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SMR/543 - 21

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

(11 February - 1 March 1991)

" Tunnelling in Conventional and High T_c Superconductors "

presented by:

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

M. Gurvitch

Two Lectures on Tunneling
(Trieste, Feb 1991)

Plan:

Lecture 1: 1. History of tunneling: Sch. eq-n, Oppenheimer, Fowler & Nordheim, Ya. Frenkel', Giaever, McMillan–Rowell, Josephson
2. Tunn across the rectangular barrier; some numbers
3. Tunneling at $V \leq IV$ - background conductance; Estimates of barrier height and width
4. Superconducting density of states
5. N-I-N, N-I-S, S-I-S tunn. curves; examples
6. Josephson effect, applications: JJ's; V_m, RSFQ.

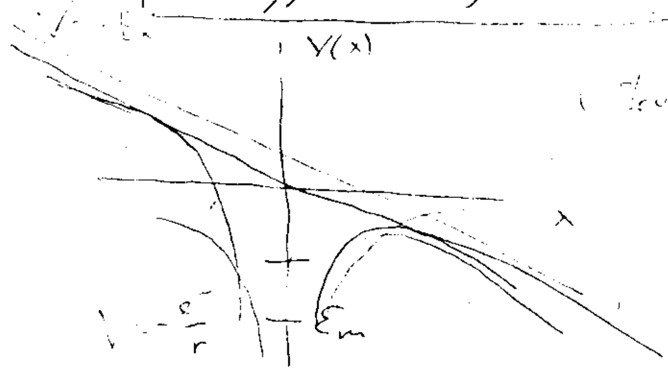
Lect. 2: ~~Tunneling in HTSC~~

1. Some points from Lecture 1 revisited:
   a.) $dI/dV = N_s(E)$
   b) Harrison's argument
2. Tunneling and coherence length
3. Tunneling spectroscopy
4. Tunneling in HTSC
   a). Different kinds of junctions
   b) Josephson tunneling; prospects for applications
   c). Large area vs point contact tunneling

1. Historical perspective:

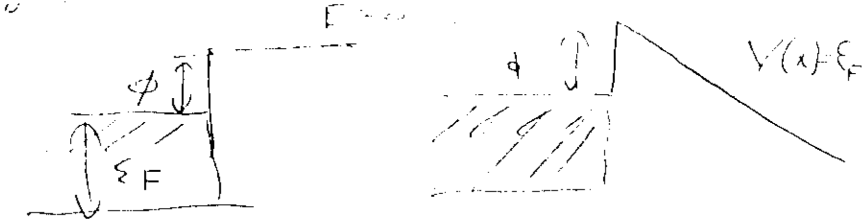
1928: field excitation of atomic hydrogen

$\boxed{\text{J. R. Oppenheimer, Phys Rev. } \underline{31}, 66 \text{ (1928)}}$



(Transfer Hamiltonian)

same year | Fowler and Nordheim | field emission
[Proc Roy Soc (London) A 119, 173 (1928)]
electrons from the bulk metal into vacuum



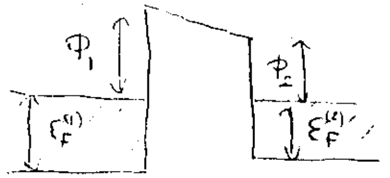
$\boxed{\text{Ya. Frenkel' (Phys. Rev. } \underline{36}, 1604 \text{ (1930))}}$ metal-vacuum-metal junctions

also

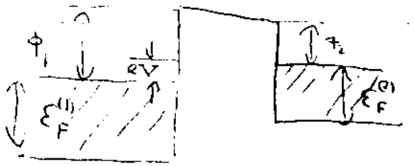
$\boxed{\alpha\text{-decay (Gamov), 1928}}$

Frenkel (1930)

metal junction



vacuum barrier



elastic or "horizontal" tunneling

A number of people considered metal-semiconductor tunneling (Wilson and others).

Sommerfeld and Bethe (1933): insulator as a barrier.
At that time results applied to present metallic contacts

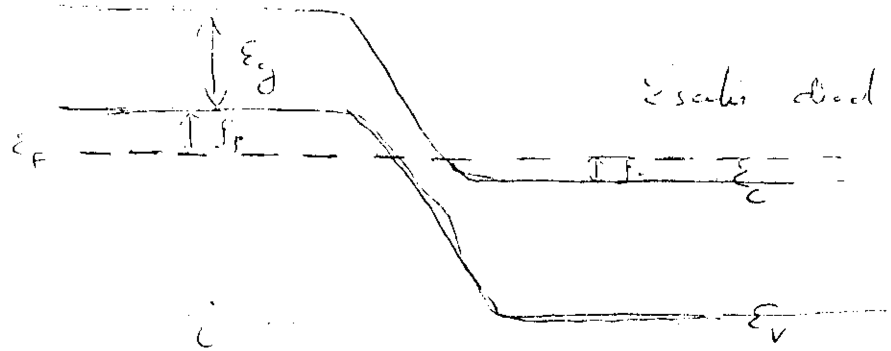
The discovery that thermal oxidation gives uniform thin oxide barriers was made only in 1960!

J. C. Fisher and I. Giaever, J. Appl. Phys. 32, 172 (1961).

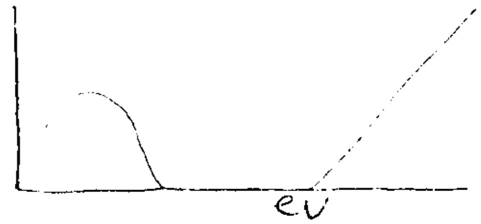
I. Giaever, PRL 5, 147 (60)
5, 464 (60).

Zener (1934) – internal field emission
Esaki (1957): tunnel diode (p-n)
degenerately doped p-n diode

Tunnel diode



Esaki diode, 1957



Giaever, 1960: Al–Al_2O_3–Pb, measured Δ_{Pb}.

NB the $G = \frac{di}{dV}$ appeared to be a direct measure of the many-body bulk DOS in contrast to the predictions of one-electron theory

McMillan & Rowell (late 60's): tunneling spectroscopy

Giaever's discovery also led to re-examination of a theory.

Also, J. Nicol, S. Shapiro and P.H. Smith, PRL 5, 461 (60).

Another major discovery was that of the Josephson tunneling effects

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B. D. Josephson, Phys. Letters 1, 251 (1962)

P. W. Anderson and J. Rowell, PRL 10, 230 (1963)

J. M. Rowell, PRL 11, 200 (63)

M. D. Fiske, Rev. Mod. Phys. 36, 221 (1964)

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2. Tunneling across the rectangular barrier:

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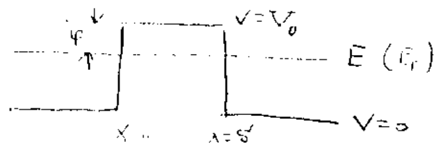


$\hat{H}\psi = E\psi$; $\hat{p} = \frac{\hbar}{i}\nabla$; $\hat{K} = \frac{\hat{p}^2}{2m} = -\frac{\hbar^2}{2m}\Delta$; $\hat{H} = \hat{K} + \hat{V} = -\frac{\hbar^2}{2m}\Delta + V(x)$

$\cancel{-\frac{\hbar^2}{2m}\Delta\psi = E\psi \quad \frac{\hbar^2}{2m}\Delta +}$

$-i = \frac{1}{i}$, $(-i)(-i) = +i^2 = -1$, $\frac{1}{i}\cdot\frac{1}{i} = -1$, ...

$\nabla^2\psi + \frac{2m}{\hbar^2}(E - V_0)\psi = 0$;

$k_1 = \frac{1}{\hbar}\sqrt{2mE}$; $k_2 = \frac{1}{\hbar}\sqrt{2m(E-V_0)}$; $k_3 = k_1$,

$x < 0$: $\psi = e^{ik_1x} + Ae^{-ik_1x}$

$0 < x < S$: $\psi = Be^{ik_2x} + Ce^{-ik_2x}$

$x > S$: $\psi = De^{ik_1x}$

A, B, C, D determined from matching of the cont. ψ, ψ' at $x = 0, S$.

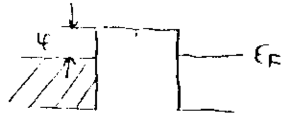
In $0<x<S$, $\varkappa_2 = \frac{1}{\hbar}\sqrt{2m(V_0-E)}$, $k_2 = i\varkappa_2$

Assume that $e^{-\frac{\varkappa S}{2}} \ll e^{\frac{\varkappa S}{2}}$, i.e. $\varkappa S \gg 1$. then transmission coefficient

$$\boxed{T = |D|^2 = \frac{16\, e^{-2\varkappa_2 S}}{\left[1 + \left(\frac{\varkappa_2}{k_1}\right)^2\right]\left[1 + \left(\frac{k_1}{\varkappa_2}\right)^2\right]}}$$

(see texts in QM, e.g. D. Bohm, Quantum Theory p. 240)

Let's use notations making an analogy with tunneling between metals



$E = \varepsilon_F$; $V_0 - E = V_0 - \varepsilon_F = \varphi$, work function, or barrier height.

[illegible] $[1+(\frac{k_2}{k_1})][1+(\frac{k_2}{k_1})]$ =

$$\frac{k_1^2 k_2^2}{(k_1^2+k_2^2)(k_1^2+k_2^2)} = \frac{k_1^2 k_2^2}{(k_1^2+k_2^2)^2} = \frac{\mathcal{E}_F \cdot \varphi}{(\cancel{E}+V-\cancel{E})^2} =$$

$$= \frac{\mathcal{E}_F\,\varphi}{(\mathcal{E}_F+\varphi)^2} = \frac{\varphi/\mathcal{E}_F}{1+\left(\frac{\varphi}{\mathcal{E}_F}\right)^2} \approx \frac{\varphi}{\mathcal{E}_F}$$ assuming that $\varphi \ll \mathcal{E}_F$ (say 2v vs 10v)

[not a very good approx for small $\mathcal{E}_F$]

$$T \approx \frac{16}{\mathcal{E}_F}\cdot \varphi\, e^{-2\frac{\sqrt{\varphi\cdot 2m}}{\hbar}\cdot S}$$ or

$$\boxed{T \simeq \frac{16}{\mathcal{E}_F}\cdot \varphi\, e^{-\frac{2^{3/2}}{\hbar} m^{1/2}\varphi^{1/2} S}}$$

Note: $G \propto T$
$R \propto T^{-1}$

[Current in a field will be $j \propto \sigma E$,

or ~~$i = \sigma V$, or~~ $i = GV$

ie $i \propto$ ~~current~~ $\cdot\, \varphi \cdot e^{-A\cdot\varphi^{1/2} S}$ — this is the correct form!]

Some numbers: $\hbar = 1.05\cdot 10^{-27}$ erg sec.
$m_o = 9.1\cdot 10^{-28}$ g.

If we use φ in eV and S in Å, we must use coefficients of $1\,\text{ev} = 1.602\cdot 10^{-12}$ erg and $1\,\text{Å} = 10^{-8}$ cm

$$\propto e^{-\alpha}; \quad \alpha = \frac{2^{3/2}}{\hbar} m^{1/2}\varphi^{1/2} S =$$

$$= \frac{2^{3/2}\cdot(9.1\cdot 10^{-28})^{1/2}\cdot(1.602\cdot 10^{-12})^{1/2}\cdot 10^{-8}}{1.05\cdot 10^{-27}}(\varphi^{1/2} S) =$$

$= 1.03\,\varphi^{1/2} S \simeq \varphi^{1/2} S$ where $[\varphi] = \text{eV}; [S] = \text{Å}$;

~~For $\varphi = 2$ eV, $S = 15$ Å~~

Note: the absence of numerical coefficient is just the coincidence; also numerical coefficient has dimensions, so that $[A\varphi^{1/2}S] = 1$.

~~$T(2\text{eV}, 15\text{Å})$~~

1-1) $$\boxed{T \simeq \frac{16\varphi}{\mathcal{E}_F}\, e^{-\varphi^{1/2} S};\ [\varphi] = \text{ev}; [S] = \text{Å};}$$

Some numbers:

Take $\varphi = 2$ eV; $S = 15$ Å; $\mathcal{E}_F = 10$ ev.

Then $T_{(2,15)} \simeq 3.2\cdot e^{-2^{1/2}\cdot 15} \simeq 2\cdot 10^{-9}$;

For a barrier one monolayer thinner,

$S = 12$ Å,

$T_{(2,13)} = 3.2\cdot e^{-17}$ $4.26\cdot 10^{-8} = 1.36\cdot 10^{-7}$,

$T_{(2,13)}/T_{(2,15)} \cong 0.7\cdot 10^{2} = \underline{70}$;

How do we get from T to the current?

T is dimensionless.

$i = GV$, therefore we will have to have $i = \text{Const}\, T \cdot \frac{e^2}{h} V$, where $\frac{e^2}{h}$ is the fundamental unit of conductance.

Let's work the incident current in the interval $E \in [E, E+dE]$ (for a wave normalized to $|a|^2=1$)

$$i^{E,dE}_{inc} = e\, v_E\, n_{E,E+dE} = e \cdot \frac{\hbar k}{m} \cdot \left(\frac{dn}{dE}\right)_{1D} \cdot f(E)\, dE \qquad (2)$$

$f(E)$ – Fermi-Dirac function.

$\frac{dn}{dE}$: 1-Dim. DOS: ~~density of~~ points in k-space are equidistant at $\frac{\pi}{L}$; so in dk, there are $\frac{dk}{(\frac{\pi}{L})}$ points, or, for $L = 1$*, $n = \frac{dk}{\pi}$; $\quad \mathcal{E} = \frac{\hbar^2}{2m} k^2$; $d\mathcal{E} = \frac{\hbar^2 k}{m} dk$; ~~then~~ so $\frac{dn}{d\mathcal{E}} = \frac{\cancel{dk}\, m}{\pi \hbar^2 k\, \cancel{dk}}$ or

$$\boxed{\frac{dn}{d\mathcal{E}} = \frac{m}{\pi \hbar^2 k}}$$

Note: velocity is $\propto k$, DOS $\propto 1/k$, hence energy dependence in the DOS cancells out: Harrison's argument PR 123, 85 (1961). In a superconductor the current does not cancell.

So we get from (2)

$$i^{E,dE}_{incident} = e\, \frac{\hbar \cancel{k}}{\cancel{m}}\, \frac{\cancel{m}}{\pi \hbar^{\cancel{2}} \cancel{k}} \cdot f(E)\, dE = \frac{e}{\pi \hbar} f(E)\, dE$$

Note: if $dE = e\delta V$, $(f = 1)$, $i(E, dE) = 2\frac{e^2}{h}\delta V$ — current units. The meaning is not clear, however (indeed, $\frac{h}{e^2} \sim 10{,}000\,\Omega$) ~~[illegible]~~ ~~[illegible]~~

* Note! $L = 1$ is equivalent to assuming $|a^2| = 1$; alternatively, $\frac{dn}{d\varepsilon} \sim L$ and $|a^2| = \frac{1}{L}$; (indeed, $\sim \frac{\pi}{L}\, n$ ~~[illegible]~~ [illegible]) Insert to 12

Tunneling

Background!

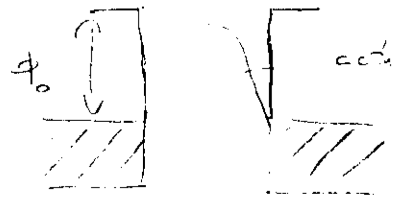


Image forces were considered by J. G. Simmons*

see J. G. Simmons, J. Appl. Phys. 34, 1793 (1963)
34, 2581 (1963)
PRL 10, 10 (1963)

cited in Burstein

also described in J. M. Rowell's article in Burstein

We said that

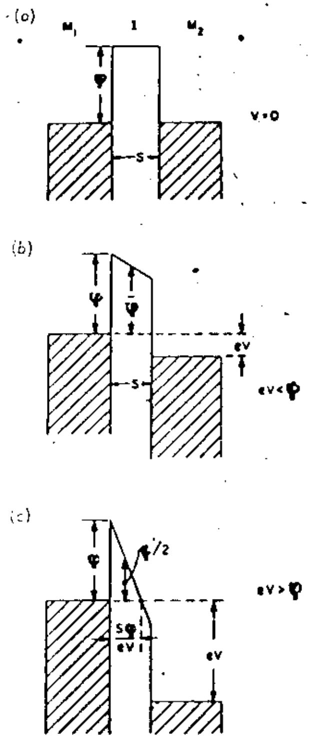
At very low eV, I_{nu} is ohmic: this regime really nonexistent, if one looks carefully above a ~~[illegible]~~ ~~[illegible]~~ ~~[illegible]~~ $T = \frac{|A|^2}{\hbar k^2}$

for mV; ~~At~~ ~~e~~$V \gtrsim 2$ Volts current becomes exponential (Fowler–Nordheim regime).

Most interesting domain is in the range 0–1V.

Look again at (11):

$$j \propto T, \quad j_{12} = J_0\, \bar{\varphi}\, \exp\left(-S\bar{\varphi}^{1/2}\right)$$



$$\bar{\varphi} = \varphi - \frac{eV}{2}$$

Fig. 1. Representation of the simplest type of potential barrier between two metals. (a) The barrier is symmetrical for $V = 0$. Shown are the average height and thickness of the barrier for (b) intermediate ($eV < \varphi$) and (c) high ($eV > \varphi$) voltage ranges.

In case of $eV < \varphi$ (intermediate range)

$$J = J_0 \left\{ \left(\varphi - \frac{eV}{2}\right) \exp\left[-S\left(\varphi - \frac{eV}{2}\right)^{1/2}\right] - \left(\varphi + \frac{eV}{2}\right) \cdot \exp\left[-S\left(\varphi + \frac{eV}{2}\right)^{1/2}\right]\right\}$$

Expanding, dropping terms of the order of V^4 and higher finds

$$I = \alpha\left(V + \delta V^3\right)$$

$$J_{21} = J_0(\bar{\varphi} + eV)\exp\left[-S_1(\bar{\varphi} + eV)^{1/2}\right]$$

Q when do they tunnel? (there are only occupied states on the other one!)

$$J = J_{12} - J_{21}^{*} \quad ; \text{(Slow barriers)}$$

in the intermediate range $eV < \varphi$

$S = \text{const}$, but $\bar{\varphi} = \varphi - \frac{eV}{2}$;

Substituting, we obtain

$$J = J_0 \left\{ \left(\varphi - \frac{eV}{2}\right) \exp\left[-S\left(\varphi - \frac{eV}{2}\right)^{1/2}\right] - \left(\varphi + \frac{eV}{2}\right) \exp\left[-S\left(\varphi + \frac{eV}{2}\right)^{1/2}\right]\right\}$$

For $eV < \varphi$, expanding and keeping terms to V^3

$$I = \alpha\left(V + \delta V^3\right) \text{ or}$$

$$\frac{dI}{dV} = \alpha + 3\alpha\delta V^2 ;$$

Note: when $\frac{dI}{dV} = 2\alpha$,

$$3\alpha\delta V^2 = \alpha \quad ; \quad V^* = \left(\frac{1}{3\delta}\right)^{1/2}; \quad \text{or } \boxed{\delta = \frac{1}{3V^{*2}}}$$

From Simmons (J Appl. Phys. 34, 238 (63)) =

Data of J. M. Rowell

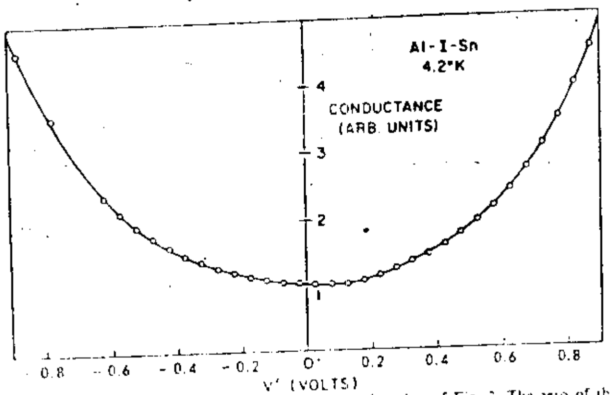
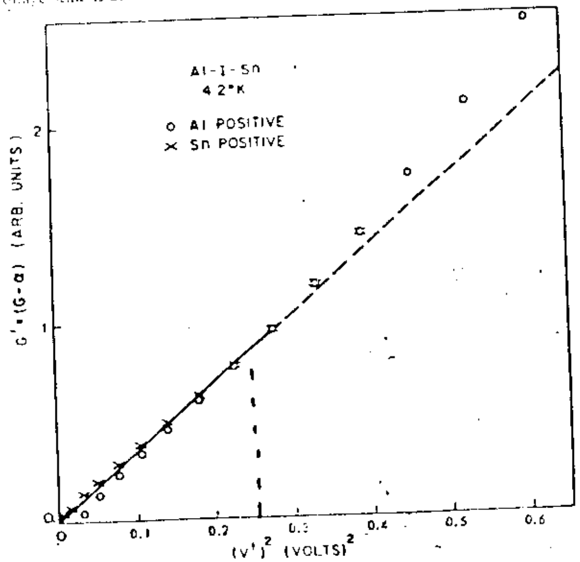
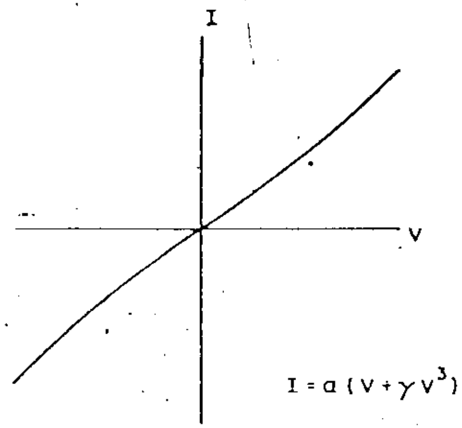


Fig. 5. Conductance versus voltage V' for the junction of Fig. 3. The zero of this V' voltage scale is at $V = -425$ mV in Fig. 3.



$G-\alpha =$
$= 3\gamma\alpha V^2$

$V' = 500$ mV



$\frac{dI}{dV} = G(V) = \alpha(1+3\gamma V^2)$

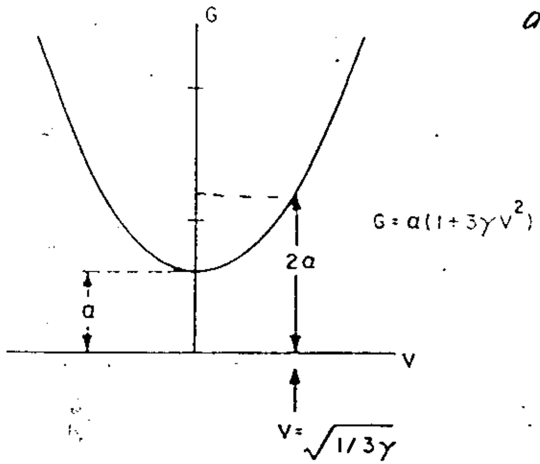


Fig. 2. Current and conductance versus voltage for an ideal symmetrical barrier of the type shown in Fig. 1 (a). The conductance is a constant plus a parabolic term which is symmetric about $V = 0$.

$\gamma = \cancel{\ldots}\, 0.0115\,\frac{S^2}{\varphi} - \frac{0.0115}{\varphi^{1/2}}\,S \approx 0.0115\,\frac{S^2}{\varphi}$;

Note: S in Å, $S > 10$(Å), i.e. $S^2 \gg S$

Also from Simmons

$$\alpha = 3.16\cdot 10^{10}\,\frac{\bar\varphi^{1/2}}{S}\exp\left(-S\bar\varphi^{1/2}\right)$$

[illegible] call $S\bar\varphi^{-1/2} = \zeta$. Then

$$\gamma = 0.0115\,\zeta^2, \text{ or } \zeta = \left(\frac{\gamma}{0.0115}\right)^{1/2} = \frac{1}{V^*}\left(\frac{1}{0.0115\cdot 3}\right)^{1/2} =$$

$$= \frac{5.38}{V^*};$$

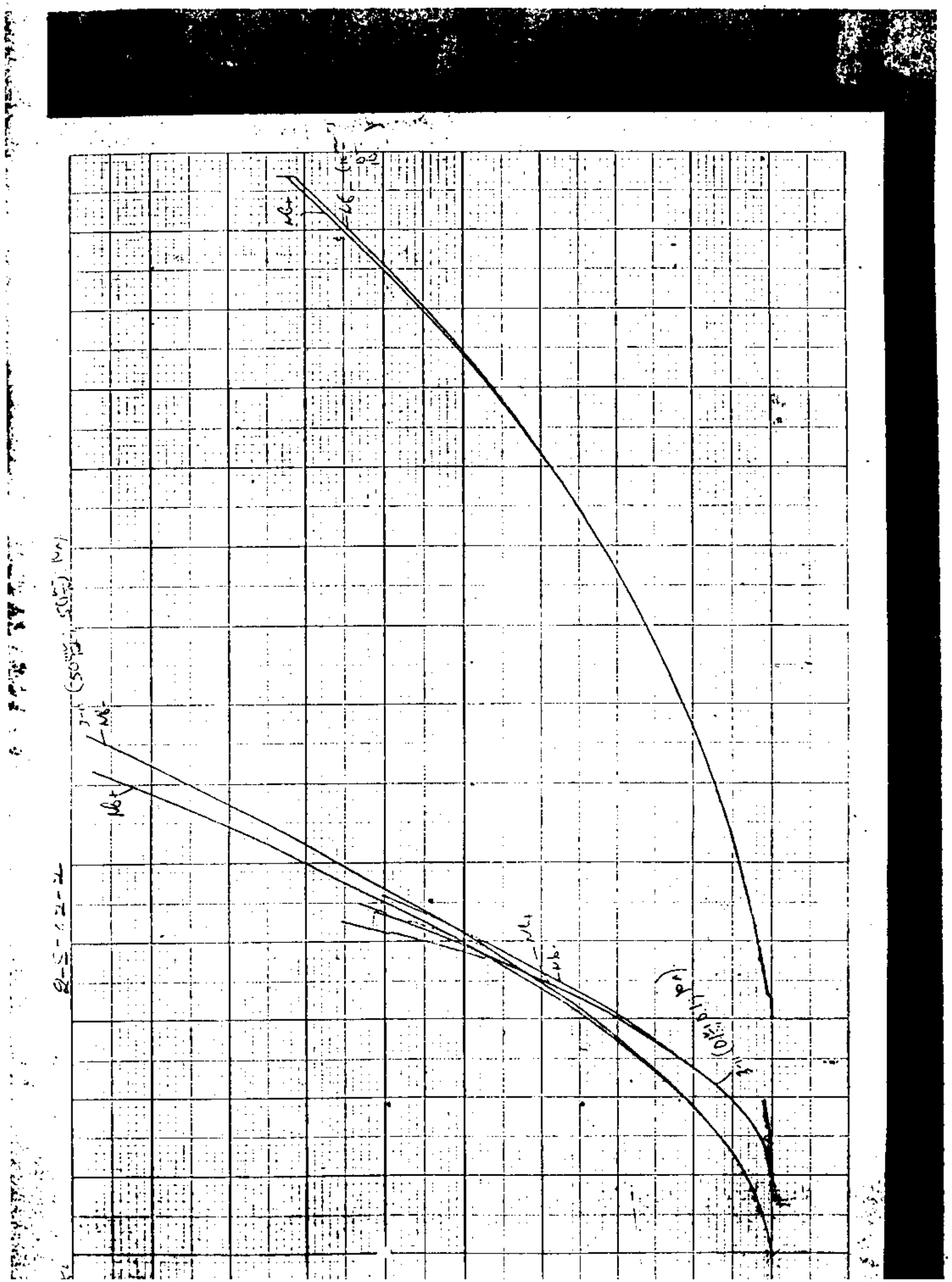
$$\frac{\alpha}{3.16\cdot10^{10}} = \frac{1}{\zeta}\exp\left(-\zeta\bar\varphi\right); \quad -\zeta\varphi = \ln\frac{\alpha\zeta}{3.16\cdot10^{10}}, \quad \zeta\varphi = \ln\frac{3.16\cdot10^{10}}{\alpha\zeta};$$

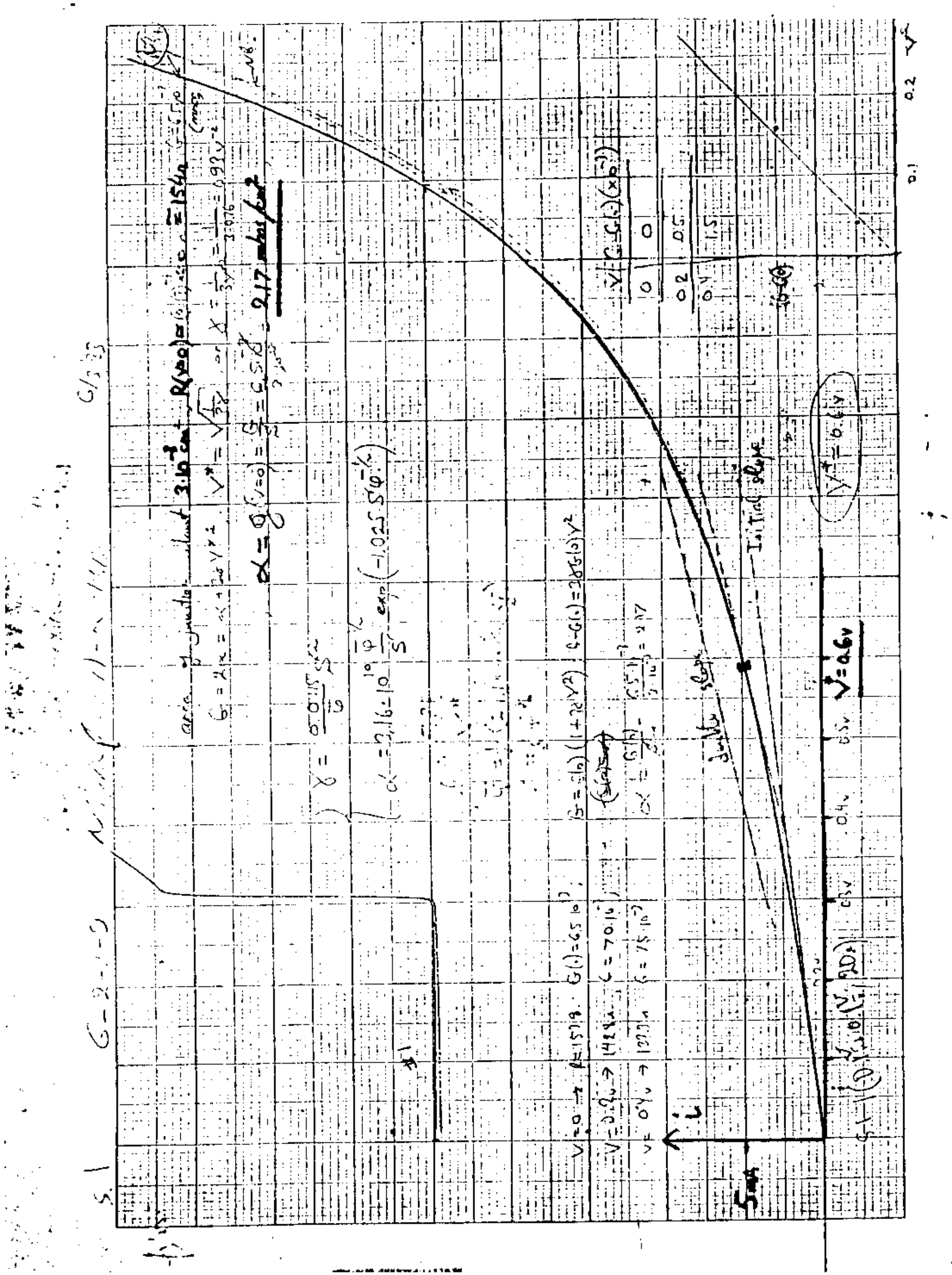
$$\bar\varphi = \frac{1}{\zeta}\left[\ln 3.16 + 10\ln 10 - \ln\alpha\zeta\right] = \frac{1}{\zeta}\left(24.18 - \ln\alpha\zeta\right)$$

So we have
$$\boxed{\begin{cases} \zeta = \dfrac{5.38}{V^*} \\ \bar\varphi = \dfrac{1}{\zeta}\left(24.18 - \ln\alpha\zeta\right) \\ S = \zeta\,\bar\varphi^{1/2} \end{cases}}$$
where we know (measure) V^* and α.

Powell's example: $V^* = 0.54$ v ; $\alpha = 6.91$ mhos/cm^2

$\zeta = 9.96$; $\bar\varphi = 2.0$ ω ; $S = 14$ Å ; (correct)





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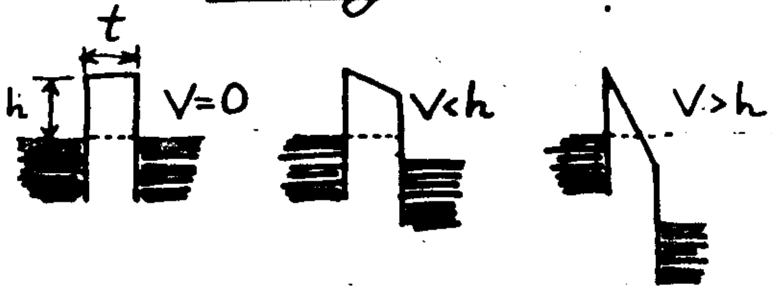
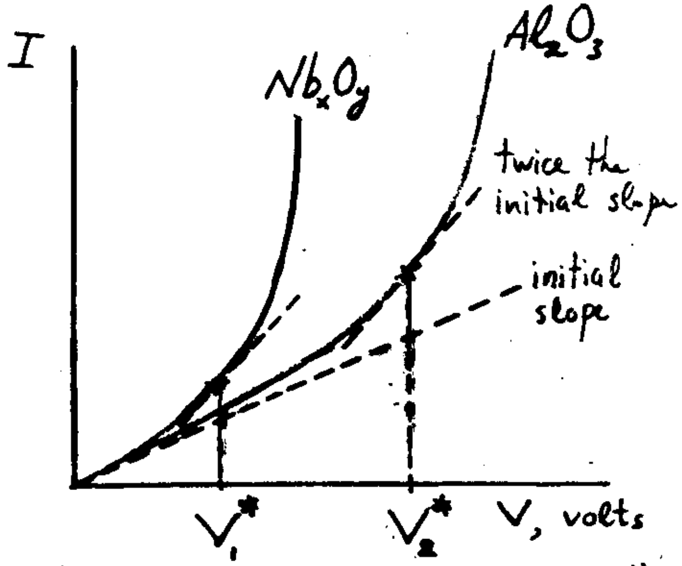
Ily example $V^* = 0.6\,v$; $\alpha = 2.17$ mho/cm².

$\xi = \frac{5.38}{0.6} = 8.97$;

$\bar{\varphi} = 2.36\,v$; $S = 13.8\,\text{Å}$;

I-V curves at higher voltage

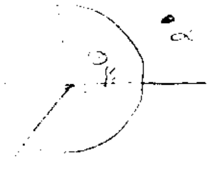




Nb: $t = 26\,\text{Å}$, $h = 0.31\,V$

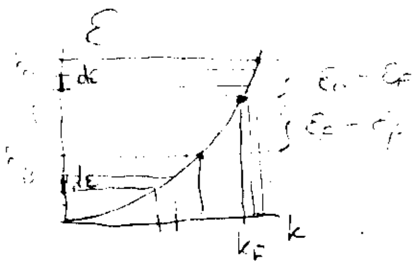
with Al: $t = 13.5 \pm 1.0\,\text{Å}$, $h = 2.0 \pm 0.2\,V$

Excitations:



We measure energies from ε_F

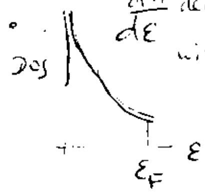
$$\varepsilon = (\varepsilon_\alpha - \varepsilon_F) + (\varepsilon_F - \varepsilon_\beta)$$

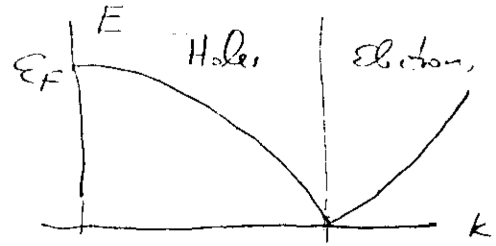


$$\varepsilon = \frac{\hbar^2 k^2}{2m}$$

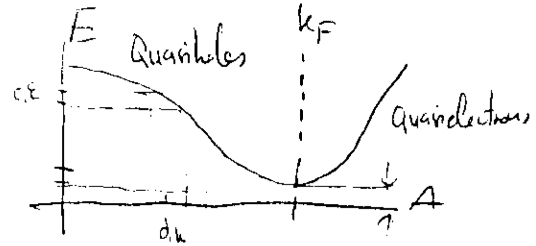
Excitation energy is always positive

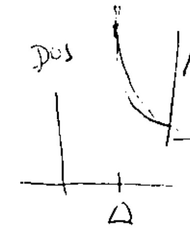
$$E = |\varepsilon - \varepsilon_F|$$



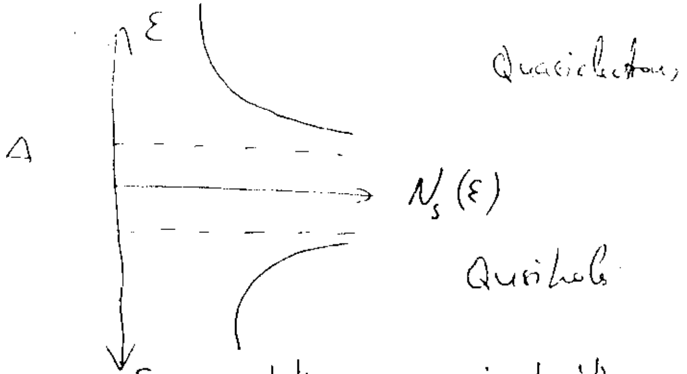


normal metal



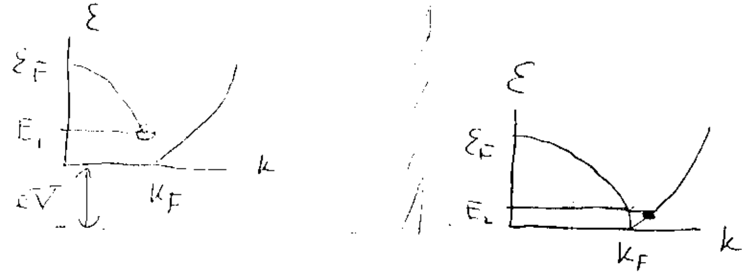


$$\boxed{N_S(E) = \frac{N_i E}{\sqrt{E^2 - \Delta^2}}}$$



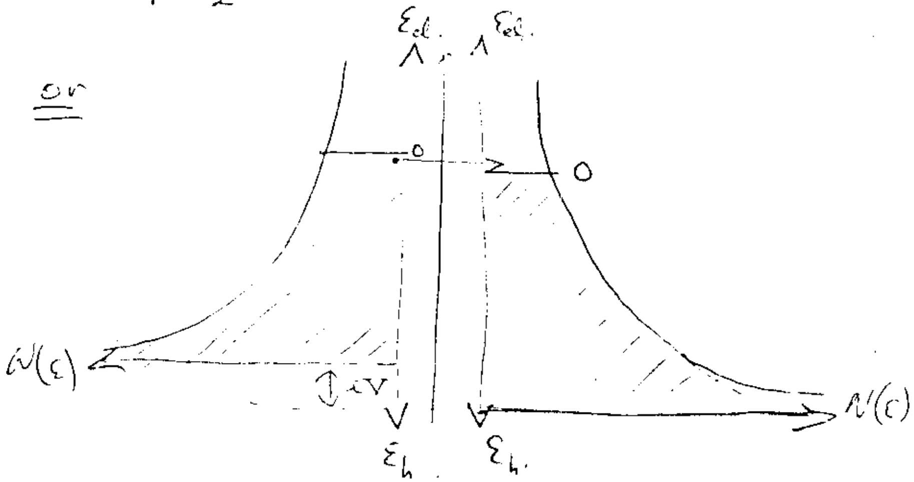
excitation energy is positive

For <u>2 normal metals</u>, tunneling can be visualized as



$$E_1 + E_2 = eV$$

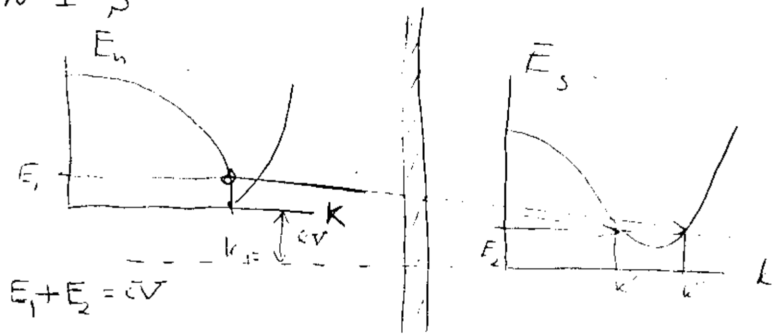
<u>or</u>



$$I_{nn}(T=0) = \frac{2\pi e A}{\hbar} \int_0^{eV} |T_{12}|^2 N_1(\varepsilon - eV)\, N_2(\varepsilon)\, d\varepsilon =$$

$$= 2\pi A \frac{e^2}{\hbar} |T_{12}|^2 N_1(0) N_2(0).$$

N-I-S'



$E_1 + E_2 = eV$

this is equivalent to considering the energy in k'' to be units and considering tunneling into states around k_F

<u>S-I-S</u>:

I-S Tunneling

$$N_s(E) = N_2(0)\, n_s(E)$$

BCS $\quad n_s(E) = \frac{E}{\sqrt{E^2-\Delta^2}}$

$$I_{ns} = ATN_1N_2 \int_{-\infty}^{\infty} \frac{|E|}{\sqrt{E^2-\Delta^2}}\left[f(E)-f(E-eV)\right]dE$$

at $T=0$ $\quad f(E-eV)-f(E) = \begin{cases} 1 & 0<E<eV \\ 0 & E<0,\ E>eV \end{cases}$

so $\quad I_{ns} = ATN_1N_2 \int_0^{eV} n_s(E)\,dE$

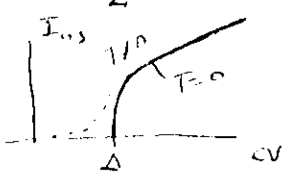
$$G_{NS} = \frac{dI_{ns}}{dV} = eATN_1N_2\, n_s(eV)$$

i.e. G_{ns} close to $T=0$ gives $n_s(E)$, $E = eV$.

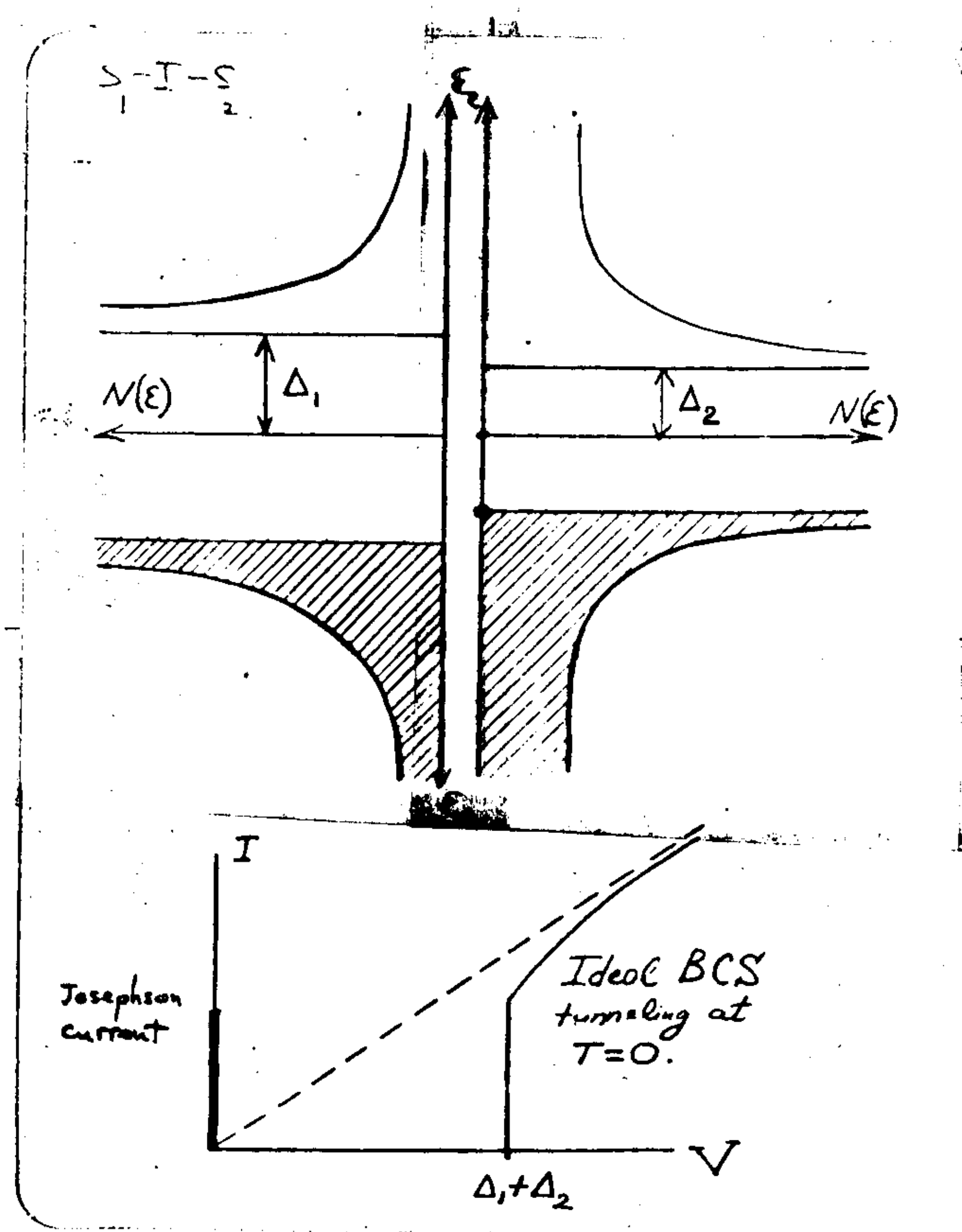
For $eV<\Delta$, $n_s=0$ and $I_{ns}=0$

For $eV>\Delta$

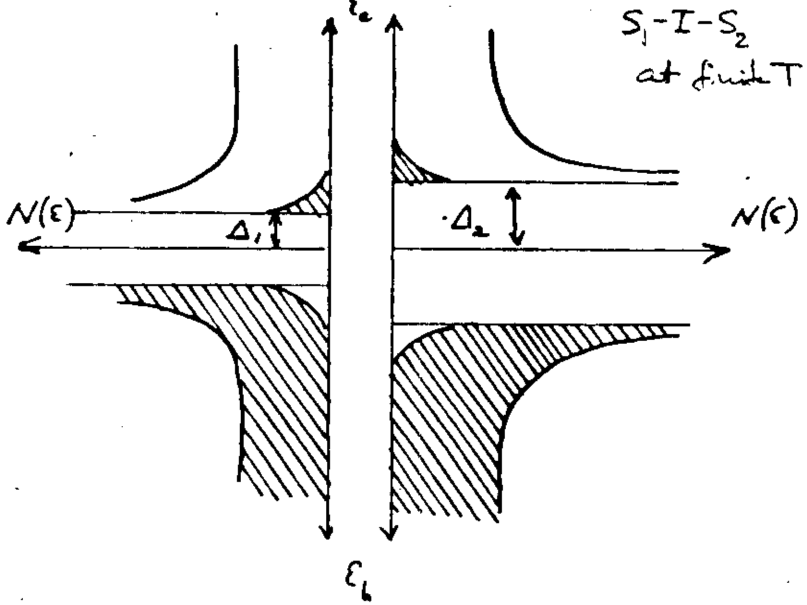
$$I_{ns} = ATN_1N_2 \int_{\Delta}^{eV} \frac{E\,dE}{\sqrt{E^2-\Delta^2}} = ATN_1N_2\sqrt{(eV)^2-\Delta^2}$$

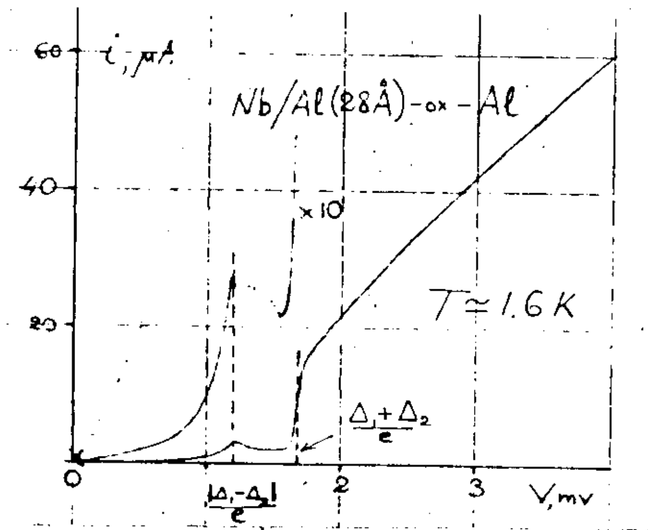


note: $eV \gg \Delta$, $I_{ns} \to ATN_1N_2\, eV$

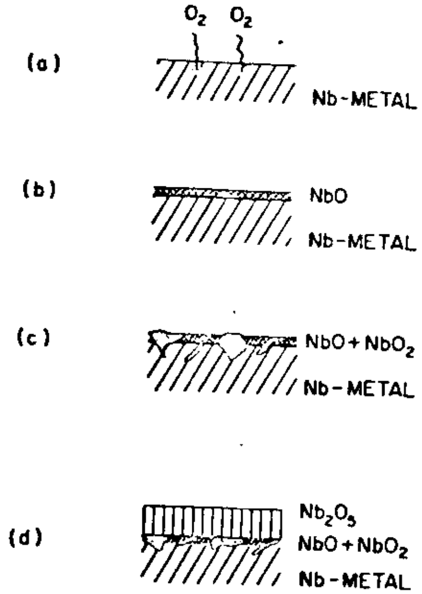


Tunneling I-V curves

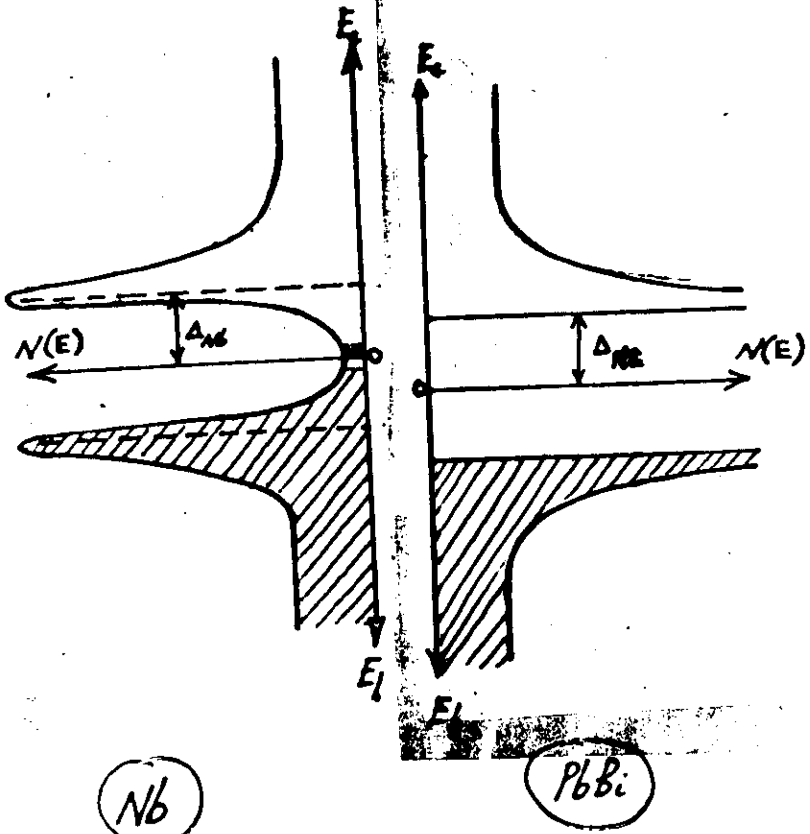




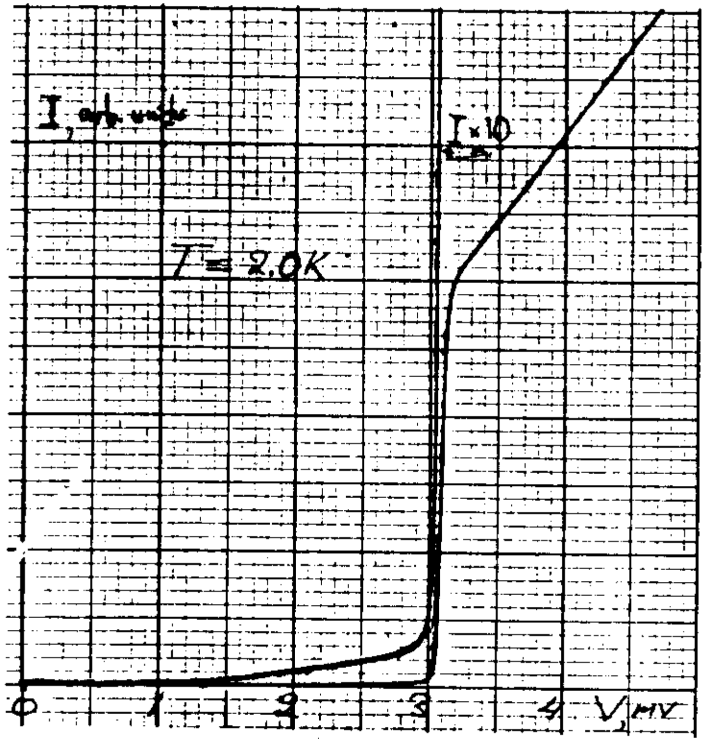
Stages of oxidation of Nb



from I. Lindau and W. E. Spicer,
J. Appl. Phys. 45, 3720 (1974)



$T = 2K = 0.17\ meV$

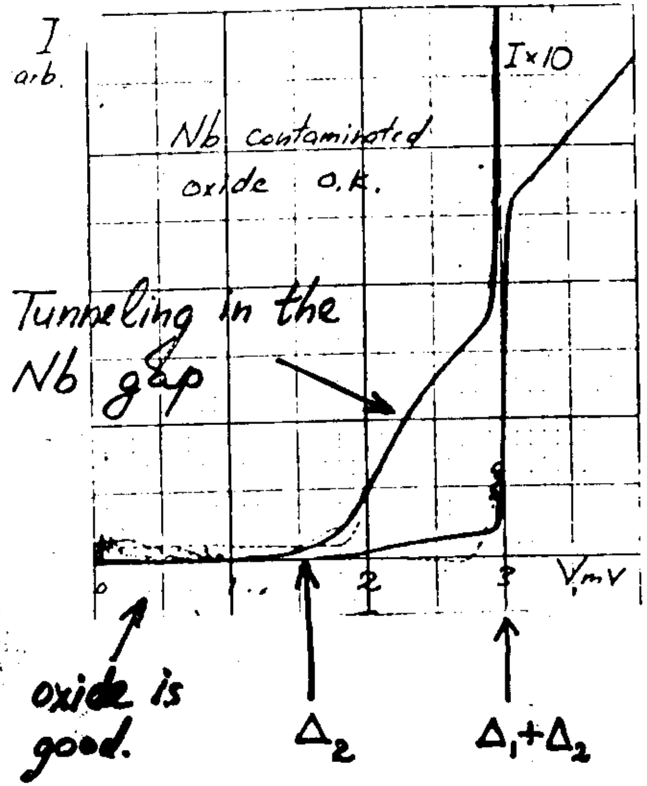


Nb/Al(21Å)-oxide (20 min, air) - $Pb_{0.9}Bi_{0.1}$

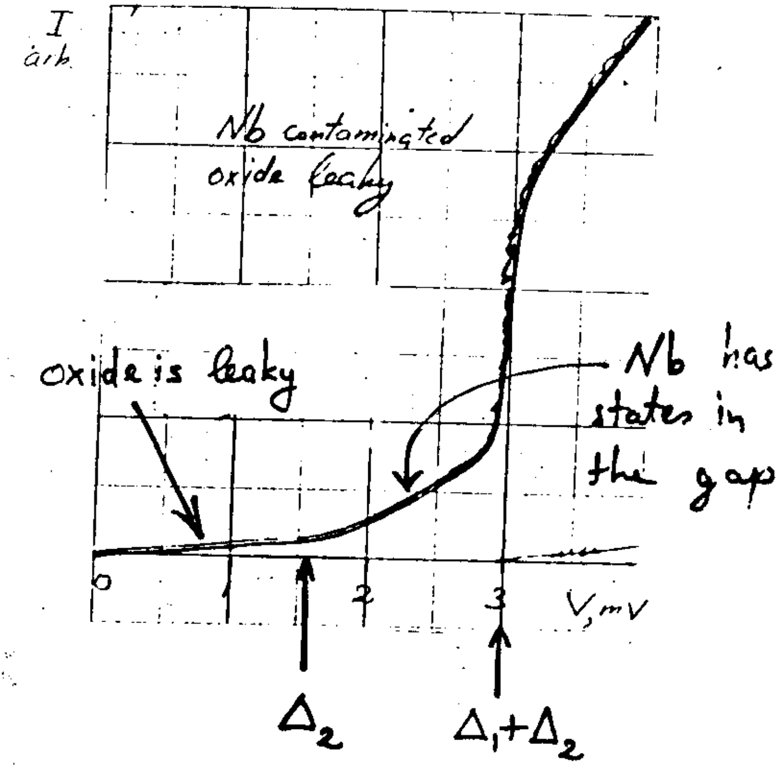
$\Delta_{Pb_{0.9}Bi_{0.1}} = 1.53 \Rightarrow \underline{\Delta_{Nb} = 1.57\ meV}$

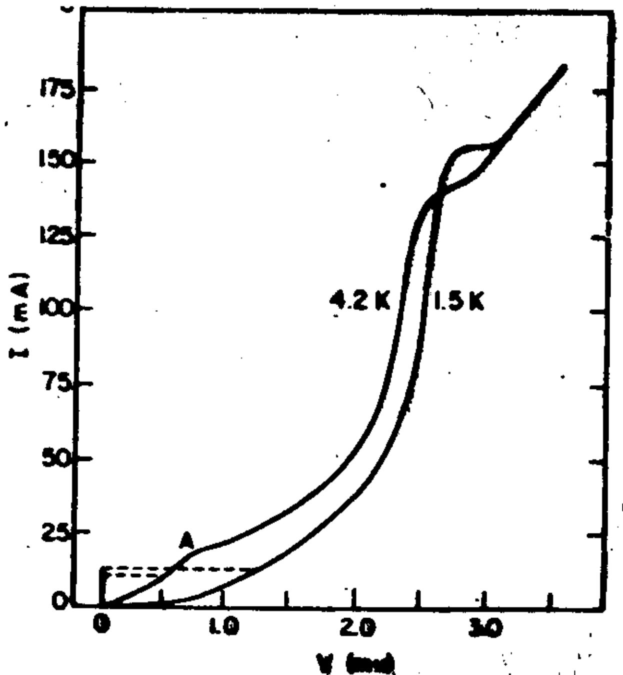
$$\frac{I(2mV)}{I(4mV)} = 2.5\cdot 10^{-3} \quad \left(\left.\frac{I(2mV)}{I(4mV)}\right|_{ideal} \sim 6\cdot 10^{-5} \right)$$

Nb/Al – oxide – $PbBi_{0.9\ 0.1}$



Nb – oxide – $PbBi$





Nb - oxide - Cu(8Å)/Nb
G. Hawkins and J. Clarke
(1975).

<u>Josephson Effect</u>

$$\frac{\partial P(\vec r, t)}{\partial t} = -\nabla \cdot \vec J$$

$$\vec P(\vec r, t) = \Psi^*(r,t)\Psi(r,t)$$

$$\frac{\partial \vec P}{\partial t} = \Psi^* \frac{\partial \Psi}{\partial t} + \Psi \frac{\partial \Psi^*}{\partial t}$$

Take Schr eq-n for $\frac{\partial \Psi}{\partial t}, \frac{\partial \Psi^*}{\partial t}$

we get $\vec J = \frac{1}{2}\left\{\left[\frac{\hat p - q\vec A}{m}\Psi\right]^*\Psi + \Psi\left[\frac{\hat p - q\vec A}{m}\Psi\right]^*\right\}$

In a superconductor $\Psi = \sqrt{\rho(\vec r)} \cdot e^{i\theta(\vec r)}$

$$\vec J = \frac{\hbar}{m}\left(\nabla\theta - \frac{q}{\hbar}\vec A\right)\cdot \rho \, ;$$

$$\left(\vec J = \rho \vec v \; \text{ or } \; m\vec v = \hbar\nabla\theta - q\vec A\right)$$

Ψ_1 – amplitude for an electron to be on the left side
Ψ_2 – " — " — " on the right

$$\begin{cases} i\hbar \frac{\partial \Psi_1}{\partial t} = U_1\Psi_1 + K\Psi_2 \\ i\hbar \frac{\partial \Psi_2}{\partial t} = U_2\Psi_2 + K\Psi_1 \end{cases}$$

K – characteristic of a junction

$$U_1 - U_2 = qV$$

[illegible] between Ψ_1 and Ψ_2:

$$\begin{cases} i\hbar \dfrac{\partial \psi_1}{\partial t} = \dfrac{qV}{2}\psi_1 + k\psi_2 \\ i\hbar \dfrac{\partial \psi_2}{\partial t} = -\dfrac{qV}{2}\psi_2 + k\psi_2 \end{cases}$$

$$\psi_1 = \sqrt{\rho_1}\, e^{i\theta_1}, \quad \psi_2 = \sqrt{\rho_2}\, e^{i\theta_2}$$

$$\rho_1 = \rho_2 = \rho_0$$

Equate real and imaginary parts, and define $\theta_1 \theta_2 = \delta$,

$$\left.\begin{aligned} \dot\rho_1 &= +\frac{2}{\hbar} k\sqrt{\rho_1\rho_2}\,\sin\delta \\ \dot\rho_2 &= -\frac{2}{\hbar} k\sqrt{\rho_1\rho_2}\,\sin\delta \end{aligned}\right\} \dot\rho_1 = -\dot\rho_2$$

$$\dot\theta_1 = \frac{k}{\hbar}\sqrt{\frac{\rho_2}{\rho_1}}\cos\delta - \frac{qV}{2\hbar}$$

$$\dot\theta_2 = \frac{k}{\hbar}\sqrt{\frac{\rho_1}{\rho_2}}\cos\delta + \frac{qV}{2\hbar}$$

$$\dot\rho_1 = -\dot\rho_2 = J,$$

$$J = \underbrace{\frac{2k}{\hbar}\sqrt{\rho_1\rho_2}}_{J_0}\sin\delta$$

$$\boxed{J = J_0 \sin\delta}$$

$$\dot\delta = \dot\theta_2 - \dot\theta_1 = \frac{qV}{\hbar}, \quad q = 2e$$

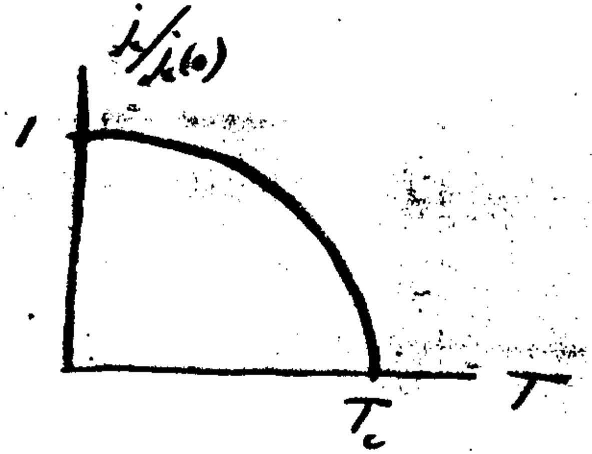
$$\boxed{\dot\delta = \frac{2e}{\hbar}V}$$ when $\omega = \frac{2e}{\hbar}V$, current flows

V. Ambegaokar and A. Baratoff

Phys. Rev. Lett. **11**, 104 (1963)

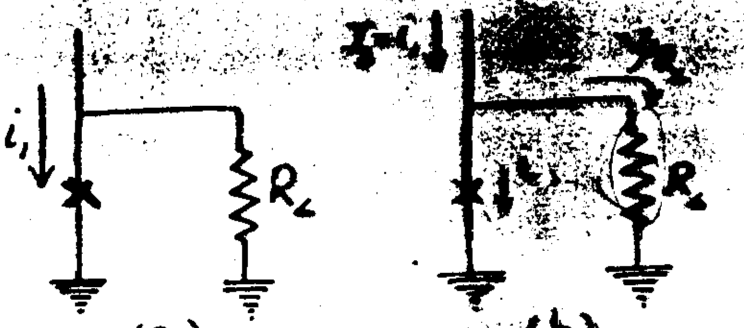
$$\Delta_1 = \Delta_2$$

$$j_c = \frac{1}{R_n S}\,\frac{\pi\Delta(T)}{2e}\tanh\frac{\Delta(T)}{2k_B T}$$



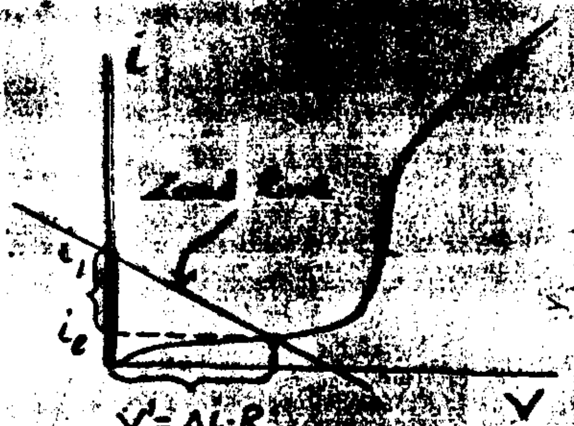
IBM ?

J.J. as a switch



Switching takes place when I_b reaches the value of i_1

$$i_1 = i + \frac{V}{R_L} \quad \text{or} \quad i = i_1 - \frac{V}{R_L}$$



$\Delta i = i_1 - i_2$ fan-out CURRENT

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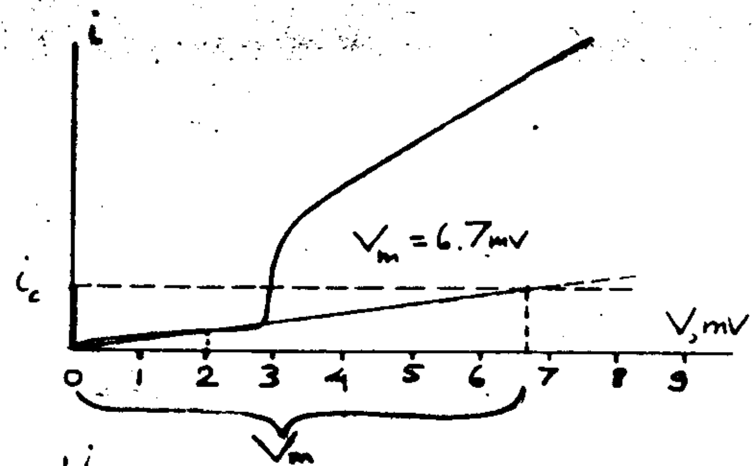
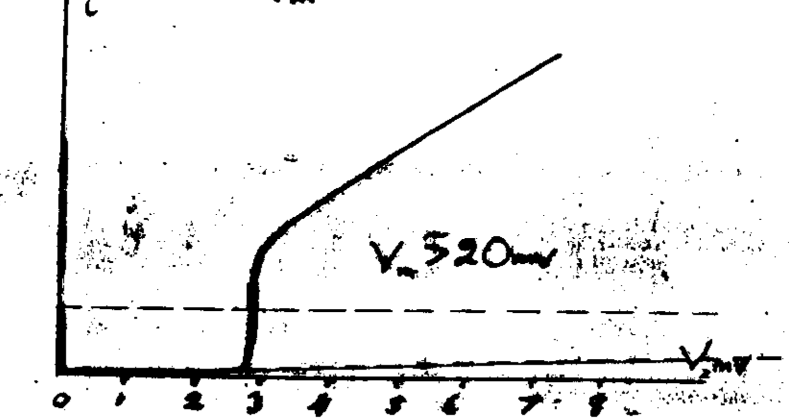
IBM ?

A quantitative measure of quality: $\underline{V_m = i_c \cdot R(2mv)} = 2 \times \frac{i_c}{i(2mv)}$;





Fan-out current

$$\Delta i = i_c\left(1 - \frac{2}{V_m}\right),$$

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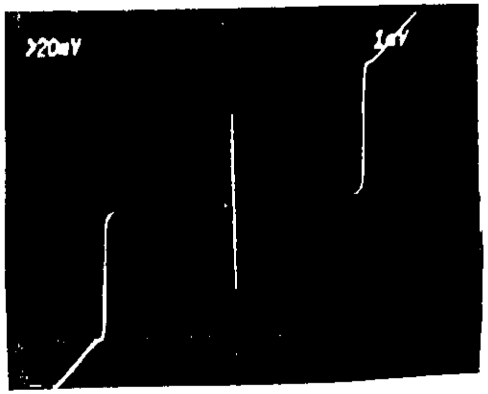
Δi ... 1 - 2 ...

$j_c = 480\ A/cm^2$

$V_m = 48\ mV$



Nb(3000Å)/Al(50Å) – oxide – Nb(3000Å)

For junction with 20μm width, and $\lambda(Pb) = 390\ \text{Å}$, Φ_0 in the junction corresponds to $B \simeq 13\cdot 10^{-4}\ \frac{Wb}{m^2}$ or 12.9 G.

Circuit applications of small or shunted junctions. RSFQ

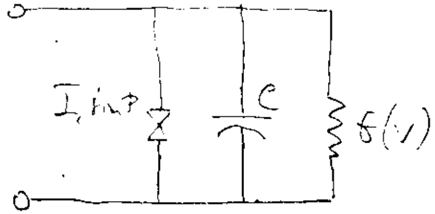
$I = I_c \sin\varphi$

$\frac{\partial \varphi}{\partial t} = \frac{2e}{\hbar} V$ $(*)$

Displacement current (C)

Leakage current, quasiparticle current $(G(V))$

Equiv. circuit



$$I = I_c \sin\Phi + G\cdot V + C\frac{dV}{dt}$$

Using $(*)$,

$$I = \frac{\hbar C}{2e}\frac{d^2\varphi}{dt^2} + \frac{\hbar G}{2e}\frac{d\varphi}{dt} + I_c \sin\varphi .$$

Let us introduce a new variable

$\theta = \omega_c t$, then $\omega_c = \frac{2e}{\hbar}\left(\frac{I_c}{G}\right)$

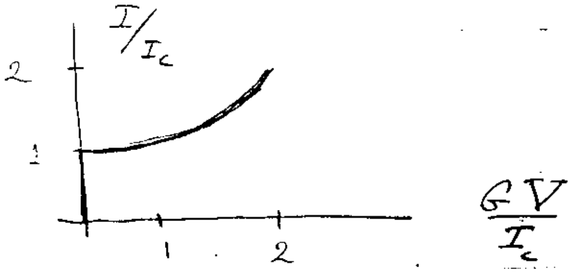
$$\beta_c = \frac{\omega_c C}{G} = \frac{2e}{\hbar}\left(\frac{I_c}{G}\right)\left(\frac{C}{G}\right) = \frac{2e}{\hbar}\frac{I_c C}{G^2}.$$

$$\boxed{\frac{I}{I_c} = \beta_c \frac{d^2\phi}{d\theta^2} + \frac{d\phi}{d\theta} + \sin\phi}$$

For $C = 0$, $\beta_c = 0$ and

$V = 0$ for $I < I_c$

$V = \frac{I_c}{G} \cdot \sqrt{\left(\frac{I}{I_c}\right)^2 - 1}$ for $I > I_c$



Mechanical analogy: Driven Pendulum.

Torque $T = M \cdot \frac{d^2\phi}{dt^2}$;

M - moment of inertia

$$T = T_{app} + \underbrace{mgl\sin\phi}_{\text{grav. torque}} + \underbrace{D\frac{d\phi}{dt}}_{\text{damping}} \text{ torque.}$$

So
$$\begin{cases} M\frac{d^2\phi}{dt^2} + D\frac{d\phi}{dt} + mgl\sin\phi = T \\ \frac{\hbar C}{2e}\frac{d^2\phi}{dt^2} + \frac{\hbar G}{2e}\frac{d\phi}{dt} + I_c\sin\phi = I \end{cases}$$
Comp.

We see that

a) the angle ϕ is the analog of the phase difference ϕ

b) $\frac{d\phi}{dt}$ (angular vel.) — " — of voltage

c) $M \Longleftrightarrow$ capacitance

d) $D \Longleftrightarrow$ conductance

e) Max. grav. torque $\Longleftrightarrow I_c$.

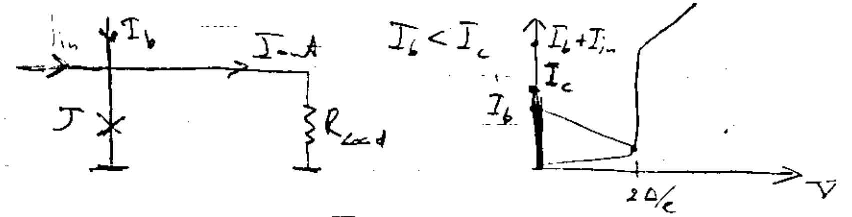
f) Applied torque $\Longleftrightarrow$ analog of source current

$\beta_c = mgl \cdot \frac{M}{D^2}$;

RSFQ:

Josephson power $P \approx \frac{V_g^2}{R_{eff}} \lesssim 1\,\mu$watt

Logic gate in "IBM-type" logic (latching logic)



$I_{in} + I_b = I_J + I_{out}$

$I = out.$

$V_J = R_J I_J$; $V_l = V_J = R_L \cdot I_{out} = V$;

$R_J I_J = R_L \cdot I_{out}$; $I_{out} = \frac{R_J}{R_L} I_J$

∇ $I_J =$

Re-setting is difficult : Latching logic.

Have to switch off I_b.

need AC (RF) power supply

This limits ~~frequency~~ clock frequency to a few GHz.

Also, punch through effect is a problem

for $f > 1$ GHz

Fujitsu 8-bit microprocessor, 22,000 JJ

Clock frequency ~ 1 GHz

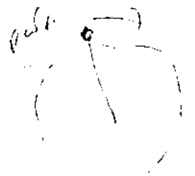
RSFQ (85): $\int V(t)dt = \Phi_0 = \frac{h}{2e} =$

$= 2.07 \text{ mV} \times \text{ps}$,

overdamped JJ's.

30 GHz operation was demonstrated in 86.

>100 GHz now, at 5 μm rules.



2π - leap of Φ

$\tau_0 = \frac{\pi}{\omega_c}$

Books:

1. C.B. Duke, Tunneling in Solids, Academic Press, NY and London, ~~1966~~ 1969 (Supplement 10, Solid State Physics,

2. "Tunneling Phenomena in Solids", Ed. by Burstein and Lundqvist, Plenum Press, N.Y 1969.

3. L. Solymar, Superconductive Tunneling and Applications, Wiley-Interscience, 1972

4. T. Van Duzer and C.W. Turner, Principles of Superconductive Devices and Circuits, Elsevier, NY-Oxford, 1981.

5. W. ~~L~~ L. McMillan and J.M. Rowell, Tunneling and Strong-coupling superconductivity, in Superconductivity, Ed. By Parks, 1969.

6. Tunneling Spectroscopy, Ed. by P.K. Hansma, Plenum, 1982.

M. Gurvitch ①

Lecture 2
(Trieste)

1. Points from L.1
2. Tunn. and G_0
3. Spectroscopy finding $\alpha^2F(\omega)$
4. Tunn. in HTSC

Lecture 2 ②

1. Return to some points from

Lecture 1:

a) We did not really show that

$$\frac{di}{dV} = N_s(E) = N_{2n}(0)\cdot\frac{E}{\sqrt{E^2-\Delta^2}} \quad (BCS)$$

$T=0$:

$$I_{ns} = \frac{2\pi e A}{\hbar}\int_{\Delta}^{eV}|T|^2 N_1(\varepsilon-eV)N_s(\varepsilon)d\varepsilon = \rightarrow$$

A – junction area.

Assuming $N_n(\varepsilon)\simeq N_n(\varepsilon-eV)\simeq N_n(0)$ (nearly constant

DOS, and $N_s(\varepsilon)\equiv N_n(0)\frac{\varepsilon}{\sqrt{\varepsilon^2-\Delta^2}}$, and $T=\text{const}(E)$

$$\rightarrow = \underbrace{\frac{2\pi e A}{\hbar}|T|^2 N_1(0)N_2(0)}_{=G_n/e}\int_{\Delta}^{eV}\frac{\varepsilon\, d\varepsilon}{\sqrt{\varepsilon^2-\Delta^2}}$$

Note: $[|T|^2 N_1 N_2 = 1$, to G_n must have another e, $e^2/\hbar$].

$$\left[\int\frac{\varepsilon\, d\varepsilon}{\sqrt{\varepsilon^2-\Delta^2}} = \frac{1}{2}\int\frac{d(\varepsilon^2-\Delta^2)}{\sqrt{\varepsilon^2-\Delta^2}} = \frac{1}{2}\int\frac{d\eta}{\eta^{1/2}} = \right.$$

$\int\frac{d\eta}{\eta^{1/2}} = 2\eta^{1/2}$

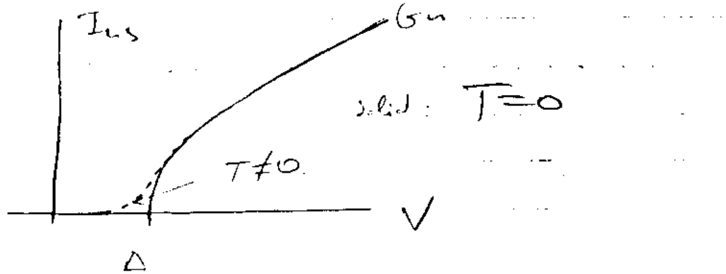
$$\left. = \frac{2}{2}\cdot\eta^{1/2}\right]$$

(3)

$$= \int_{\Delta}^{eV} \frac{\varepsilon\, d\varepsilon}{\sqrt{\varepsilon^2-\Delta^2}} = \cancel{(eV)^2\Delta^2}$$

$$= \sqrt{\varepsilon^2-\Delta^2}\Big|_{\Delta}^{eV} = \sqrt{(eV)^2-\Delta^2}\,;$$

$$I_{ns} = G_n \frac{G_n}{e}\sqrt{(eV)^2-\Delta^2}, \quad I_{ns}=0 \text{ for } eV<\Delta$$



$$\boxed{\frac{dI_{ns}}{dV} = \frac{G_n}{e}\frac{1}{\cancel{2}}\frac{\cancel{2}eV}{\sqrt{(eV)^2-\Delta^2}} = G_n\frac{V}{\sqrt{V^2-\left(\frac{\Delta}{e}\right)^2}}}$$

for $eV>\Delta$;

$$\frac{dI}{dV} = 0 \quad \text{for} \quad eV \le \Delta.$$

(4)

b) "Harrison's argument."

In the most simplified form it is a demonstration that normal state density of states can not be measured by tunneling – the energy dependence cancells out ~~at the wavefunction on the left be~~ $\Psi(x)=ae^{ik_1x}$.

Consider current incident on a tunnel barrier in the energy interval $(\varepsilon, \varepsilon+d\varepsilon)$

$$i_{in}(\varepsilon,\varepsilon+d\varepsilon) = e\, v_\varepsilon\, n_{\varepsilon,\varepsilon+d\varepsilon} = e|a|^2\frac{\hbar k_1}{m}\left(\frac{dn}{d\varepsilon}\right)_{1D} f(\varepsilon)\,d\varepsilon$$

where $k_1 = \frac{1}{\hbar}\sqrt{2m\varepsilon_1}$, and $\left(\frac{dn}{d\varepsilon}\right)_{1D}$ is the 1-D DOS and $f(\varepsilon)$ – F-D occupation function

$$N = \left(\frac{dn}{d\varepsilon}\right)_{1D} = \frac{mL}{\pi\hbar^2 k_1} = \frac{mL\cancel{\hbar}}{\pi\hbar^{\cancel{2}}\sqrt{2m\varepsilon}} = \frac{m^{1/2}L}{2^{1/2}\pi\hbar}\,\varepsilon^{-1/2}$$

(5)

from normalization of the wavefunctions we find

$$|a|^2 = \frac{1}{L} \;;\quad f(\varepsilon) = \begin{cases} 1 & \varepsilon < \varepsilon_F \\ 0 & \varepsilon \geq \varepsilon_F \end{cases}$$

We can consider infinitesimal voltage

$$e\delta V = d\varepsilon$$

So $i_{inc}(\varepsilon, \varepsilon + d\varepsilon) = \frac{mL}{\pi}$

$$= e^2 \underbrace{|a|^2}_{=1/L} \cdot \frac{\hbar k_1}{m} \cdot \frac{mL}{\pi\hbar^2 k_1}\,\delta V = 2\,\frac{e^2}{h}\,\delta V;$$

(Note: the transmitted current will be $i_{inc} \cdot T$.)

The point is that k_1 from the velocity cancells with $\frac{dn}{d\varepsilon} \propto \frac{1}{k_1}$; there is no energy dependence left.

Tunneling current $i_{inc} \cdot T$ will be independent on the energy variation of the DOS.

2. Tunneling and coherence length

a) Meaning of the coherence length:

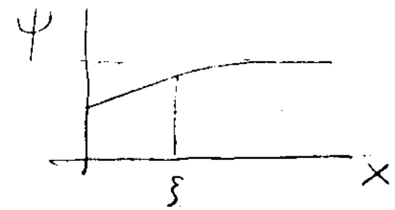
Complex Order parameter or a macroscopic wavefunction $\Psi(\vec r) = |\Psi(\vec r)| \cdot \exp i\theta(\vec r)$

Ginzburg-Landau postulated an additional contribution to the free energy $\frac{\hbar^2 |\nabla\Psi|^2}{2m}$.

We say that Ψ is "stiff", or that it opposes rapid spacial variations.

$|\Psi|^2$ - density of electron pairs.

Solving G-L eq-ns for non-uniform superconductors, one finds that Ψ can change over characteristic length $\xi_{GL}(T)$



$$\left[\ \xi_{GL}(T) = \frac{\hbar\,|\Psi_0(T)|}{(2m^*\mu_0)^{1/2} H_c(T)}\ \right]$$

Pippard Coherence Length

Non-local character of London eq-n $\vec{J} = C\vec{A}$

$\vec{J}$ current density at a certain point will be affected by $\vec{A}$ in a region $\sim \xi$ around this point — range of phase coherence of a wavefunction.

$$\xi_0 = 0.18\,\frac{\hbar v_F}{k_B T_c}$$

In the presence of impurities (l = m.f.p.)

$$\frac{1}{\xi} \cong \frac{1}{\xi_0} + \frac{1}{l}$$

Conditions: $l/\xi_0 \gg 1$: pure limit

$\frac{l}{\xi_0} \ll 1$ dirty limit

order parameter $\Delta(\vec{r}) = \frac{3.07 k_B T_c}{(\pi \chi)^k} \cdot \psi(\vec{r})$]

in the pure limit (applicable to HTSC):

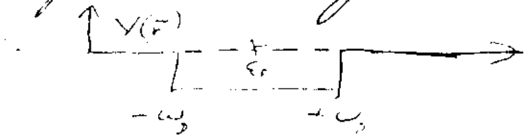
$$\xi_{GL}(T) = \frac{0.74\,\xi_0}{\sqrt{1-\frac{T}{T_c}}},$$

In proximity systems | S | N |

Pair potential $\Delta(\vec{r})$ can be expressed as

$$\Delta(\vec{r}) = V(\vec{r})\,F(\vec{r}) \text{ where}$$

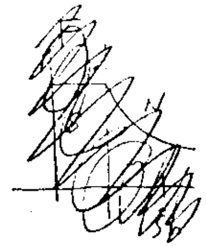
$V(\vec{r})$ is the e-ph interaction potential (very short range)



and $F(\vec{r})$ is the condensation amplitude ($|F|^2$ give the density of pairs)

The main result is

$$(*)\quad F_{C0}(x) = \Phi(x)\cdot e^{-k_n|x|}$$



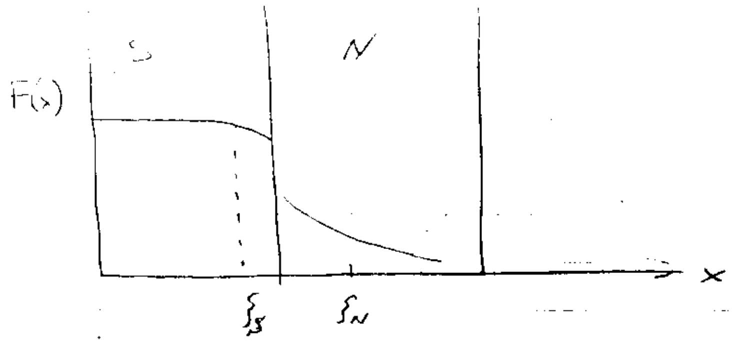
$\Phi(x)$ - slowly varying function of x;
($x \gg \frac{1}{k_n}$ required for $(*)$ to be true).
k_n depends on a number of factors (l, T_{cN}, etc)

For clean Normal and superconducting materials

$$\frac{1}{K_n} = \frac{\hbar v_{Fn}}{2\pi k_B T} = \xi_n \text{ - coherence length in a normal metal}$$

(if Δ can $V_n < 0$ (repulsion))

⑨



$\xi_S = 0.18\,\frac{\hbar v_S}{k_B T_c}$; $\xi_N = 0.16\,\frac{\hbar v_N}{k_B T}$,

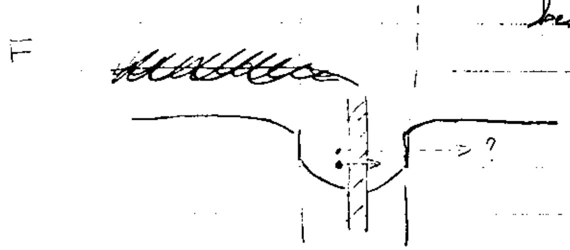
Note: can not gain indefinitely by reducing T.

In reality $\xi_N \simeq 0.16\,\frac{\hbar v_N}{k_B T_c}$ also.

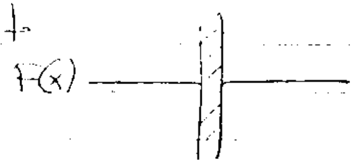
~~electron gas~~ ← insert

Tunneling and ξ: suppose we have N regions near the barrier.

Does Electron go just across, or a distance l from the barrier?



as opposed to



$$\frac{dI_{NS}}{dV} = C_{NN}\frac{eV}{[(eV)^2 - \Delta^2]^{1/2}}, \qquad eV > \Delta,$$
$$= 0, \qquad eV < \Delta.$$

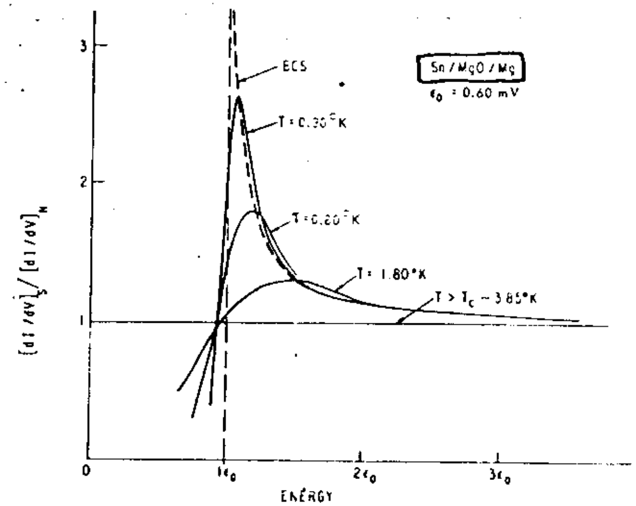


Fig. 5. The density of states in a superconductor obtained by taking the ratio of the derivatives of the current–voltage characteristics in the superconducting and normal states. As the smearing due to temperatures is reduced, the curves approach the BCS redictions. From I. Giaever, H. R. Hart, and K. Megerle, Phys. Rev. 126:941 (1962).

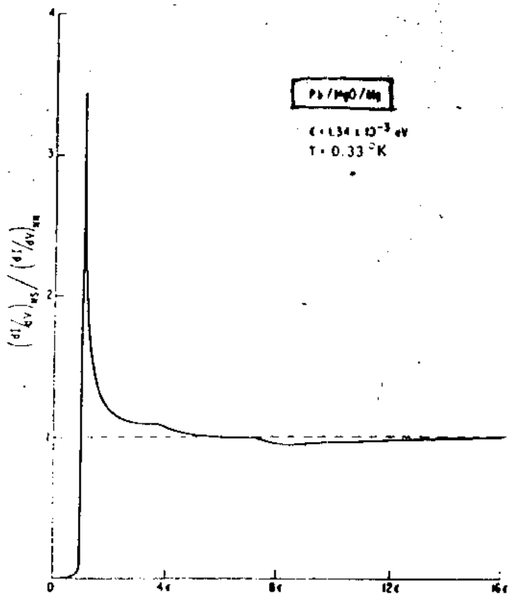
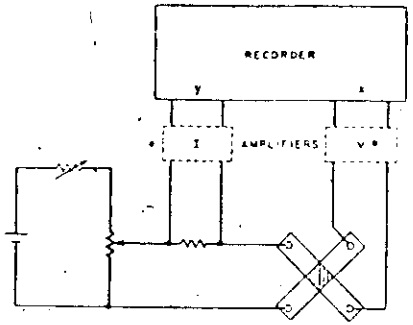
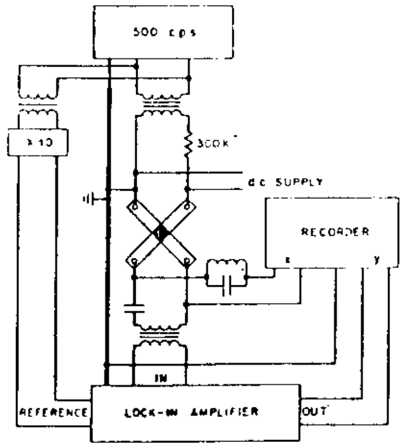
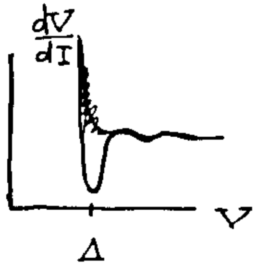


Fig. 6. The density of states for Pb, definitely different from the BCS theory. It turns out that the bumps in the curve reflect the phonon spectrum in Pb. Mg is a normal conductor. From I. Giaever, H. R. Hart, and K. Megerle, Phys. Rev. 126:941 (1962).



Circuit to display the I-V characteristic of a junction on an XY-recorder.





Circuit to measure directly dV/dI of a junction by the ac modulation technique.

Applied DC bias current is modulated with a small constant AC current δI; the generated voltage is picked up with the lock-in ~~Ap~~ amplifier.

$$\frac{dV}{dI} = \frac{1}{\left(\frac{dI}{dV}\right)}$$

Schrieffer, Scalapino and Wilkins simulated the phonon spectrum of lead with two Lorentzian peaks and reproduced structure in $\Delta(\omega)$ very well

$\Delta(\omega)$ was complex, and

$$\frac{di}{dv} \propto Re\left[\frac{E}{\sqrt{E^2-\Delta^2(E)}}\right]$$

$\alpha^2F(\omega)$ – electron-phonon matrix element (interaction) times the phonon density of states.

$\alpha^2F(\omega)$ and μ^* (renormalized Coulomb repulsion) are the central parameters of the Eliashberg theory.

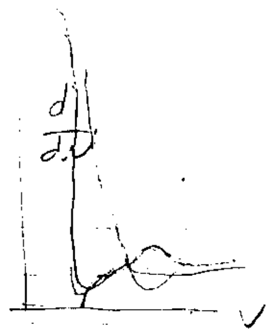
McMillan and Rowell: procedure to bring calculated $N(\omega)$ in agreement with measured $N(\omega)$, and find α^2F, μ^*, $\Delta(\omega)$ as a result: show the change

Discuss circuits (show circuits).

1. I–V 2. dV/dI

One needs to measure $\left(\frac{dV}{dI}\right)_S$ and $\left(\frac{dV}{dI}\right)_{normal}$ at the same V.

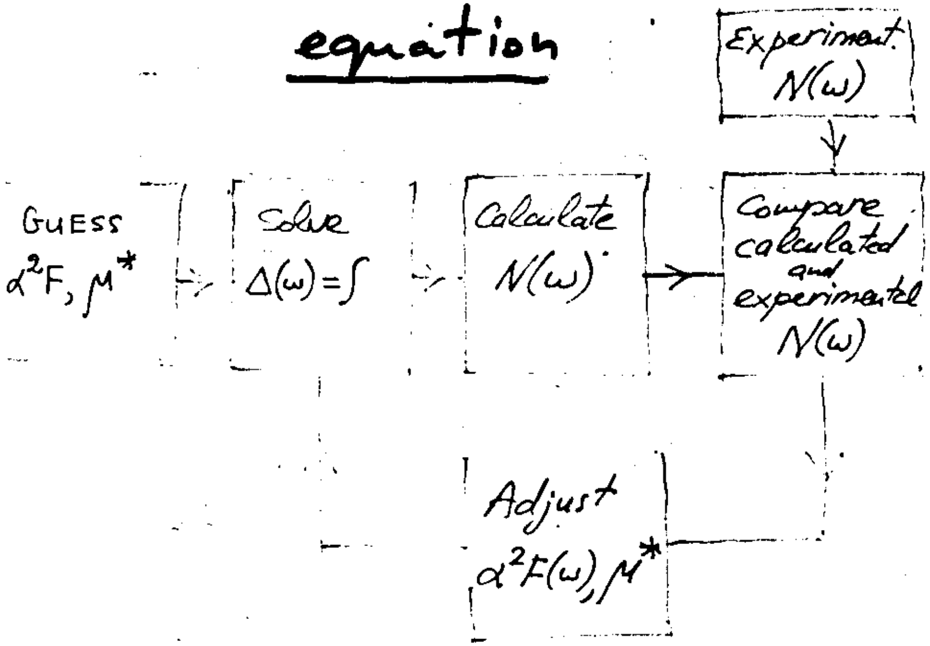
Second derivative is also measured.



Normal state measured in H or at $T>T_c$.

From McMillan & Rowell,

Schematic of the method used to "invert" the gap equation



After 6–8 solutions, $\alpha^2F(\omega)$ reproduced measured $N(\omega)$ to one part in 10^3

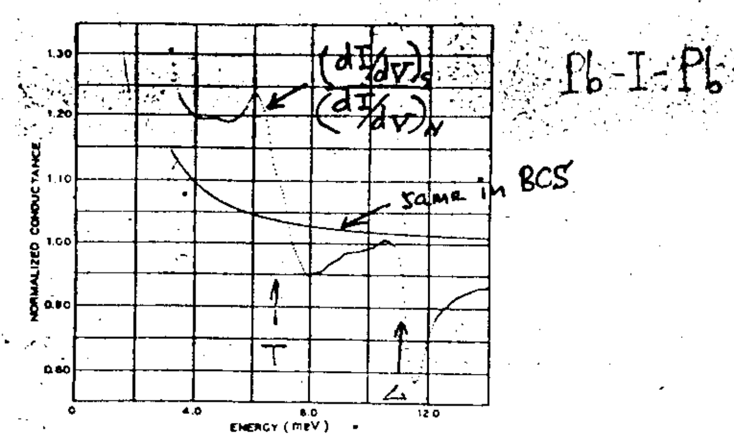
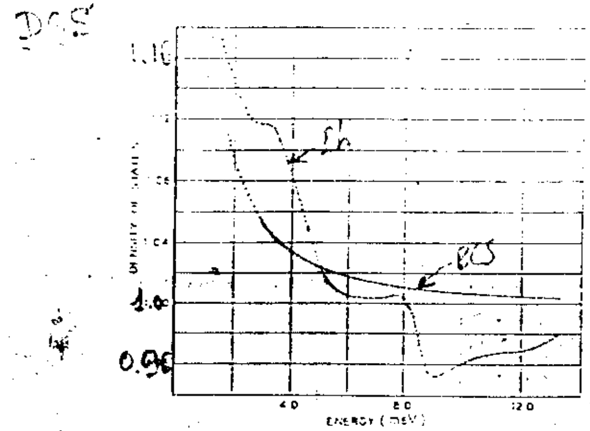
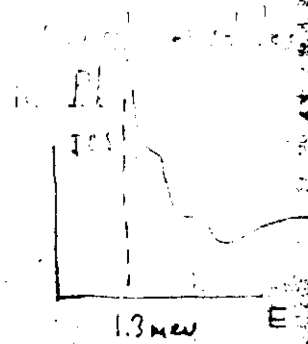


Fig. 19. Conductance dI/dV of a Pb–I–Pb junction in the superconducting state normalized by the conductance in the normal state vs. voltage. Also shown is the two-superconductor conductance calculated from the BCS density of states which contains no phonon structure.

Phonon energy corresponds to $(E_{dip} - 2\Delta)$





Electronic density of states $N(E)$ for lead vs. $E - \Delta_0$ obtained from the data of Fig. 19. The smooth curve is the BCS density of states.

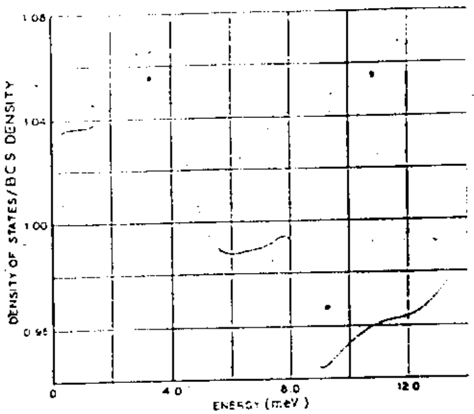


Fig. 24. Electronic density of states of Pb divided by the BCS density of states vs. $E - \Delta_0$.

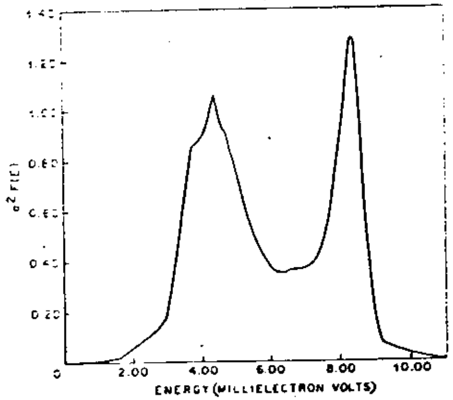


Fig. 25. $\alpha^2 F(\omega)$ for Pb found by fitting the data of Fig. 24.

$\alpha^2 F(\omega)$
for Pb
$\mu^* = 0.12$

$$\lambda = 2 \int_0^\infty \frac{\alpha^2 F(\omega)}{\omega} d\omega$$ → e-ph inter. constant.

$(m^* = m_{BS}(1+\lambda)\,;\ v_F^* = \frac{v_F^{BS}}{1+\lambda}, \text{etc.})$

Find $\lambda_{Pb} = 1.5$

Table I

T_D (°C)	Δ (meV)	λ	μ^*	$\tilde{\omega}$ (meV)	$\langle\omega\rangle$ (meV)	$\langle\omega^2\rangle$ (meV^2)	T_c calc.
<75°C	1.51	0.96	0.15	17.2	14.6	252	8.4
800°C	1.52	0.97	0.15	16.8	14.2	240	8.4

T_D is the deposition temperature.
Δ_0 is the energy gap.
$\lambda = 2\int_0^\infty \frac{\alpha^2(\omega)F(\omega)}{\omega} d\omega$; $A^2 = \int_{0^+}^\infty \alpha^2(\omega)F(\omega)\, d\omega$; $\bar{E} = \int_0^\infty \alpha^2(\omega)F(\omega)\omega\, d\omega$.
$\tilde{\omega} = \bar{E}/A^2$; $\langle\omega\rangle = 2A^2/\lambda$; $\langle\omega^2\rangle = 2\bar{E}/\lambda$.
T_c is calculated from the McMillan equation.

proximity effect [23] on the same junctions, as after some months, including sending them by mail from Murray Hill to Karlsruhe, they had increased in resistance and the characteristics had deteriorated to such an extent that the well-known Nb problem of a small or negative μ^* resulted when $\alpha^2(\omega)F(\omega)$ was unfolded conventionally. This results from the weakened $N(E)/N_{BCS} - 1$, especially at low energies, as the deteriorated characteristics for $10 < t < 30$ Å

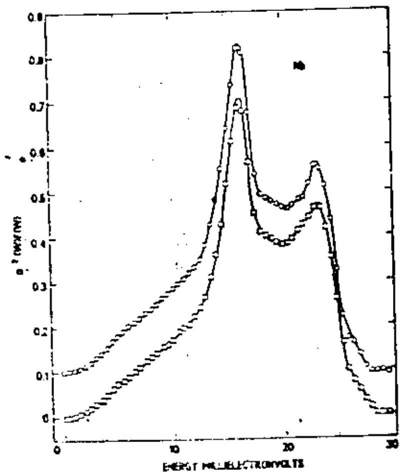


Fig. 11. The electron–phonon coupling function, $\alpha^2(\omega)F(\omega)$ derived from two Nb/Al-oxide–Ag junctions, the upper having a Nb film made at 600°C, the lower at <75°C.

Table II

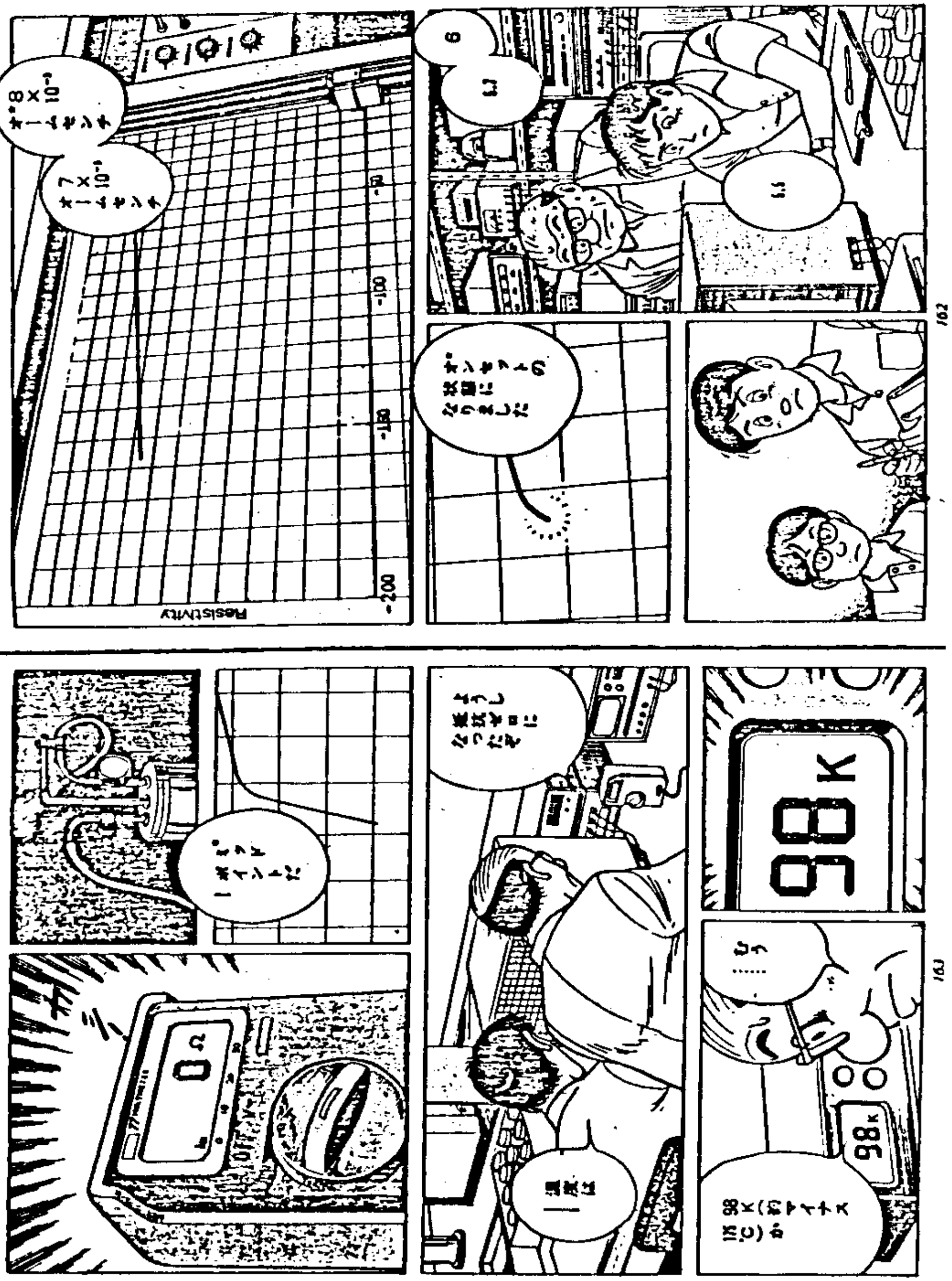
Sample	t	Δ_0 (meV)	λ	μ^*	RMS dev. (%)	d/ℓ	R
J152	14	1.53	1.04	0.18	0.7	0.04	0.006
J152	10	1.53	1.07	0.19	0.9	0.05	0.005
J192	7	1.50	1.00	0.17	1.7	0.04	0.005
J292	42	1.50	0.95	0.18	0.6	0.07	0.008
J294	22	1.47	1.00	0.19	0.8	0.06	0.006
J252	16	1.50	0.95	0.16	0.6	0.08	0.009
J274	8	1.49	0.96	0.18	0.3	0.09	0.011
J122	22	1.49	1.05	0.19	0.6	0.05	0.004
J122	22	1.49	0.97	0.16	0.5	0.03	0.006
NbO5	0	1.49	1.09	0.17	0.4	0.14	0.010

t is the Al overlayer thickness.
d = thickness of assumed proximity layer.
v_F = Fermi velocity of electrons in the proximity layer.
ℓ = mean free path of electrons in the proximity layer.
$R = 2d/\hbar v_F$.

gave values comparable to the data of fig. 10 for the sample with only 1.8 Å of Al. The criteria used for the convergence of the proximity effect program were to minimize the RMS deviation between the measured and calculated density of states and ensure that $\alpha^2(\omega)F(\omega)$ became zero above its high energy cutoff. Using these criteria, $\alpha^2(\omega)F(\omega)$ for eight different junctions agrees excellently with the data of fig. 11 and the resulting parameters are given in table II.

7. Conclusions

We have shown that a few monolayers of Al

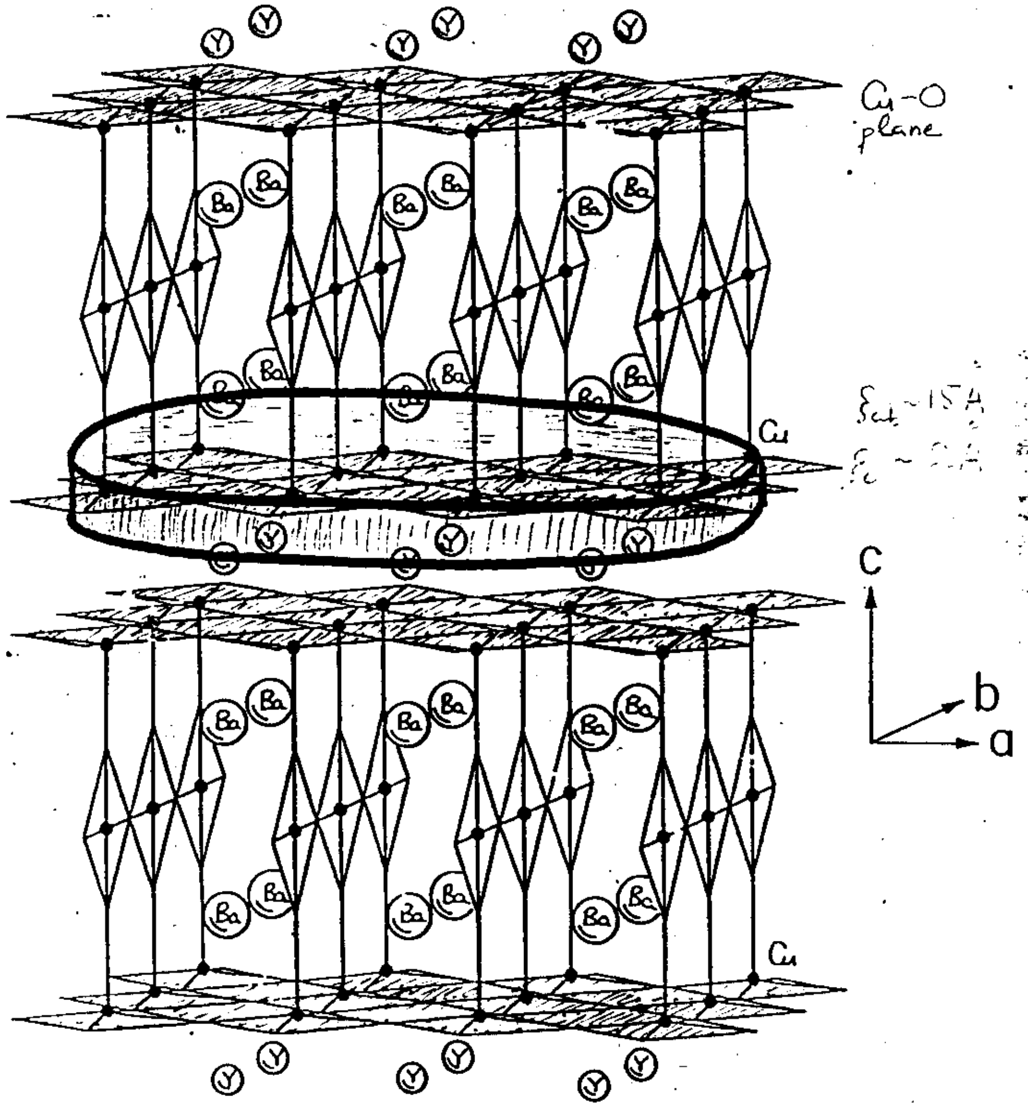


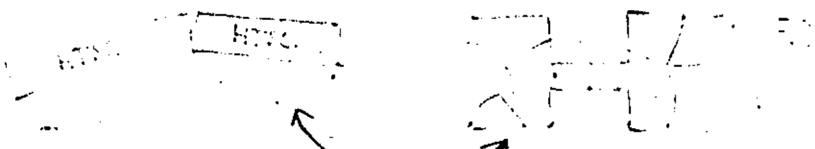
HTSC

for a review of tunneling see J. R. Kirtley, Int. J. of Modern Physics B ....

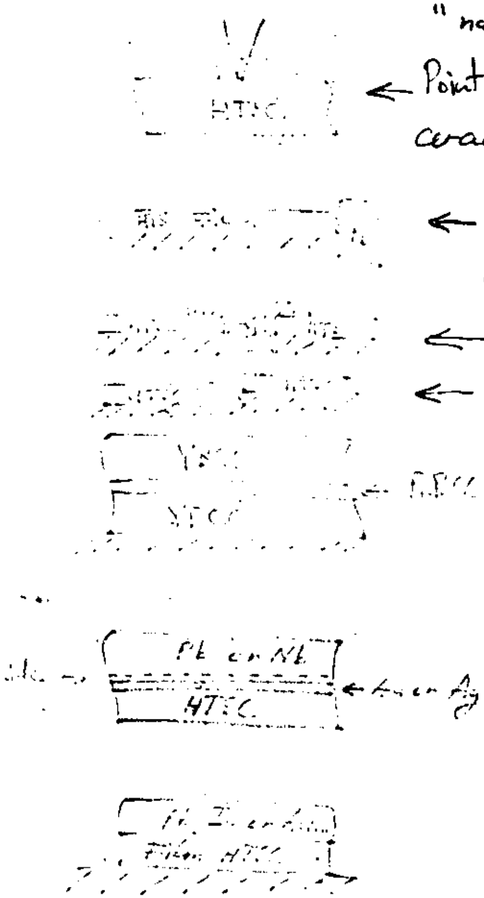
M. Gurvitch, in Superconductivity and Applications, Ed. Kwok et. al. Plenum Press, N.Y. 1990.

Cooper pair in $YBa_2Cu_3O_7$





"natural" tunnel junctions



← Point contact tunn. into bulk ceramic, single crystal or film

← tunneling into freshly cleaved surfaces, including films

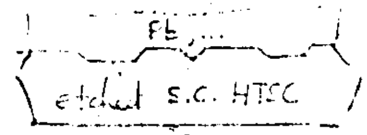
← microbridges

← bridges on microsteps

← epi structures with lattice matched insulators (sandwich structures)

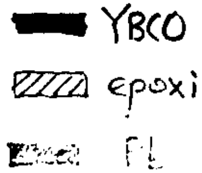
← hybrid HTSC – CS structures of various sorts

good surfaces (films) covered with Pb (sandwich junctions)

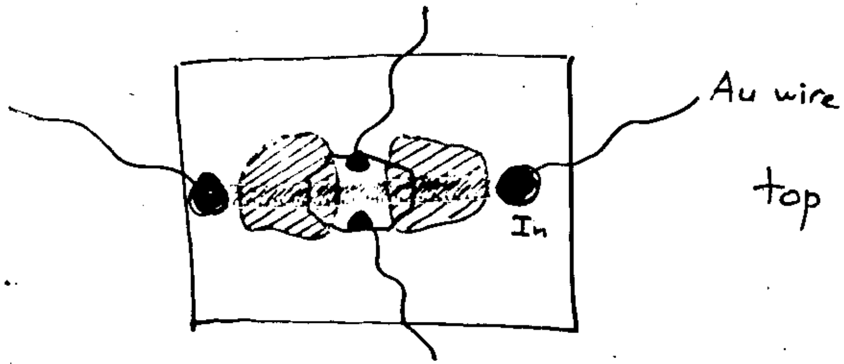


sandwich junctions on etched surfaces

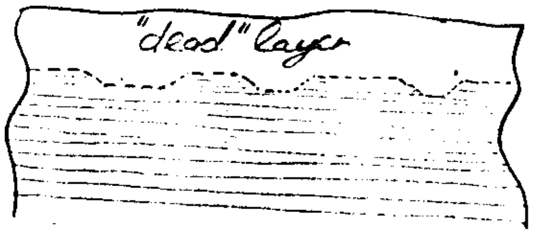
Tunnel junction



side view



top view

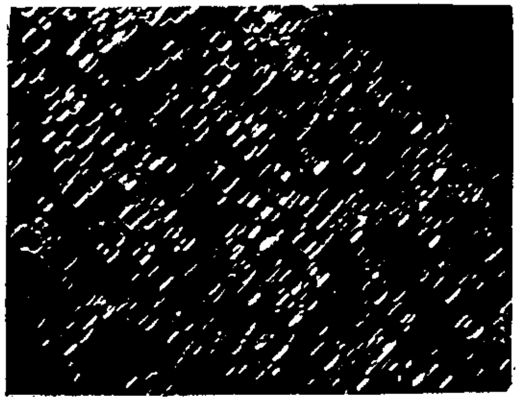


← contamination, off-stoichiometry, carbonate ...

(1÷10)

1. 1 mMole $HClO_4$ / 1 Mole $NaClO_4$ in H_2O
(B. Miller, Bell)

2. 1% Br in methanol (or ethanol)
(R.P. Vasquez et. al. APL 53, 2692 (88))



(×160)

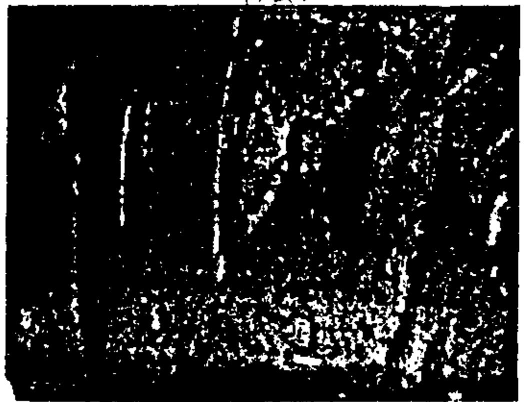
Etch-pits after 5min in
10 mMole $HClO_4$ / 1 Mole $NaClO_4$; H_2O.

Thick Ribbon after 50min in 10mM ×160

"Thick Ribbon after
50min in 10mM

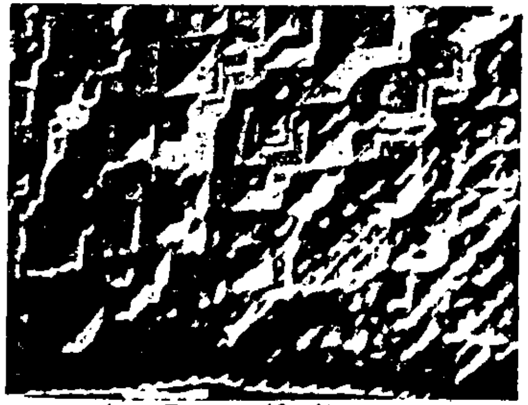
×160

T. Ribbon



Pit after 50min in 10mM ×400

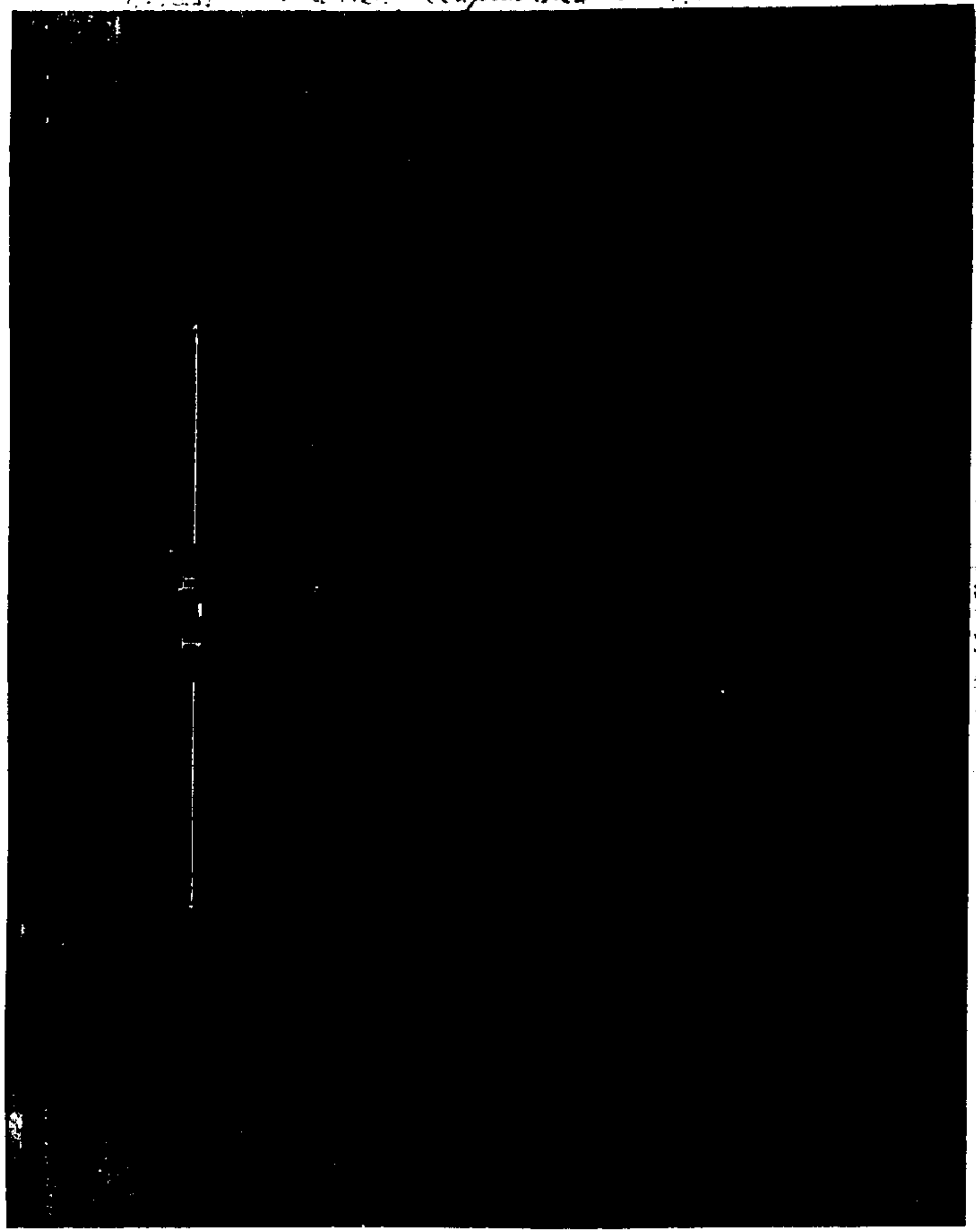
Single pit (see above



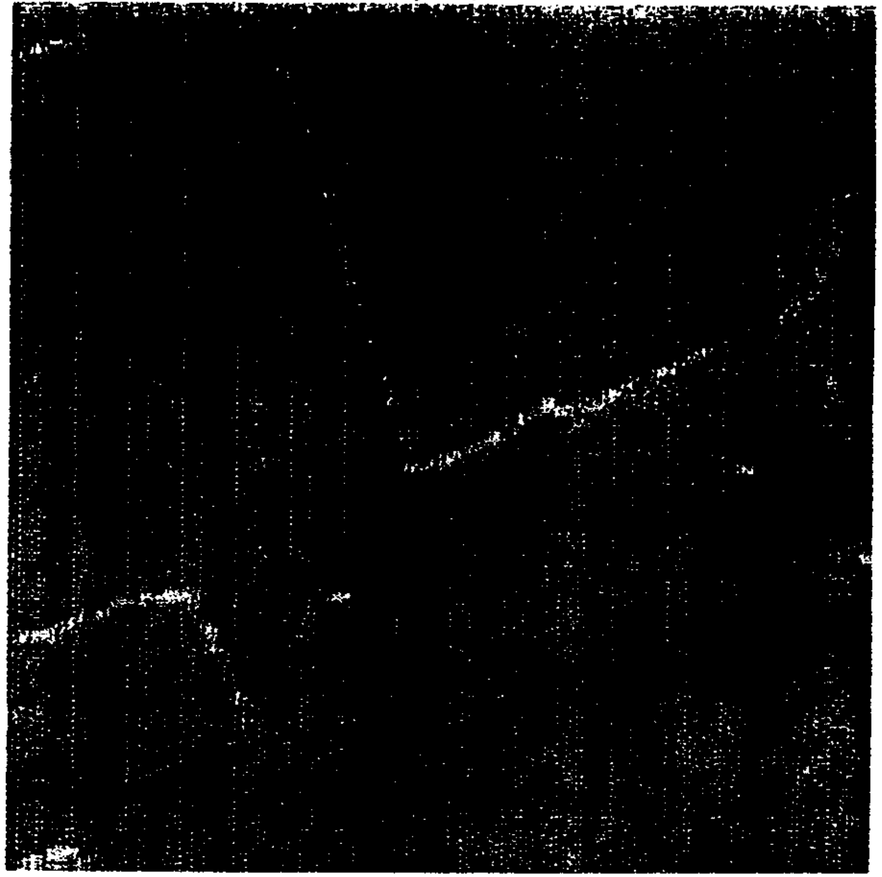
Sway after 50 min 10mM ×160

"Sway" after
50min. 10mM

H. Hess, M. Gurvitch, unpublished STM.

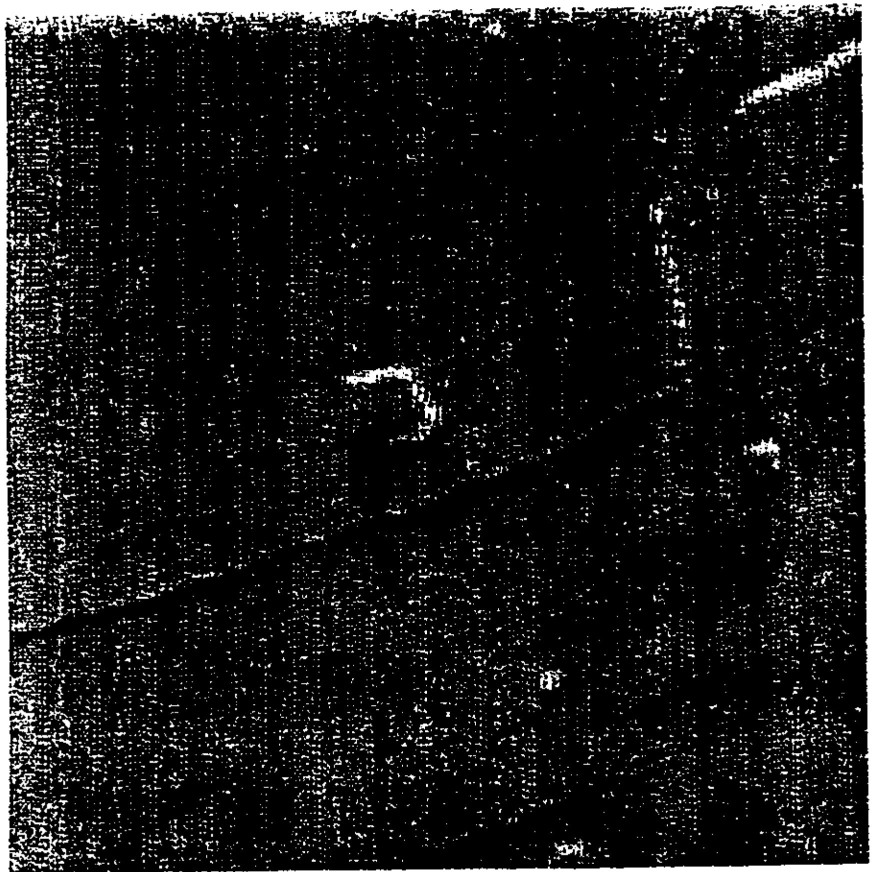


H. Hess, M. Gurvitch, unpublished STM



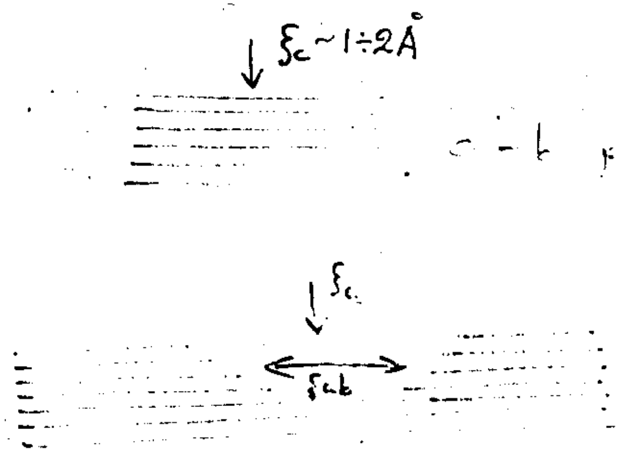
FILE:e:\rc\hh022589.005
Scan angle = 0 degrees, Scan range = 600 Angstrom.
Time delay = 800, there are 128 data points.
Bias = 0 volts.
There are 78 integral values of height ranging over 0.4 A.

H. Hess, M. Gurvitch, unpublished STM

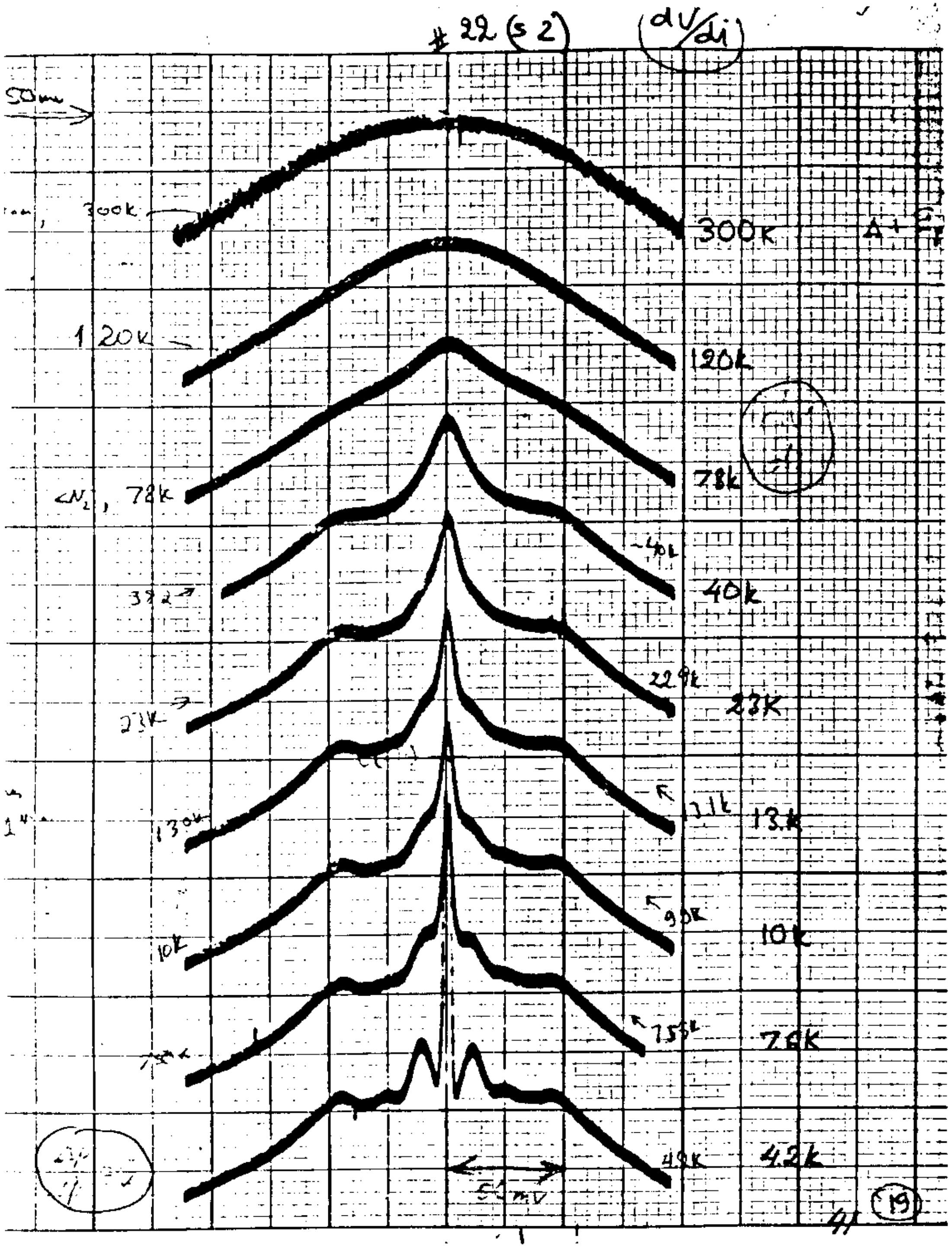


FILE:e:\rc\hh022589.003
Scan angle =   0 degrees, Scan range =   500 Angstrom.
Time delay =   800, there are   128 data points.
Bias = 0 volts.
There are 89 integral values of height ranging over 0.45 A.

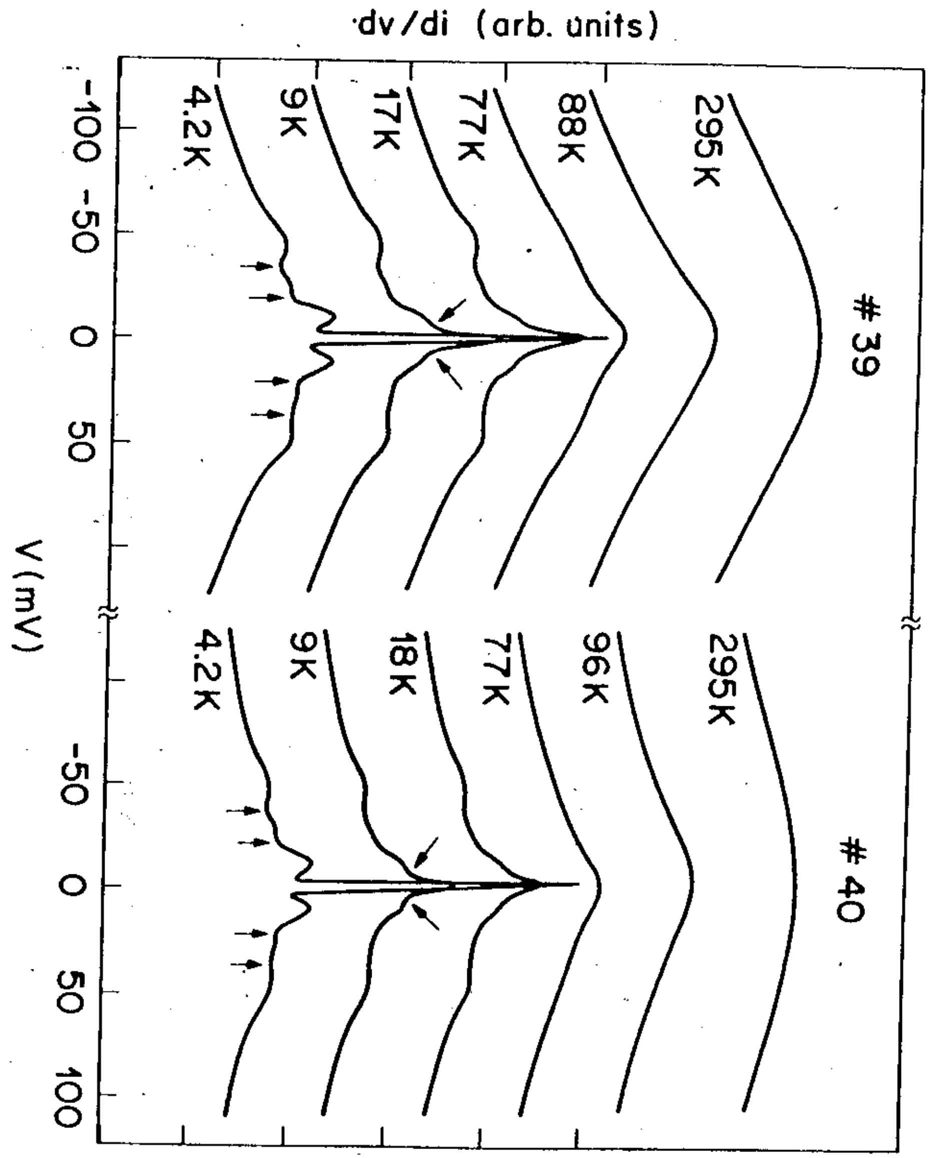
Etch pits and tunneling



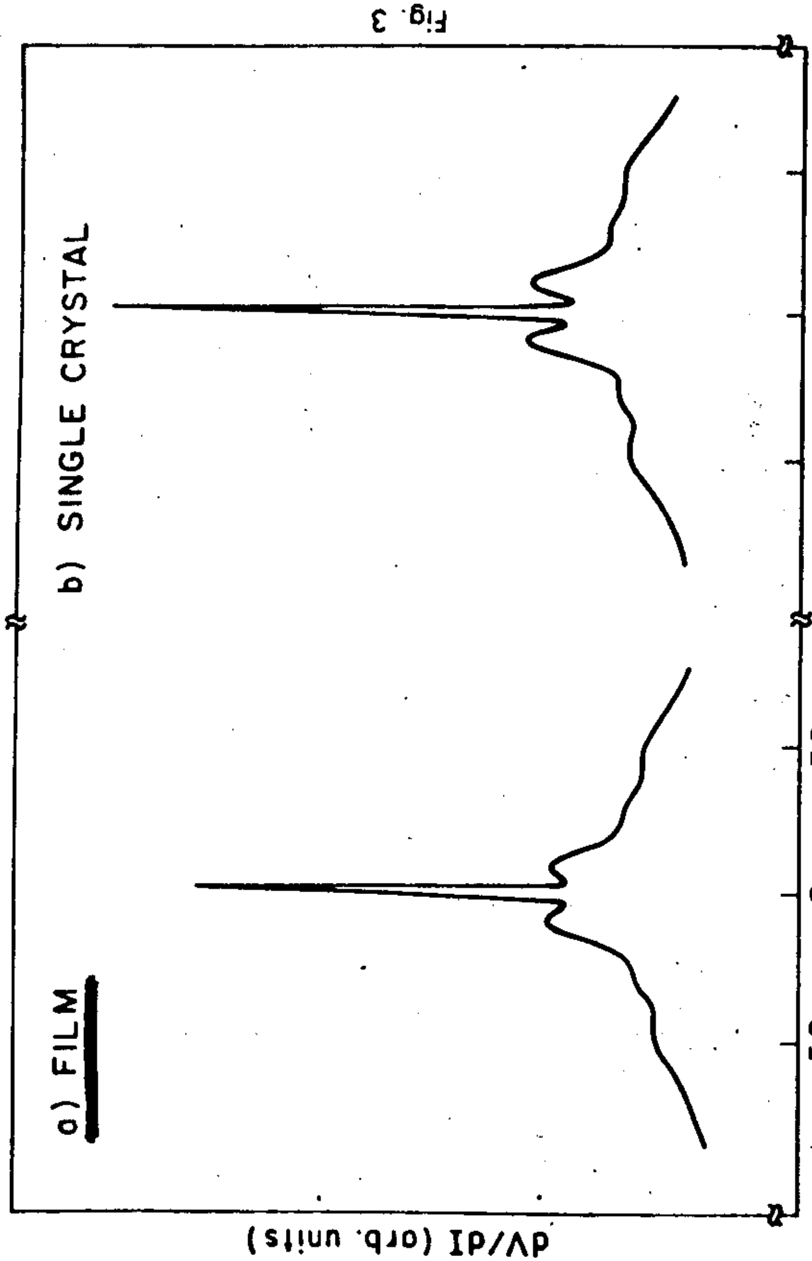
$\xi_{ab} \sim 10-15$ Å



22 (S 2)
dV/di
300K
120K
78K
40K
23K
13K
10K
7.6K
4.2K
54 mV



dv/di (arb. units)
V(mV)
4.2K
9K
17K
77K
88K
295K
39
4.2K
9K
18K
77K
96K
295K
40
-100
-50
0
50
100

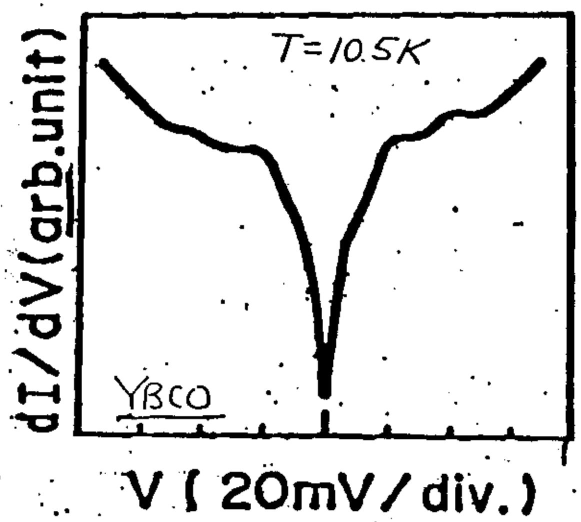


I. Takeuchi, J. S. Tsai et al. Physica C158, 83 (89).

1:2:3
2212
2223

CERAMIC sample — Pb, Al
~1mm²

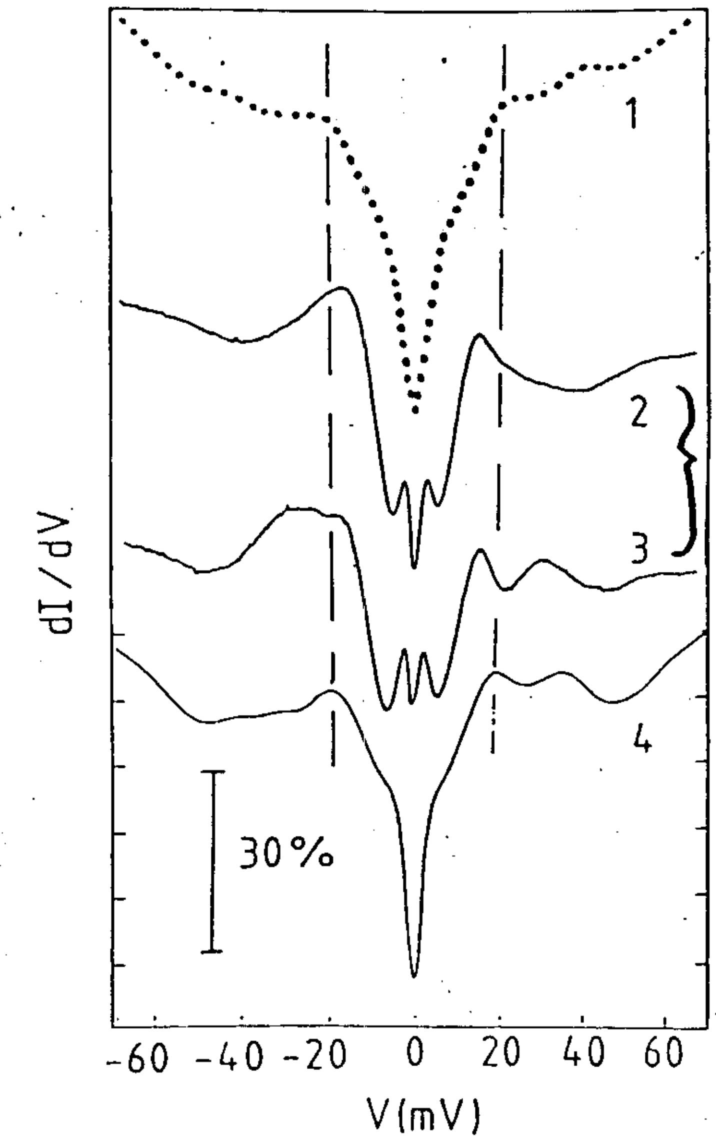
- natural surface
- cleaved at He
- sand paper

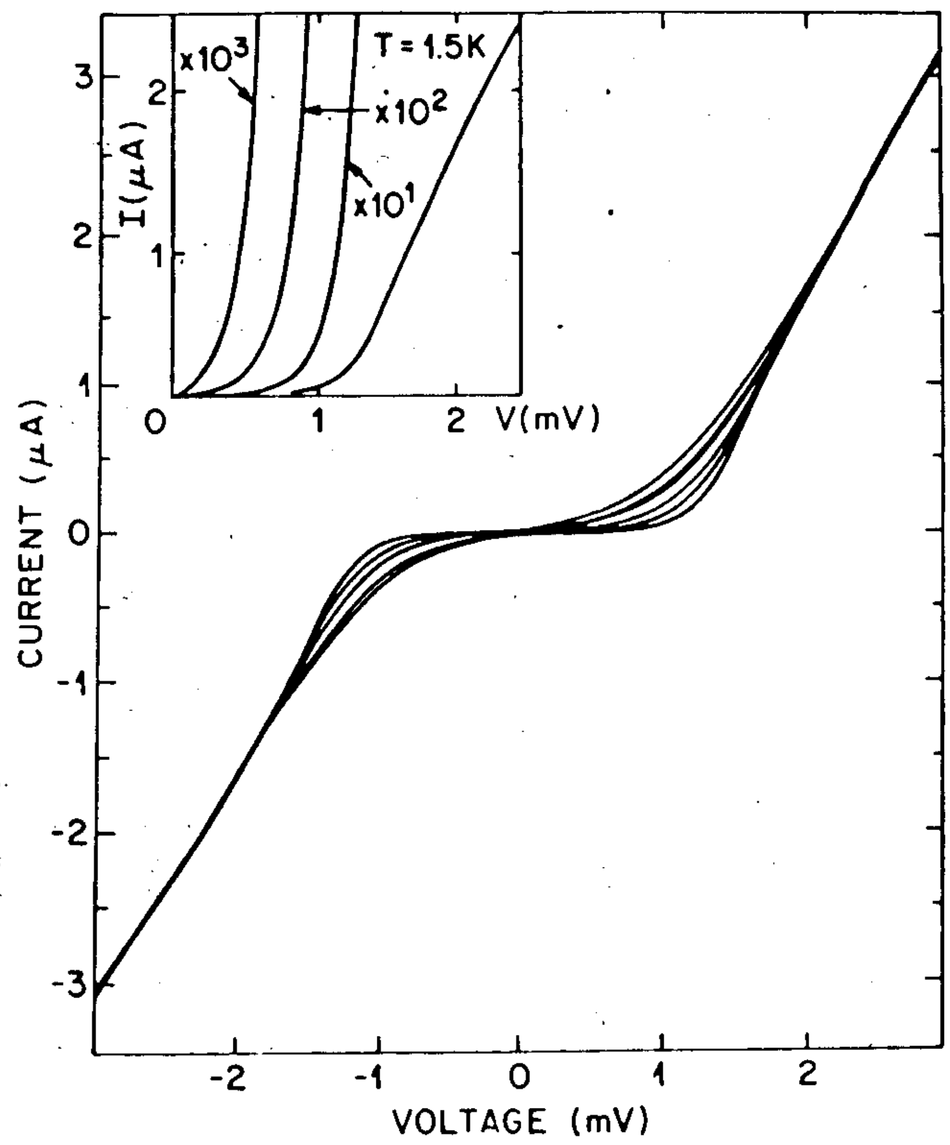


Authors: internal SIS ?

(30) 38

Comparison from J. Geerk et. al.
N'S-HTSC, Stanford





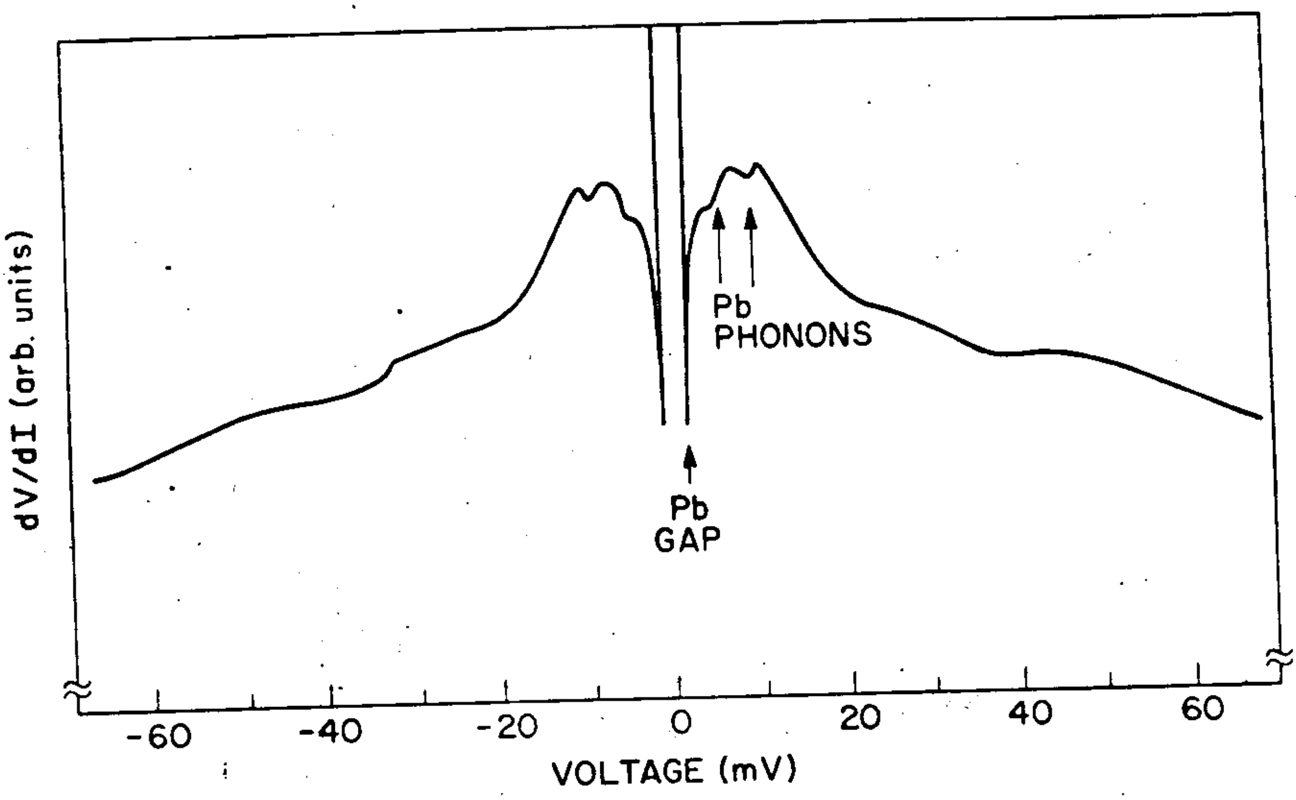
~~Fig 1~~

20

2k

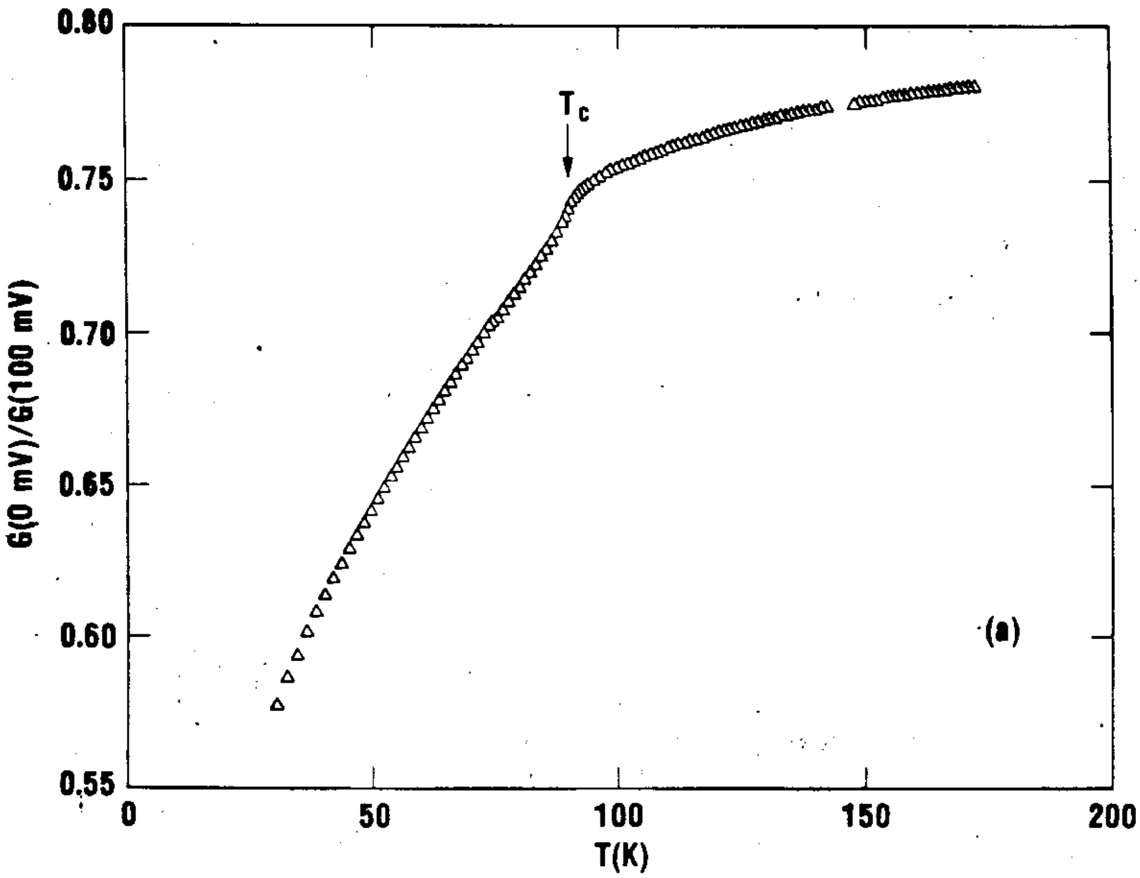
39

44



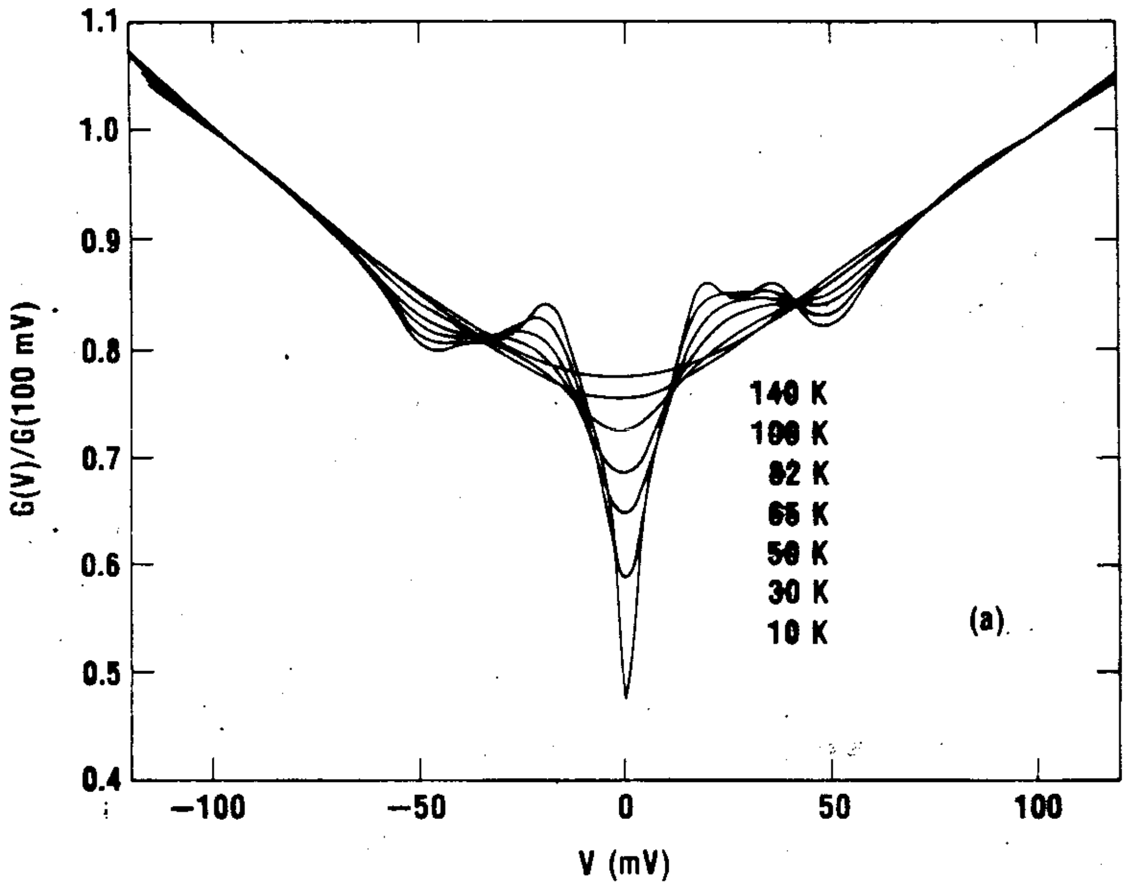
TOP
DO NOT AFFIX OVERLAYS ALONG THIS SURFACE

VG. NO.________



TOP
DO NOT AFFIX OVERLAYS ALONG THIS SURFACE

VG. NO.



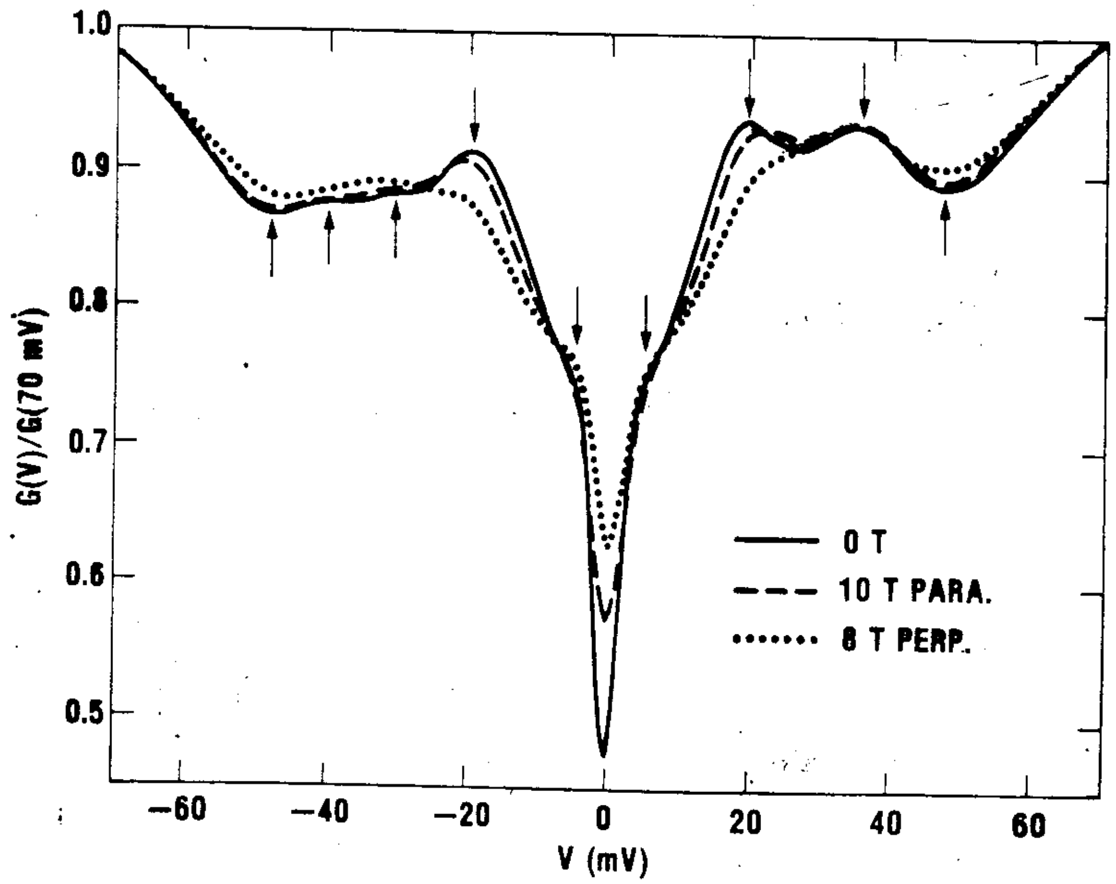
E-9148 (6-85)
&T BELL LABORATORIES

AT&T

15

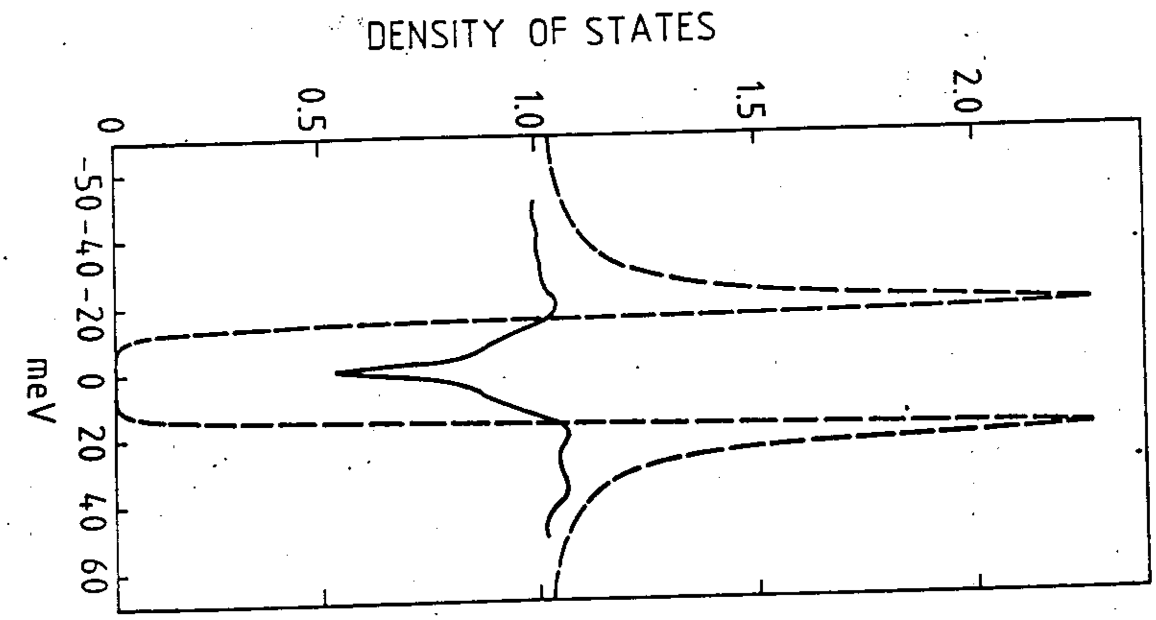
TOP
DO NOT AFFIX OVERLAYS ALONG THIS SURFACE

VG. NO.



27

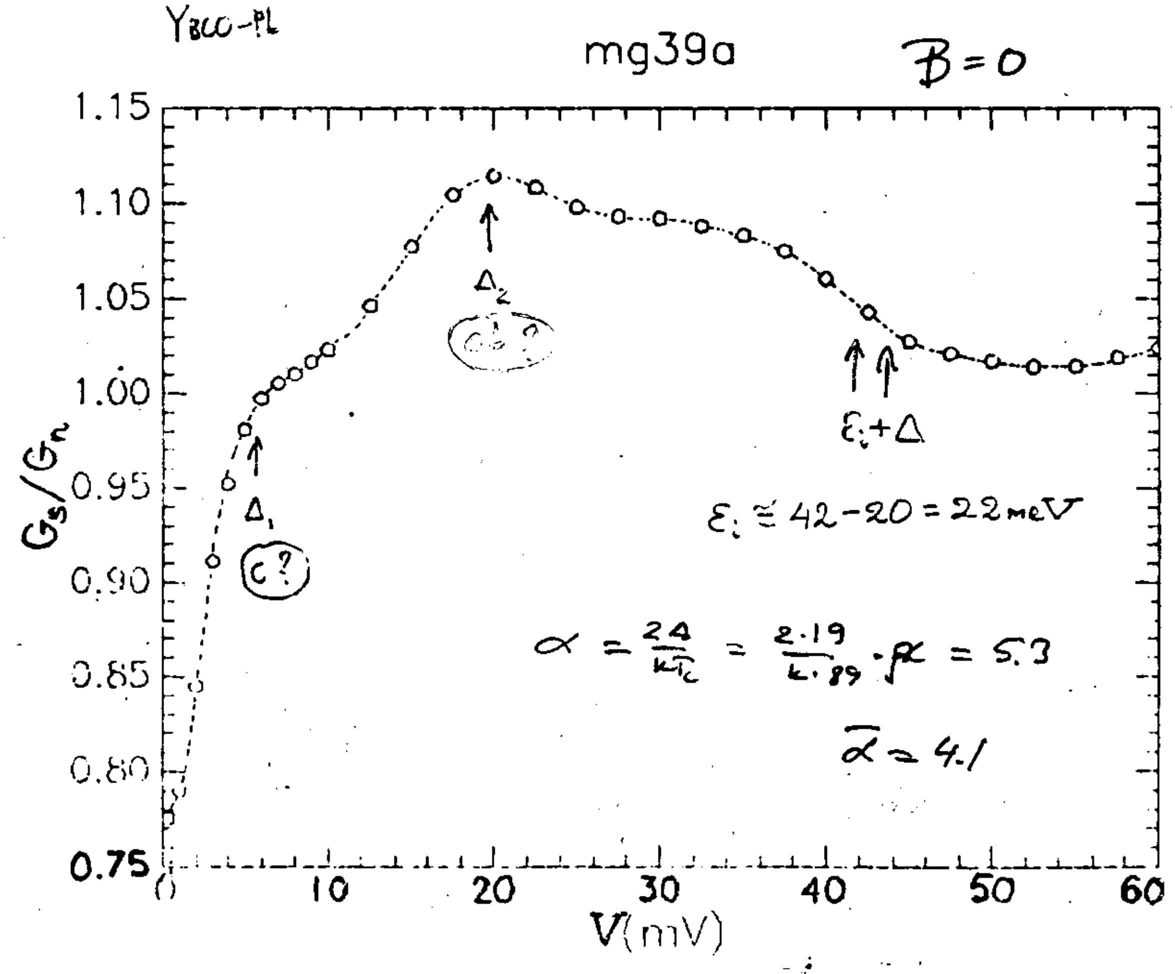
E-9148 (6-85)
T BELL LABORATORIES



S-I-N

24 M. Gurvitch, J.M. Valles, K.C. Dynes, H.M. Gurcolo, and L.F. Schneemeyer 2|24

57



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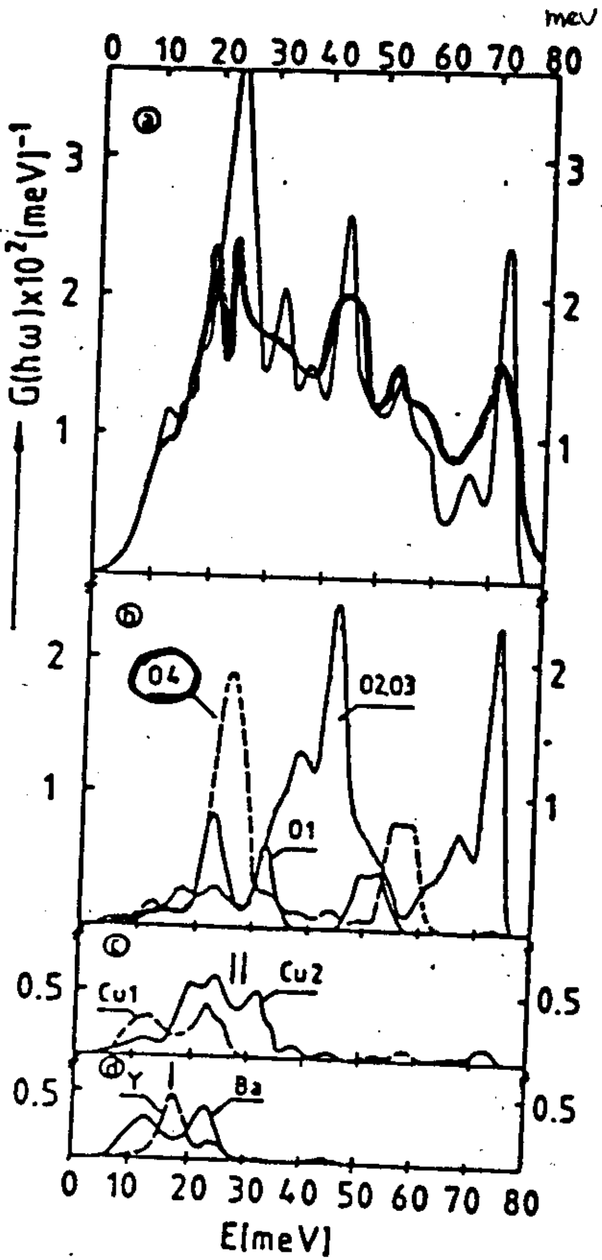


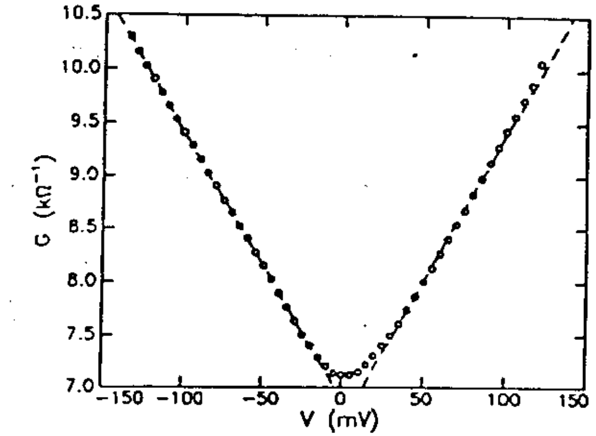
phonon $G(\omega)$

Renker et. al.

Physica C153-155

(272), 1988.

Tunneling conductance $G(V)$ in the normal state



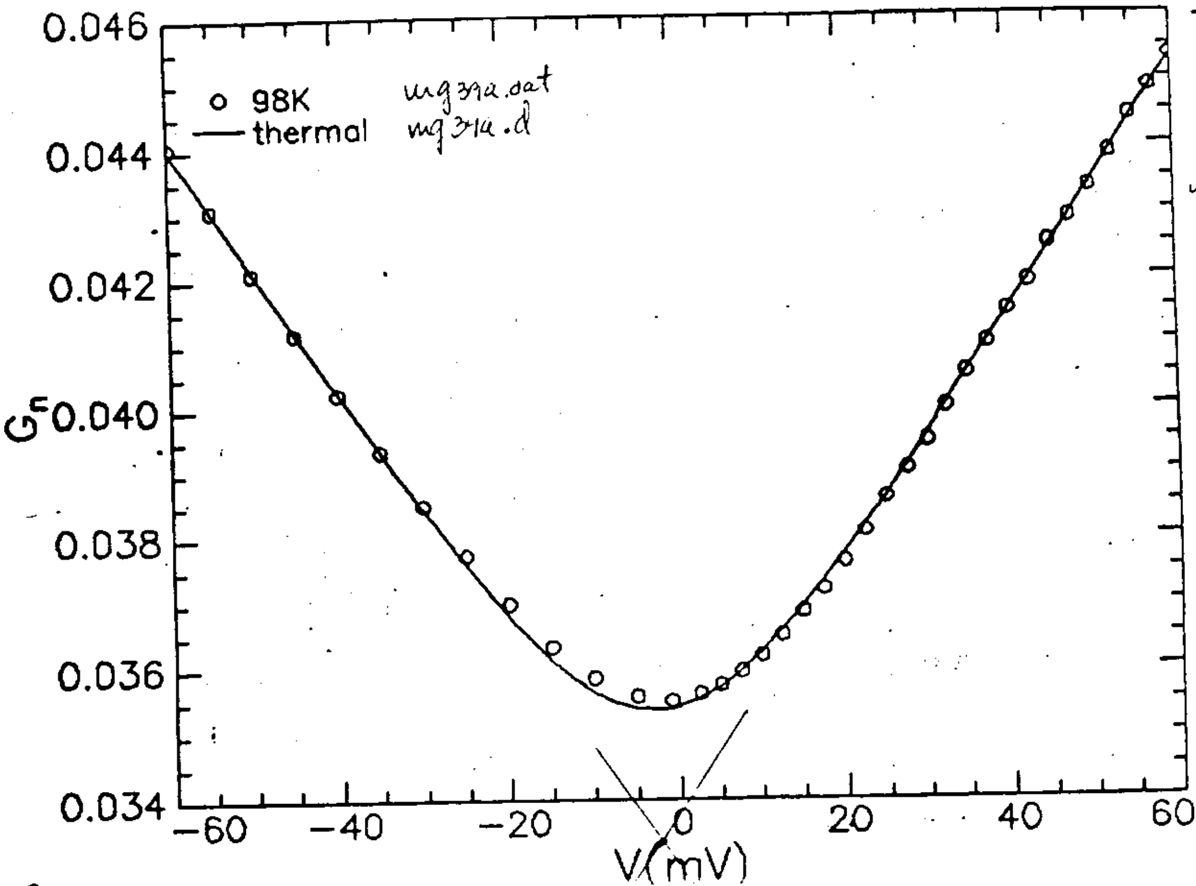
Tunneling conductance of $YBa_2Cu_3O_{6.9}$, from Ref. (6), M. Gurvitch et. al., and J. Valles (unpublished).

FIGURE 3

...alized PDOS. solid line: calculation:

3/6/89

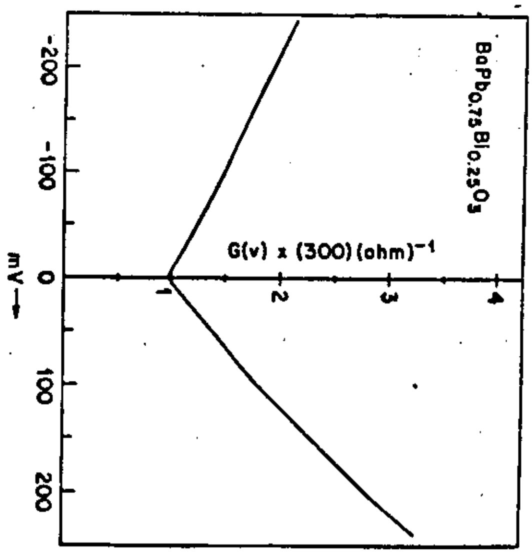
mg39a.dat and mg39a.d (tline1.f)



thermal fit using tline1.f

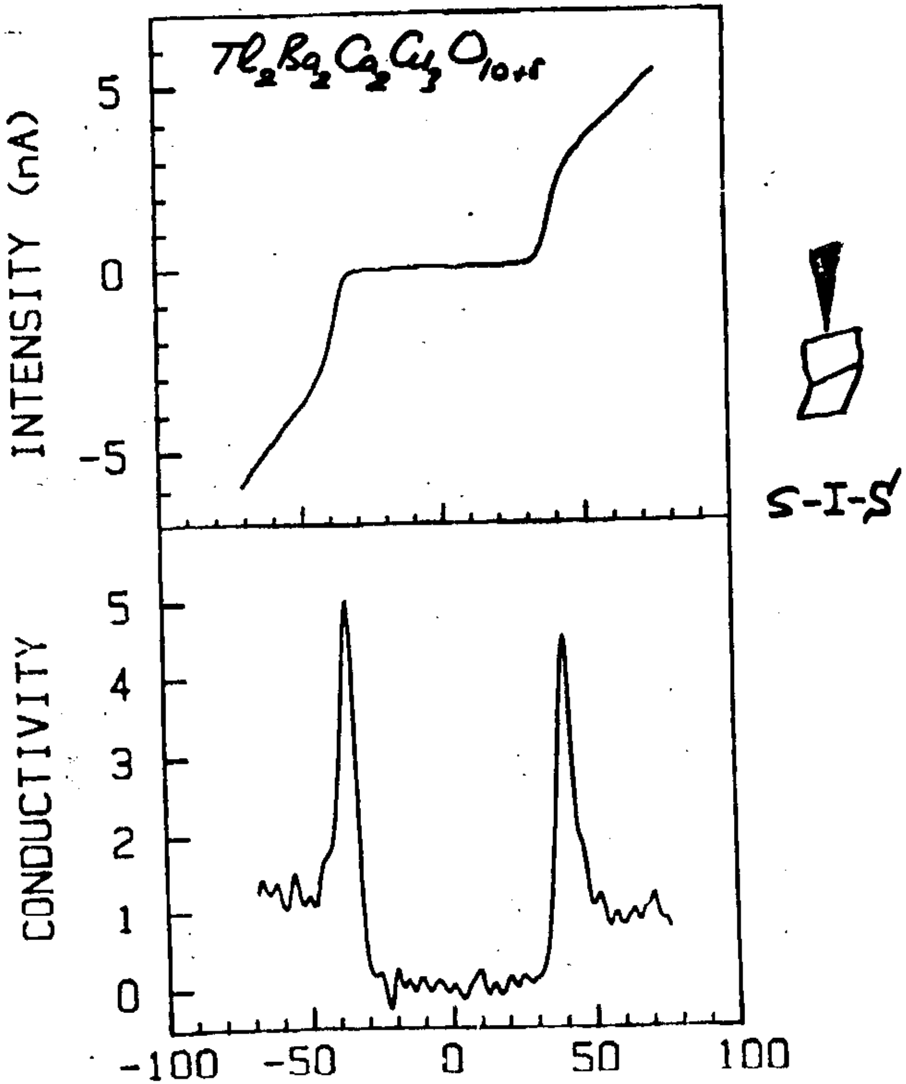
w/ mp = .1946E
bb = .3367
mn = -.1908E
bn: .3257
intersection = -.

55



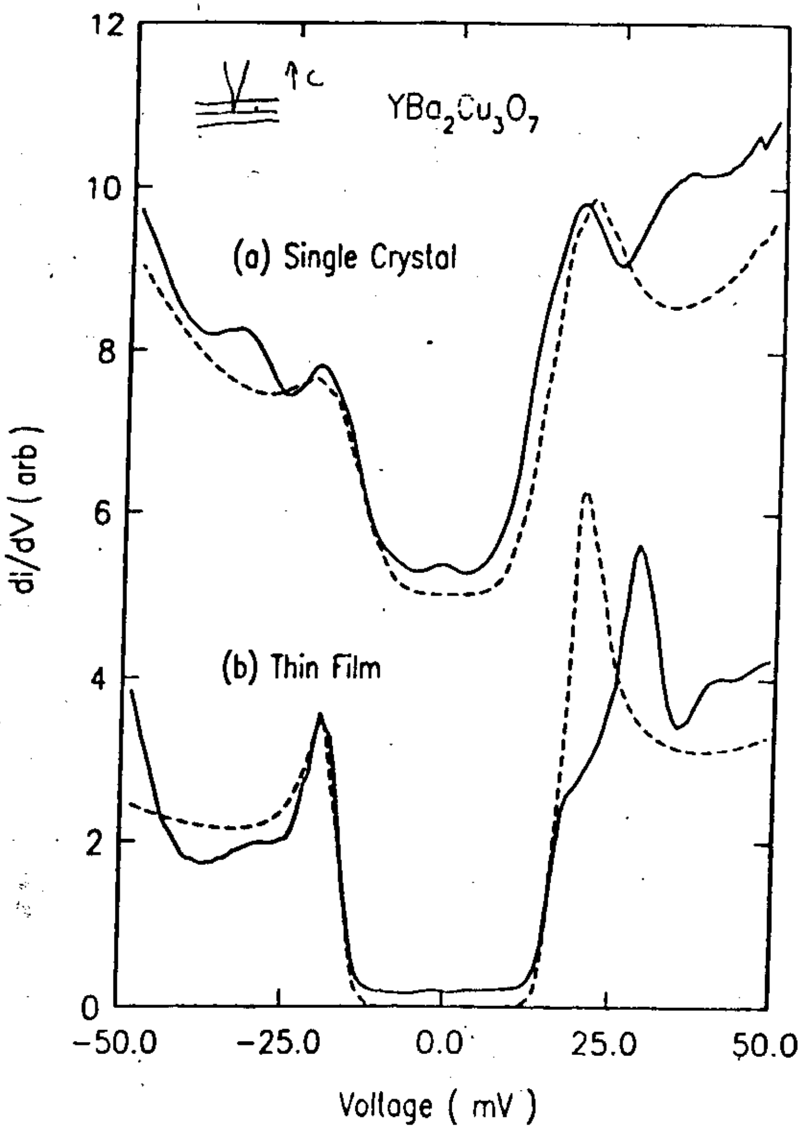
Tunneling conductance of $BaPb_{0.75}Bi_{0.25}O_3$ (R.C. Dynes)

S. Vieira, J.G. Rodrigo, M.A. Ramos, K.V. Rao and Y. Makino (Phys. Rev. Rapid Comm.)

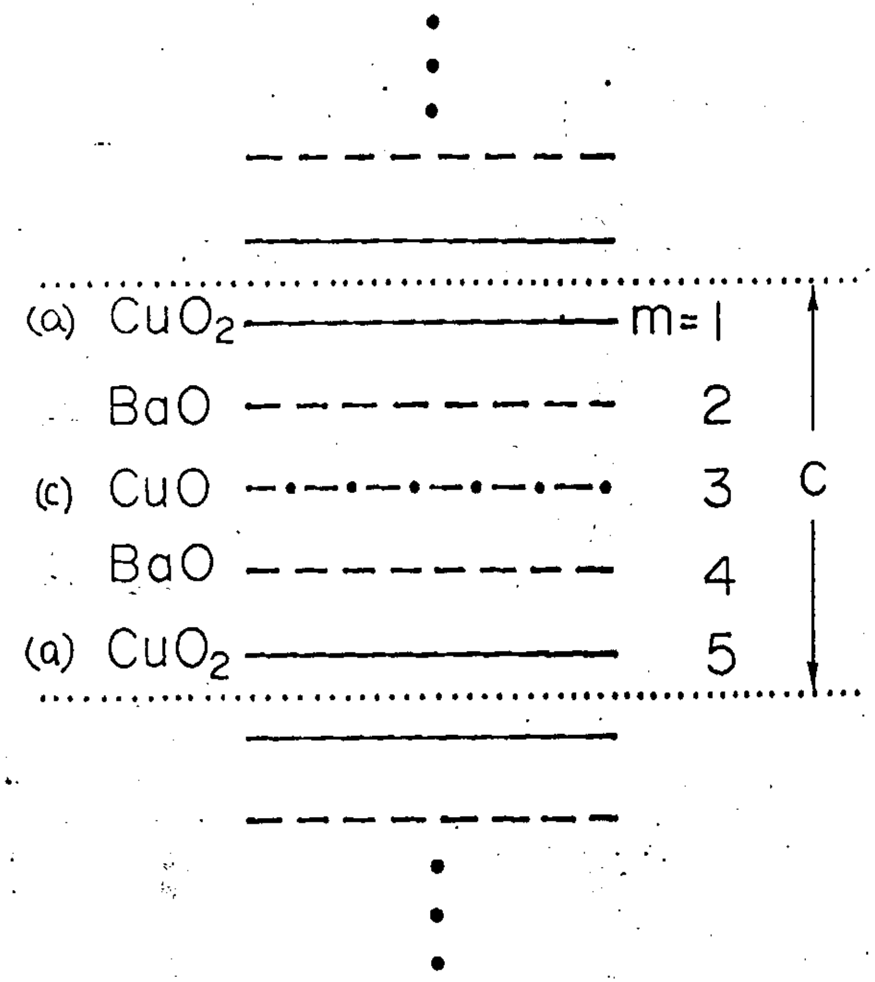


J.R. Kirtley et al. PR B35, ... (87)

Point contact data

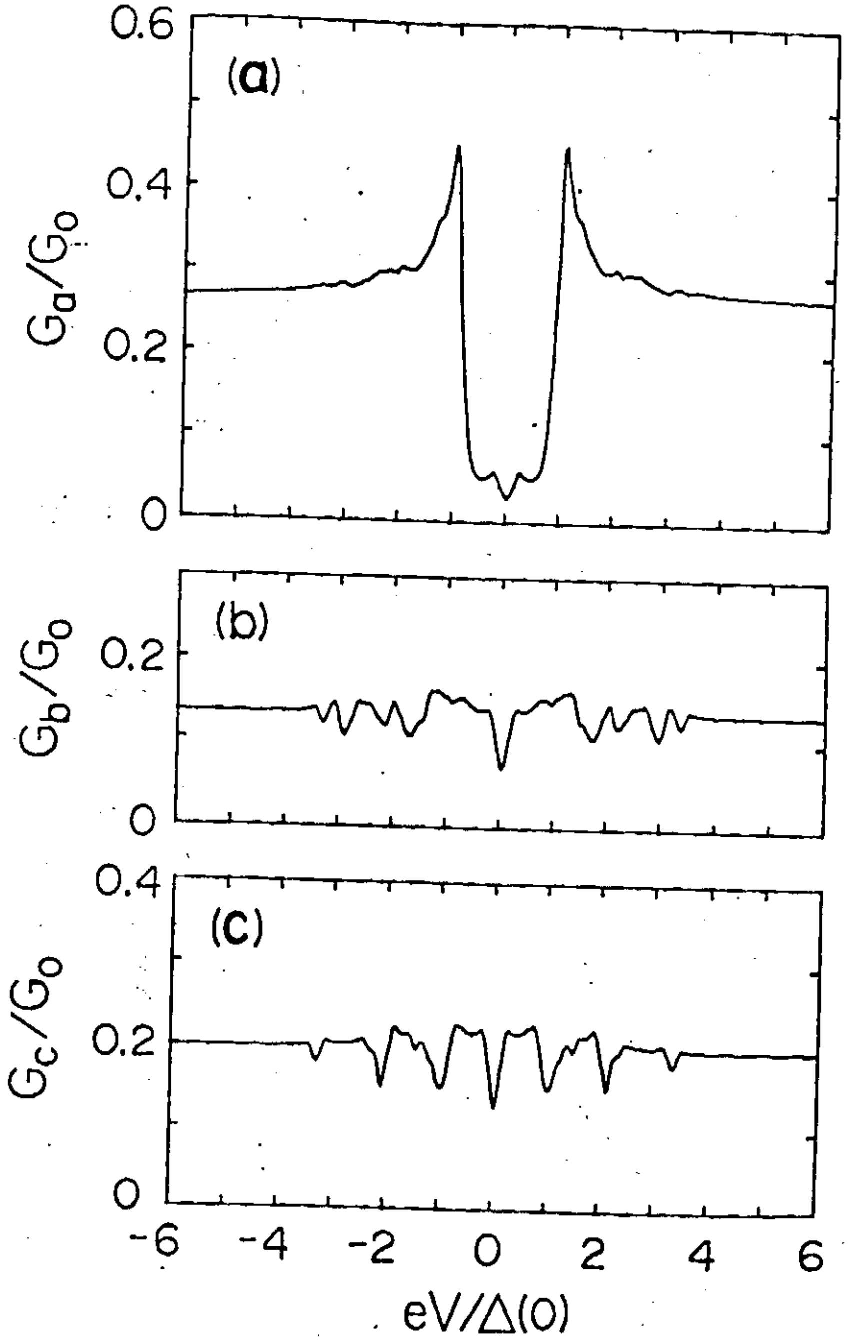


45



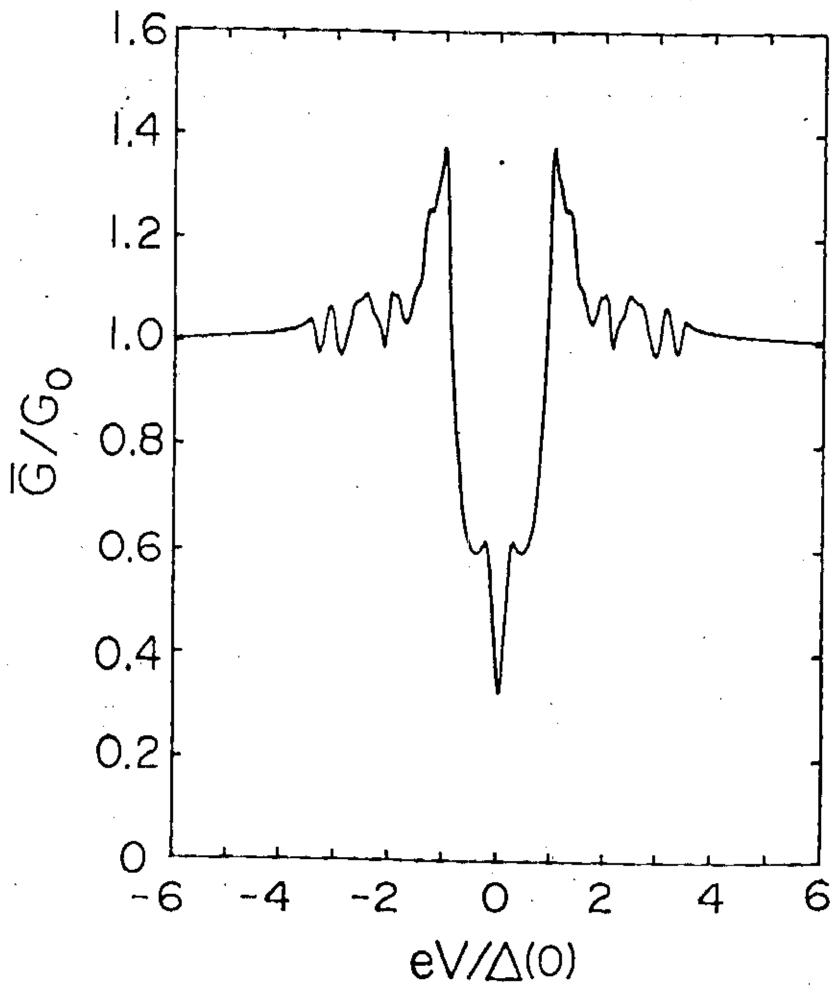
(a) CuO2 m=1
BaO 2
(c) CuO 3
c
BaO 4
(a) CuO2 5

Fig.1



(a)
Ga/Go
0.6
0.4
0.2
0
(b)
Gb/Go
0.2
0
(c)
Gc/Go
0.4
0.2
0
-6
-4
-2
0
2
4
6
eV/Δ(0)

Fig.3



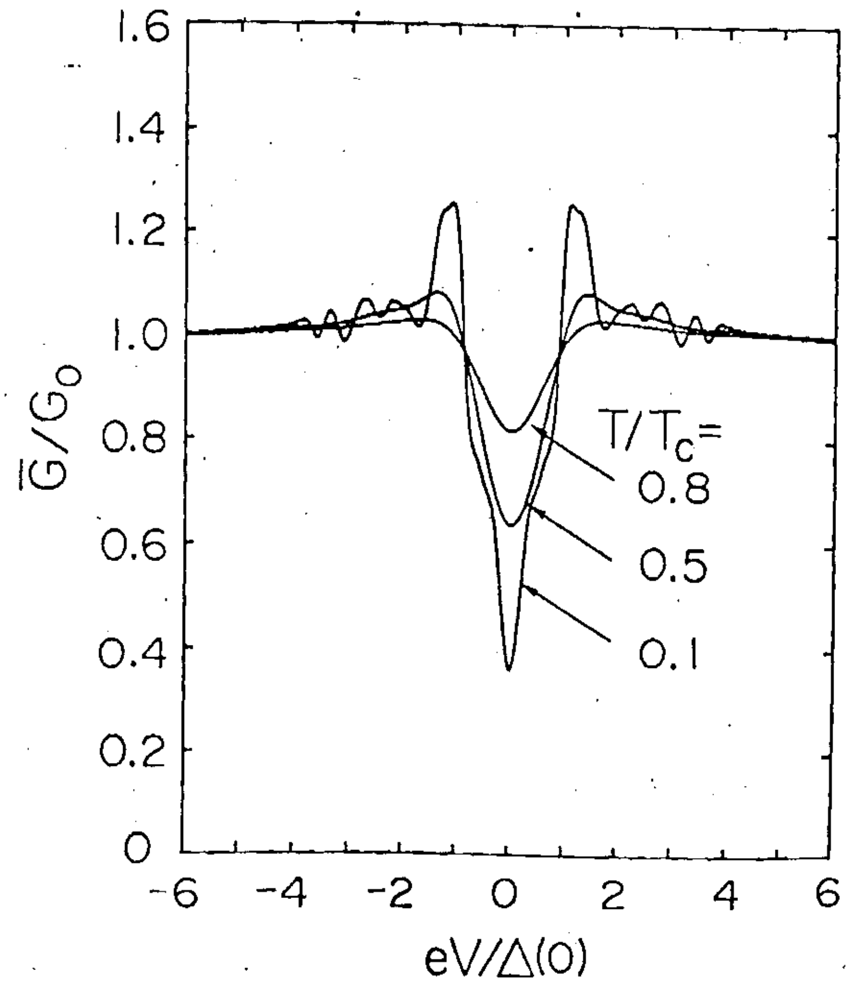


Fig.11

Fig.5

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