INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION

INTERNATIONAL CENTRE FOR SCIENCE AND HIGH TECHNOLOGY

c/o INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS 34100 TRIESTE (ITALY) VIA GRIGNANO, 9 (ADRIATICO PALACE) P.O. BOX 586 TELEPHONE 040/22472 TELEFAX 040/224575 TELEX 460449 APH I

SMR/543 - 10

EXPERIMENTAL WORKSHOP ON
HIGH TEMPERATURE SUPERCONDUCTORS AND RELATED MATERIALS
(BASIC ACTIVITIES)

(11 February - 1 March 1991)

" High Temperature Superconducting Thin Films and Their Applications "

PART I

presented by:

N.F. PEDERSON
The Technical University of Denmark
Physics Laboratory I
Building 309
DK-2800 Lyngby
Denmark

# HIGH TEMPERATURE SUPERCONDUCTING THIN FILMS AND THEIR APPLICATIONS

N.F. PEDERSEN

PHYSICS LABORATORY 1, TECHN. UNIV DENMARK
DK-2800 LYNGBY, DENMARK.

3 LECTURES

1) THIN FILMS
2) JOSEPHSON JUNCTIONS
3) APPLICATIONS

I MAKE REFERENCE TO LOW $T_c$ TO PUT IN PERSPECTIVE.

PRESENTATION OF LABORATORY.
(PHYSICS LABORATORY I)

| Low $T_c$ | high $T_c$ |
|---|---|
| since 1970 | since 1987. |
| thin films. | thin films |
| Niobium technology | YBCO , BSCCO |
| Josophson junctions | ↓ |
| Superconducting circuits | |
| samplers | to come |
| mixers | |
| paramps | |
| SQUIDS | |

## Low $T_c$

Tin → Lead → Niobium → Niobium nitride

$\xi \sim 500 - 1000$ Å

Niobium is a getter for oxygen
it took many years to get good junctions

now : Niobium based thin film electronics

## high $T_c$

$\xi \sim 5 - 30$ Å

materials problems

???

[illegible]

HTS thin film fabrication

Materials
- YBCO
- BSCCO
- TBCCO

Substrates

Fabrication methods
- sputtering
- laser deposition
- e-beam coevaporation
- effusion cells —"—
- MOCVD

ESTEC CONTRACT No. 8007/88/NL/PB(SC) March 1990

# HIGH TEMPERATURE SUPERCONDUCTORS:

# ASSESSMENT STUDY FOR SPACEBORNE SENSORS APPLICATIONS.

Prepared by:

G. Brorsson, T. Claeson, M. Danerud, J. Edstam, Z. Ivanov, and P.-Å. Nilsson, Chalmers University of Technology, Göteborg, Sweden.

U. Helmersson, Linköping University, Linköping, Sweden.

S. Rudner, Swedish Defence Research Establishment, Linköping, Sweden.

S. Dahl-Petersen, T. Freltoft, J. Hyldtoft, and P. Vase, NKT A/S, Brondby, Denmark.

M.T. Levinsen, University of Copenhagen, Copenhagen, Denmark.

J.B. Hansen, C.S. Jacobsen, and N.F. Pedersen, Technical University of Denmark, Lyngby, Denmark.

Contractor:

Physics Laboratory 3, Technical University of Denmark, DK-2800 Lyngby, Denmark.
Report No. RP9001A.

Technical supervisor from ESA:

E. Armandillo, ESTEC.

Contractual management:

P.J. De Boer, ESTEC.

## General Requirements for Thin Films and Multilayers

PHYSICAL/GEOMETRICAL:

* Formation at lowest possible processing temperature (preferably near room temperature - for lift-off patterning)
* Minimal interdiffusion at interfaces
* Adhesion to substrate
* Thermal compatibility with substrate (comparable thermal expansion coefficients)
* Surface smoothness (1 to 10 nm)
* Large, uniform area, e.g. on a 7.5 to 10 cm diameter wafer
* Chemically passive or protected/passivated surface
* Phase purity
* Epitaxial compatibility with substrates (epi-films)
* Controllable orientation, low defect concentration, no grain boundaries (epi-films)

ELECTRICAL:

* Critical temperature: $T_c \geq 2T_{op}$
* Lower critical field: $H_{c1}(T_{op}) >> H_{op}$ (most cases)
* Self-field critical current density: $J_c(T_{op}) > 10^6$ A/cm$^2$
* Rf surface resistance: $R_s(f_{op},T_{op},H_{op}) << 0.01R_s(f_{op},T_{op})$ of Cu
* Low $\epsilon'$ and low tan$\delta$ film substrate: $\tan\delta(f_{op},T_{op}) < 10^{-6}$
* Flux noise power: $S_\Phi(f,T_{op}) < 10^{-10}\,\Phi_o^2 Hz^{-1}$ at $f > 1$ Hz (measured in a ring specimen)
* Depth of surface/interface $T_c$ ($\Delta$) degradation: $d_c << \xi(T_{op})$

reference: A. Braginski 1990

# MATERIALS

YBCO

Epitaxial C-axis films — best

lowest noise

TBCCO — very promising

BSCCO

too much flux flow noise

# SUBSTRATES

| Group | | Crystal System | Structure | Lattice Constants | Thermal expansion coefficient |
|---|---|---|---|---|---|
| MATERIALS | YBCO | orthorhombic | oxygen deficient perovskite | a=3.82Å<br>b=3.89Å<br>c=11.68Å | 10-15E-6/K |
| | BiSrCaCuO | pseudo tetra | Bi-layered structure | a=5.4Å<br>c=30Å, 36Å | 12E-6/K |
| | TlBaCaCuO | pseudo tetra | Bi-layered structure | a=5.4Å<br>c=36Å | |
| SUBSTRATES | $Al_2O_3$ | trigonal | corundum | hex axes<br>a=4.763Å<br>c=13.003Å | 7.5-8E-6/K |
| | MgO | cubic | NaCl | a=4.203Å | 13.8E-6/K |
| | $SrTiO_3$ | cubic | perovskite | a=3.905Å | 10.8E-6/K |
| | YSZ | cubic | flourite | a=5.16Å | 10E-6/K |

ref. Wasa et al.

ESA report 1990
C.S. Jacobsen

| Epi-Substrate | SrTiO$_3$ | MgO | ZrO$_2$(YSZ) | LaAlO$_3$ |
|---|---|---|---|---|
| Orientation for c ⊥ plane | (001) | (001) | (001) | (001) |
| ε' | 1900 | 9.6 | 25 | 24.5-26 |
| tan δ at: | | | | |
| 77-80K | $6x10^{-2}$ | $4x10^{-5}$ | $7.5x10^{-3}$ | $8.3x10^{-5}$ |
| 4.2K | -- | $1x10^{-6}$ | $2\text{-}6x10^{-4}$ | $5x10^{-6}$ |
| at f, GHz | 10-1000 | 10-1000 | 10-1000 | 10 |
| References | 22 | 22,23 | 22 | 23 |

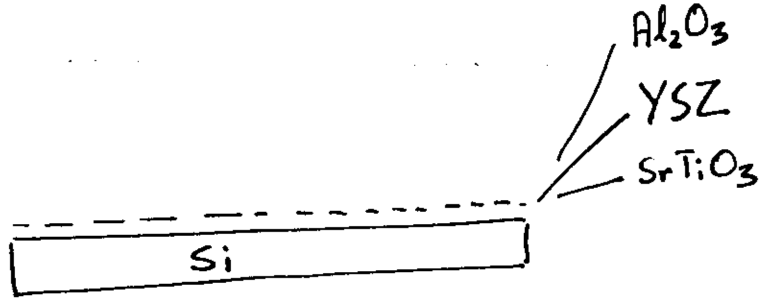
reference: A. Braginsky 1990.



# BUFFER - LAYER.

To prevent interdiffusion at high temperatures.

Example.




TYPICAL

YSZ ($Y_2O_3$) on Si

$SrTiO_3$ on $Al_2O_3$

# FABRICATION PROCESSES.



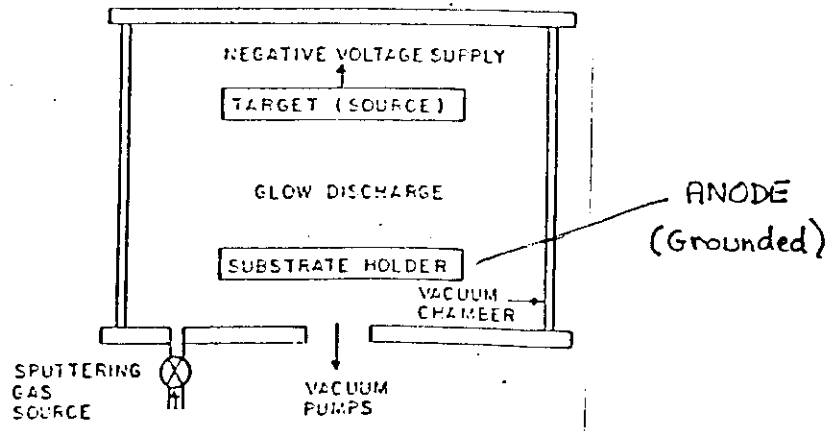
## SPUTTERING

dc sputtering : conducting target

rf sputtering : insulating target possible

YBCO : often dc sputtering

Bi - materials : rf - sputtering




possibly Magnetron Sputtering (concentrate plasma

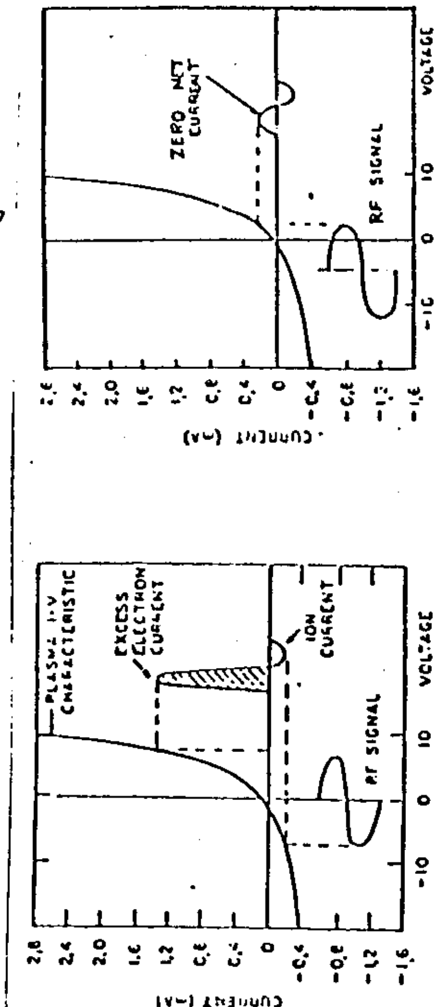
backgroundpressure : ~ $10^{-6}$ mbar

sputter gas (argon) : ~ $10^{-3}$ mbar or higher

ions in the plasma bombards target
and eject material to substrate

# RF - sputtering

Electrical characteristics of glow discharge.




plasma IV curve :

Target obtains negative selfbias. (necessesary to have ions bombard target) due to zero net current.

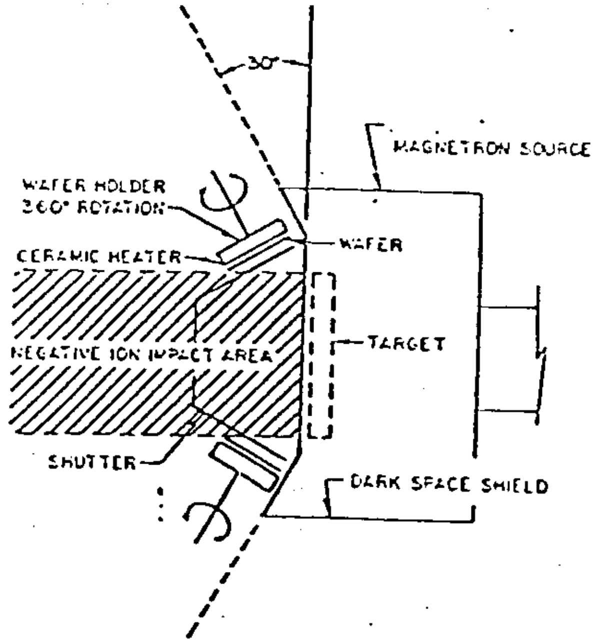
ESA report 1990
C.S. Jacobsen



# OFF-AXIS SPUTTERING

(to minimize oxygen resputtering)

high sputtergas pressure (~0.5 torr)
thermalise oxygen



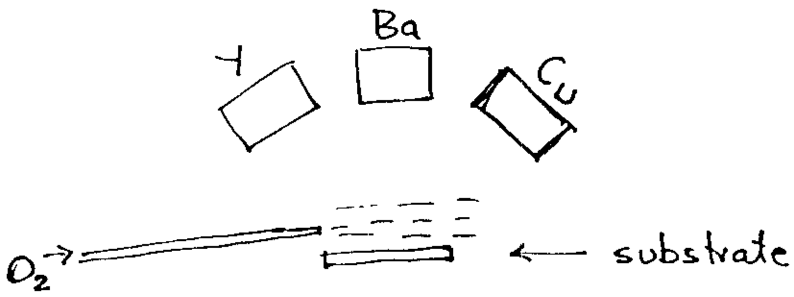

Substrate is placed outside the main stream of oxygen atoms.

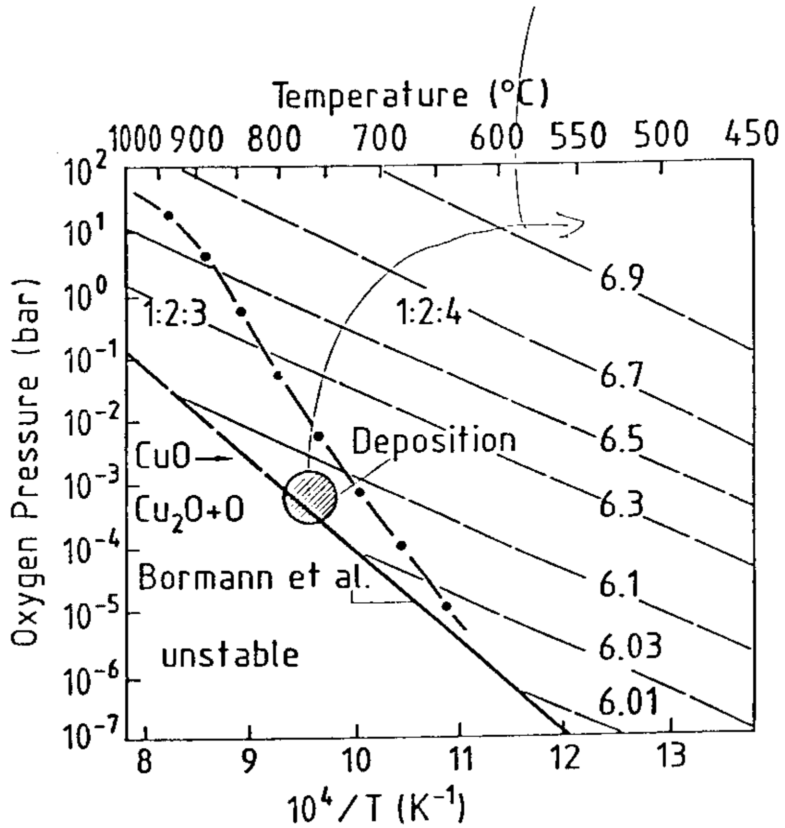
Stoichiometry preserved.

ESA report 1990 C.S. Jacobsen

SPUTTERING.

Multiple target system.

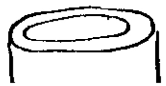



Geerk et al 1990 (Karlsruhe)

possibility of oxygen injection (bleeding)

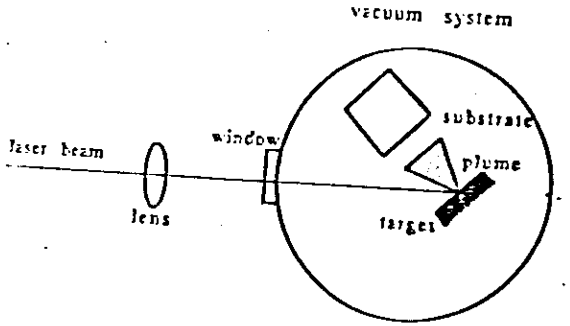
cylindrical targets



# LASER DEPOSITION

stoichiometry preserved.

details of process complicated.
(clusters, small explosions, plasma ~ $10^4$ K ...)
moderate vacuum.




Lasers: excimer laser — ArF 193 nm, KrF 248 nm, XeCl 308 nm
Nd-YAG

pulsed operation: 5-30 ns
10-100 MW
1-10 Hz

energy density per pulse: 1-5 J/cm$^2$

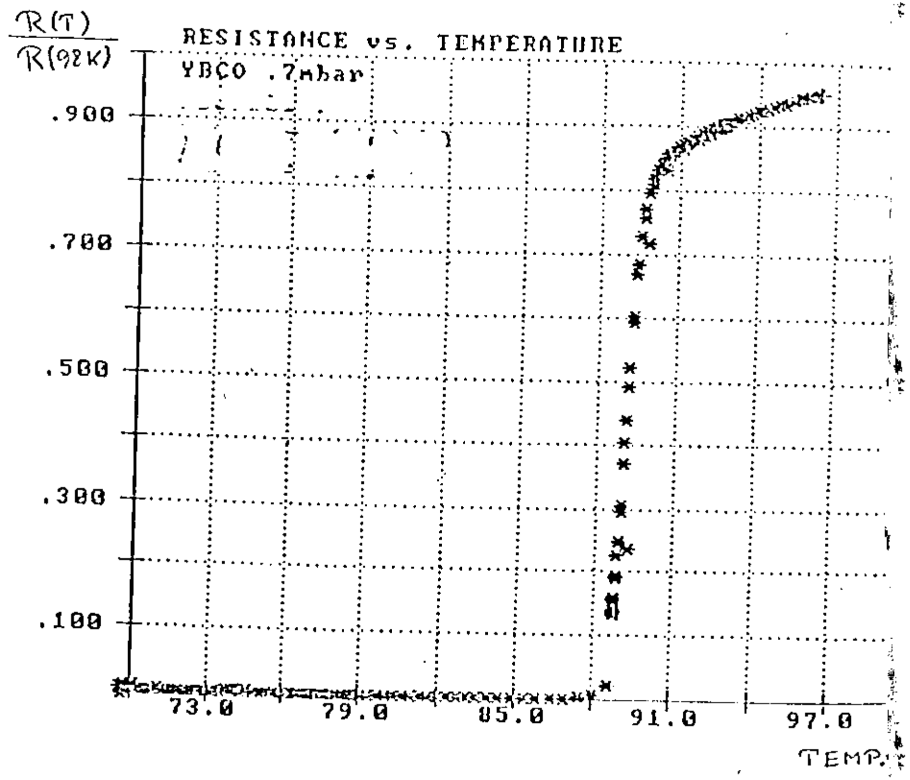



Fig. 3.8 Resistive transition in a laser deposited YBCO thin film (on (100) MgO) from NKT A/S. $T_{c0}$ = 87 K.

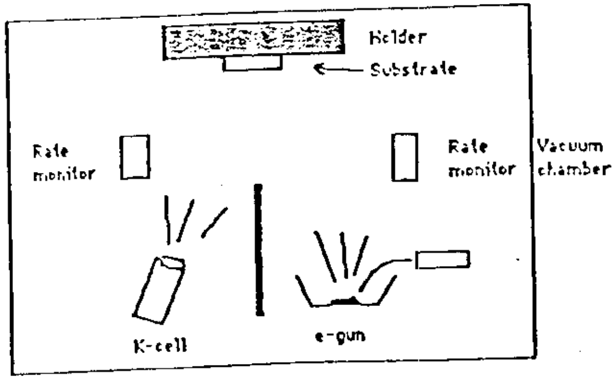
ESA-report 1990: C.S. Jacobsen.

CO-EVAPORATED FILMS

(E-GUN or EFFUSION CELL.)

High vacuum

Very good process control?




MBE: Deposition of single layer at a time.

ESA Report: C S Jacobsen 1990

Oxydation

for <u>in situ</u> fabrication.

oxygen bleeding, differential pumping

atomic oxygen (O)

ozone ($O_3$)

Evetts and Moore (1990)

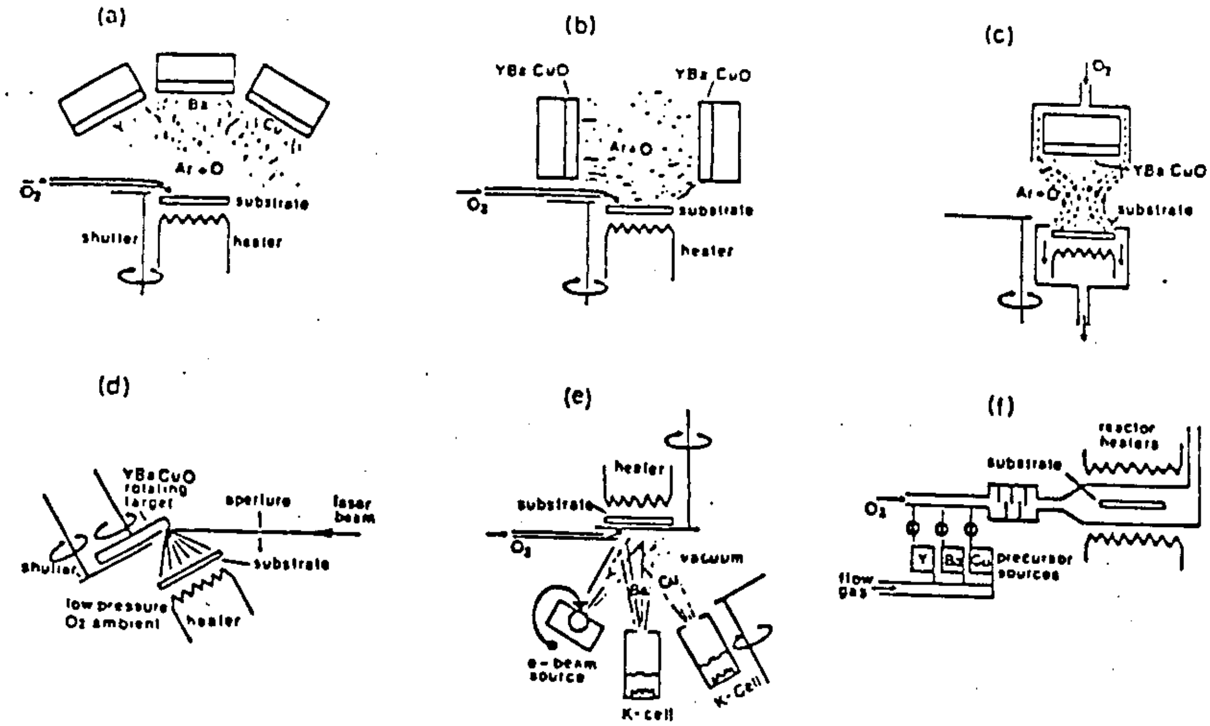



Fig.1 Schematic diagrams showing the essential features of: (a), (b), (c) sputter deposition methods for high $T_c$ materials; (d) laser deposition; (e) physical vapour deposition; and (f) chemical vapour deposition.

Table 3. Representative Best Properties of "As-Grown" c-Axis Epitaxial YBCO Films on $SrTiO_3$, $MgO$, $ZrO_2$ or $LaAlO_3$ Substrates.

| Film grown by: | PLD | | Sputtering | |
|---|---|---|---|---|
| d, nm | 10 | 200±100 | 10 | 200±100 |
| $T_c(R = 0)$, K | 82 | 92 | 88 | >90 |
| $J_c(77K)$, $A/cm^2$ | $>10^2$ | $8\times10^6$ | $8\times10^6$ | $4-5\times10^6$ |
| $R_s(77K)$, ohm | | $<7\times10^{-3}$ | | $<7\times10^{-3}$ |
| at f, GHz | | 86 | | 86 |
| $f(R_s = \alpha R_{sCu})$, GHz | | | | |
| $\alpha = 0.1$ (scaled) | | 73 | | 73 |
| $\alpha = 0.01$ (scaled) | | 13 | | 13 |
| $S_\Phi(77K)$, $\Phi_o^2 Hz^{-1}$ | | $8\times10^{-10}$ | | - |
| at f, Hz | | 1 | | |
| References | | 18, 19, 20 | | 12, 15, 21 |

reference: A. Braginsky 1990

THE MOST PROMISING METHODS
PRESENTLY FOR YBCO FABRICATION

AS GROWN – c-axis.

| | LASER DEPOSITION | OFF-AXIS SPUTTERING |
|---|---|---|
| le target composition | V | V |
| osition rate | ~ 100 Å/sec | 0.1 Å/sec |
| n Area | ~ 1 cm² (beam) | large (5 cm$^{\phi}$ wafer) |
| ssure | $O_2$ – 200 mtorr | 50 – 200 mtorr ($O_2$ + Ar) |
| ition temperature | ~ 700 °C | ~ 700 °C |
| (77k) | 5×10⁶ A/cm² | 5×10⁶ A/cm² |

C.S. Jacobson, ESA Report 1990

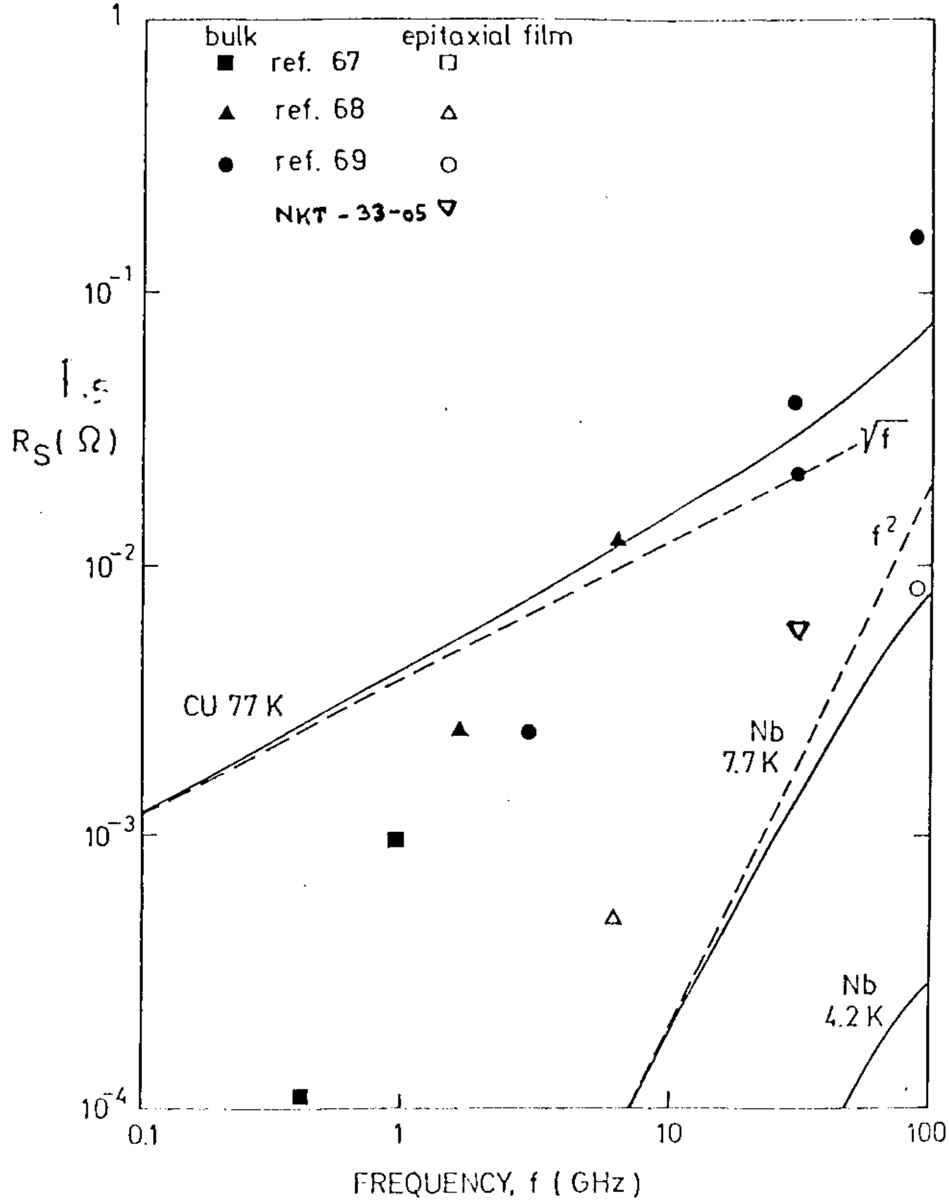
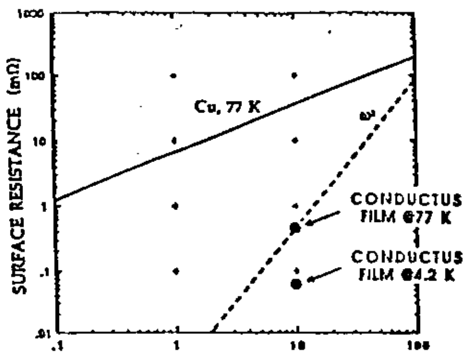



Fig. 3.9 Frequency dependence of the microwave surface loss, $R_S$, for a number of YBCO bulk and thin film samples (77 K) and copper and niobium at various temperatures.

CONDUCTUS

Superconducting Thin Films for Microwave Applications

SURFACE RESISTANCE VS. FREQUENCY




Conductus is routinely producing microwave films using the off-axis sputtering process. The results shown above illustrate significantly reduced surface losses in comparison with copper at 77 K. Such films offer the potential for improved performance of microwave resonators, filters, antennas, and other "single-layer" microwave device structures.

Films with the best properties are currently being produced on 1 cm² $LaAlO_3$ substrates. We can assure the following film specifications:

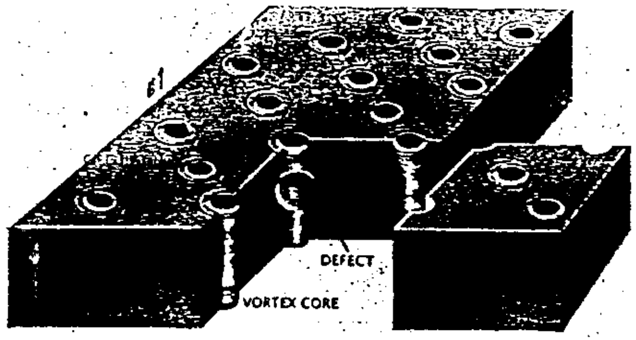
| | | |
|---|---|---|
| surface resistance | at 77 K: | < 2 mΩ |
| | at 4.2 K: | < 200 μΩ |
| $T_c$ (zero resistance) | ≈ 89.0 K | |
| $\Delta T_c$ (10-90%) | < 1.0 K | |

Discuss your custom film needs with us: i.e. unusual substrate sizes or materials, patterned films and contacts.

Contact: Dr. Roger Barton at (408) 737-6700

# High Tc SQUIDS.

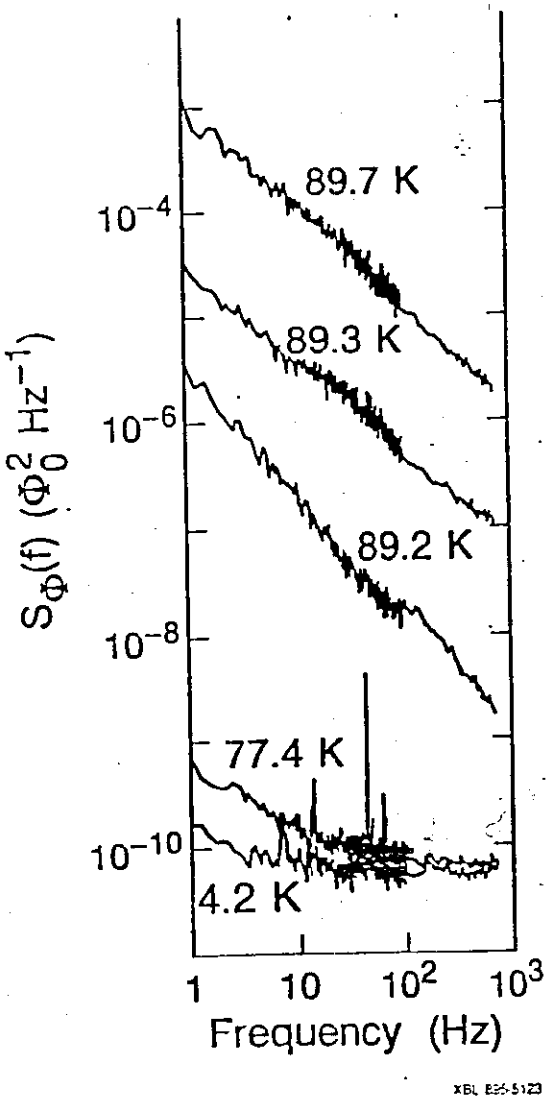
Flux flow noise is a problem
gives large 1/f noise




*MAGNETIC FLUX CREEP can be diminished by introducing defects into a superconducting crystal. An external magnetic field, B, induces vortices (areas of magnetic flux surrounded by circulating current) in the crystal, which align themselves in a hexagonal matrix. A current passed through the sample pushes the vortices—the flux-creep effect—dissipating energy and so inhibiting the current. Defects in the crystal "pin" the vortices. Source: R. Bruce van Dover, AT&T Bell Laboratories.*

Flux lines penetrating film.

solution? Flux trapping / arresting
better quality films
understanding of flux motion
pankake vortices ....




Ferrari et al. (1989)

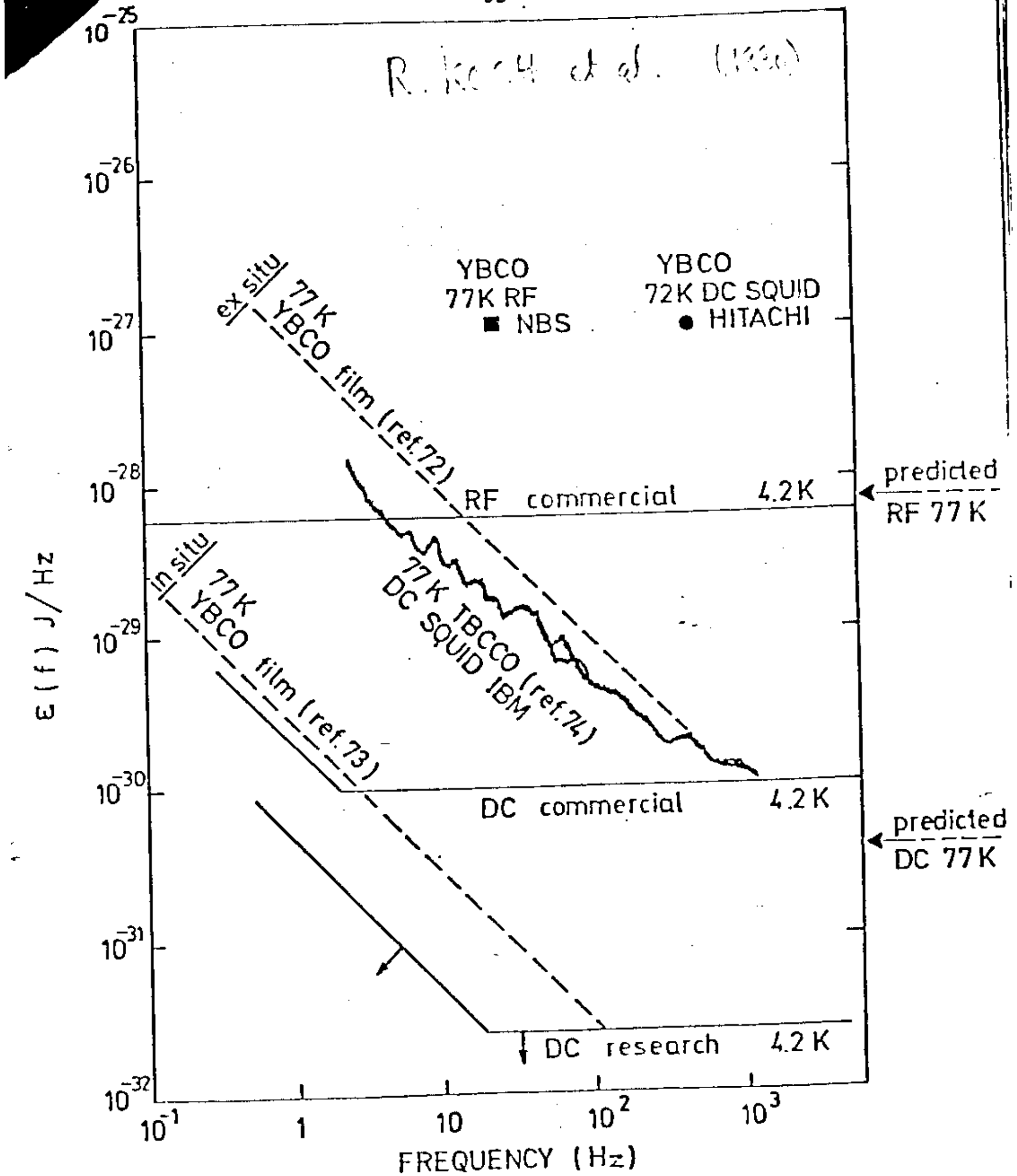



Fig. 3.9 Noise energy $\varepsilon(f)$/Hz versus frequency for several SQUID's (both low-$T_c$ and high-$T_c$)