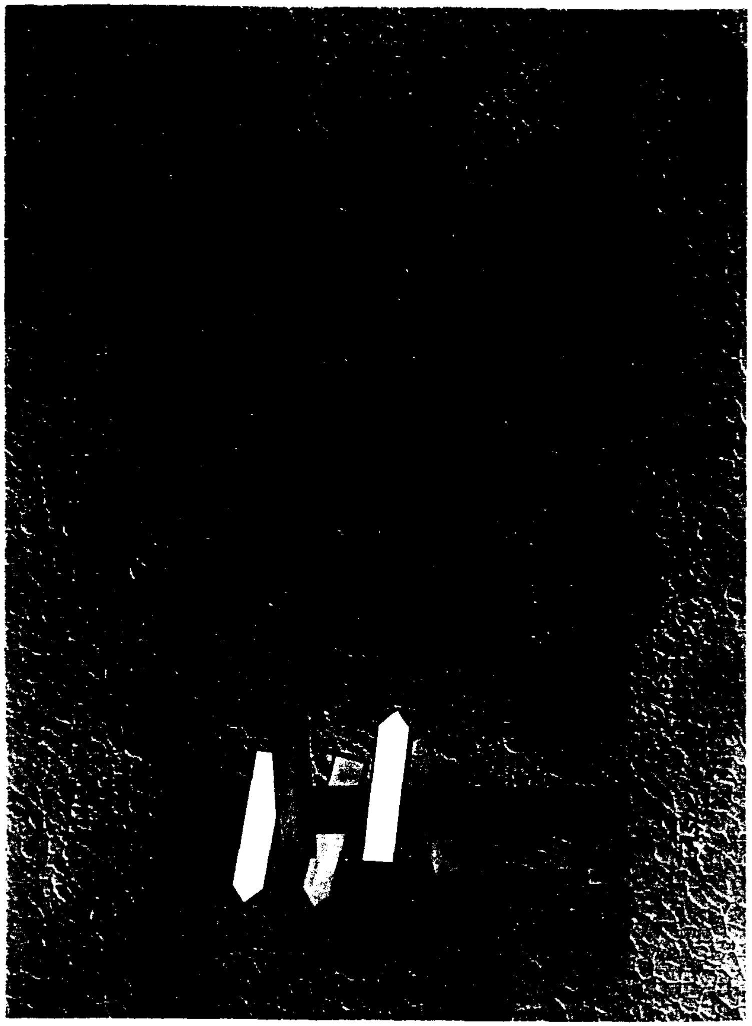


I **Planar Quasiparticle Tunneling Spectroscopy:**

Introduction and Experimental Methods

Tuesday: 7/18/00

II (Wednesday)
Tunneling in High-Temperature Superconductors: Spectroscopy of Broken Symmetries

III (Friday)
Broken Time-Reversal Symmetry: Measurements (Tunneling and ESR)

Laura H. Greene
University of Illinois at Urbana-Champaign

NSF
Boulder School for Condensed Matter Physics
July, 2000

L. Greene
Lecture 1

SOME REFERENCES:

Excellent general texts on tunneling: (Lecture I)

L. Solymar, *Superconductive Tunnelling and Applications* (Wiley, London, 1972).

E. L. Wolf, *Principles of Electron Tunneling Spectroscopy* (Oxford, NY, 1985).

W. L. McMillan and J. M. Rowell, "Tunneling and Strong-Coupling Superconductivity" in *Superconductivity in Two Volumes*, R. D. Parks, ed. (Marcel Dekker, NY 1969).

J. M. Rowell, "Tunneling Density of States – Experiment", and "Tunneling Anomalies – Experiment", both in *Tunneling Phenomena in Solids* (Plenum, NY 1969).

Some of our relevant papers (Lectures II and III)

High-T_c film growth and tunneling.

1. L. H. Greene, J. Lesueur, W. L. Feldmann and A. Inam, "Superconductive Tunneling in $YBa_2Cu_2O_7$ Thin Films: Dependence Upon Crystallographic Orientation" in *High Temperature Superconductivity: Physical Properties, Microscopic Theory and Mechanisms*, J. Ashkenazi, S. E. Barns, F. Zuo, G. C. Vezzoli and B. M. Klein, eds., (Plenum Press, New York, 1991) pp. 137-146
2. L. H. Greene, B. G. Bagley, W. L. Feldmann, J. B. Barner, F. Shokoohi, P. F. Miceli, B. J. Wilkins, V. Pendrick, D. Kalokitis and A. Fathy, "Off-Axis Sputter of $YBa_2Cu_3O_7$ Films for Microwave Applications", Applied Physics Letters **59**, 1629-1631 (1991).
3. M. Covington, R. Schurerer, K. Bloom, and L. H. Greene, "Tunneling and Anisotropic Charge Transport and Properties of Superconducting (110)-oriented $YBa_2Cu_3O_7$ Thin Films" Applied Physics Letters **68**, 1717 (1996).
4. D. E. Pugel and L. H. Greene "Influence of Target-Substrate Angle on the Elemental Concentration of c-axis $YBa_2Cu_3O_{7-x}$ Thin Films", Applied Physics Letters **75**, 1589–1591 (1999).
5. J. Lesueur, L. H. Greene, W. L. Feldmann and A. Inam, "Zero Bias Anomalies in $YBa_2Cu_3O_7$ Tunnel Junctions", Physica C **191**, 325-332 (1992).

Andreev bound state tunneling / BTRS

6. M. Covington, M. Aprili, E. Paraoanu, L. H. Greene, F. Xu, J. Zhu and C. A. Mirkin "Observation of Surface-Induced Broken Time-Reversal Symmetry in $YBa_2Cu_3O_7$ Tunnel Junctions" Physical Review Letters, **79**, 277 (1997). (Published in conjunction with theory Letter: M. Fogelström, D. Rainer and J. A. Sauls "Tunneling into Current-Carrying Surface States of High T_c Superconductors" Physical Review Letters, **79**, 281 (1997).
7. M. Aprili, M. Covington, E. Paraoanu, B. Niedermeyer and L. H. Greene "Tunneling Spectroscopy of the Quasiparticle Andreev Bound State in Ion-Irradiated $YBa_2Cu_3O_7$/Pb Junctions", Physical Review **B 57**, R 8139 (1998).
8. L. H. Greene, M. Covington, M. Aprili, E. Paraoanu, "Tunneling into Andreev Bound States of $YBa_2Cu_3O_7$: Observation of Broken Time-Reversal Symmetry", The Journal of Physics and Chemistry of Solids, **59,** 2021-2025, (1998).
9. L. H. Greene, M. Covington, M. Aprili and E. Paraoanu, "Tunneling into High-Temperature Superconductors: Andreev Bound States and Broken Time-Reversal Symmetry". Solid State Communications, **107**, 649-656 (1998).
10. M. Covington and L. H. Greene, "Planar tunneling spectroscopy of $Y_{1-x}Pr_xBa_2Cu_3O_7$ thin films as a function of crystallographic orientation", (Submitted to Physical Review B).
11. M. Aprili, E. Badica and L. H. Greene "Doppler Shift of the Andreev Bound States at the YBCO Surface", Physical Review Letters, 83, 4630-4633 (1999).
12. **L. H. Greene, M. Covington, M. Aprili, E. Badica and D. E. Pugel, "Observation of Broken Time-Reversal Symmetry with Andreev Bound State Tunneling Spectroscopy", Physica B 280 (Part 1), 159-164 (2000). [THIS IS A REVIEW UP TO AUGUST 1999]**
13. L. H. Greene, M. Aprili, M. Covington, E. Badica, D. E. Pugel, H. Aubin, Y. -M. Xia, M. B. Salamon, Sha Jain and D. G. Hinks, "Spectroscopy of the Andreev Bound State of High-Temperature Superconductors: Measurements of Quasiparticle Scattering, Anisotropy and Broken Time-Reversal Symmetry", M^2S-HTSC-VI, February 20-25, 2000, Houston, TX, to be published in Physica C (North-Holland, Elsevier Science, 2000) in press.
14. D. E. Pugel, Yao-Min Xia, M. B. Salamon and L.H. Greene, "Effects of the Target-to-Substrate Angle on Off-Axis Sputter Deposition and EPR Studies of Near-Surface Magnetic Properties of YBCO Thin Films", M^2S-HTSC-VI, February 20-25, 2000, Houston, TX, to be published in Physica C (North-Holland, Elsevier Science, 2000, in press.
15. H. Aubin, D. E. Pugel, E. Badica, L. H. Greene, Sha Jain and D. G. Hinks "Planar Quasiparticle Tunneling Spectroscopy of Bi2212 Single Crystals", M^2S-HTSC-VI, February 20-25, 2000, Houston, TX, to be published in Physica C (North-Holland, Elsevier Science, 2000). in press.
16. E. Badica, M. Aprili, M. Covington and L. H. Greene, "Andreev Bound State Tunneling Spectroscopy of Unconventional Superconductivity", SPIE Invited Proceedings, "*Superconducting and Related Oxides: Physics and Nanoengineering IV*", Davor Pavuna and Ivan Bozovic, editors (SPIE Proceedings, SPIE, Bellingham, 2000) in press.
17. L. H. Greene, "Andreev Bound State Tunneling Spectroscopy and Detection of Broken Time-Reversal Symmetry in Unconventional Superconductors", Proceedings of the Conference on Major Trends in Superconductivity for the New Millennium (MTSC-2000), March 31 – April 5, Klosters, Switzerland, in press.
18. D. E. Pugel, Yao-Min Xia, M. B. Salamon and L.H. Greene, "Observation of Broken Time-Reversal Symmetry at YBCO Surfaces with Electron Paramagnetic Resonance" (preprint).

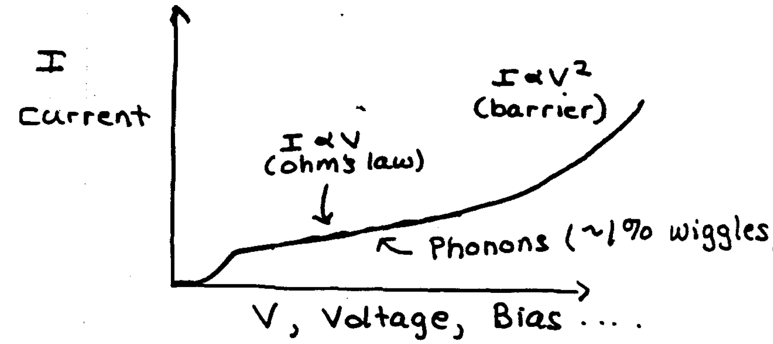
Outline

Quasiparticle tunneling spectroscopy: Defn'
Planar vs stm
Semiconductor model
- NIN - basics
- NIS - Spectroscopy
  - 1st breakdown (el-ph strong coupling)
  - Important limits
  - thermal population effects
- SIS - Mention for completeness
- barrier calculation / diagnostic

Some important pitfalls
- Schottky barrier
- Charging effects (coulomb blockade)
- Inelastic processes
- Imperfect barriers
  - (critical currents / heating / Andreev processes)

CRUCIAL DIAGNOSTICS

SPECTROSCOPY:

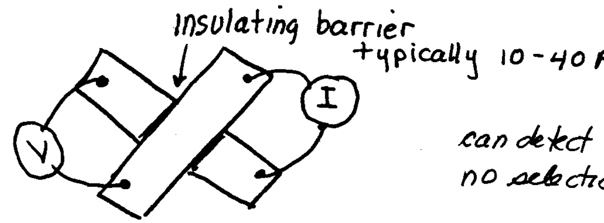


gap (~1meV LTS — ~50meV HTS)

Phonon excitations
few → hundreds meV

Inelastic tunneling processes
0 → ~1eV

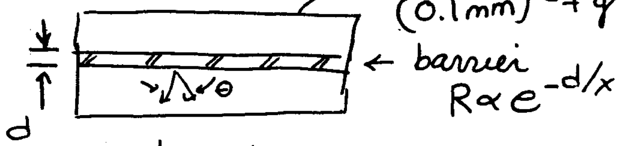
barrier effects



can detect < 10^{16} electrons
no selection rules

7

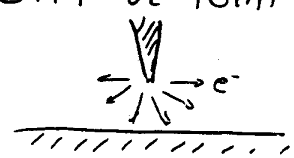
Planar tunneling



θ = tunneling cone
few degrees for "reasonable" barrier
maybe 20° for low barrier

⇒ Poor spatial resolution / high momentum resolution
& Easier to establish ∃ tunneling!

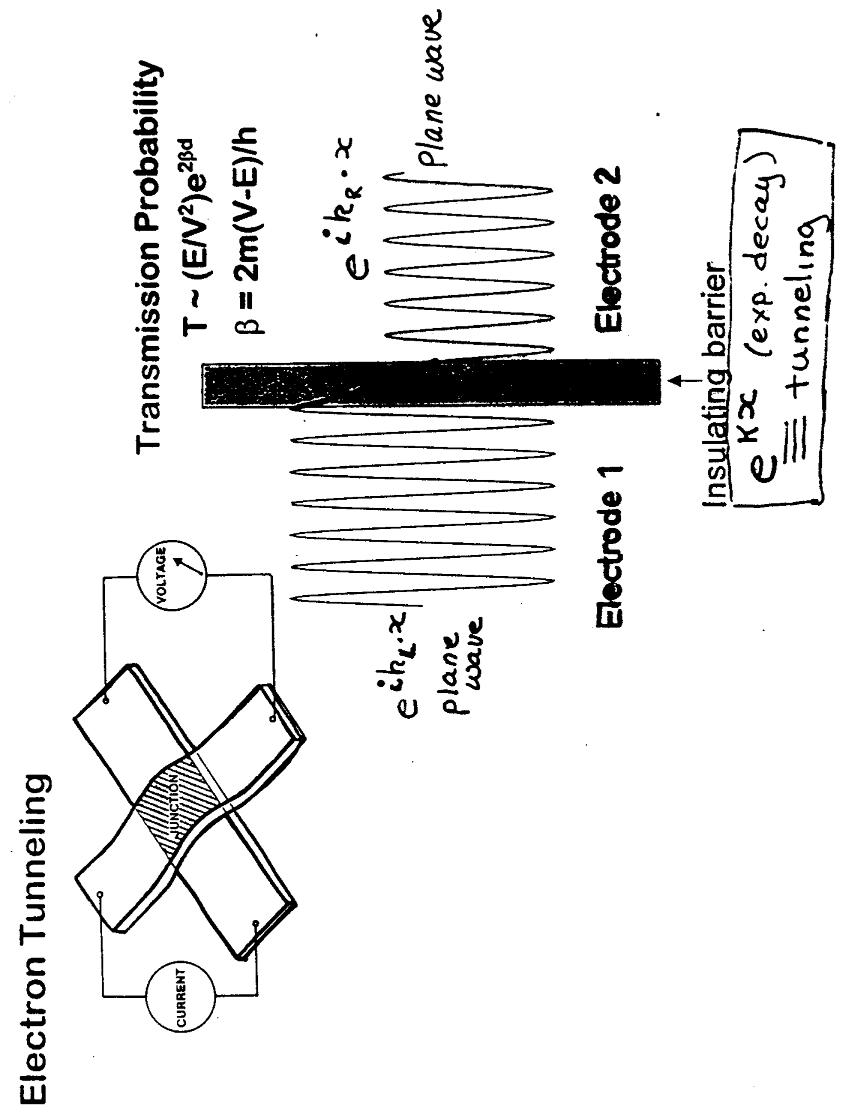
STM or Point Contact
θ large

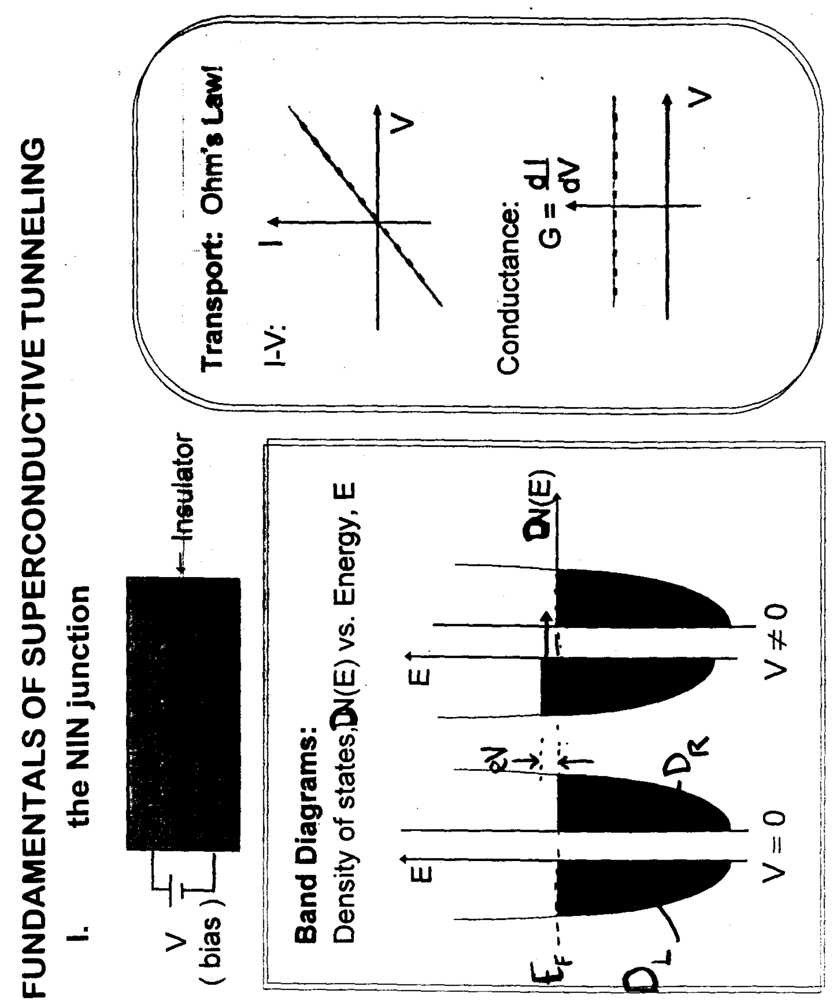


⇒ high spatial resolution (atomic!)
poor momentum resolution

$\Delta p \Delta x \geq \hbar/2$

8





Semiconductor model ; NIN *continued*

At $V \neq 0$, # of electrons transmitted (within dE) is:

(a) Proportional to the number of <u>occupied</u> states on the <u>left</u> : or:

$$\underbrace{D_L(E-eV)}_{\text{DoS density of states}} \; \underbrace{f(E-eV)}_{\text{Fermi function}} \, dE \qquad f \sim \left(1 + e^{E/k_BT}\right)^{-1}$$

<u>and</u>

(b) Proportional to the number of <u>empty</u> states on the <u>right</u> : or:

$$D_R(E)\,[1 - f(E)]\, dE$$

So, the total current accross the junction is:

$$I \propto \int (I_{L \to R} - I_{R \to L})\, dE$$

$$\propto \int T(E)\, D_L(E-eV)\, D_R(E)\, f(E-eV)\,[1-f(E)]\,dE$$
$$- \underbrace{T(E)}_{\text{barrier transmittance}}\, D_L(E-eV)\, D_R(E)\, f(E)\,[1-f(E-eV)]\,dE$$

$$I \propto \int dE\; T(E)\, D_L(E-eV)\, D_R(E)\,[f(E-eV) - f(E)]$$

Now some assumptions:

$T(E) = T(0)$: good for small E

$D_L(E) = D_L(0)$, $D_R(E) = D_R(0)$: OK for N ~ "free electron metals"

Then we can write: (prop. constant; includes $T(0)$)

$$I = A D_L(0) D_R(0) \int dE \left[f(E - eV) - f(E) \right]$$

at low E : $f(E-eV) - f(E) \approx eV \dfrac{df(E-eV)}{dE}$

and at low T $\quad -\dfrac{df}{dE} \approx \delta(E - eV)$

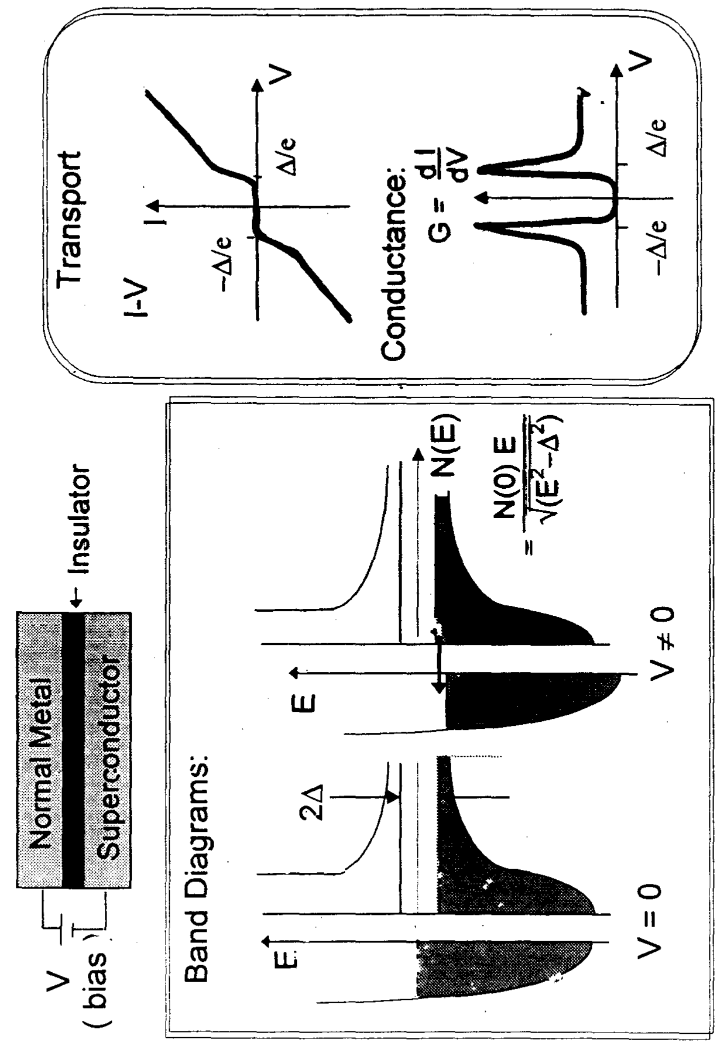
Then we finally have:

$$I = A\, D_1(0)\, D_2(0)\, eV$$

$I \propto V$ or Ohm's Law!

"quantum-mech derivation: remember, electrons traverse classically-forbidden region"

II. the NIS junction



Semiconductor model; NIS continued

recall, for NIN, before assumptions we had

$$I \propto \int dE\, T(E)\, D_L(E-eV)\, D_R(E)\left[f(E-eV)-f(E)\right]$$

can still assume $T(E)=T(0)$ and $D_L(E)=D_L(0)\equiv D_N(0)$

BUT $D_R(E)=D_S(E)$, use BCS DoS:

$$D_S(E)=\begin{cases} D_S(0)\dfrac{E}{\sqrt{E^2-\Delta^2}} & ; |E|\geq\Delta \\ 0 & ; |E|<\Delta \end{cases}$$

So we can write

$$I = A\,D_N(0)\int_0^\infty dE\, D_S(E)\left[f(E-eV)-f(E)\right]$$

consider low-temperature limit: $(T\to 0)$

$$f(E-eV)-f(E)=\begin{cases} 1 & ; 0<E<eV \\ 0 & ; \text{otherwise} \end{cases}$$

so:

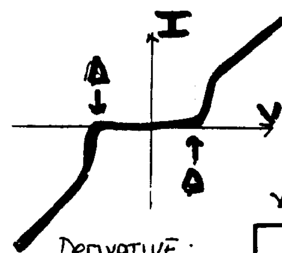
$$I = A\,D_n(0)\int_0^{eV} dE\, D_S(E)$$

The Differential Conductance $G=dI/dV$ is:

$$G = A\,D_n(0)\,D_S(eV)$$

or $G \propto D_S(eV)$

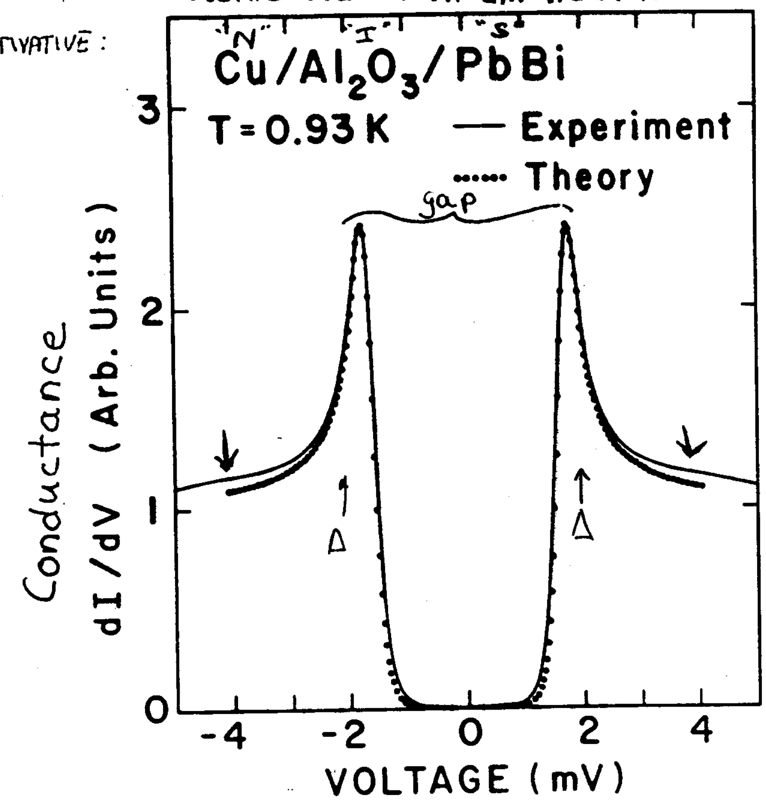
* Tunneling conductance is a direct measure of the SC DoS (in the gap region) *



Derivative:

example of Real Data: SIN tunnel junction

WORKS WELL FOR GAP REGION



Away from gap;
theory deviates from experiment.

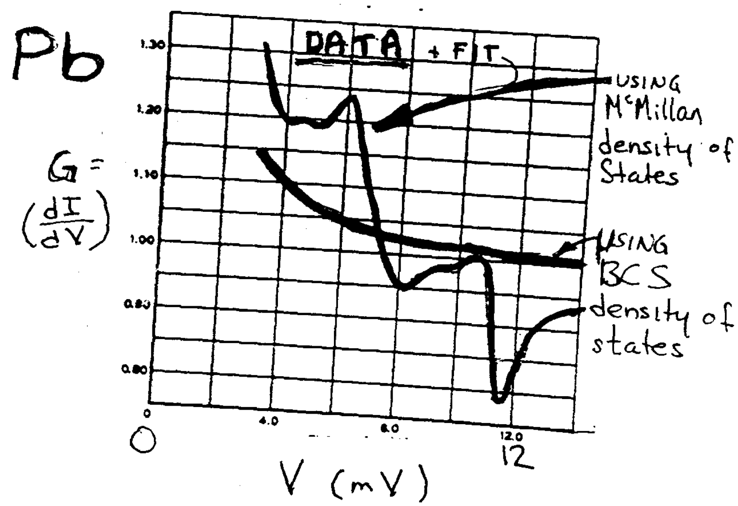
McMillan density of states... (to get DOS)

Away from gap:

McMillan Density of States

$$N(\omega) = \mathrm{Re}\left[\frac{\omega}{\sqrt{\omega^2 - \Delta^2(\omega)}}\right]$$

complex & energy dep. gap function



Phonon structure then compared with neutron scattering.

Important limits:

(a) as $T \to 0$ (just showed)

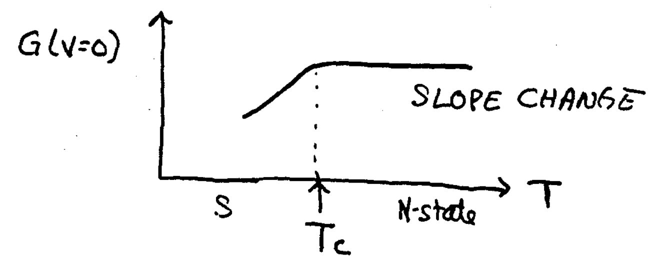
$$G = \frac{dI}{dV}\Big|_{T\to 0} \propto D_s(eV$$

(b) as $V \to 0$ (can easily be shown)

$$G(V\to 0) = \frac{dI}{dV}\Big|_{V\to 0}$$

$$\propto \left(\frac{\Delta}{k_B T}\right)^{1/2} e^{-\Delta/k_B T}$$

Temp-dep of Zero-Bias conductance



Important because Δ at high T (near Tc) is difficult to determine.

Gap is small and Thermal Population Effects

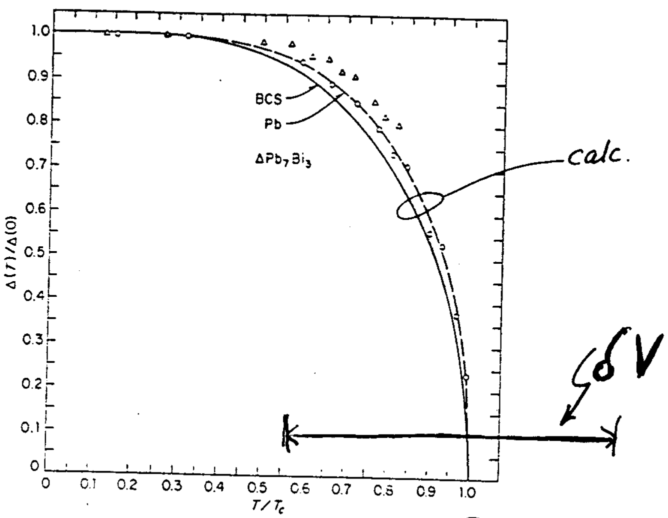
$$\Delta \sim \frac{1}{(1-T/T_c)^{1/2}}$$

Notes on Thermal Population Effects

For $T \to T_c$:

$$\Delta(T) \sim 1.8\,\Delta(0)\,(1 - T/T_c)^{1/2}$$

but how well can you measure this?



Thermal "smearing": df/dE ~ $3k_BT = \delta V$

(population of normal-state excitations)

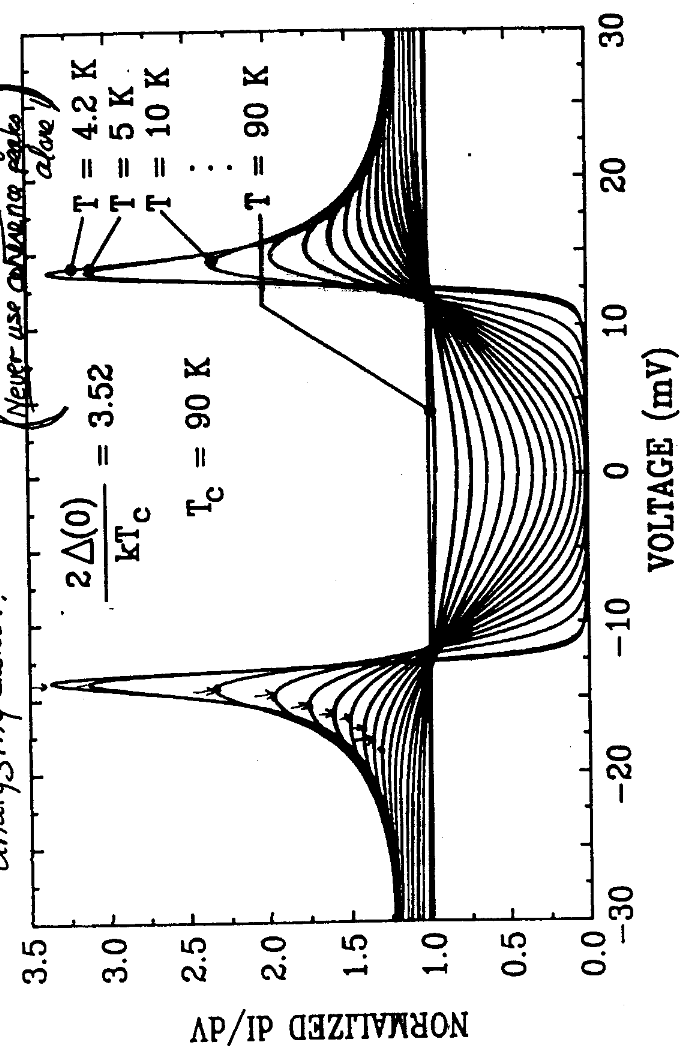
T (K)	δV (mV)
4.2	1
42	10
90	21

} $\delta V \sim O(\Delta)$ near T_c in conv. SC's

Cute effect of temp: Thermal population effects can make it appear that Δ actually increases with decreasing temperature:

- MUST account for temp effects when analyzing data!!

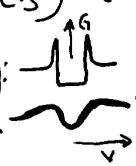
(also need model to get Δ. Never use ... peaks alone)



Thermal analysis of tunneling data is **BASIC**

To observe any T-dep DoS changes (like $\Delta(T)$) **must** extract thermal pop effects

Simplest recipe (for conv., low-T_c SC's):

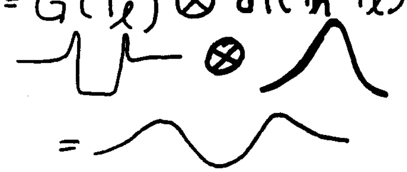


ⓐ Take low-temp data : $G(T_l)$

ⓑ **Take higher-temp data $G(T_h)$**

ⓒ Convolve low-temp data with derivitive of Fermi function at higher temp

$$G(T_h \text{ from } T_l) = G(T_l) \otimes df(T_h - T_l)/dE$$



→ ⓓ Compare $G(T_h)$ with $G(T_h \text{ from } T_l)$

If they match: Changes in tunneling spectra are accounted for by thermal effects

If not: DoS exhibits T-dep changes (eg $\Delta(T)$, pseudogap, Andreev bound state, Broken time-reversal symm .... etc...

Semiconductor model SIS (Shown for completeness)

$$D_{L,R} = \begin{cases} 0 & ; |E| < 0 \\ D_{L,R} \dfrac{E}{(E^2 - \Delta_{L,R}^2)^{1/2}} & ; |E| \geq 0 \end{cases}$$

note: Δ_L may be $\neq \Delta_R$

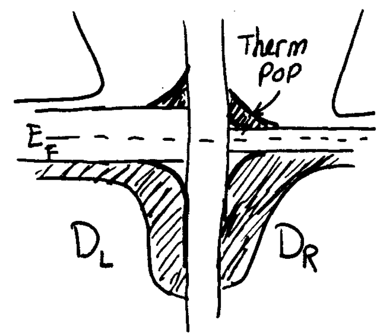
I-V's and G-V's are calc by numerical methods

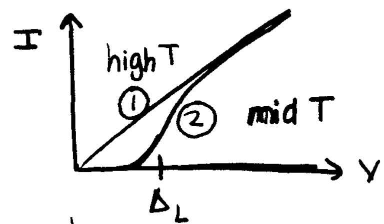
Results in 3 T-regions (assuming $T_{c_L} > T_{c_R}$

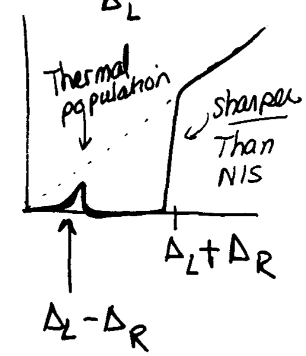
① **$T > T_{c_L} > T_{c_R}$: Simply NIN (solved earlier)**

② **$T_{c_L} > T > T_{c_R}$: NIS (shown earlier)**

③ $T_{c_L} > T_{c_R} > T$: SIS







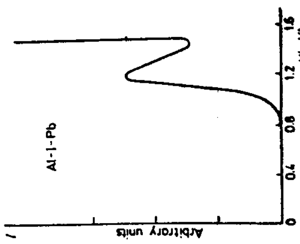


Fig. 4.8 The I-V characteristic of an Al-I-Pb junction, both Al and Pb superconducting. After Giaever [45].

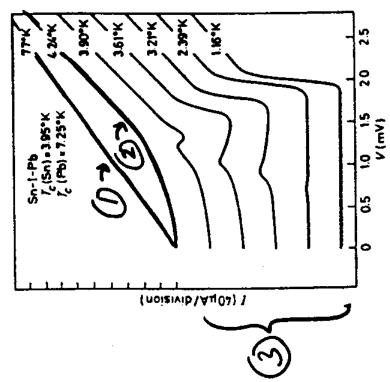


Fig. 4.9 I-V characteristics of an Sn-I-Pb junction.

Quasiparticle tunneling between superconductors of differing gaps

1. $T > T_{cL} > T_{cR}$
2. $T_{cL} > T > T_{cR}$
3. $T_{cL} > T_{cR} > T$

discussed in more detail in Section 7.1.

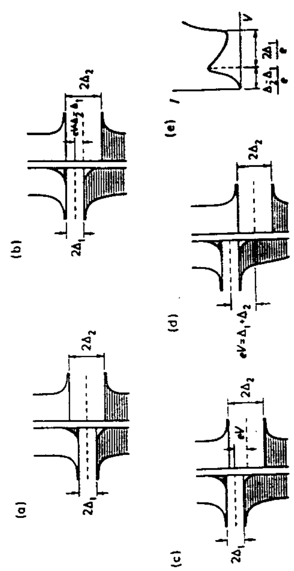
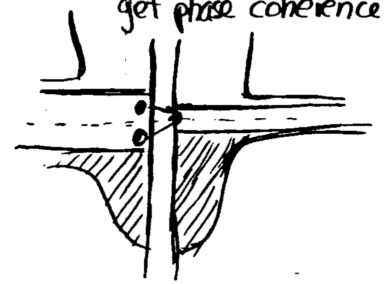


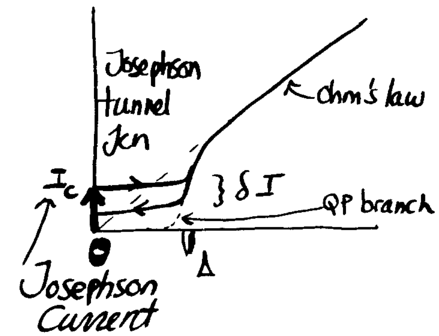
Fig. 4.7 The energy diagram and I-V characteristic of an S_1S_2 junction at finite temperature; (a) $V = 0$, (b) $V = (\Delta_2 - \Delta_1)/e$, (c) $(\Delta_2 - \Delta_1)/e < V < (\Delta_2 + \Delta_1)/e$, (d) $V = (\Delta_1 + \Delta_2)/e$, (e) the I-V characteristic.

SIS

Finally: a very quick note on Josephson tunneling (only bringing up to show a zero-bias effect)

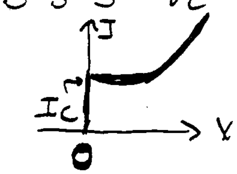
When insulating barrier is thin (~10Å, typically) get phase coherence between Ss across barrier.

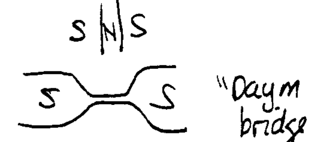




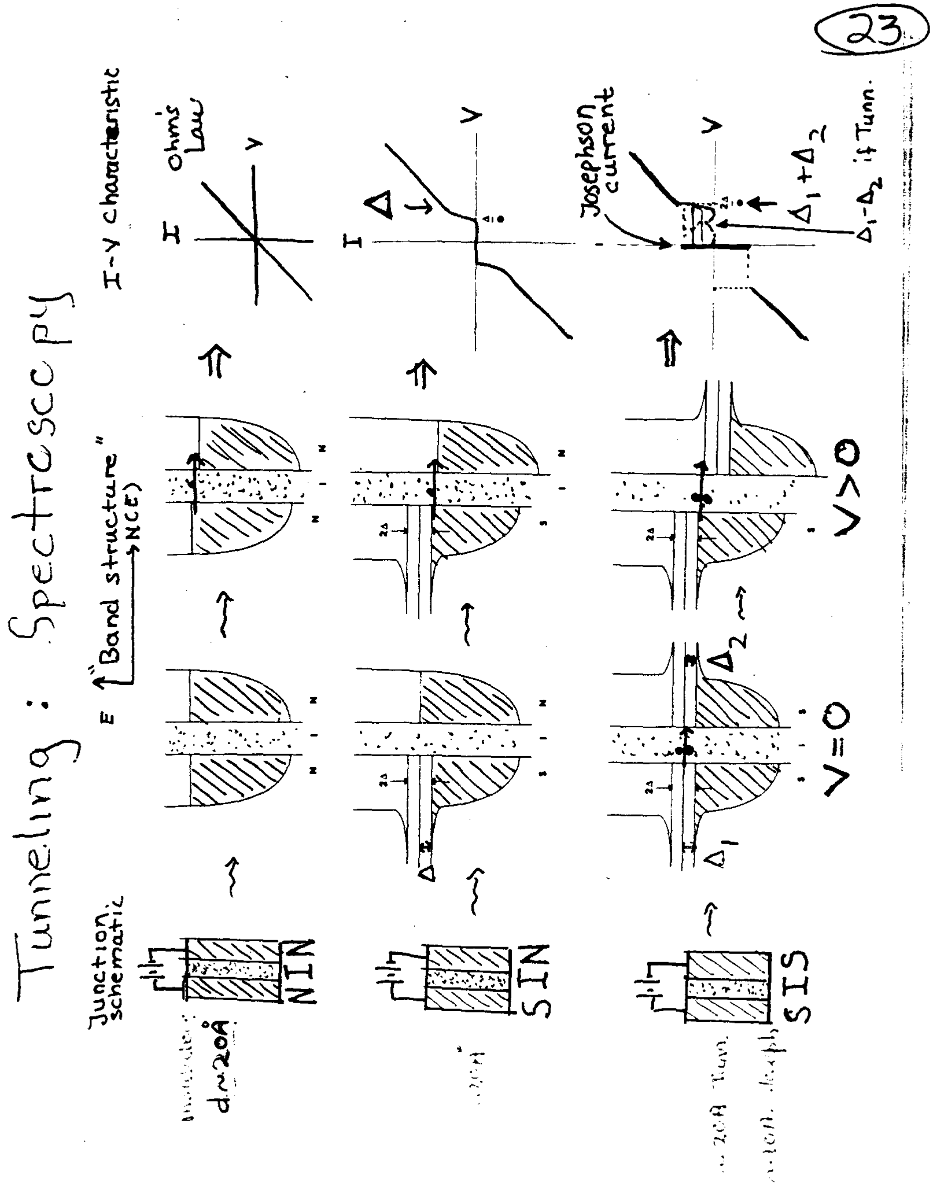
SI hysteresis is particularly promising for applications (Change δV ≥ get big Voltage change ~Δ)

note: can also get a Josephson transport jcn S·S'·S or SNS:

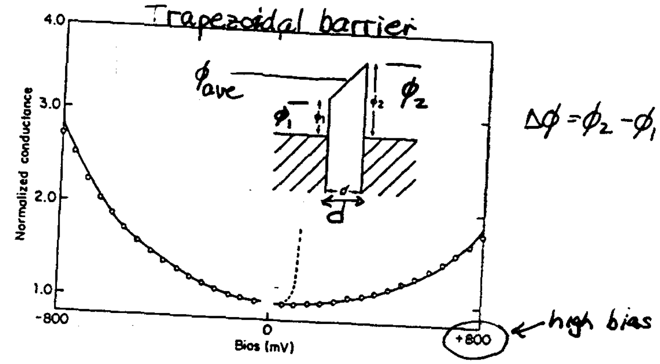




etc, etc . . .



Another standard analysis:
Barrier calculation from data
Brinkman, Dynes & Rowell J. APPL. Phys **41**, 1915 (1970).



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

$$\frac{G(V)}{G(0)} = 1 - \left(\frac{A_0\,\Delta\phi}{16\,\phi_{ave}^{3/2}}\right)(eV) + \frac{9}{128}\,\frac{A_0^2}{\phi_{ave}}\,(eV)^2$$

$$G(0) = \frac{1}{R_N A}$$

$$A_0 = d4(2m)^{1/2}/3\hbar = 0.683\,d$$

fit background conductance to parabola
obtain asymmetry, $\Delta\phi$, ϕ_{ave} (height)
and width, d

need: to go $eV \gg \Delta$
- Voltages to double conductance
  100's of mV for reasonable barriers:
  $\phi_{ave} \lesssim 1\,V \quad d \simeq 20\,Å$

a few Pitfals of Quasiparticle Tunneling Spectroscopy

Many thanks to
* John Rowell *
Jochen Geerk
Bob Dynes
others, and
Experience

please note:
this is tricky stuff. *
feel free to contact me about any questions (Data, analysis theoretical int., etc) and we can be confused together. This section is not at all complete - but mentions the most common pitfalls.

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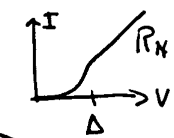
Examples given here:

1. Schottky barriers: Thermionic emission
2. Charging effects: (Coulomb blockade/staircase)
3. Inelastic tunneling processes
4. Barrier effects
   - critical currents (pinholes/shorts)
   - heating
   - Andreev reflections (shorts)

CHECKS: DIAGNOSTICS



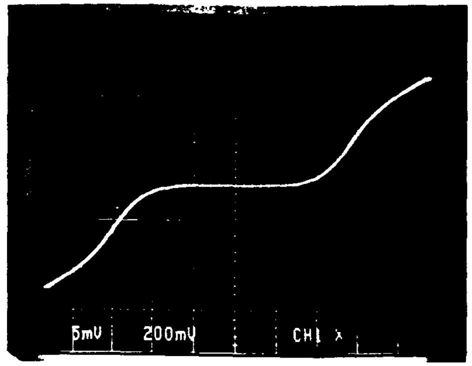
- Always present I-V
  $R(V=0) \sim 20 \times R_N$
- Use SC counterelectrode to establish tunneling
- Lack of R_N temperature dep (tunneling is inherently non T-dep)
- Areal dependence. Area $\propto 1/R_N$
- REPRODUCIBILITY

HAYAKAWA, 1988

(27)

YBCO–YBCO Tunnel Junction

Dr. Hisao Hayakawa of the Department of Electrical Engineering at Nagoya University has fabricated a sandwich-type YBCO–YBCO junction with an I–V curve showing remarkably sharp gap-like characteristics. This early laboratory study may bring us one step closer to high-T_c electronics applications.



Dr. Hayakawa's group is apparently the first to report a junction in a technologically significant configuration with both electrodes made from high-T_c materials. Other researchers have built hybrid tunnel junctions containing a high-T_c base electrode and a low-T_c counter electrode. Dr. Hayakawa's all-YBCO junction shows better current–voltage characteristics than these hybrids.

How does Dr. Hayakawa explain his group's success? "Important question! Nowadays many people want to make devices. But they think it is very important to perfect the films first — to make good epitaxial films, to get a smooth surface, and to examine a lot of things about the films. After they have good films, then they go to devices. Very nice approach! To get good films is quite important. I'd like to make good films. But I'm mainly interested in making tunnel junctions and devices, not in making films. So we start now, even though our films are not as good as other people's. We succeed because we have the courage to try. That's my opinion."

Structure

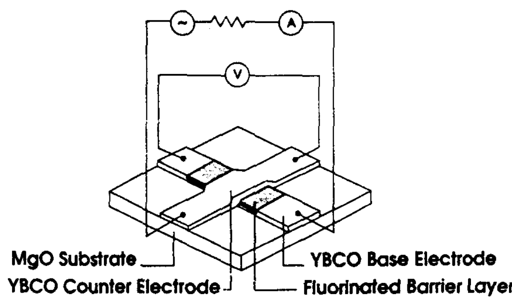
The tunnel junction consists of two YBCO superconducting thin films configured as crossing strips separated by a resistive layer, as illustrated in the drawing at right.

Fabrication Technique

Dr. Hayakawa deposited a YBCO thin film onto a magnesium oxide substrate by RF magnetron sputtering to create the base electrode. He then created a resistive barrier by subjecting the surface of the base electrode to plasma fluorination. Finally he deposited the YBCO counter electrode, again by RF magnetron sputtering. Details of the procedure appear in the shaded area at the end of this article.

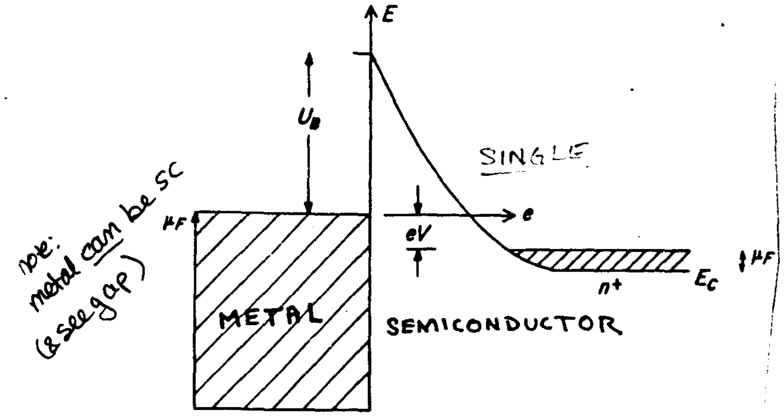
Current–Voltage Characteristics

The photograph above shows the current–voltage characteristics of Dr. Hayakawa's junction at 4.2K. The curve displays two figures of merit: a distinct gap voltage (equal to about 18mV) and a small sub-gap leakage current. (For basic information about superconductive tunneling, please see the previous article.)

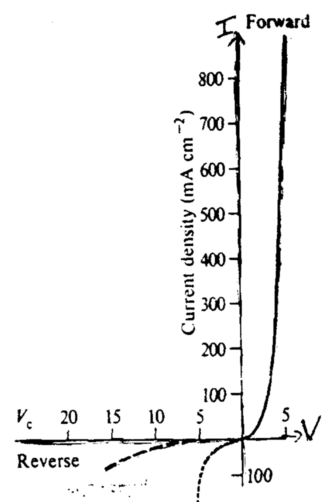


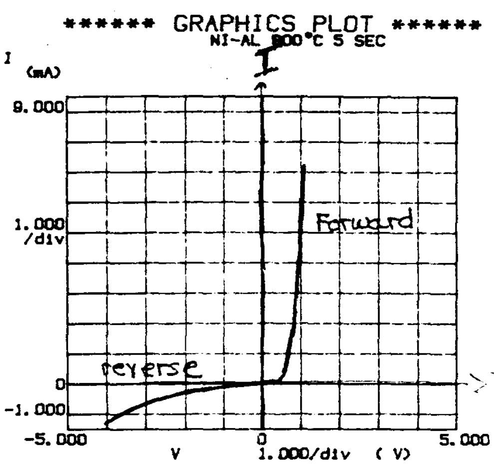
(28)

Schottky Barrier:



I-V Characteristics:





Double, "back-to back" Shottky barrier:

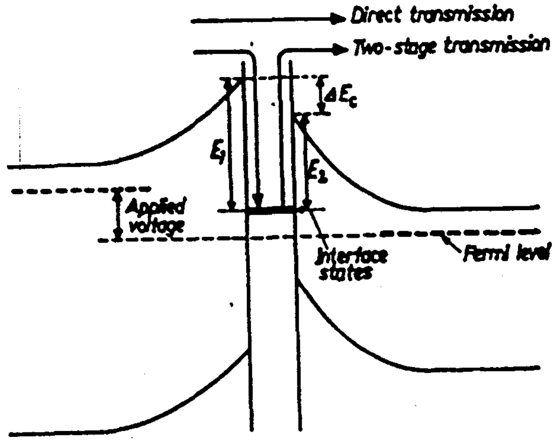


FIG. 1. Schematic band diagram for n–n heterojunction with double depletion layer and applied voltage. The arrows indicate two possible current mechanisms.

I-V of Grain Boundary:

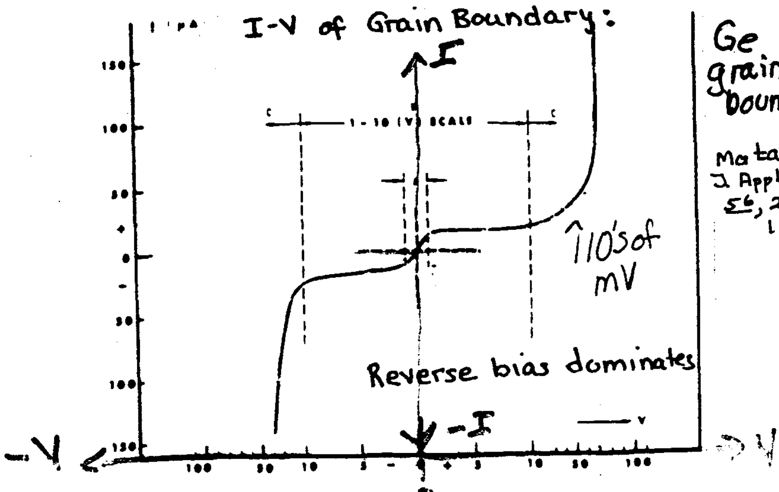
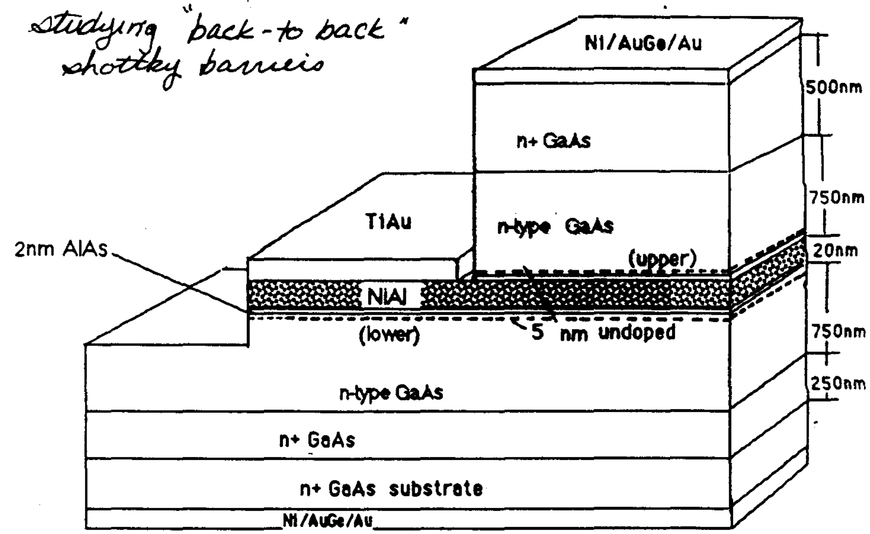


FIG. 7. *I-V* characteristics of typical GB in germanium.[60]

Ge grain boundary

Matare' J. Appl Phys 56, 2605 1984

T. Sands
T. Cheeks et. al:
studying "back-to back" shottky barriers

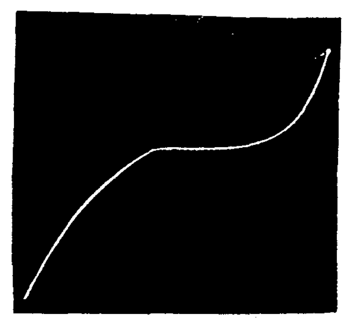


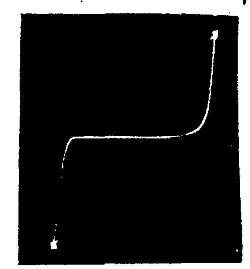
Schematic of Double Schottky Diode Structure

I-V Characteristics: ("leaky")

50μA/div

5V/div



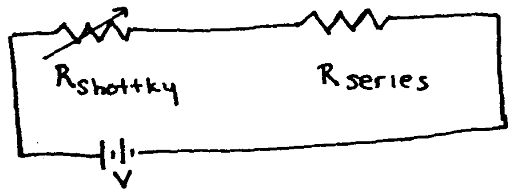


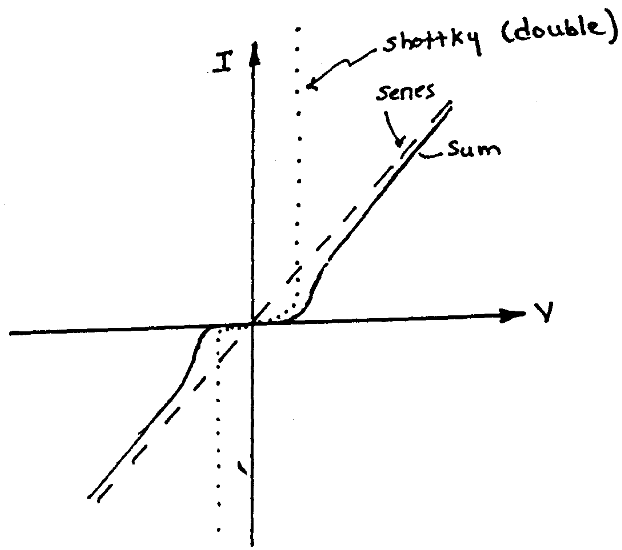
Room Temp Data

Theresa Cheeks
Bellcore

Sketch of this:

Shottky barrier + Series resistor





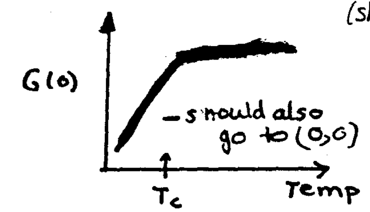
(or: single, [illegible] [illegible] barrier, relatively thick gives the same)

Best check is Temp dep:

1. Does gap-like structure disappear for $T > T_c$?

2. Does SLOPE of zero-bias conductance increase (inflection) below T_c ?

(shown earlier)

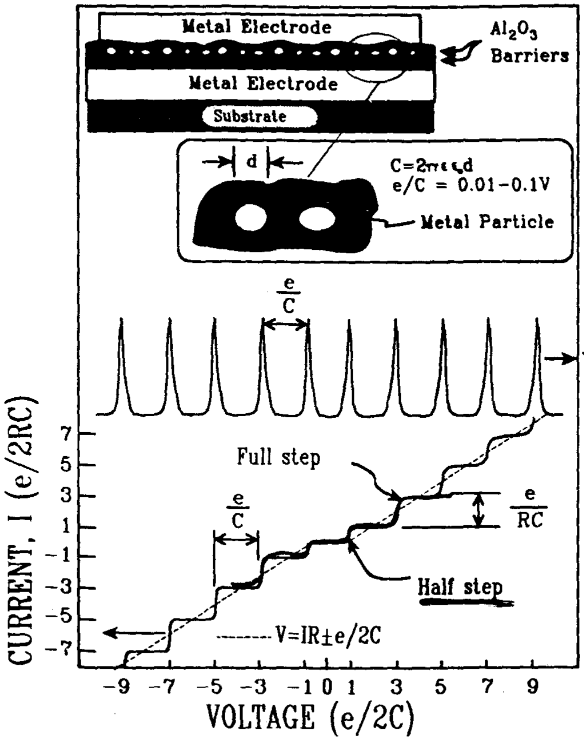


$$G(0) = \left.\frac{dI}{dV}\right|_{V=0}$$

Note:

- There is evidence that YBCO surfaces form shottky barriers. (See recent work by Jochen Manhardt)
- free Cu, Ba ... at grain boundries may act like interface states to form double shottky barriers at grain boundries.

CHARGING EFFECTS: Coulomb blockade/staircase

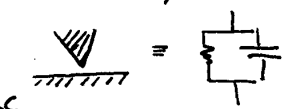


Coulomb Blockade ~~/ Coulomb Staircase~~*

Giaver & Zeller
Müller & Ben Jacobs
Licharev & Avaren
Fulton & Dolan
Iasanti & others w/ Tinkham (Ralph's work!)
Banner & Rugenio

lower dimensionality important to this problem

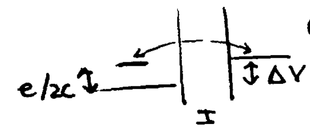
Consider a Small Junction



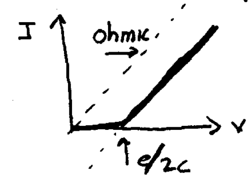
Voltage over capacitor: $V = e/2C$
⇒ need small C to resolve V

$G = Q/V$

Energy level diagram



capacitance causes junction to charge } tunneling occurs when applied voltage $V > e/2c$



get staircase:

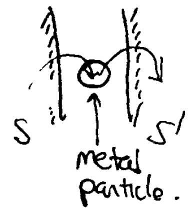
Energy to add 1 electron

$E_n = \frac{1}{2}(ne)^2/C$

$\Delta E = E_n - E_{n+1}$

$= \frac{1}{2}\frac{e^2}{C}[(n^2+1)-n]$

$$\Delta E = \frac{1}{2}\frac{e^2}{C}(2n+1)$$



VOLTAGE STEPS ⟶ CURRENT STEPS

$V = E/C$

$\Delta V = \frac{1}{2}\frac{e}{C}(2n+1)$

$I = V/R$

$= \frac{2n+1}{2}\frac{e}{C}\frac{1}{R_J}$

"blockade"

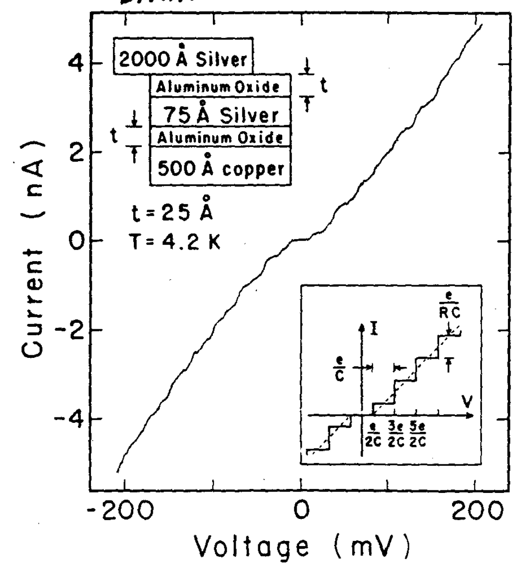
n	E	V ($e/2C$)	I		
0	$\frac{1}{2}\, e^2/C$		$\frac{1}{2}$	e/C	$1/R_J$
1	$\frac{3}{2}\, e^2/C$		$\frac{3}{2}$	e/C	$1/R_J$
2	$\frac{5}{2}\, e^2/C$		$\frac{5}{2}$	e/C	$1/R_J$
3	$\frac{7}{2}\, e^2/C$		$\frac{7}{2}$	e/C	$1/R_J$
	⋮		⋮		

Theoretical Picture explained

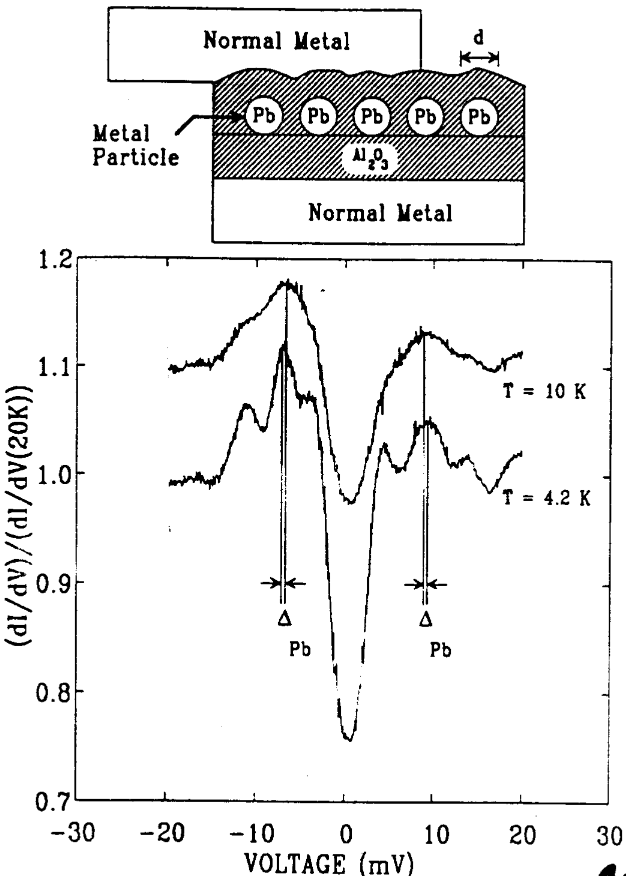
now for DATA!

Barner + Ruggierio

DATA:



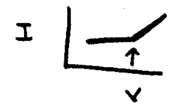
[redacted]



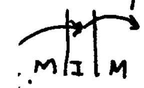
Barner + Ruggiero

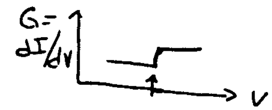
Inelastic Tunneling Processes

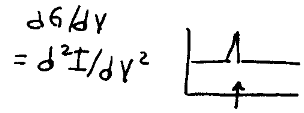
Jackelevic & Lamb : Organic impurities in barrier
Rowell et al : Phonons in oxide barriers
impurities in metal film adj. to barrier
Duke : barrier excitations as $V \to 0$
Hansma : Excellent book "Inelastic Electron Tunneling Spectroscopy" IETS
(This is a spectroscopy w/o selection rules)



Increase in slope of I-V
(New tunneling channel opened)







INELASTIC TUNNELING PROCESSES

EXAMPLES — NOT SC.

B = G

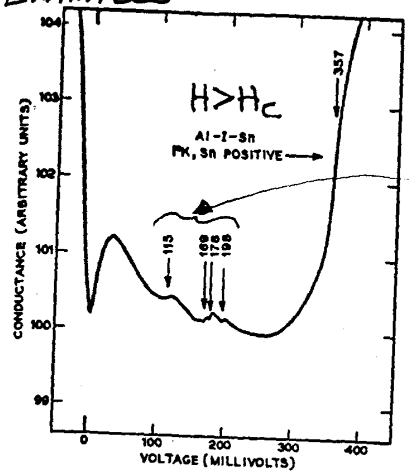


FIG. 3. Conductance versus voltage for an Al-*I*-Sn junction at 1°K with magnetic field applied to quench superconductivity.

phonons from organics in Laboratory atmosphere

A = $G = \frac{dI}{dV}$

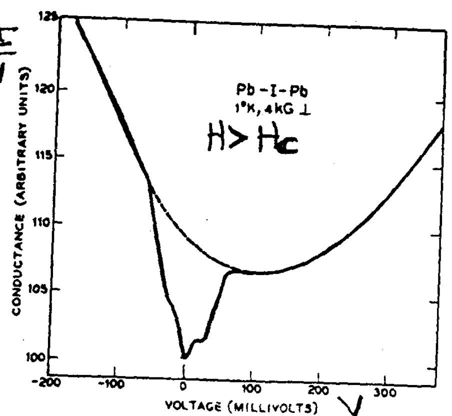


FIG. 4. Conductance versus voltage for a Pb-*I*-Pb junction at 1°K. A magnetic field was applied to produce the normal state.

← no SC

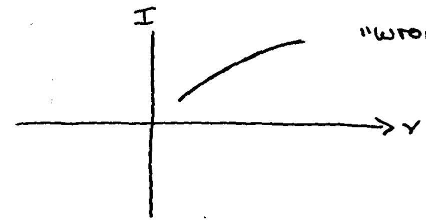
dip at ø bias due to Pb_xO_y Phonons in barrier. OR Pb surface states?

CHECK: THESE PHONONS SHIFT OUT IN V by the gap value when the temp is lowered to below the T_c of a counter Electrode

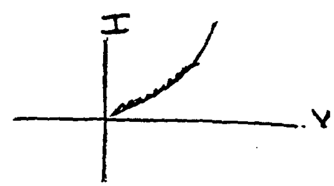
Non linear I-V with

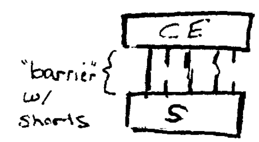
Junction Heating: "Pinholes" (R↗)

Critical current breakdown between grains in film



Burning-[redacted] shorts in "barrier" (R↘)

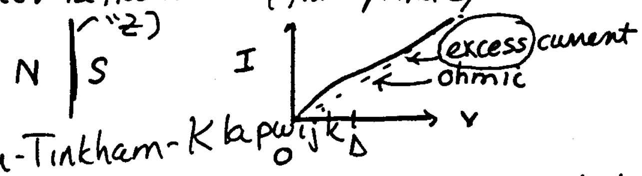




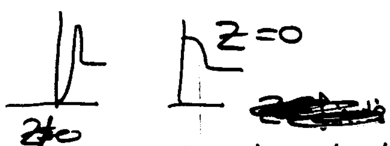
Excess Conductance at Zero Bias

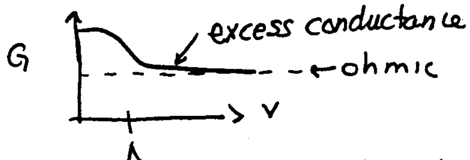
1. Josephson tunneling (shown earlier)

2. Andreev Reflections (from pinholes/shorts in barrier

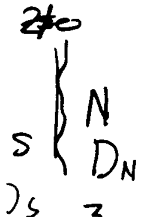


Blonder-Tinkham-Klapwijk





(recall coulomb blockade had current deficit
+ Single-step elastic tunneling is ohmic
above the gap.

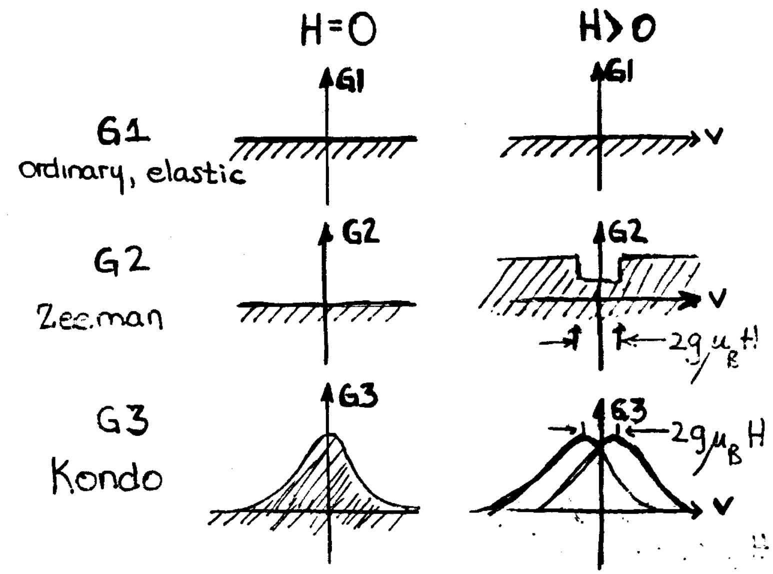


3 Magnetic impurities
- spin-flip scattering
- Kondo effect

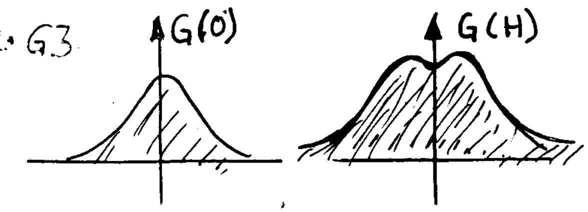
} in barrier

next V.G.

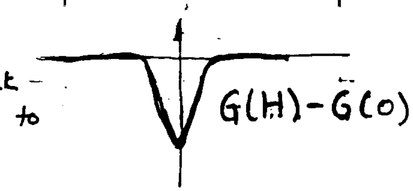
Anderson-Applebaum Model:



G = G1 + G2 + G3

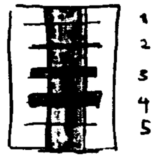


SUBTRACT B=0
to remove KONDO peak –
USUALLY not observed to
split with H ....



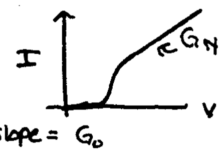
IMPORTANT CHECKS

① $R_{Jcn} \underset{\sim}{\propto} \frac{1}{Area}$
(~20%)



② Barrier resistance T-independent
(increase only a few % RT → 100K)
schottky, metal shorts

③ Zero-bias conductance well below Tc
↳ $G(0)_{T\to 0} \ll G_N$
much smaller than normal conductance



$G_0 \sim 10^{-3} G_N$

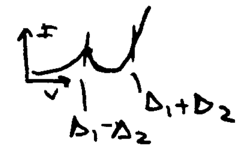
note: $\Delta \simeq 1.76 kT_c$ $\quad T_c(Sn) = 3.7K)$
$I_s \sim I_N\, e^{-\Delta/kT}$
$\sim 10^{-3}$ at 0.95 K
if one measures 10^{-2}, then
1% of current is not due to tunneling
Xtra current from metallic shorts
can give spurious results
in derivative

MUST SHOW I-V IN PUBLICATION
(not only derivative)

④ Junction resistance $\propto$ (Junction area)$^{-1}$

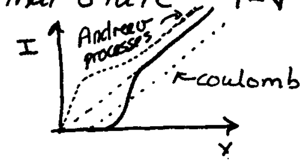
⑤ ● dissimelar sc's $\quad$ S | I | S'

$\Delta_1 - \Delta_2$ → SHARP cusp
well defined negative
resistance region



⑥ ● MUST USE sc counter-electrode
to establish sc tunneling exists
– inelastic peaks shift w/ Δ.

⑦ ● Normal-state I-V extrapolates to Ø.



⑧ ● Temperature dependence
– schottky, inelastic, coulomb .....

⑨ REPRODUCIBILITY ! MOST IMPORTANT

CHECKS FOR SUPERCONDUCTIVE TUNNELING

- $R_J \propto \frac{1}{Area}$
- $R_{barrier} \sim$ T-indep
- $G(0) \ll G_N$: SHOW I-V'S
- Superconducting Counter electrode
- $I\text{-}V|_{Normal\ state} \longrightarrow 0,0$
- Temp Dependence
- Reproducibility

→REQUIREMENTS←

(or I have a bridge to sell to you)