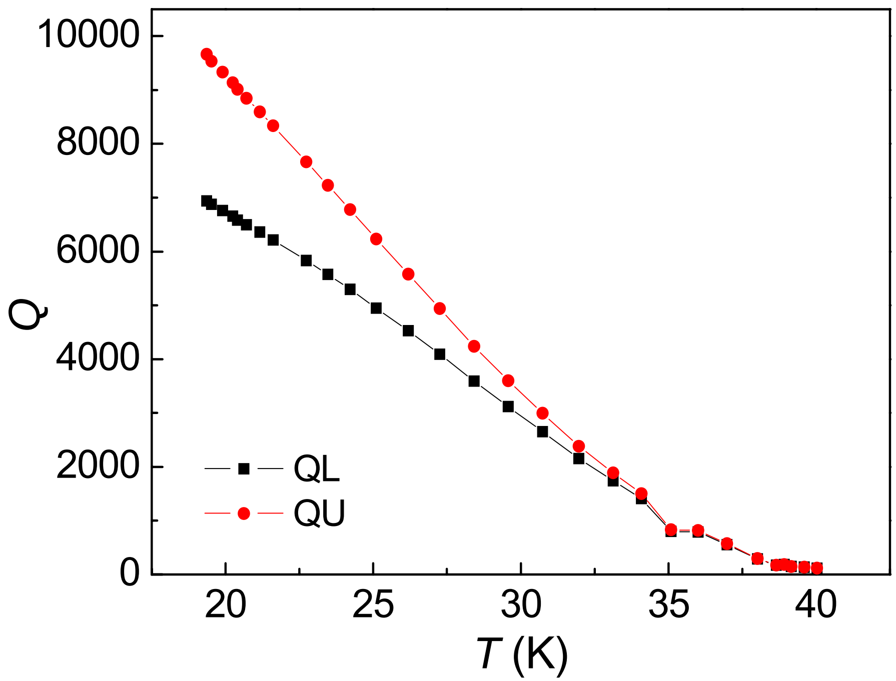
HPCVD Lab

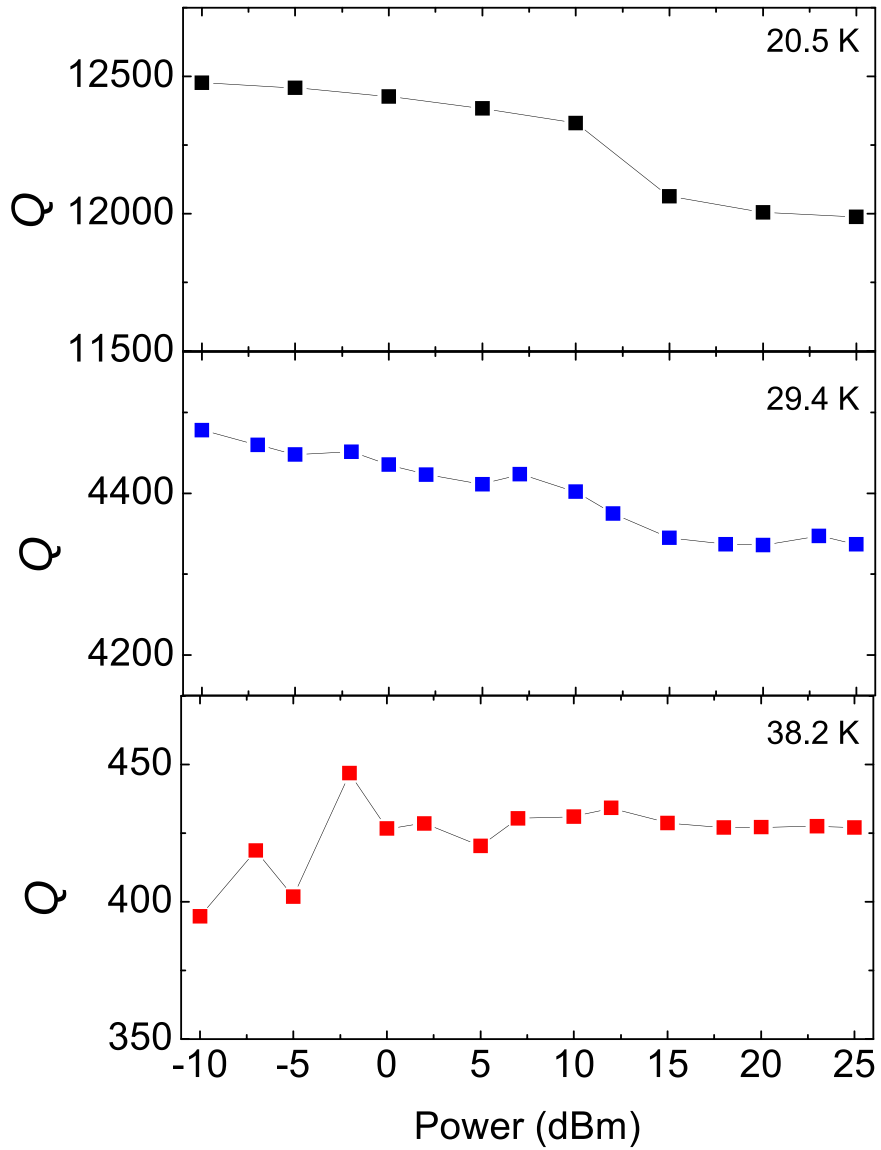
HPCVD Reactor

Microwave Properties of PKU HPCVD Films

Transmission Line Measurement at 10 GHz



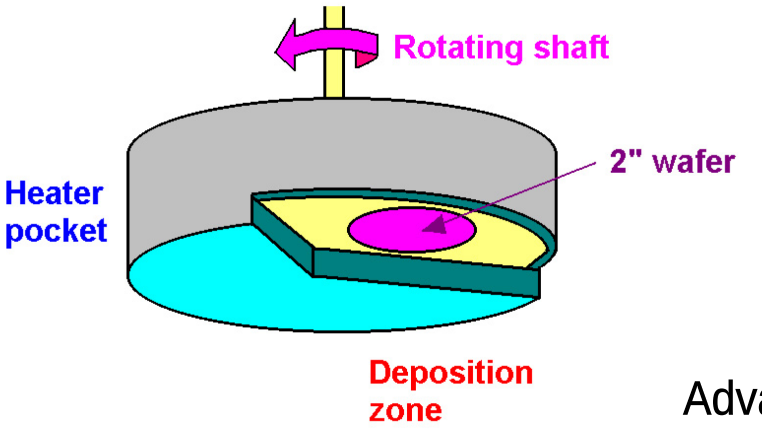




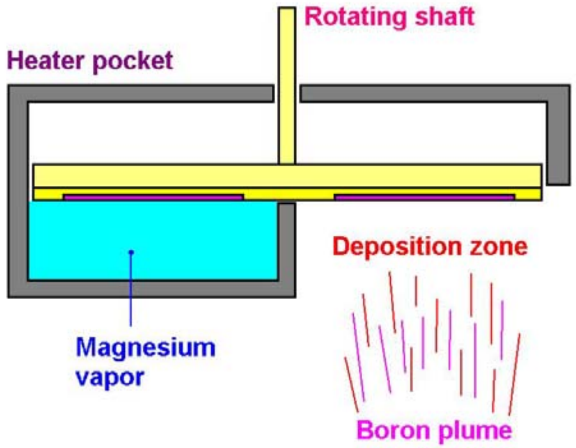
He *et al*, IOP, CAS

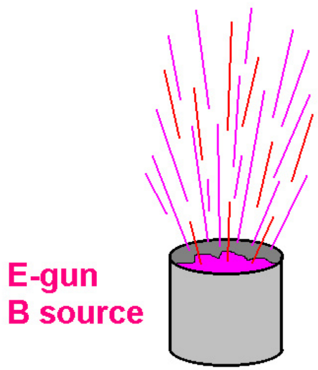
Technical Approach

Reactive evaporation using the *pocket heater*
Directly addresses MgB_2 growth difficulties



Rotating blackbody heater



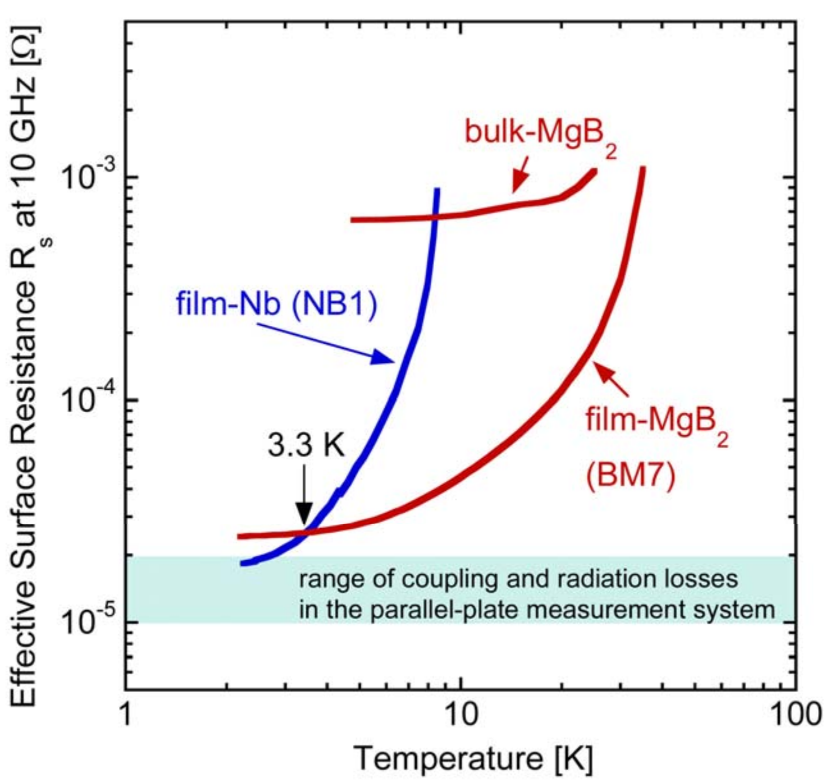


Advantages:

- Localized source of high-pressure Mg vapor
- Negligible MgO in the pocket
- B evaporation in vacuum
- No need to control Mg/B flux ratio
- Ability to separate substrate *T* from Mg *T*
- Uniform growth on multiple large-area substrates
- Non-contact: Double-sided deposition possible
- Can try a variety of substrate materials at once

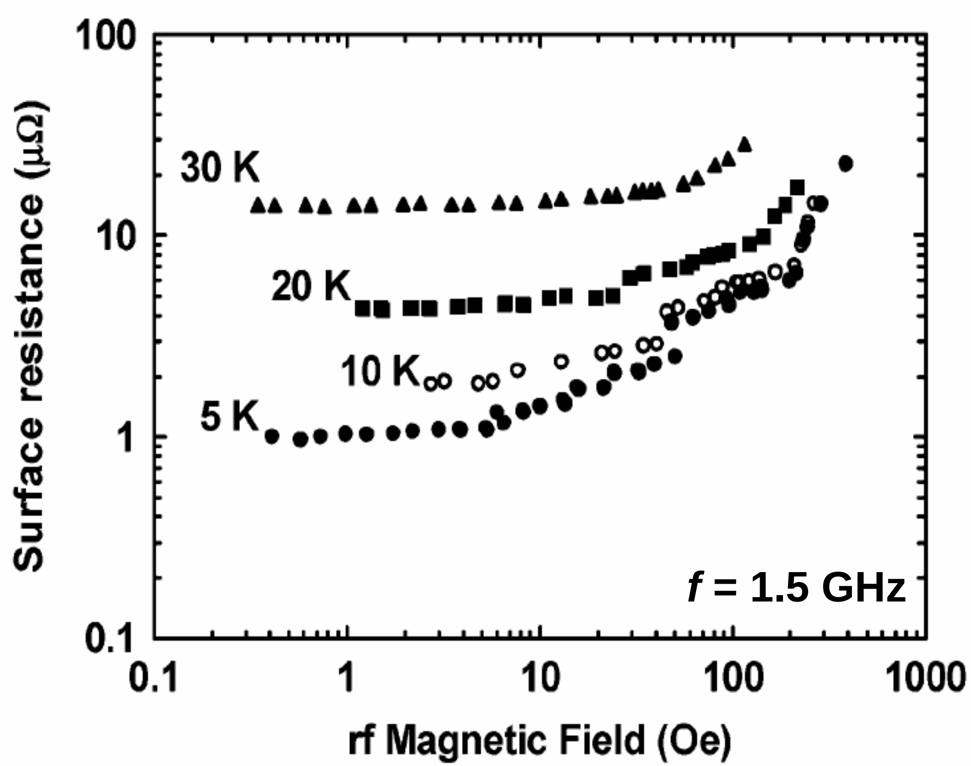
Microwave Nonlinearity in STI Films

Parallel Plate Resonator Measurement



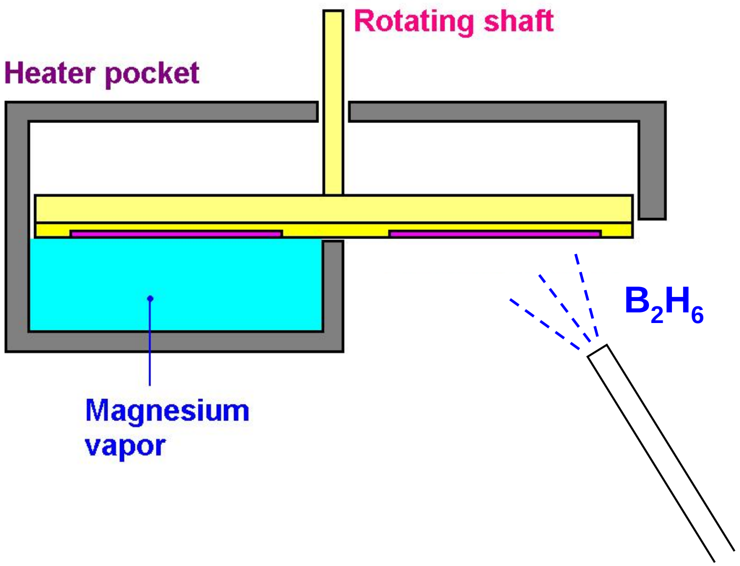
(Moeckly *et al*. IEEE Trans. Appl. Supercond. 15, 3308 (2005))

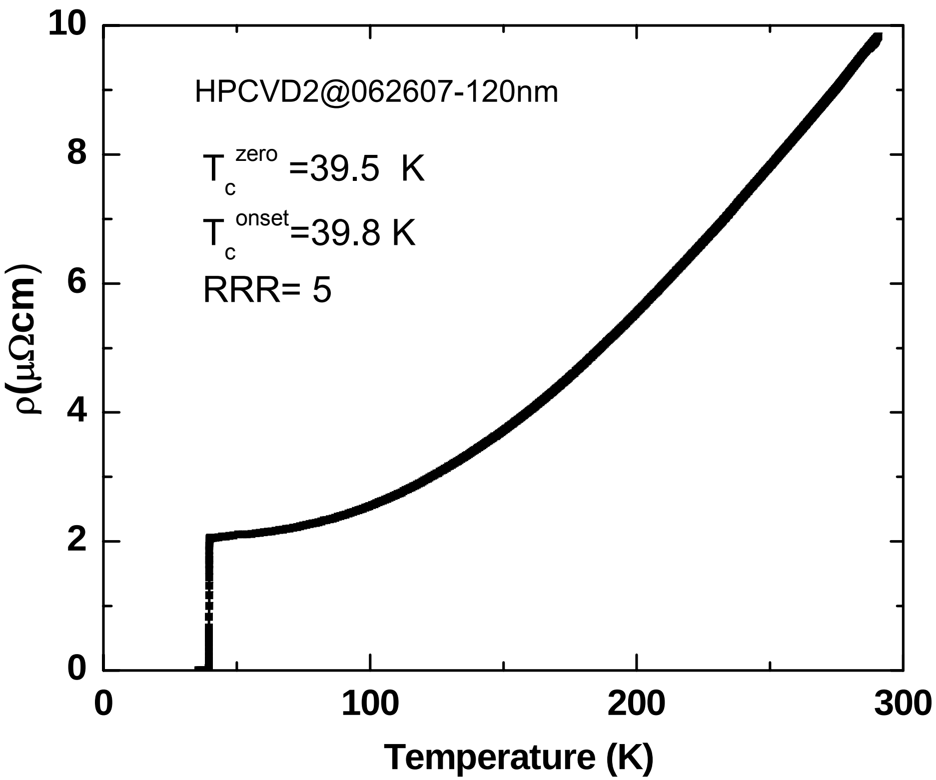
Stripline Resonator Measurement



Oates, Agassi, and Moeckly, IEEE Trans. Appl. Supercond. 17, 2871 (2007)

HPCVD Using Pocket Heater





Differences from reactive co-evaporation:

— B_2H_6 used as boron source instead of e-beam evaporation

— Hydrogen used as the carrier gas instead of HV

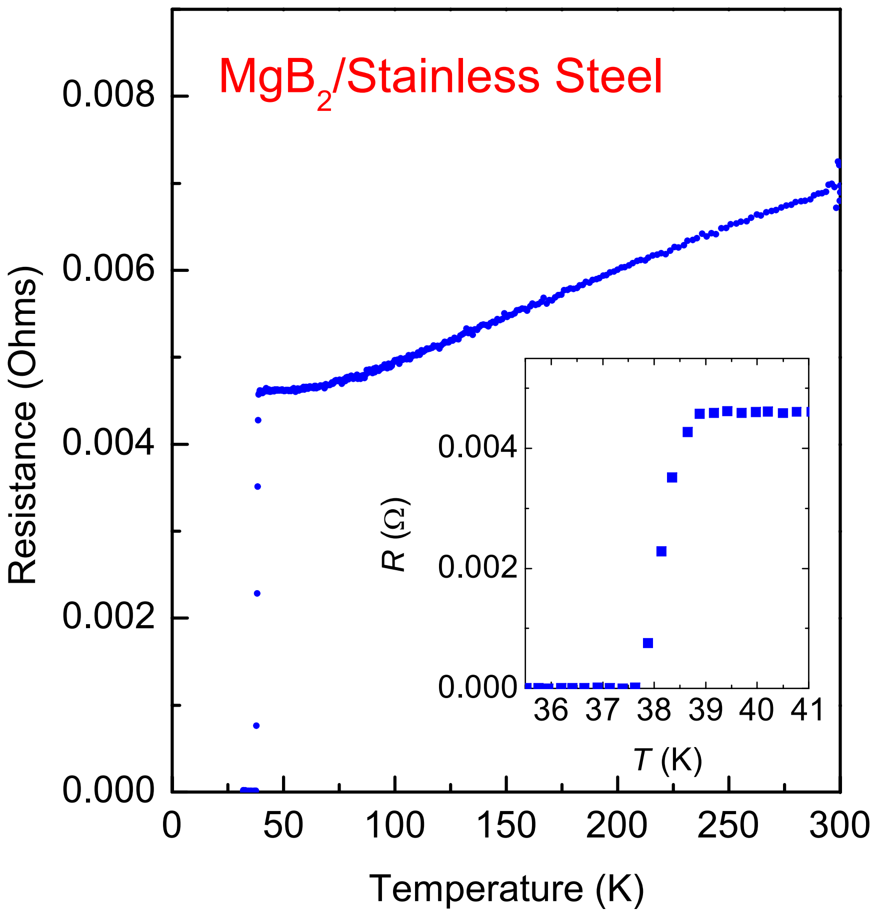
— Deposition temperature in broader range

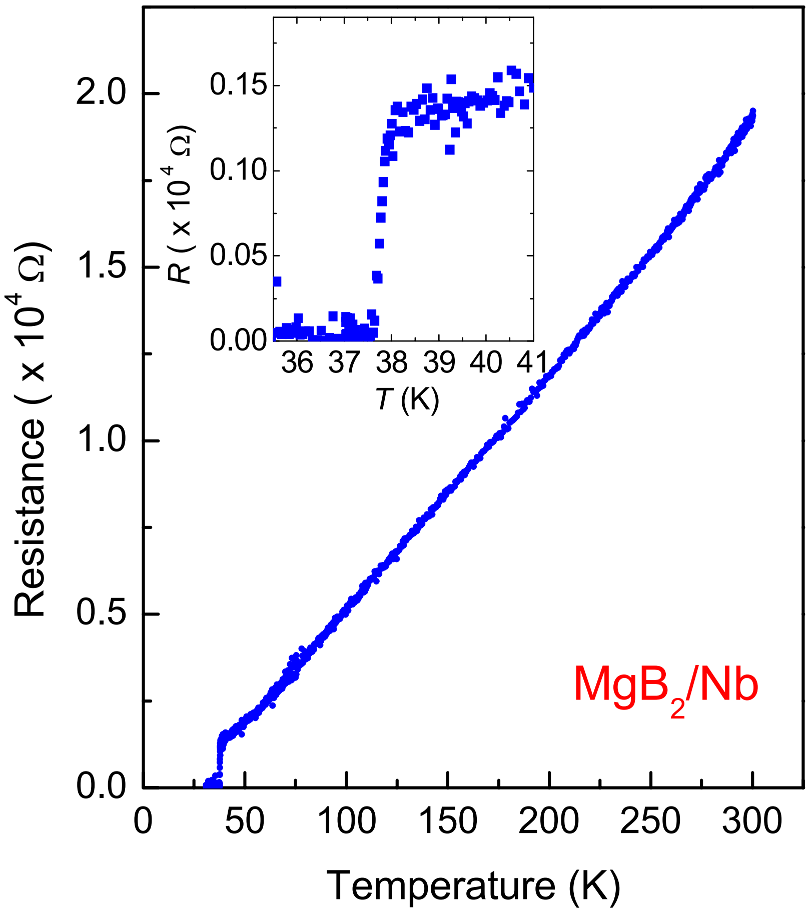
Advantages:

— Large area and double sided films

— Potential for scale up for wires

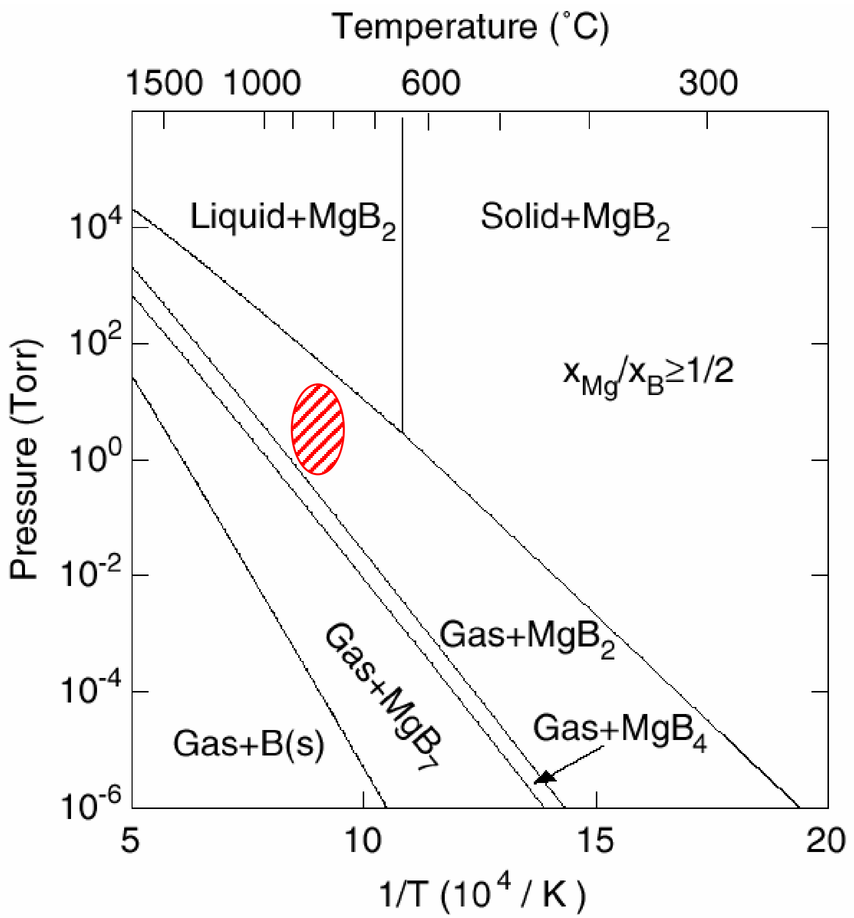
HPCVD MgB_2 Films on Metal Substrates

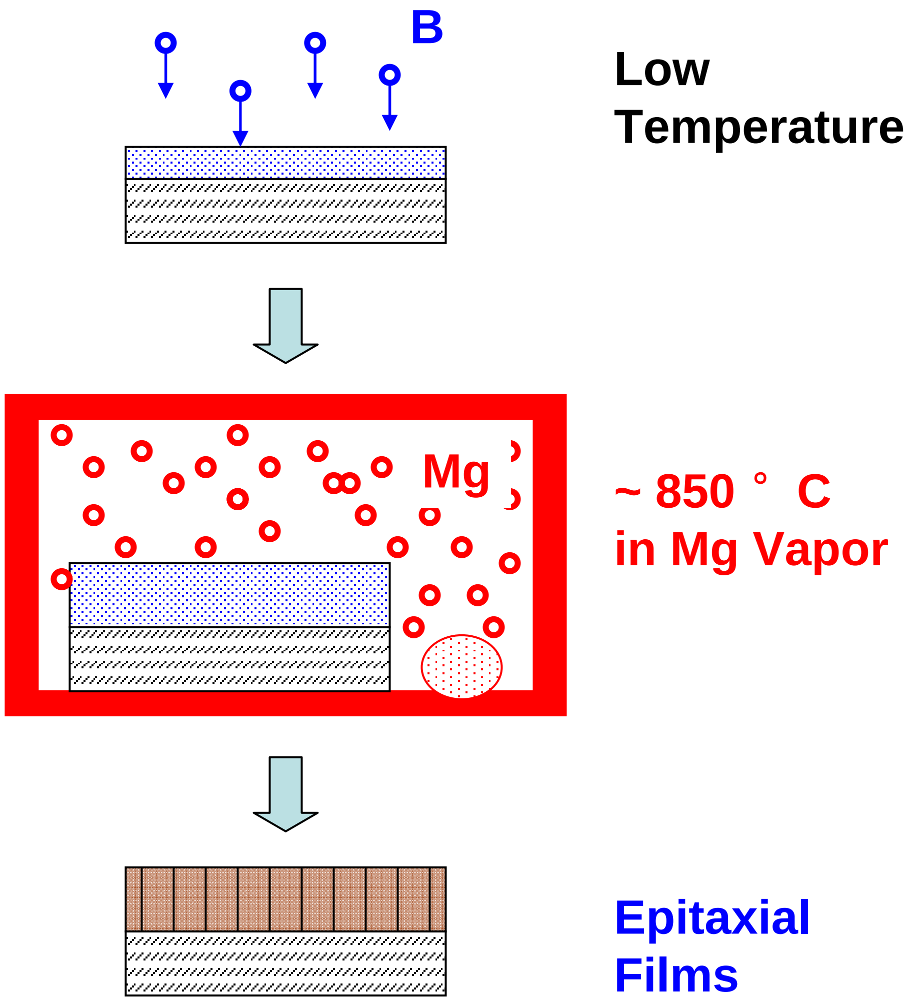




High T_c has been obtained in polycrystalline MgB_2 films on stainless steel, Nb, TiN, and other substrates.

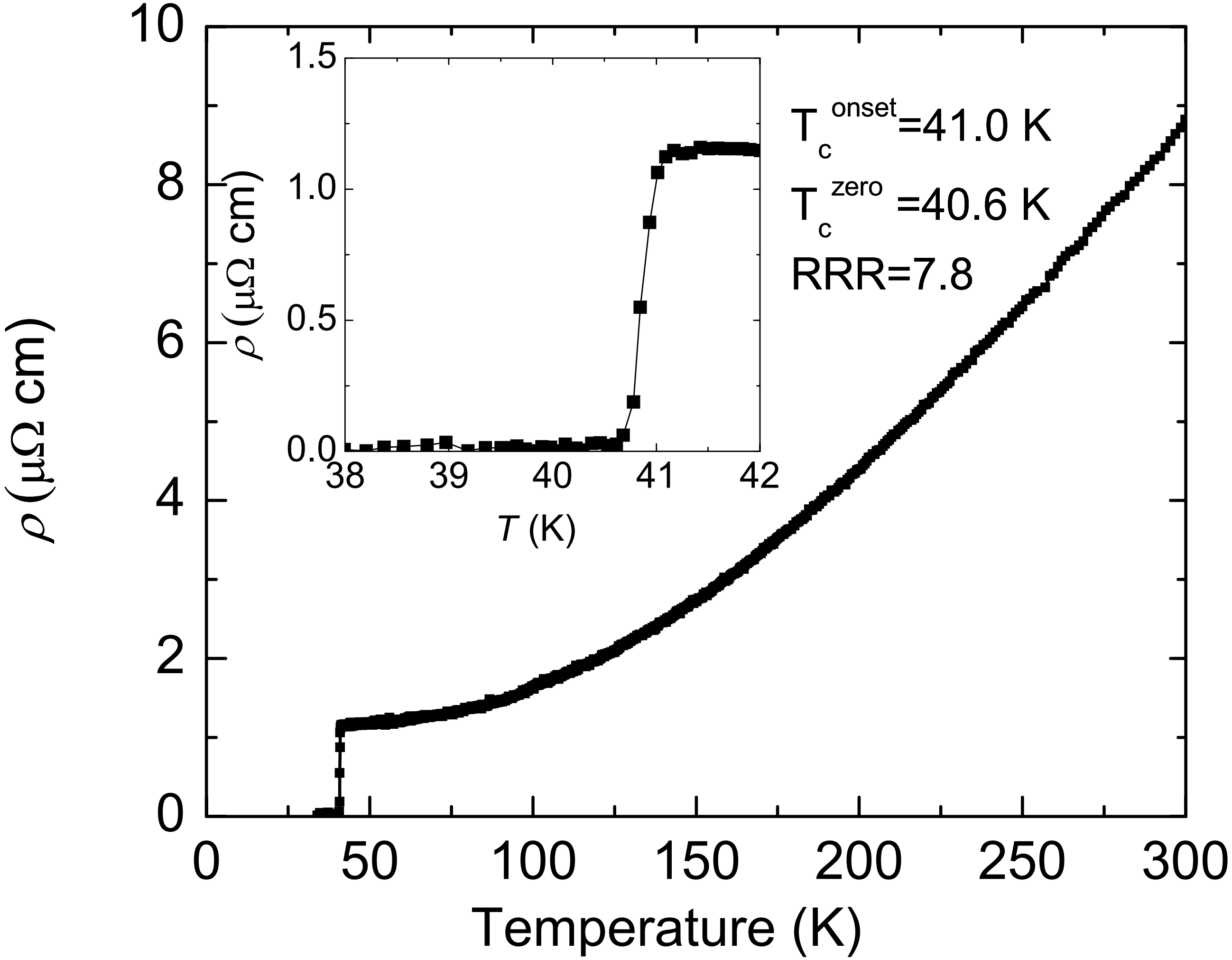
High-Temperature *Ex-Situ* Annealing





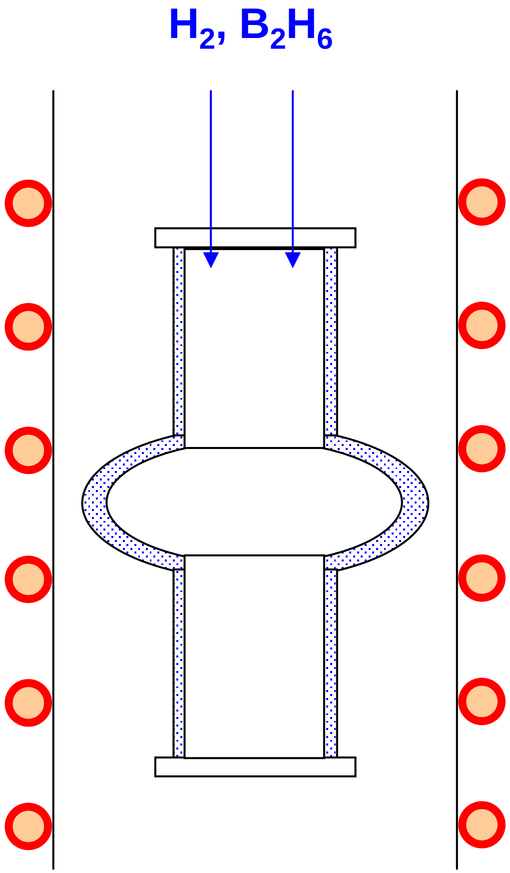
Kang *et al*, Science 292, 1521 (2001)
Eom *et al*, Nature 411, 558 (2001)
Ferdeghini *et al*, SST 15, 952 (2001)
Berenov *et al*, APL 79, 4001 (2001)
Vaglio *et al*, SST 15, 1236 (2001)
Moon *et al*, APL 79, 2429 (2001)
Fu *et al*, Physica C377, 407 (2001)

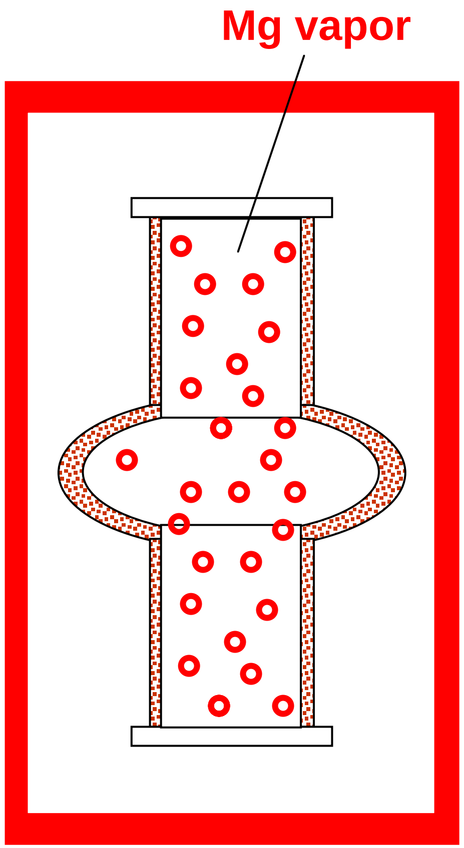
MgB_2 Film by Reaction of CVD B Film



Clean B precursor layer leads to clean MgB_2 film.

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

Conclusion

— For higher T_c superconductors beyond Nb for RF cavities, materials with high T_c, low residual resistivity, low microwave nonlinearity, and high H_c and H_{sh} are required for high Q and high ultimate RF critical field

— A15 compounds such as Nb_3Sn are promising

— Due to short coherence length and *d*-wave gap symmetry, high-T_c cuprate superconductors show poor power dependence

— Clean MgB_2 thin films have excellent properties:

- low resistivity (<0.1 $\mu\Omega$cm) and high T_c promise low BCS surface resistance
- long coherence length and short penetration depth promise high H_c ~ 820 mT
- smooth surface (RMS roughness < 10 Å)
- well connected grains and clean grain boundaries
- good thermal conductivity (free from dendritic magnetic instability)
- nonlinearity properties can be tuned by changing scattering in the two bands, e.g. by carbon doping

— Coating RF cavities with MgB_2 is feasible:

- films on some metallic substrates, polycrystalline films maintain good properties
- MgB_2 films prepared by reacting CVD boron films with Mg vapor show good properties. The technique is compatible to coating of cavities.