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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 II

presented by:

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

These are preliminary lecture notes, intended only for distribution to participants.

II HTS JOSEPHSON JUNCTIONS

N.F. PEDERSEN

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DK-2800 LYNGBY

1) FILMS
2) JUNCTIONS
3) APPLICATIONS

For almost all electronic applications, Josephson junctions (active elements) are required.

comparison:

Same role as transistors in normal electronics *falsig.*

ESTEC CONTRACT No. 8007/88/NL/PB(SC) January 30, 1990

(DRAFT FINAL REPORT)

HIGH TEMPERATURE SUPERCONDUCTORS:

ASSESSMENT STUDY FOR SPACEBORNE SENSORS APPLICATIONS.

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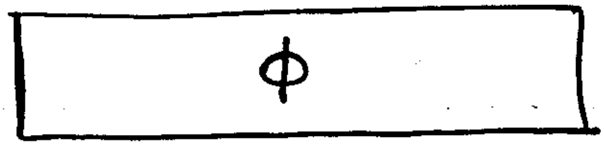
EUROPEAN SPACE AGENCY
CONTRACT REPORT.

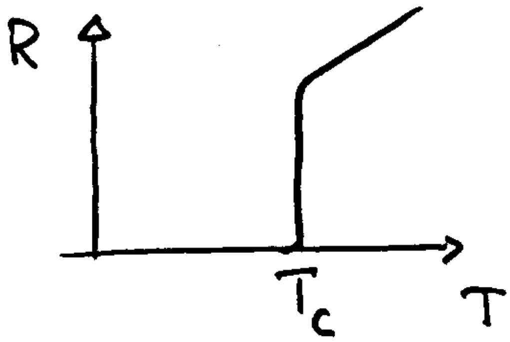
The work described in this report was done under ESA contract. Responsibility for the contents resides in the author or organisation that prepared it.

SUPERCONDUCTIVITY

1) Macroscopic phase coherence

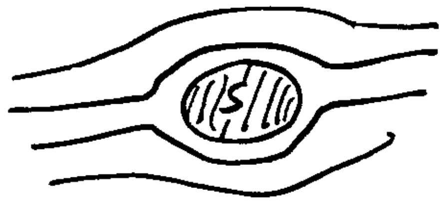


2) zero resistance



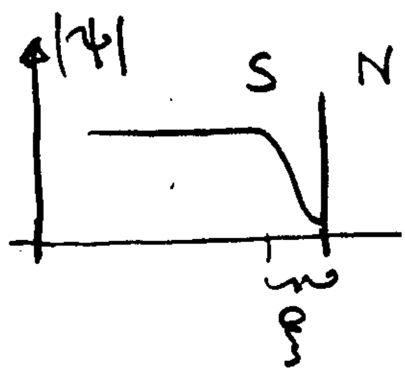
3) Meissner effect

flux (exclusion) expulsion



4) Coherence length ξ

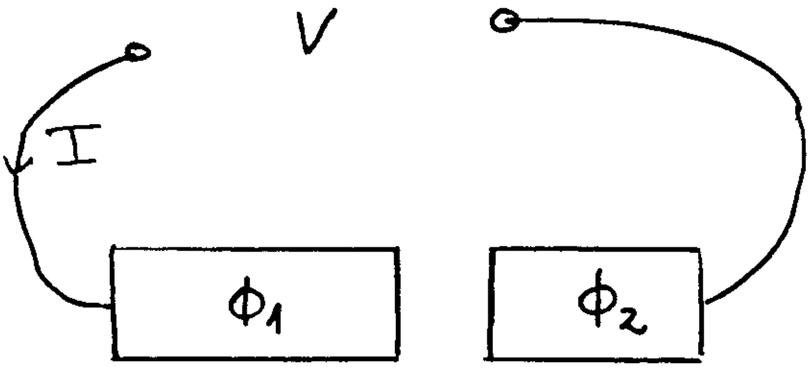
(size of pairs)

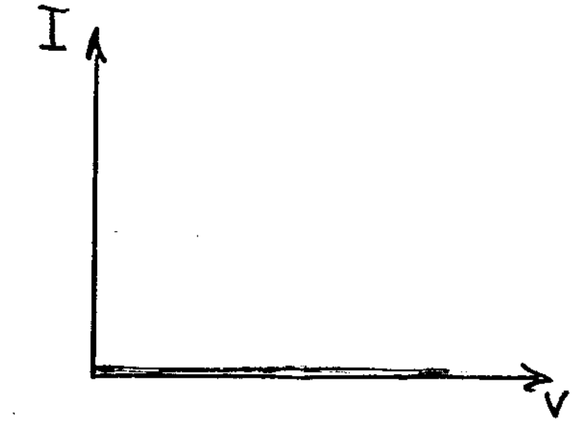


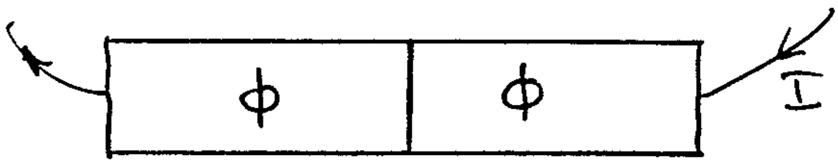
5) Penetration depth λ

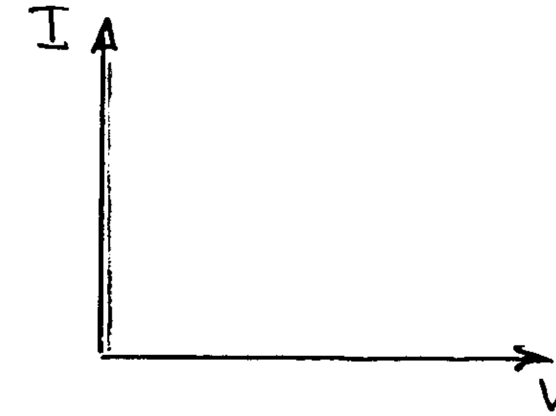
magnetic field penetration

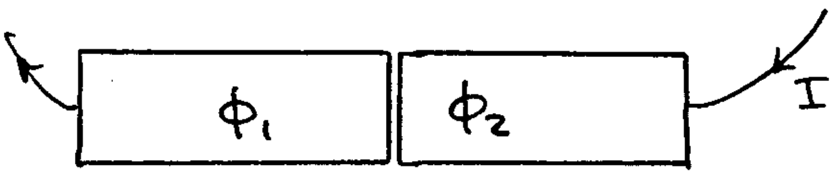
WEAKLY COUPLED SUPERCONDUCTORS

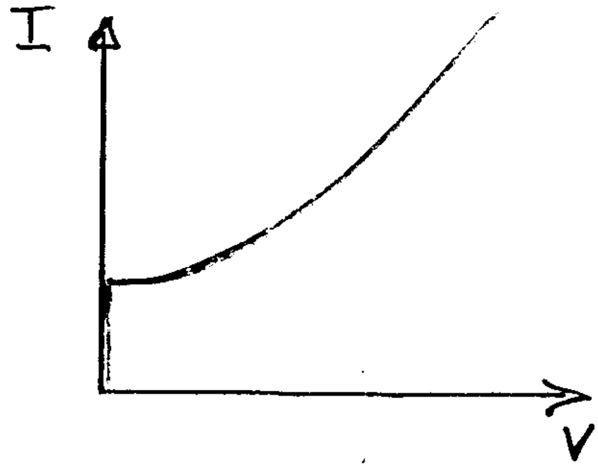






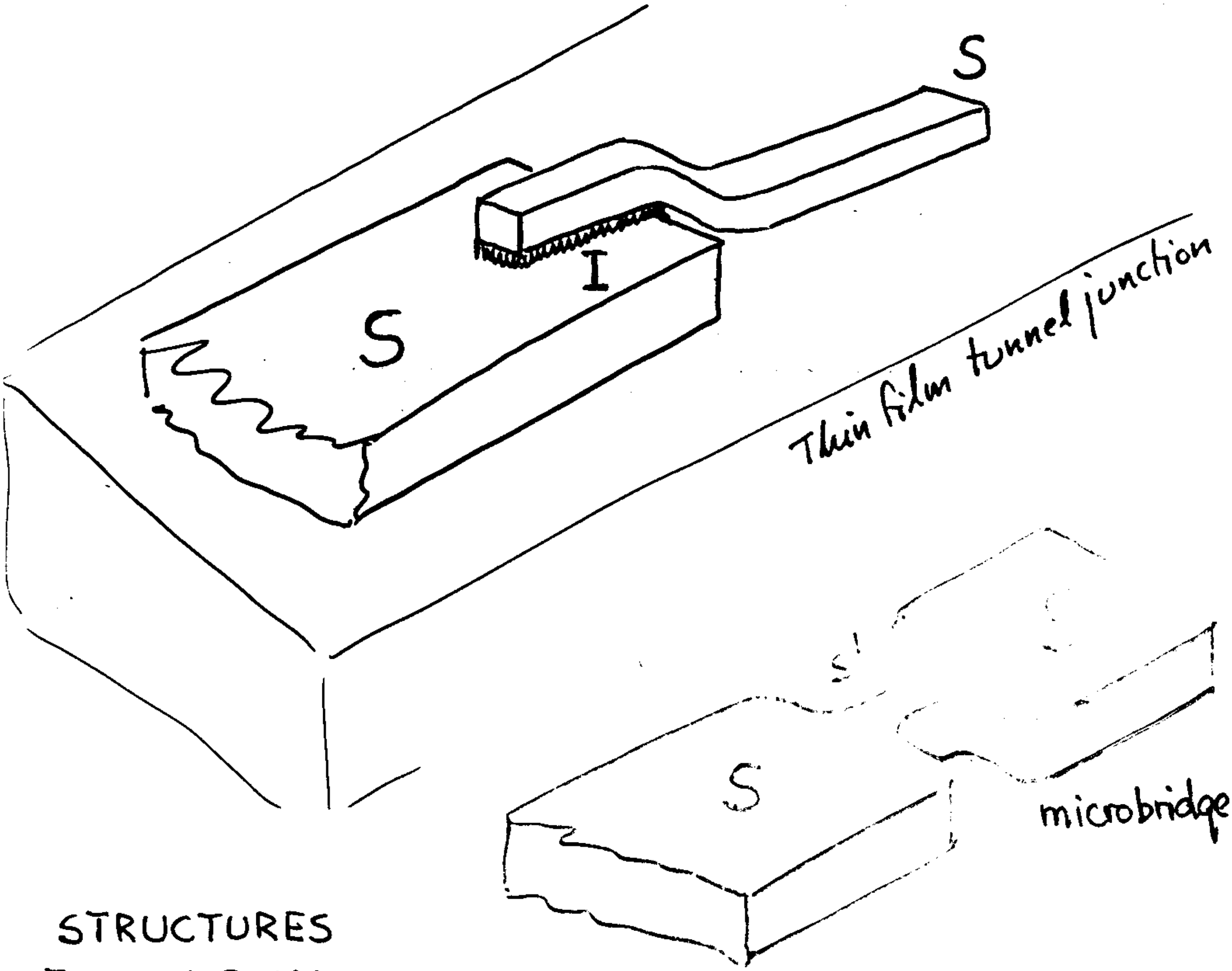




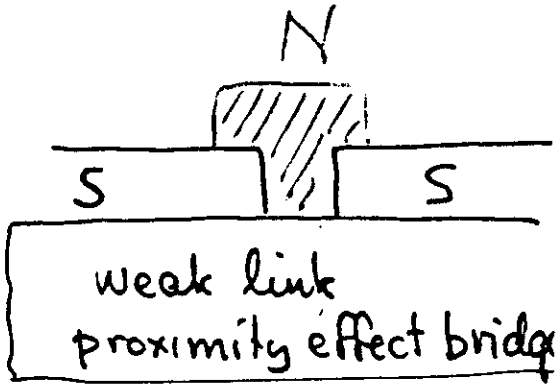


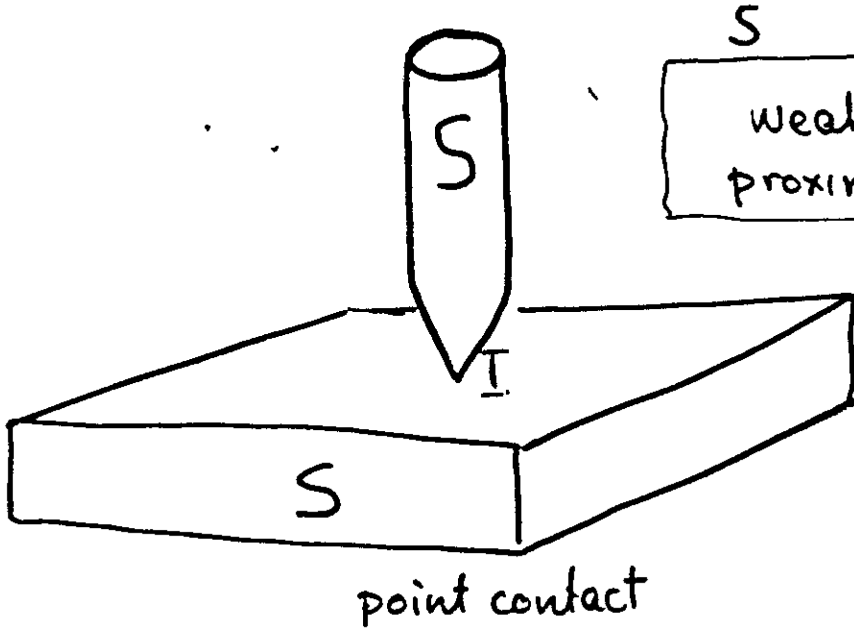
$$\phi = \phi_1 - \phi_2$$

supercurrent + ohmic current.

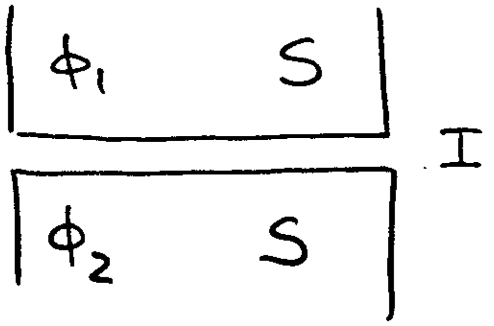


STRUCTURES
FOR WEAKLY
COUPLED
SUPERCONDUCTORS

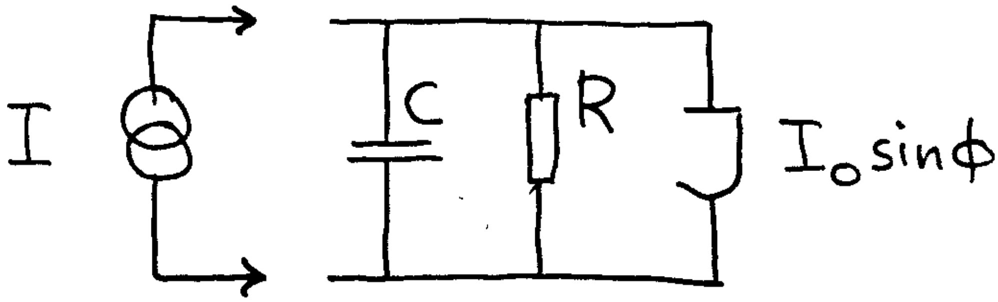




JOSEPHSON JUNCTIONS

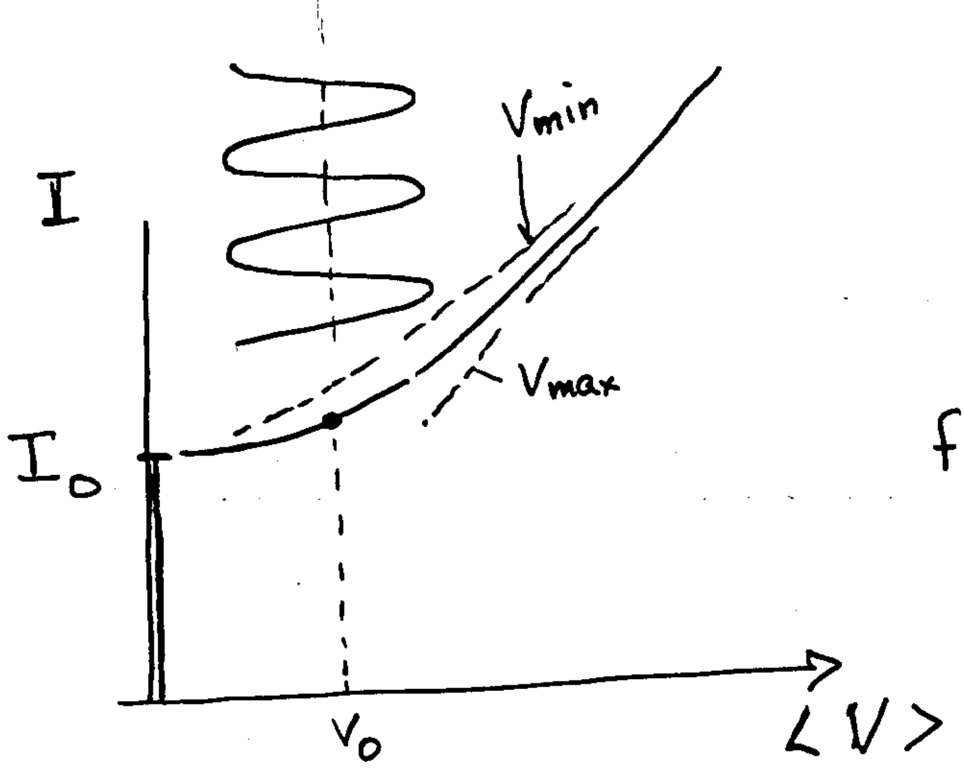


low T_c



$$I = I_0 \sin\phi + \frac{V}{R} + C\,\frac{dV}{dt}$$

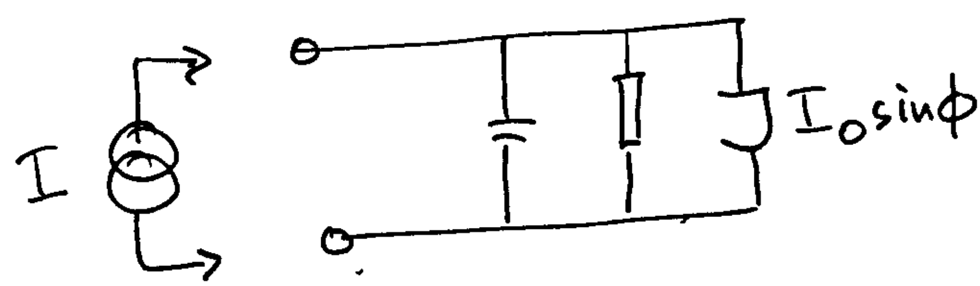
$$\frac{d\phi}{dt} = \frac{2e}{\hbar} \cdot V \qquad \left(484\ \frac{\text{GHz}}{\text{mV}}\right)$$

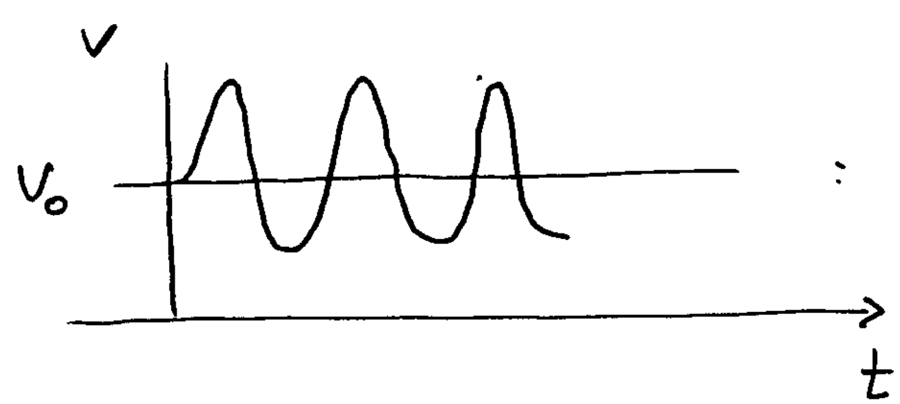


$$f = \frac{2eV_0}{2\pi\hbar}$$

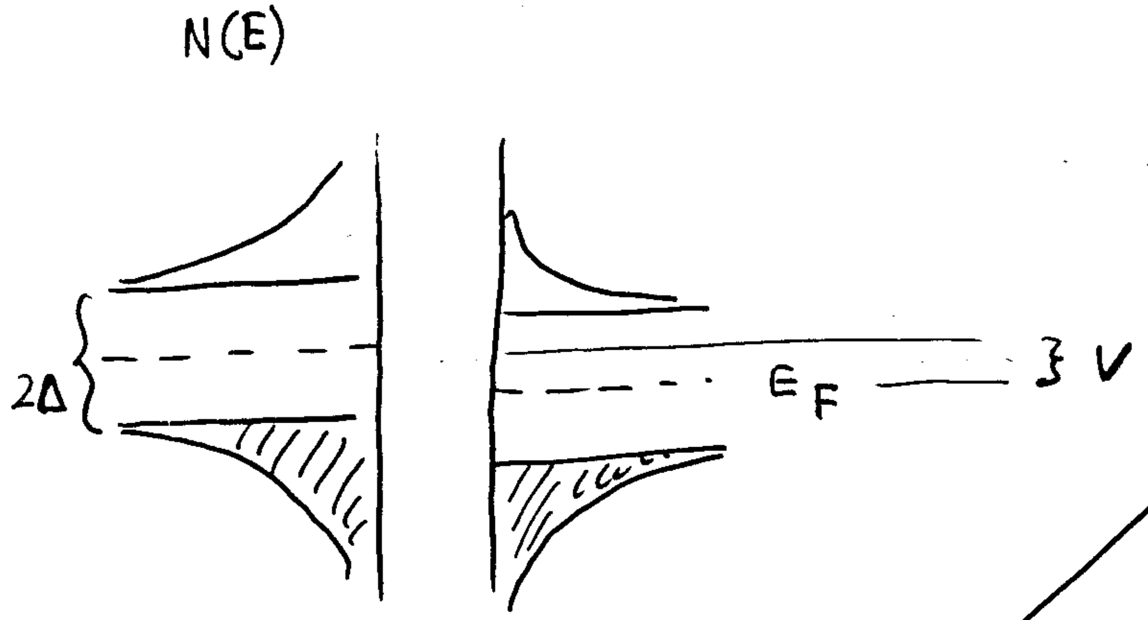
$$I = I_0 \sin\phi + \frac{V}{R} + C \cdot \frac{dV}{dt}$$

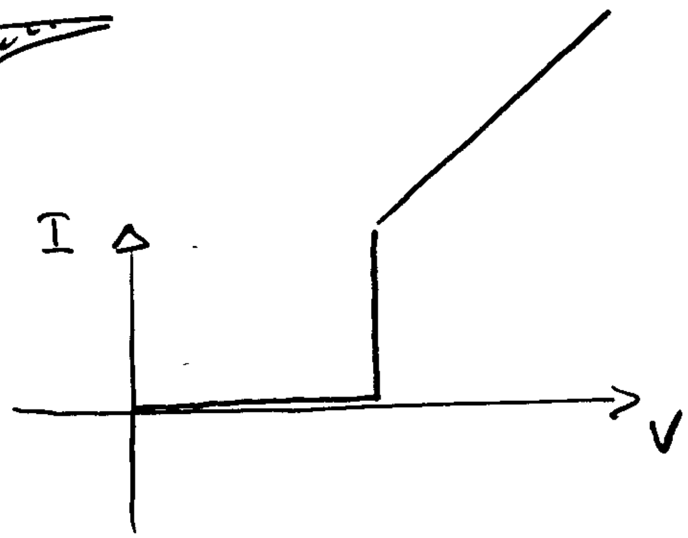
$$\frac{d\phi}{dt} = \frac{2e}{\hbar} \cdot V$$





: nonsinusoidal.



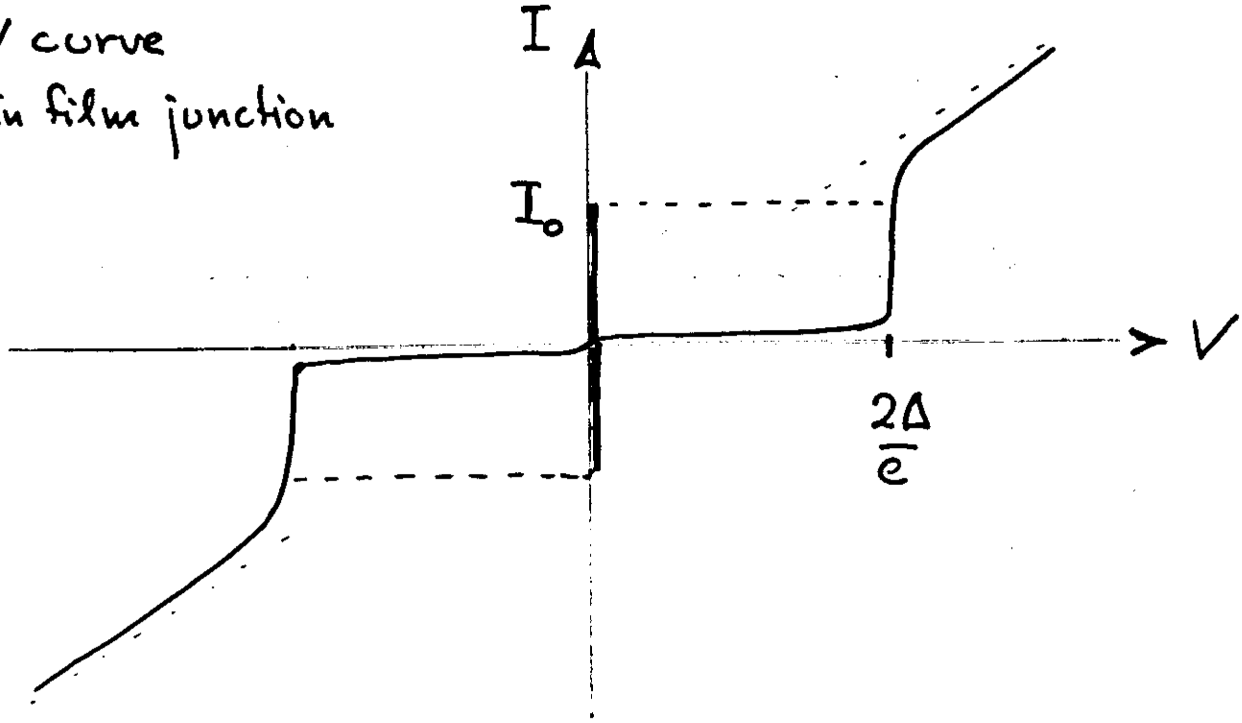


Tunneling of quasiparticles
(normal electrons)

Supercurrent: Tunneling of Cooper pairs.

low T_c Josephson junctions

IV curve
thin film junction



Materials $Nb / Al_2O_3 / Nb$

Pb / Pb oxide / Pb

⋮

Area 10 μm × 10 μm

Fabrication Sputtering, E-beam, ...

Photolithography ....

Example: microprocessor 2×10^4 junctions on one chip.

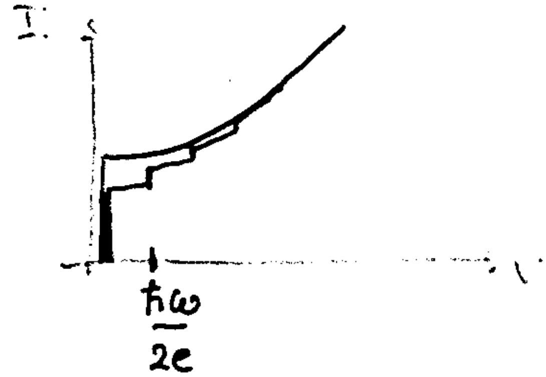
JOSEPHSON JUNCTIONS

Two characteristic properties lead to two tests.

1) AC - Josephson effect

$$f_J = \frac{2e}{h} V = 483.6 \times 10^{12} \text{ Hz/V}$$

lead to „Shapiro" steps with applied microwave radiation.



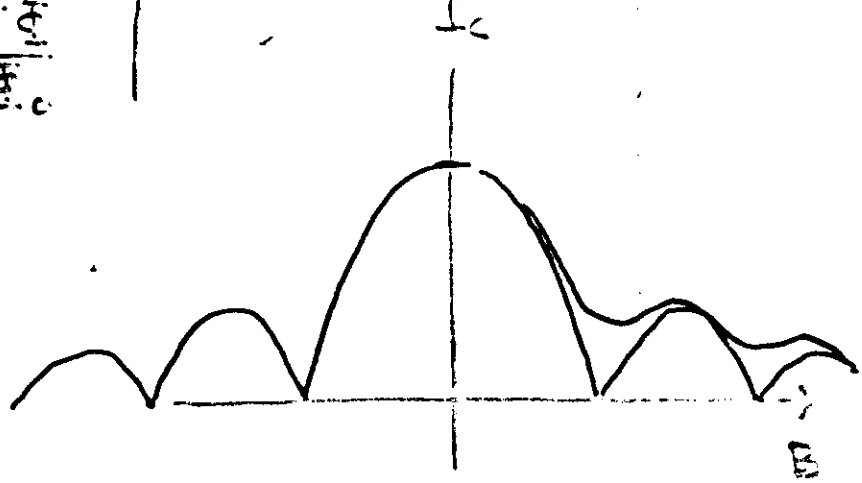
Frequency to voltage

$\phi = \phi_0 + \phi_1 \cdot \sin\omega t$

$\sin\phi$

2.) Periodic dependance of I_c on magnetic flux.

$$I_c(\Phi) = I_c(0) \left| \frac{\sin \frac{\pi \Phi}{\Phi_0}}{\frac{\pi \Phi}{\Phi_0}} \right|$$



Flux to voltage.

JOSEPHSON JUNCTIONS

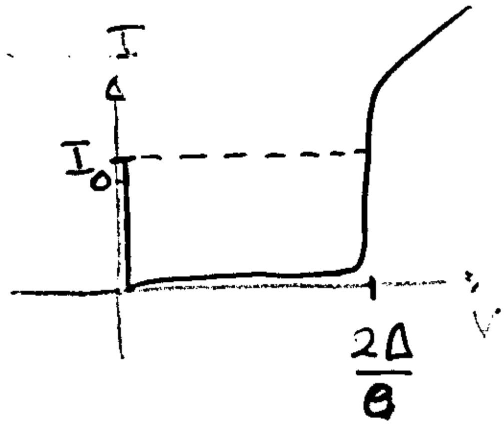
Low T_c.

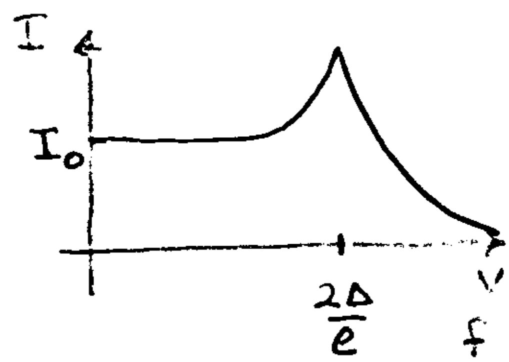
BCS theory
Werthamer theory
fully developped.

RI_0 = Measure of quality

$$RI_0 = \frac{\pi}{4} \frac{2\Delta}{e}$$

$$2\Delta \sim 3.5 \cdot kT_c$$



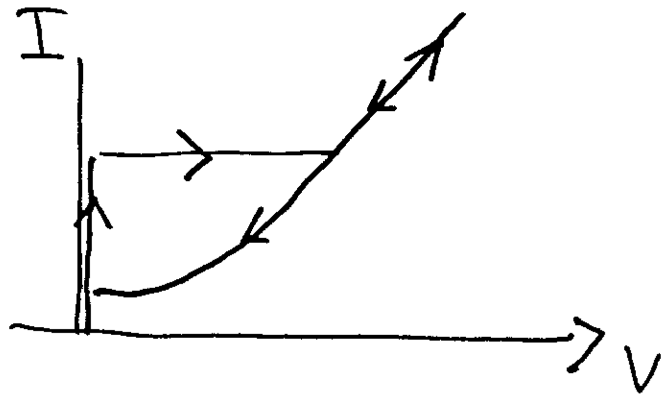


RI_0 measures high frequency cutoff.

	RI_0	T_c	f_{cutoff}
Low T_c	~3 mV	~10K	1 THz
high T_c	~30 mV	~100K	10 THz

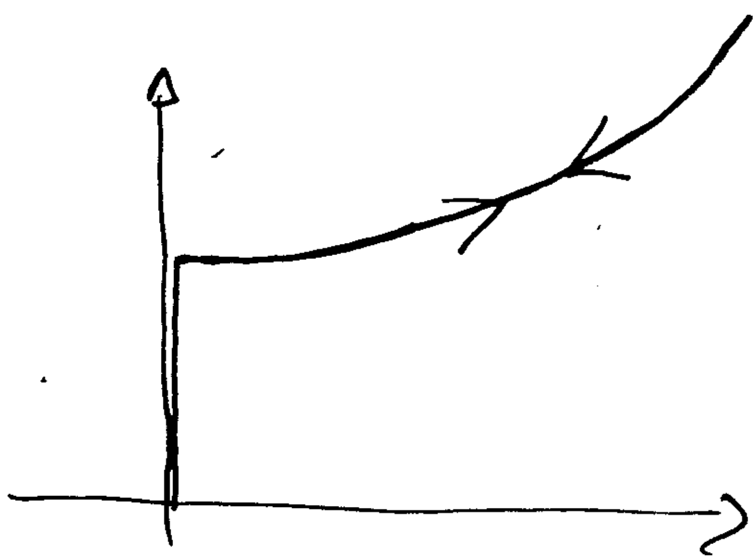
IV curve :

Hysteresis



or

not hysteresis



$$I = I_0 \sin\phi + \frac{V}{R} + C\frac{dV}{dt}$$

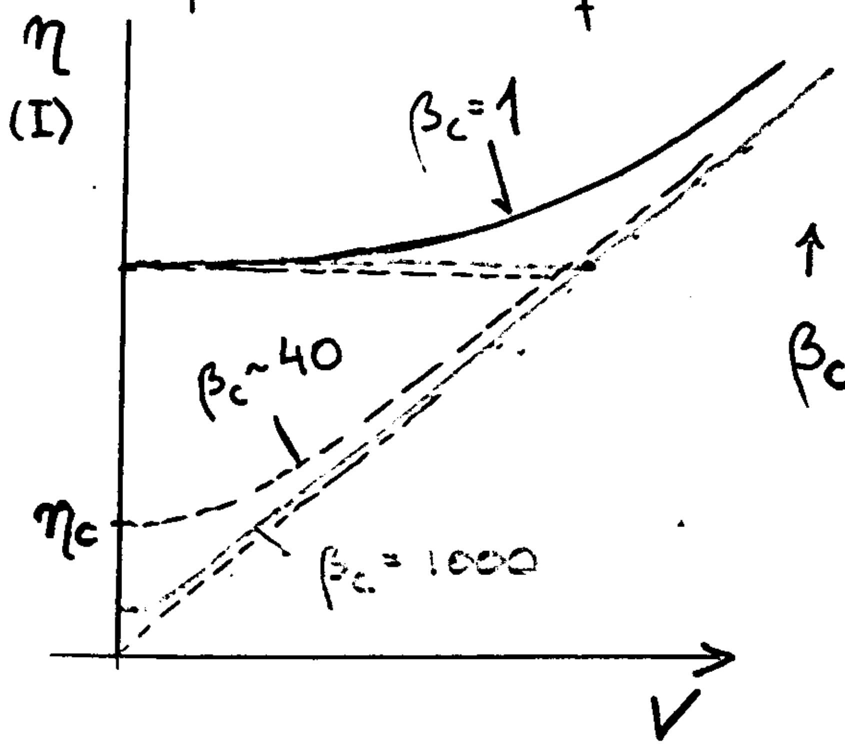
$$\frac{d\phi}{dt} = \frac{2eV}{\hbar}$$

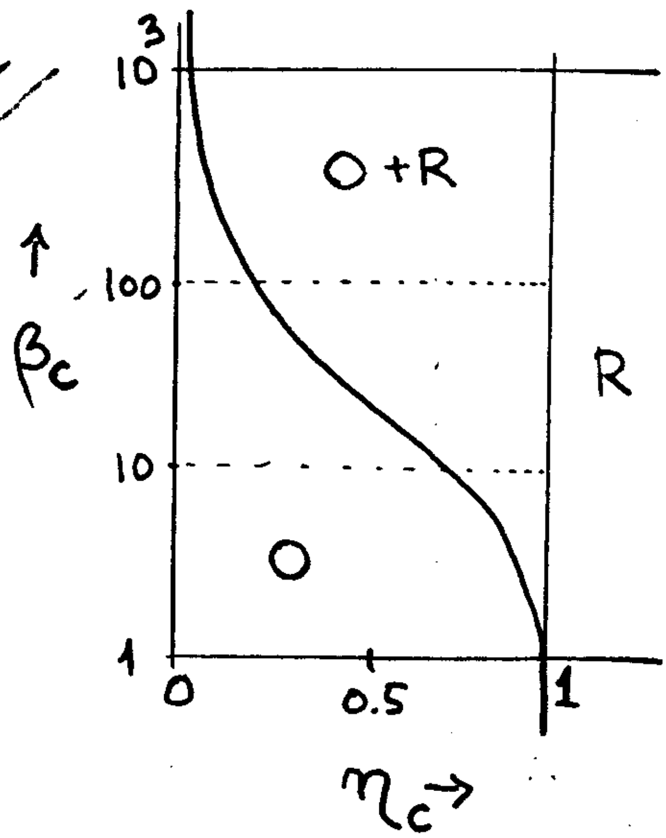
$$\boxed{\frac{d^2\phi}{d\tau^2} + \alpha\frac{d\phi}{d\tau} + \sin\phi = \eta}$$

$$\alpha = \frac{1}{\sqrt{\beta_c}}, \quad \beta_c = \frac{2e}{\hbar} I_0 R^2 \cdot C, \quad \eta = \frac{I}{I_c}$$

new time $\tau = \omega_0 t$, $\omega_0 = \sqrt{\frac{2e I_0}{\hbar C}}$

pendulum equation.

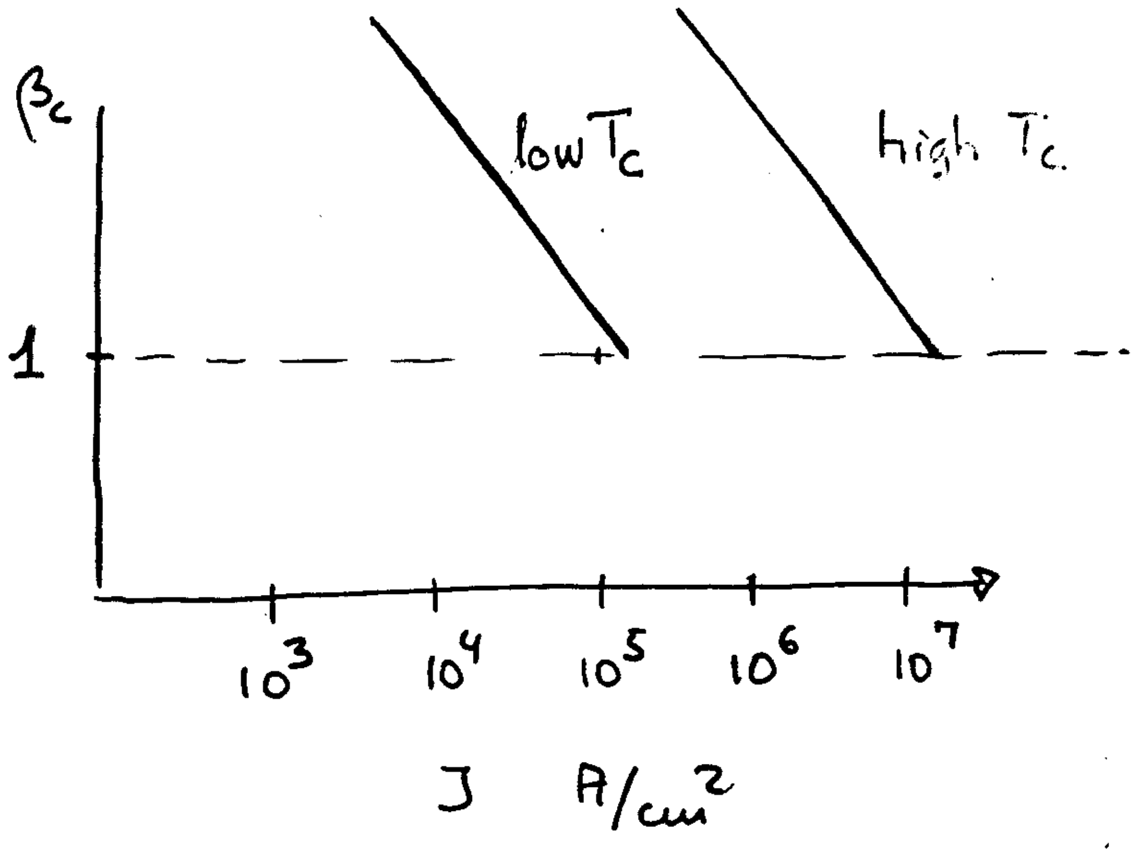




large damping $\alpha \sim 1$, $\beta_c \sim 1$ } no hysteresis

$$\beta_c = \frac{2e}{\hbar} I_0 R^2 C \sim (R I_0)^2 \cdot \frac{C}{I_0}$$

$$\beta_c \propto I_0^{-1} \cdot \Delta^2$$



Remember: Film current density $\sim 10^7 \frac{A}{cm^2}$

Hysteresis :

A word of caution:

Thermal effects (heating)

multiple junctions

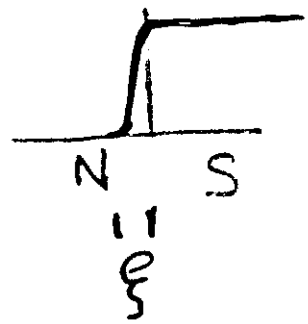
and other irregularities

may lead to hysteresis,

and wrong interpretation of IV curves.

High T_c

ξ, the coherence length measures extension of superconductivity



For thin film junctions

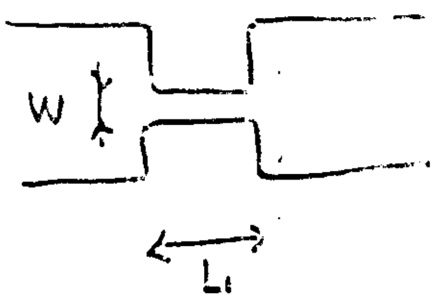
1) Oxide thickness $d \ll \xi$

2) Surface planar to better than ξ

Low T_c $\quad \xi = 500 - 1500\,\text{Å}$

High T_c $\quad \xi_\perp \simeq 5\,\text{Å}$, $\xi_{//} \simeq 30\,\text{Å}$

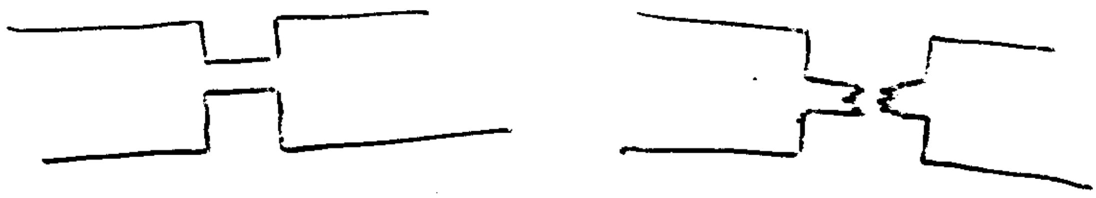
For weak links:



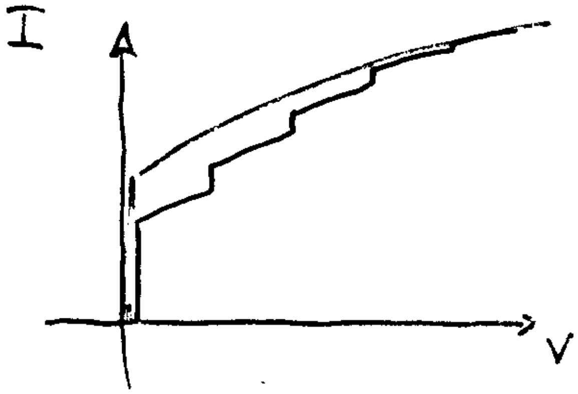
To destroy superconductivity in weak section dimensions must be small compared to ξ.

$L, W \ll \xi$.

HTS point contact junctions



break junction



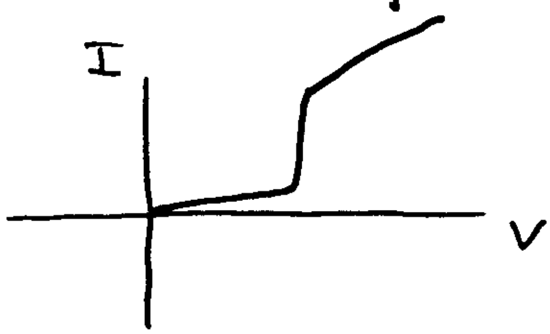
Test: rf induced steps.
ok

but unstable.

Work in several groups
Nanjing, Lyngby, Chalmers
- - - - - - -

~

Scanning tunneling microscope (STM)



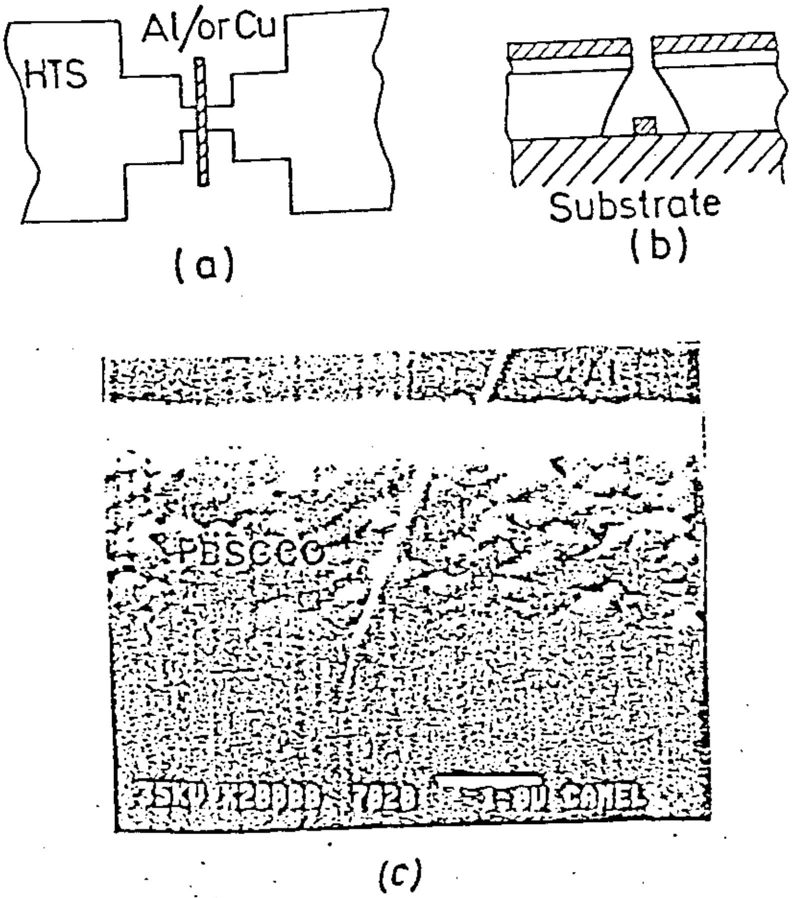


Fig. 3. Device design (a), fabrication process (b) and SEM micrograph of the experimental device (d).

ESA report 1990. C.S. Jacobsen

deposited. To form the weak link, the HTS strip was annealed in oxygen at different temperatures. Several weak links have been produced and some preliminary results are discussed below.

Fig. 4 shows the I-V curves for the proximity effect bridge of YBCO with Al strip before (a) and after (b) heating in oxygen at 430°C for 15 minutes. Even at such a low temperature the diffusion of Al was crucial for the superconducting properties of the YBCO strip and the supercurrent was depressed completely. The next proximity effect bridge was developed by using BSCCO film with a T_c of 65K. The heating was performed in air at 300°C for 3 min in O_2. In Fig. 5 it is shown the I-V curve of this weak link measured at temperature 24K. Note the positive curvature characteristic of a Josephson junction at low bias. The I-V curve was non-hysteretic with a critical current times normal resistance product of 40 μV.

ESA - report 1990 : C.S. Jacobsen

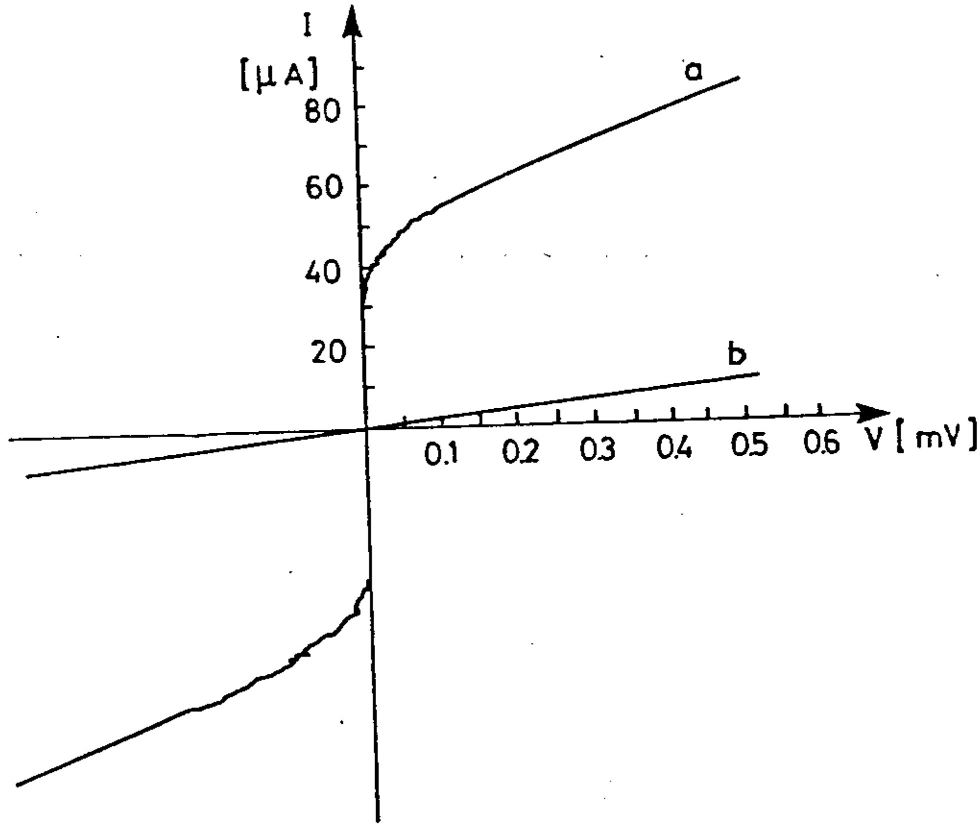
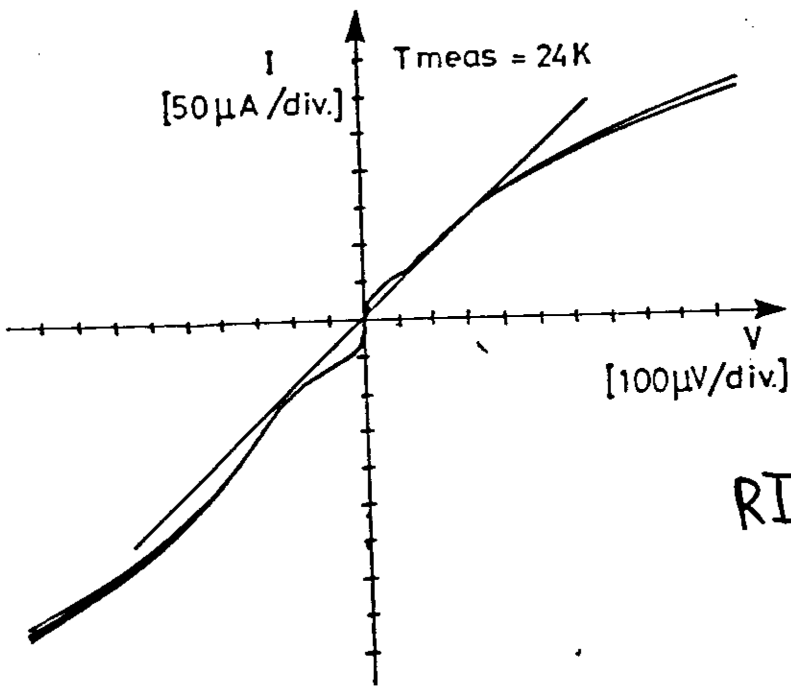


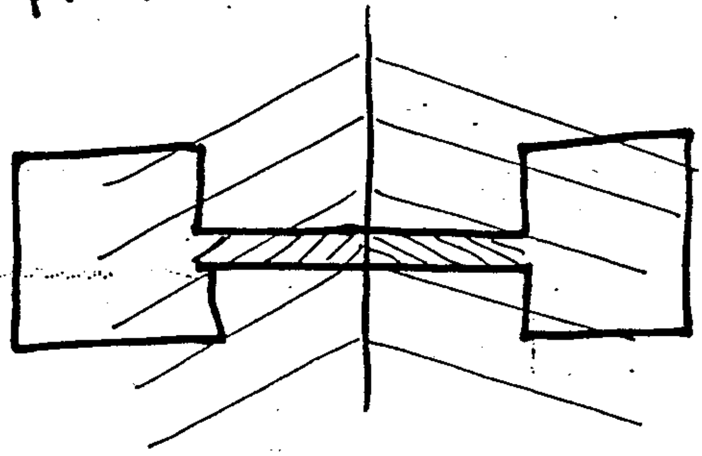
Fig. 4. I-V curves of the proximity effect bridge of YBCO with 70 nm wide Al strip line: (a) before heating; (b) after heating at 430 C for 15 min.



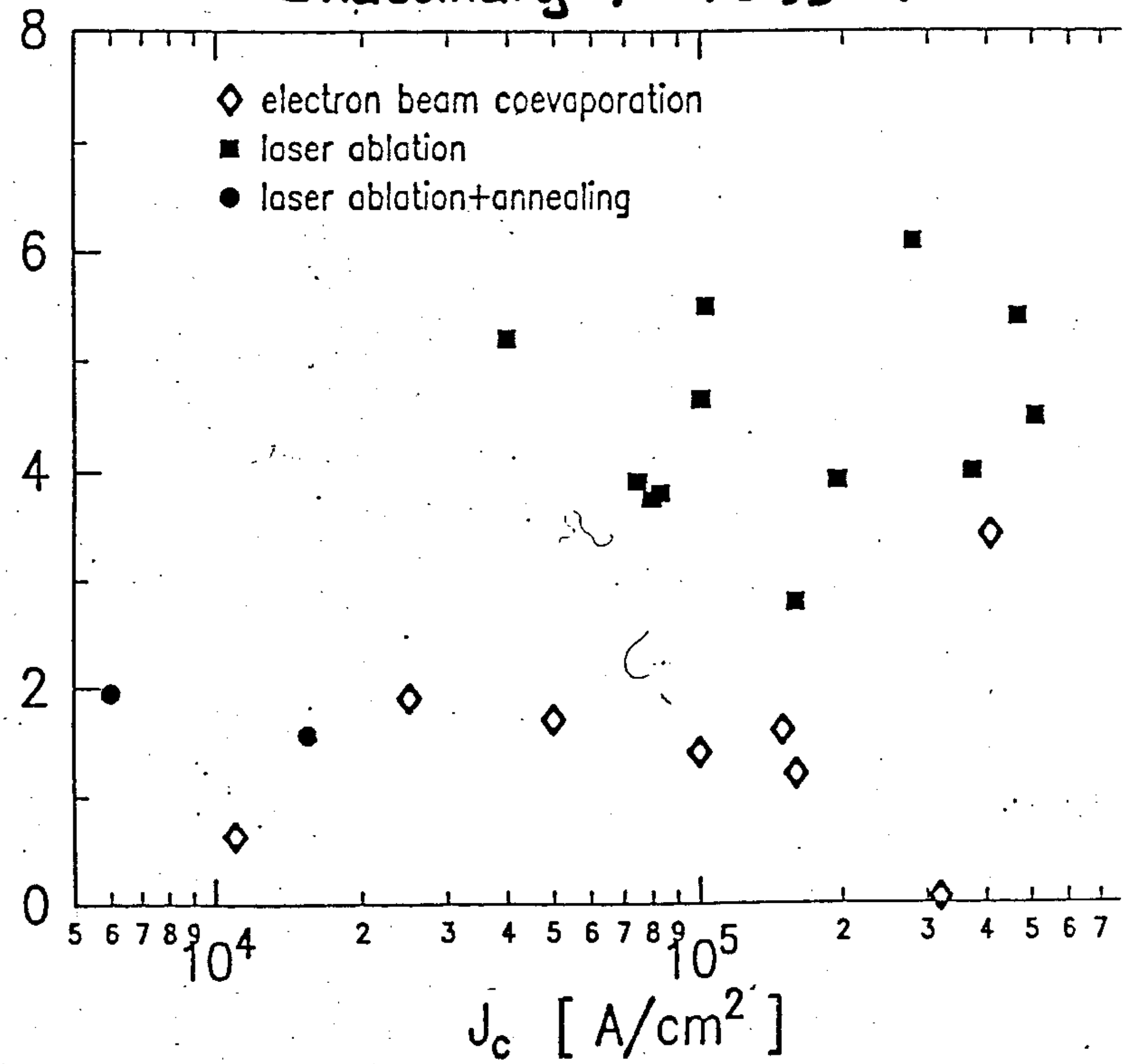
$RI_c \sim 40 \mu V$

Fig. 5. I-V curve of the proximity effect bridge of BPSCCO film with 70 nm wide Al strip line after heating at 300 C for 3 min.

Grain boundary junctions : epitaxial film on $SrTiO_3$ substrate



Chaudhary . Gross . IBM



Z. Ivanov et al.
(ESA-report 1990 : C.S. Jacobsen)

BICRYSTAL GRAIN BOUNDARY WEAK LINKS

SrTiO3

* D.Dimos, P. Chaudhari, J. Mannhart, and F.K. LeGoues, Phys. Rev. Lett., 61 (1988) 219.
* R.Gross, P.Chaudhari, M.Kawasaki, M.B.Ketchen, and A.Gupta, Appl.Phys.Lett., 57 (1990) 727.

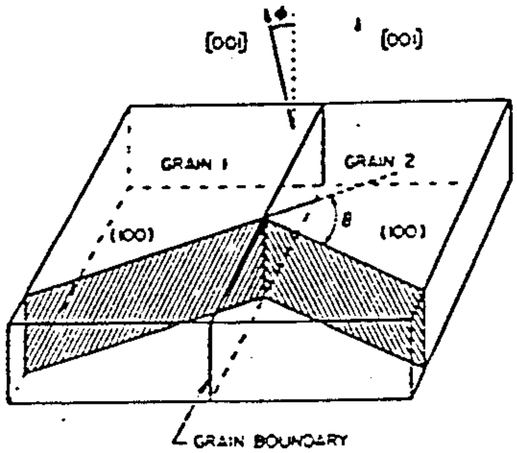


FIG. 1. Schematic diagram showing the important crystallography of the $SrTiO_3$ bicrystals which were used as substrates for the thin-film deposition.

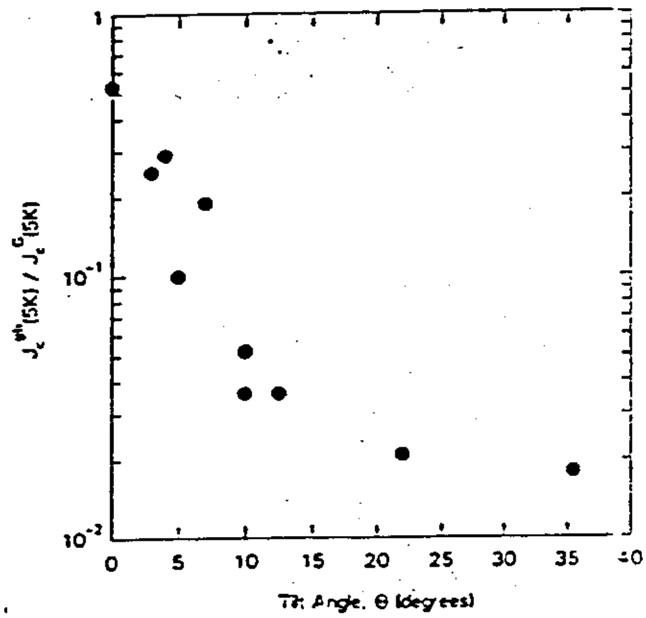


FIG. 3. Plot of the ratio of the grain-boundary critical current density to the average value of the critical current density in the two grains at 4.2–5 K vs the misorientation angle in the basal plane.

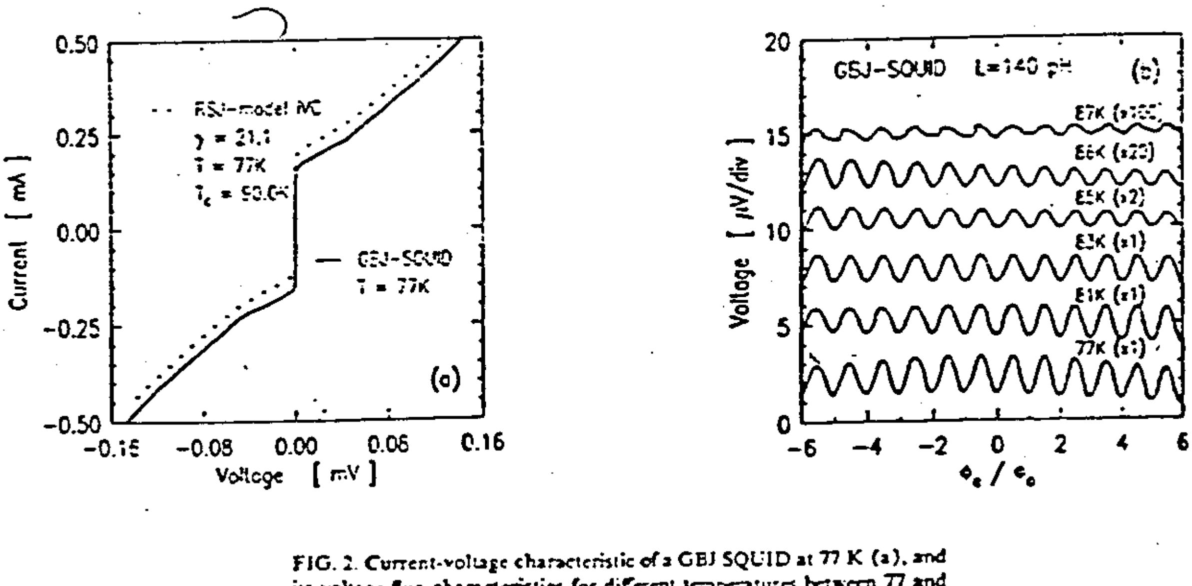


FIG. 2. Current-voltage characteristic of a GBJ SQUID at 77 K (a), and its voltage-flux characteristics for different temperatures between 77 and 87 K (b). The $V(\Phi_e)$ curves are displaced along the voltage axis.

2, Ivanov et al.

VARIABLE THICKNESS BRIDGES

* M.G.Forrester, J.Talvacchio, J.R.Gavaler, M.Rooks, J.Lindquist, IEEE Trans.Magn. MAG-27 (1991) to be publ.

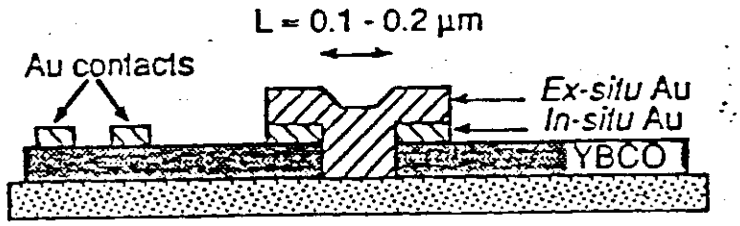


Figure 1. (a) Micrograph of a ≈ 0.1 µm-wide slot in a Au/YBCO bilayer, formed by electron-beam lithography and broad-beam ion milling. (b) Schematic diagram of completed planar junction.

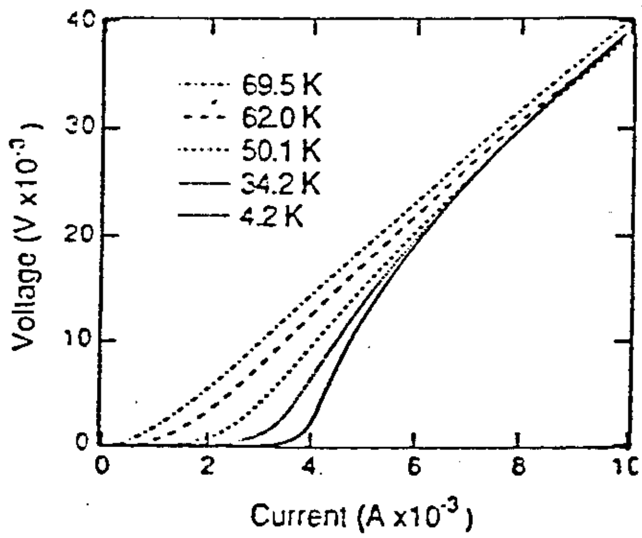


Figure 2. Current -voltage characteristics for a ≈ 0.1 long e-beam-fabricated YBCO/Au/YBCO junction.

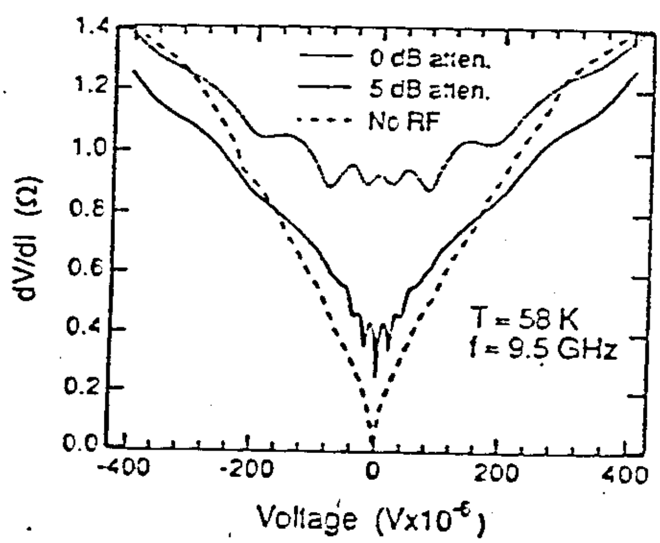
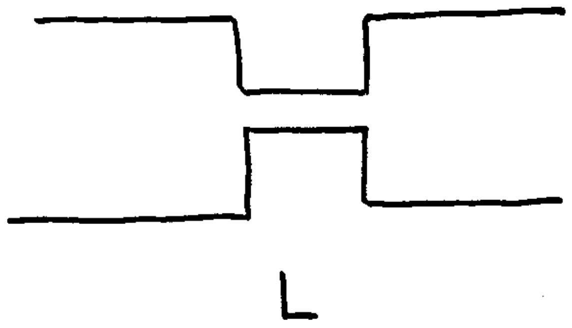


Figure 5. Differential resistance vs. voltage for the e-beam junction of Fig. 2, showing rounded Shapiro steps induced by 9.5 GHz radiation. The "0 dB" and "5 dB" curves are displaced vertically by 0.5 Ω and 0.25 Ω, respectively, for clarity.

ESA report 1990 : CS Jacobsen

YBCO microbridges



$L \gg \xi$

Large microbridges $L \gg \xi$

may show behaviour somewhat similar to small (e.g. Josephson effect)

This is due to coherent vortex flow and show „shapiro steps" etc.

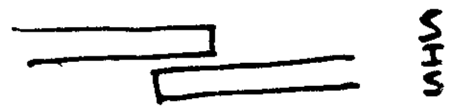
λ rather than ξ sets the length scale for such behaviour

Less desirable than „real" Josephson effect but may be used in SQUIDS

Susceptible to defects, hysteresis.

HTS

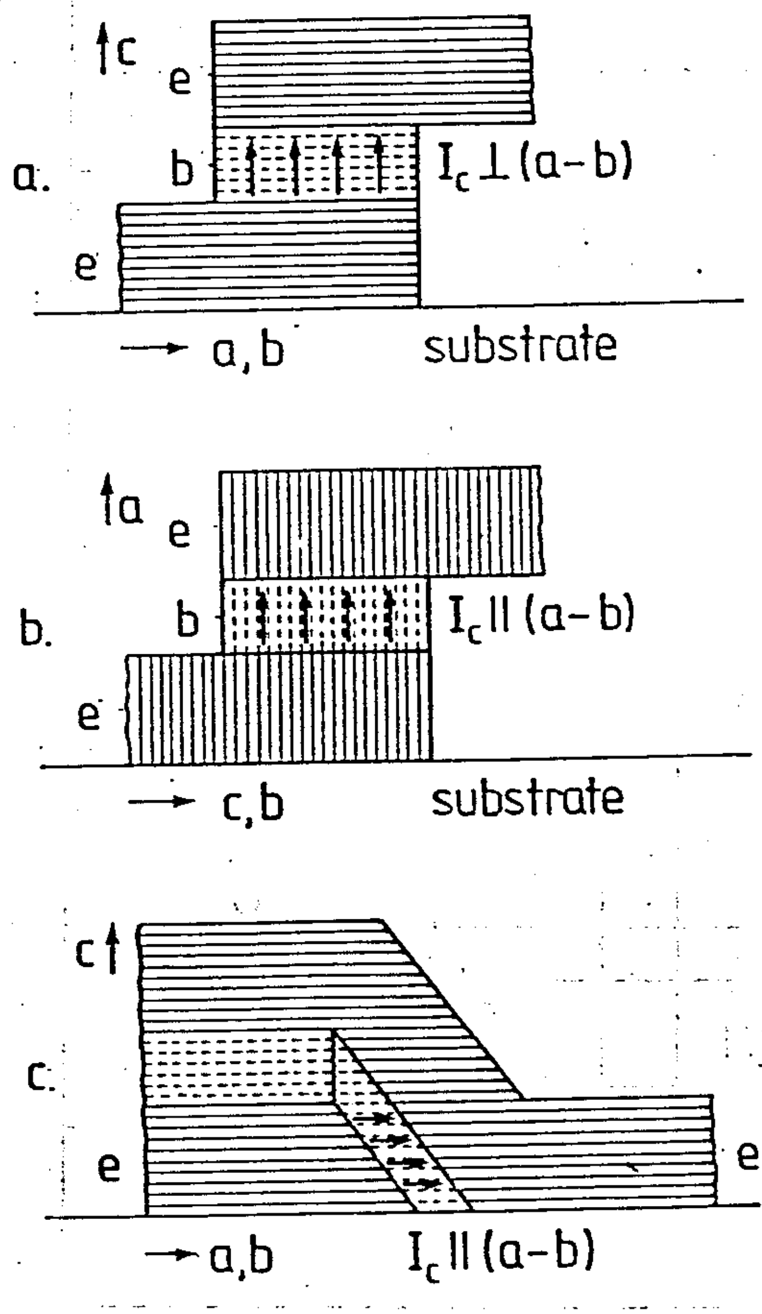
Sandwich thin film tunnel junctions ?



probably only candidate for large scale electronics

In situ fabrication

$$\xi = \begin{cases} 5\,\text{Å} & c \\ 30\,\text{Å} & a, b \end{cases}$$



A. Braginski 1990

Fig 5

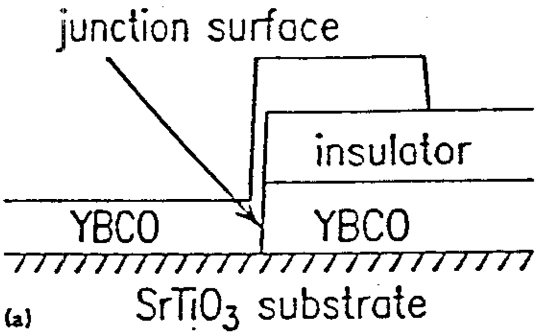
(ESA report 1990 : C.S. Jacobsen)

EDGE TYPE WEAK LINKS

Z. Ivanov et al

* All high T_c edge junctions and SQUIDs

R.B.Laibowitz, R.H.Koch, A.Gupta, G.Koren, W.J.Gallagher, V.Foglietti, B.Oh, and J.M.Viggiano, Appl.Phys.Lett., 57 (1990) 686.



(a)

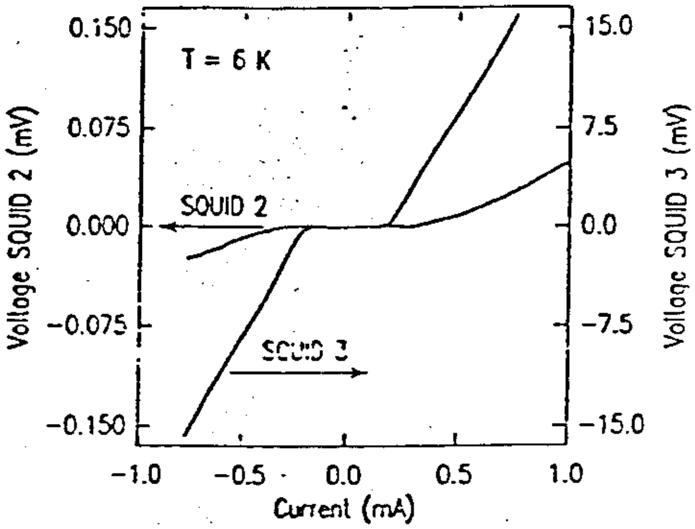
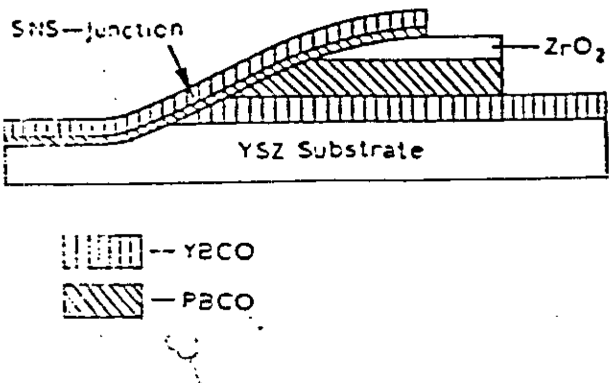
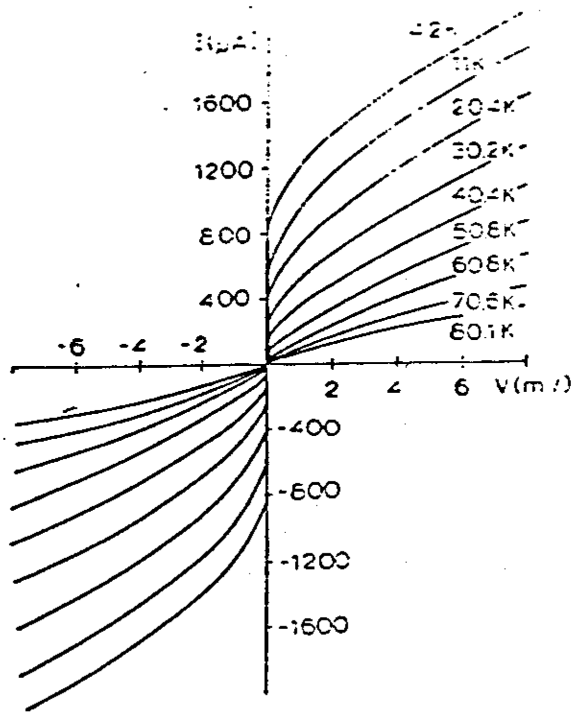


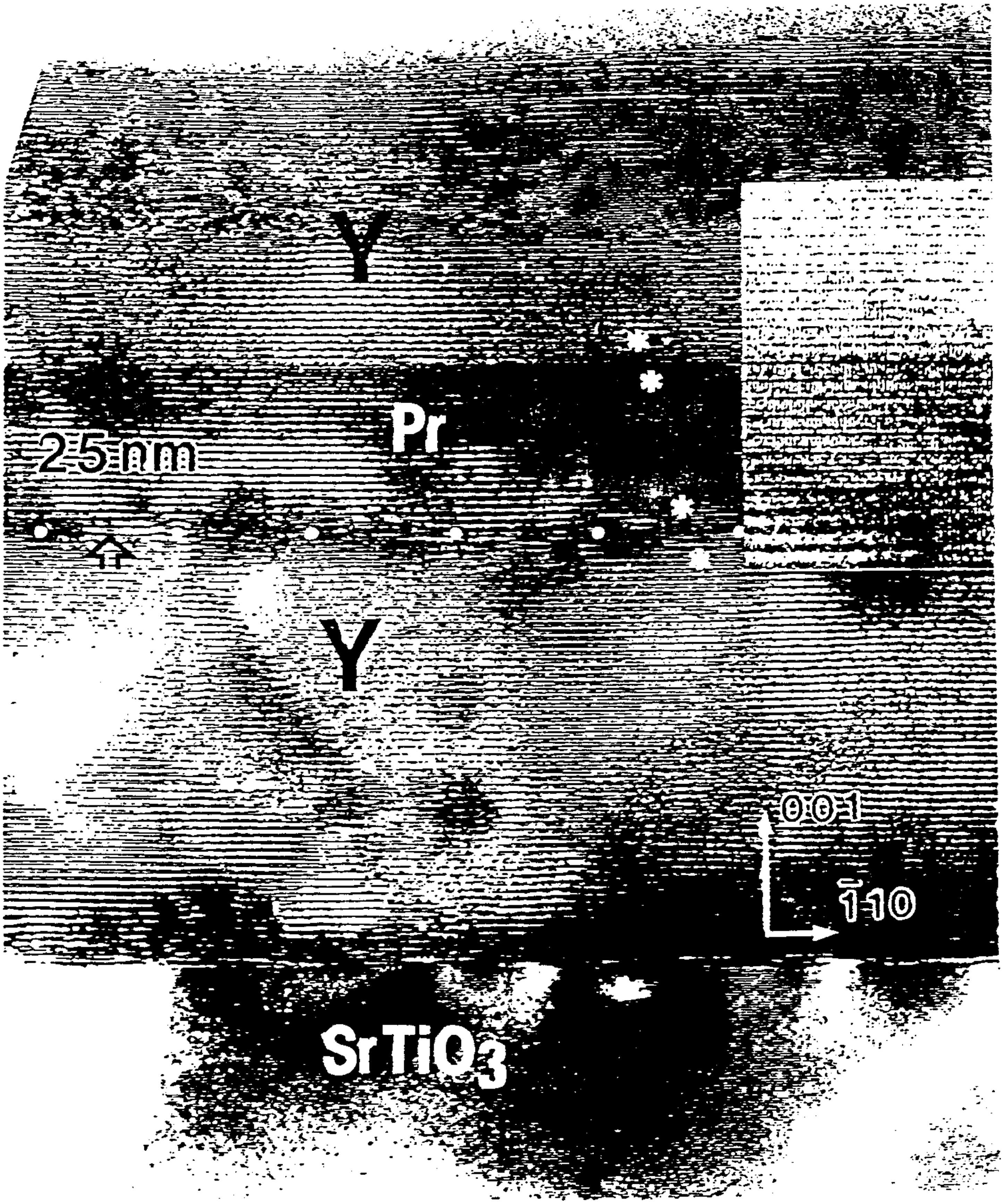
FIG. 2. Current-voltage characteristics for two SQUIDs fabricated in different runs measured at 6 K.

**Controlled Preparation of All High-T_c SNS-type Edge Junctions and Dc-SQUIDs

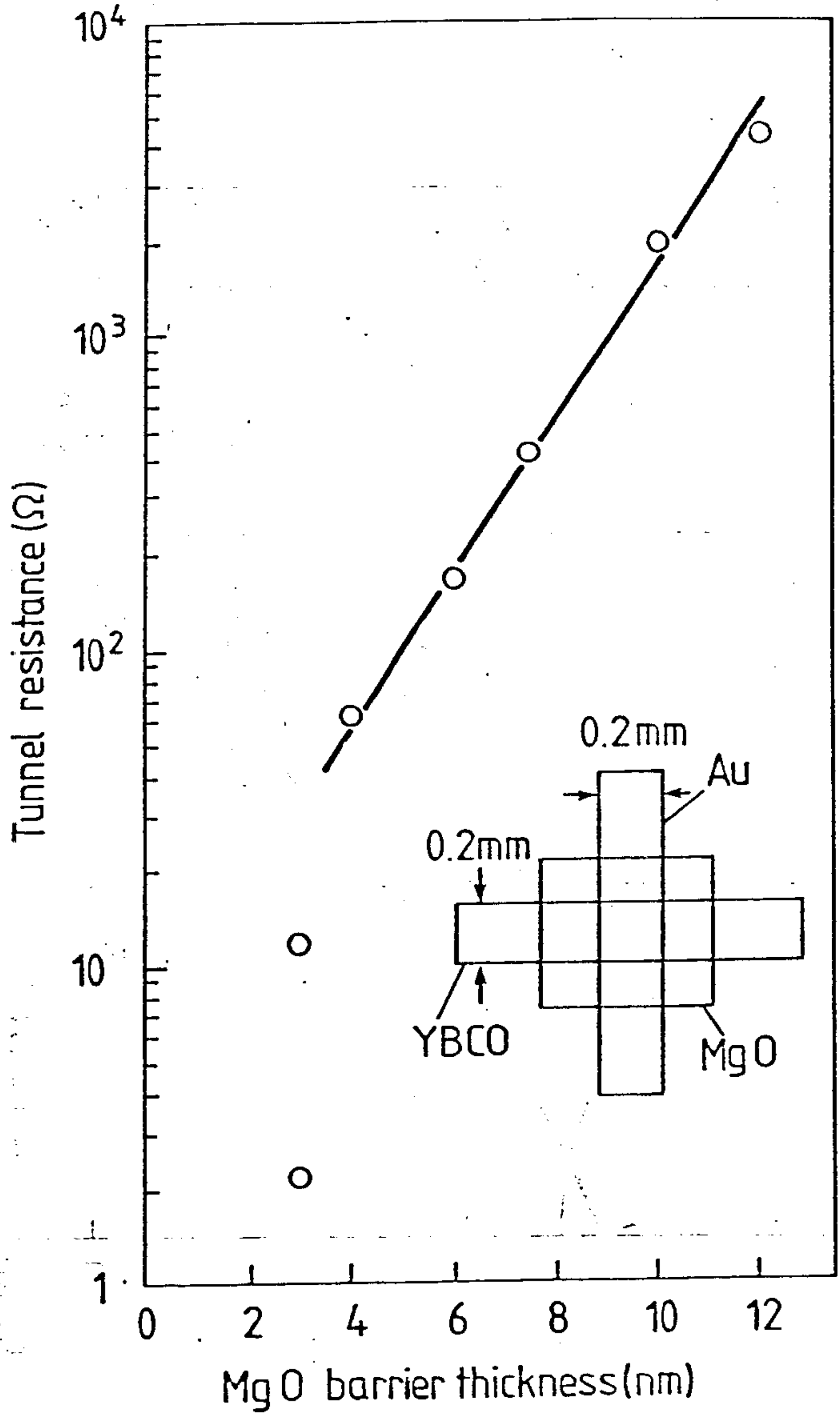
J.Gao, W.A.M.Aarnink, G.J.Gerritsma, and H.Rogalla, Physica C (1990) 126.







ref: C.L. Jia et al



M. Furuyama et al.

Fig. 6a