

Early Days of Superconducting Electronics: 1950 to 1970

John M. Rowell

Arizona State University

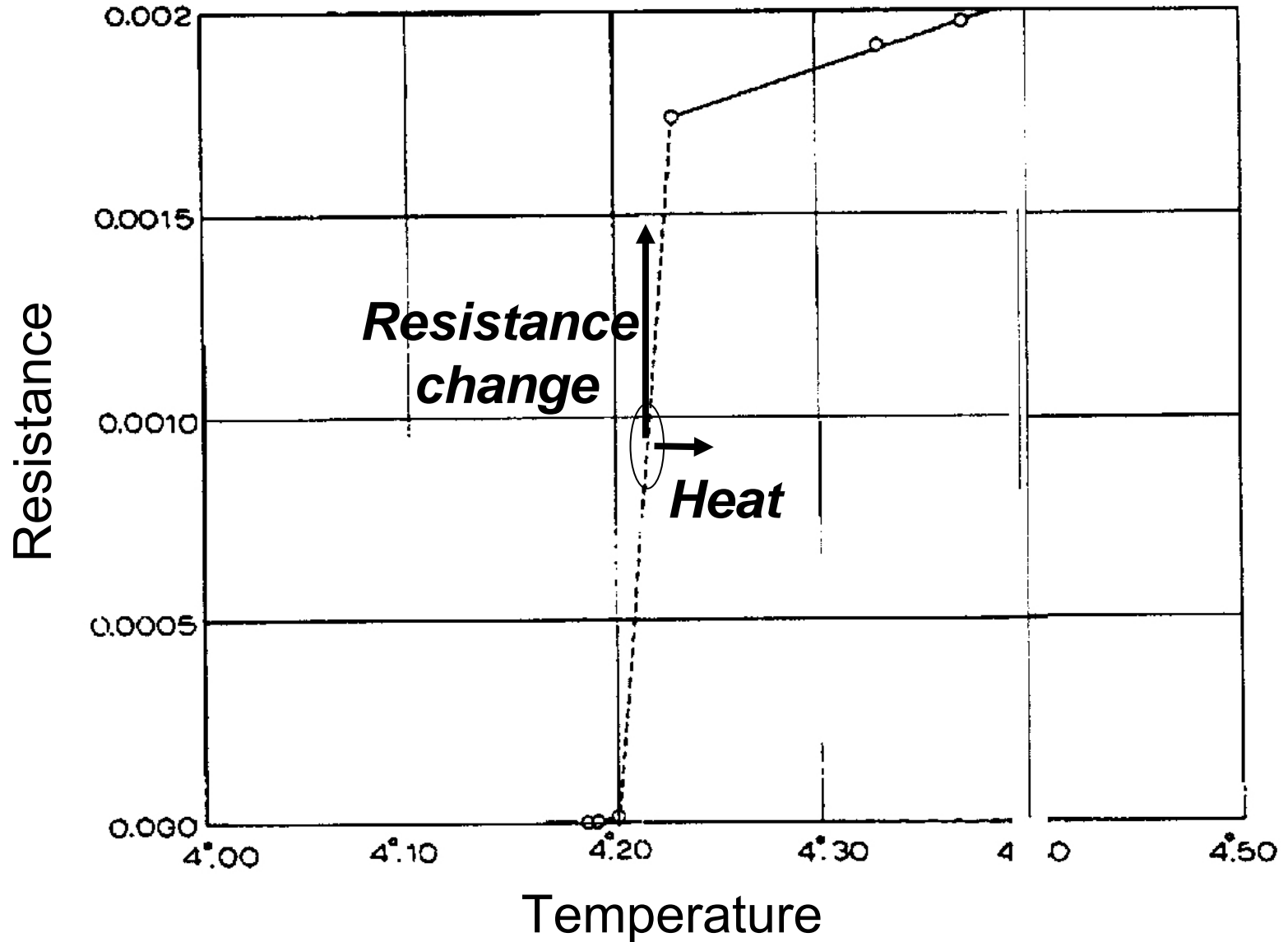
Bell Labs 1961-83

Outline

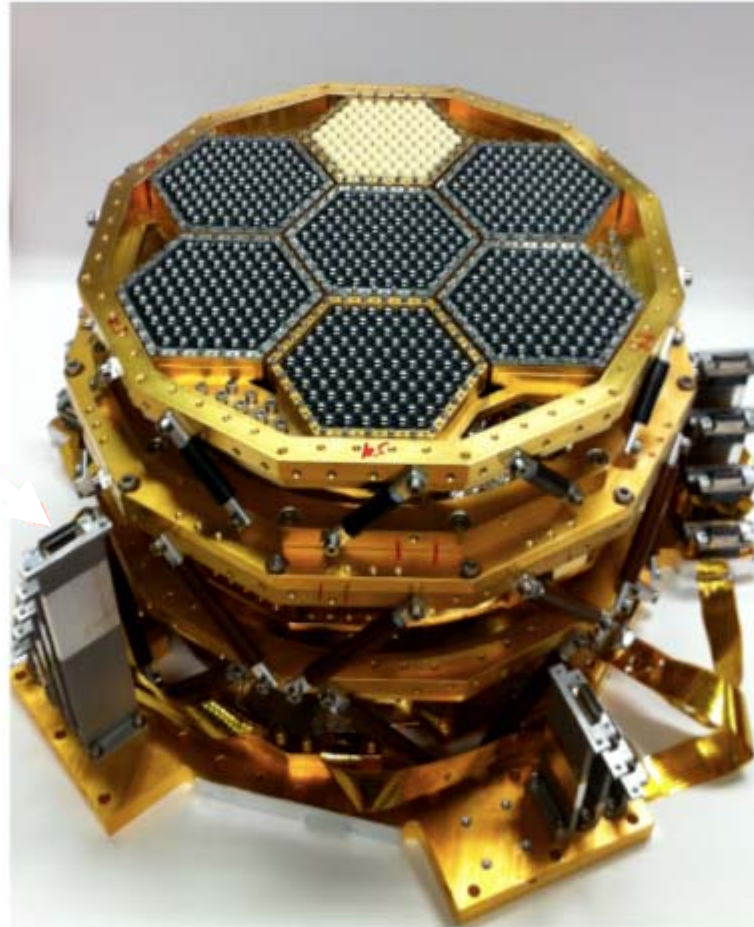
- **Bolometers**
- **Cryotrons**
- **BCS Theory**
- **Ivar Giaever - Tunneling**
- **Tunnel Junctions as detectors**
- **Tunneling Spectroscopy of “The Mechanism”**
- **Brian Josephson - Pair Tunneling**
- **Observations of Josephson’s Effects**
- **The First SQUID**
- **Weak Links**
- **Early Patents**
- **Digital Circuits**

Bolometer

D.H. Andrews et al. 1942

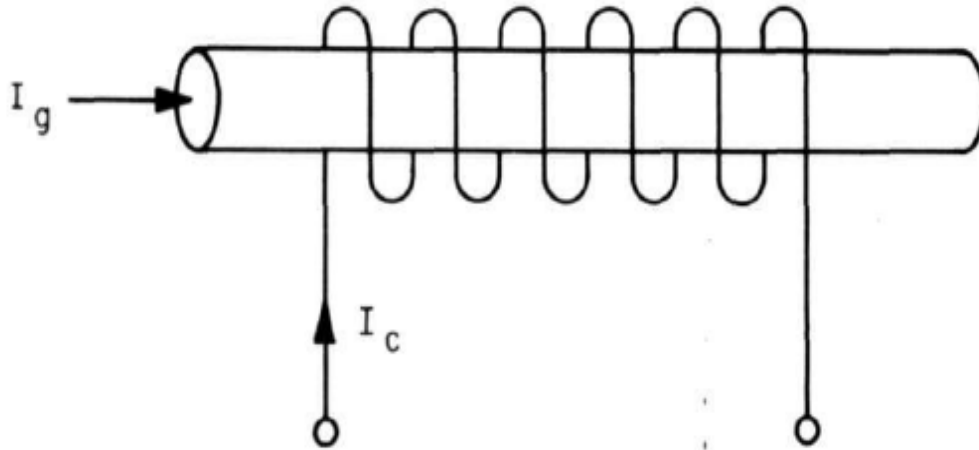


Focal plane assembly

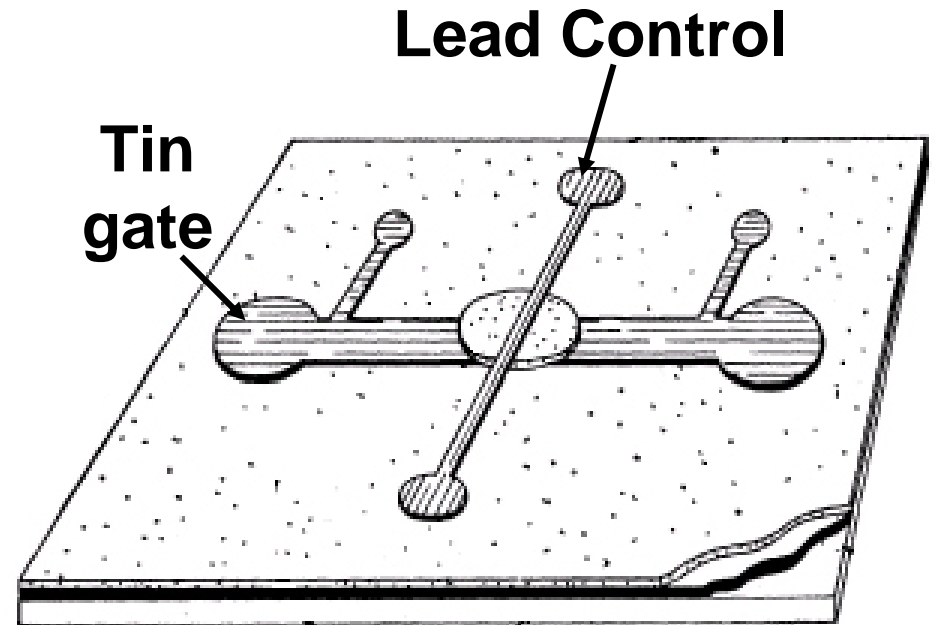


1300 Superconducting Bolometers

Cryotron



Dudley Buck, 1955

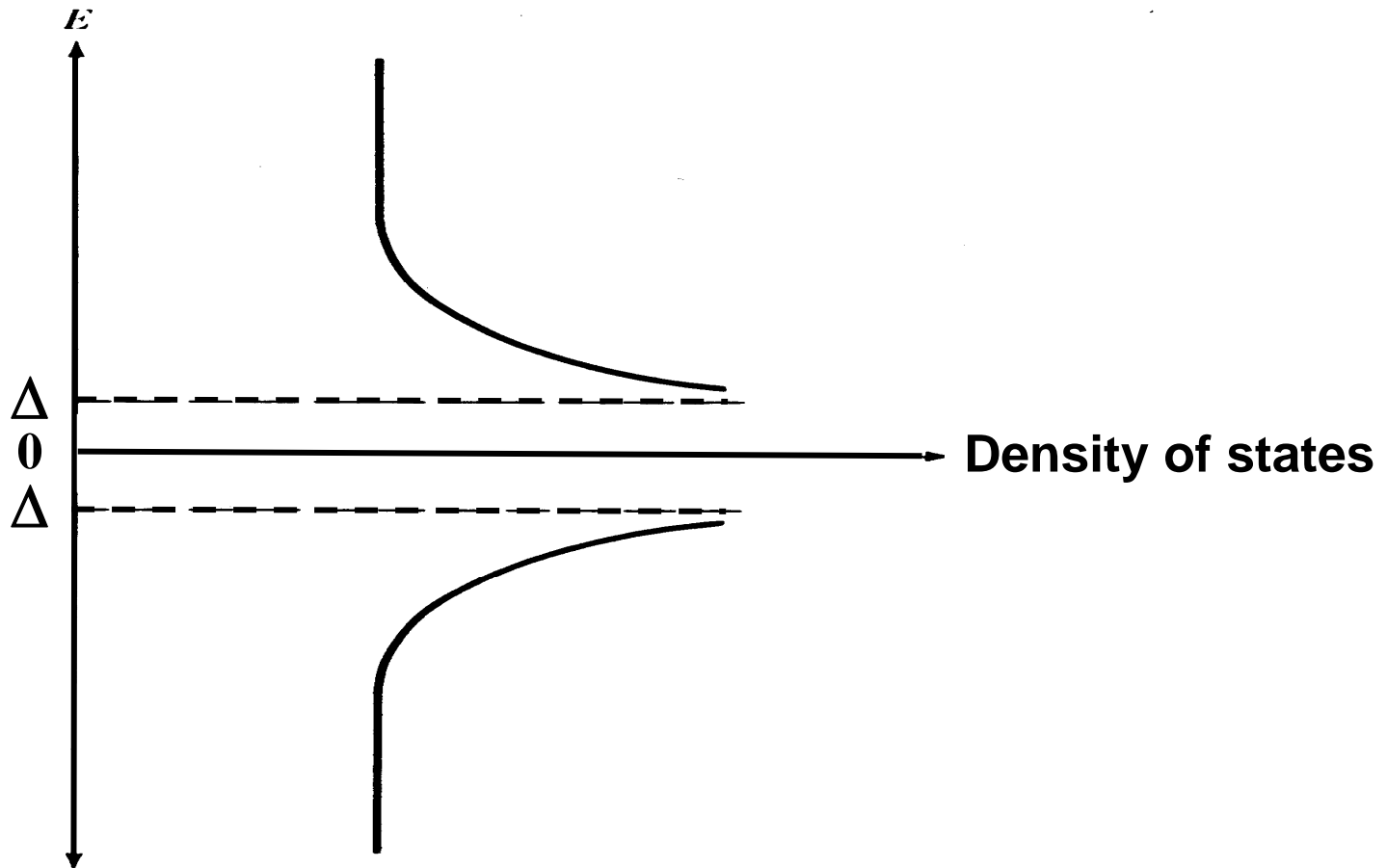


Slade, 1960

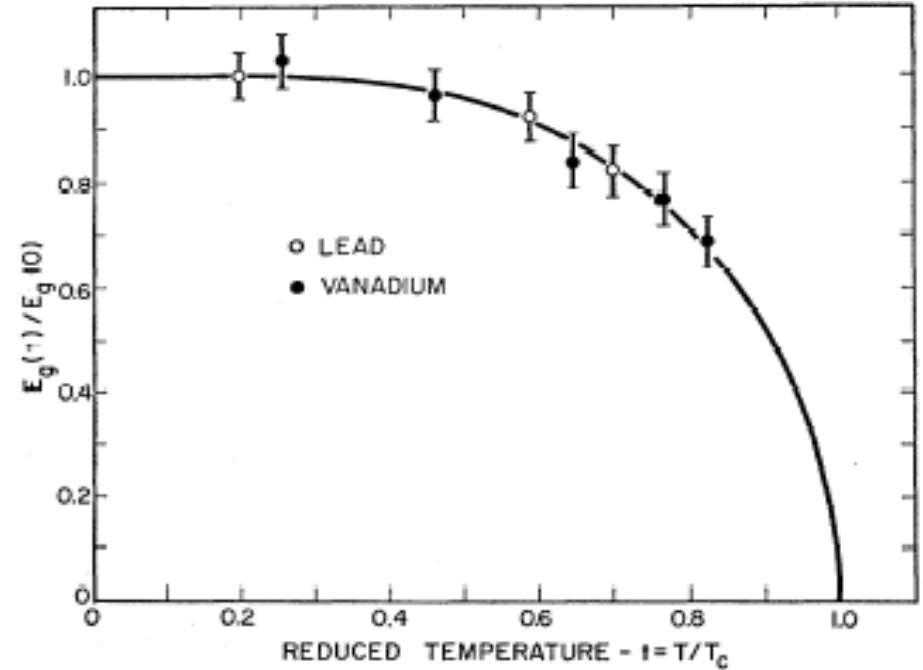
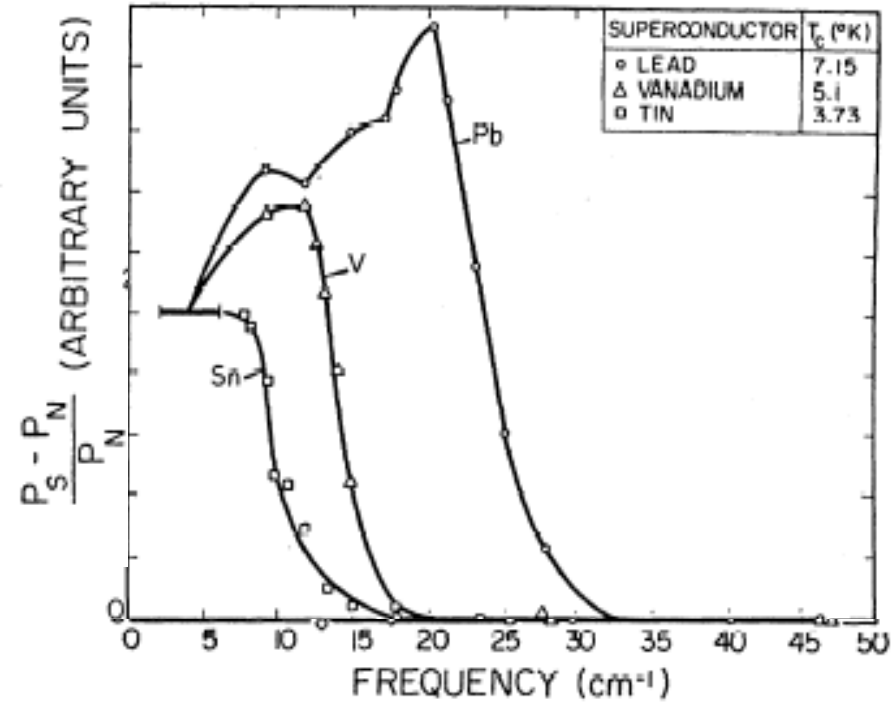
Bardeen, Cooper and Schrieffer, U. Illinois, 1957.

“There is an energy gap for individual-particle excitations which decreases from about $3.5 kT_c$ at $T=0K$ to zero at T_c .”

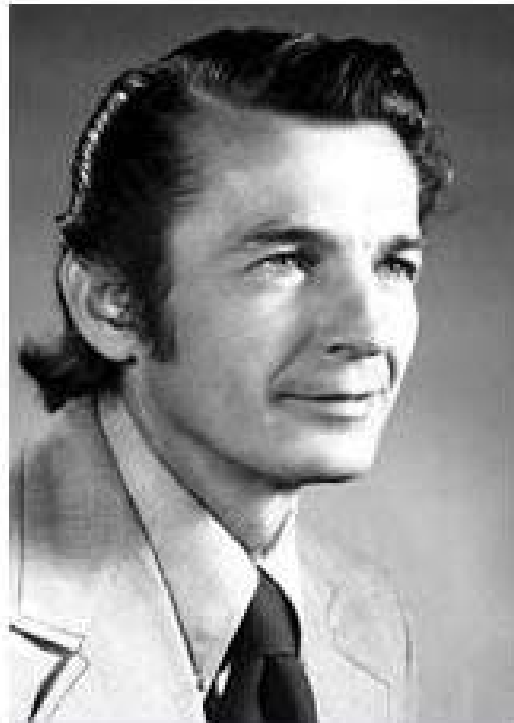
Bardeen, Cooper, and Schrieffer, U. Illinois, 1957.



Energy Gap by Far Infrared Measurements

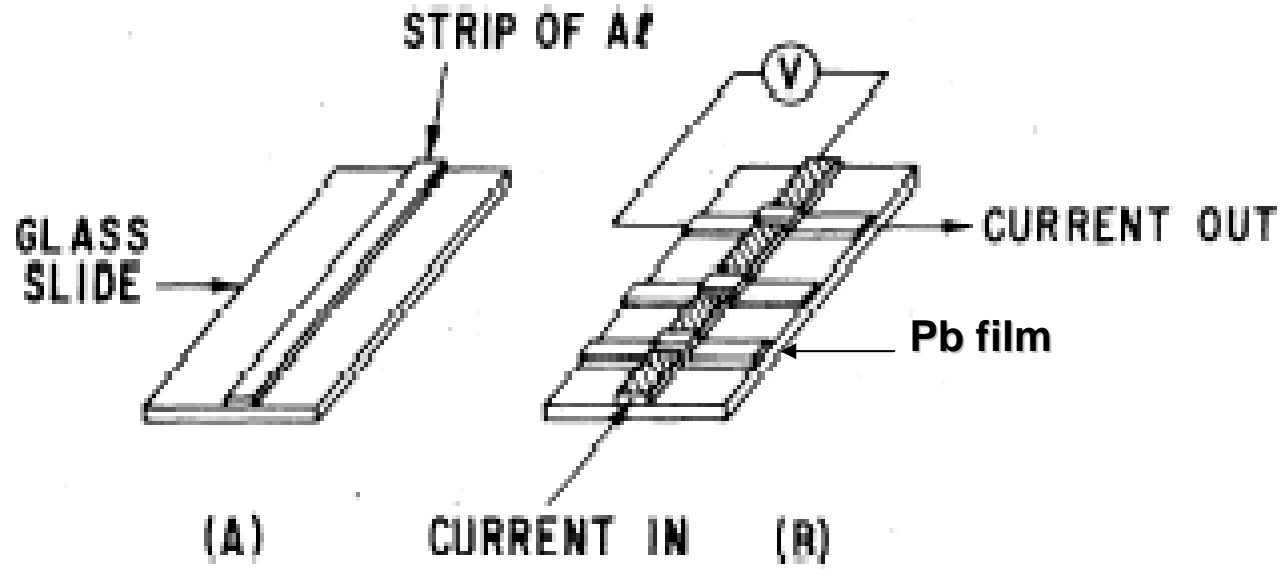
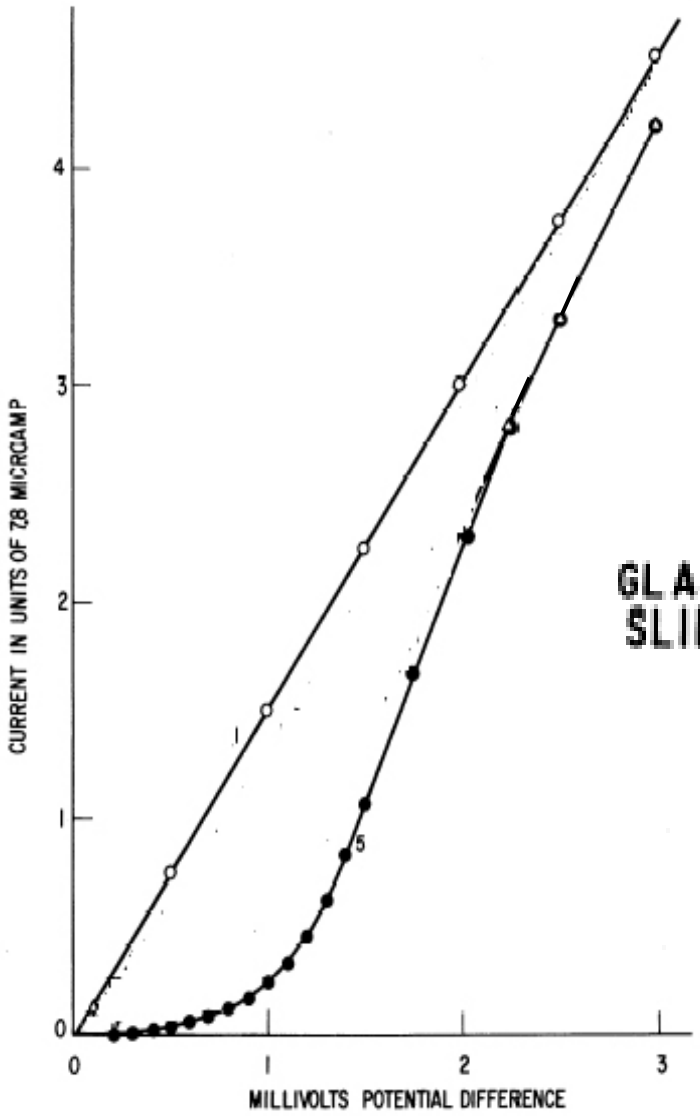


Glover, Richards, Ginsburg, and Tinkham, U.C. Berkeley, 1957-60



Ivar Giaever

Studying for his Ph.D. while working at GE

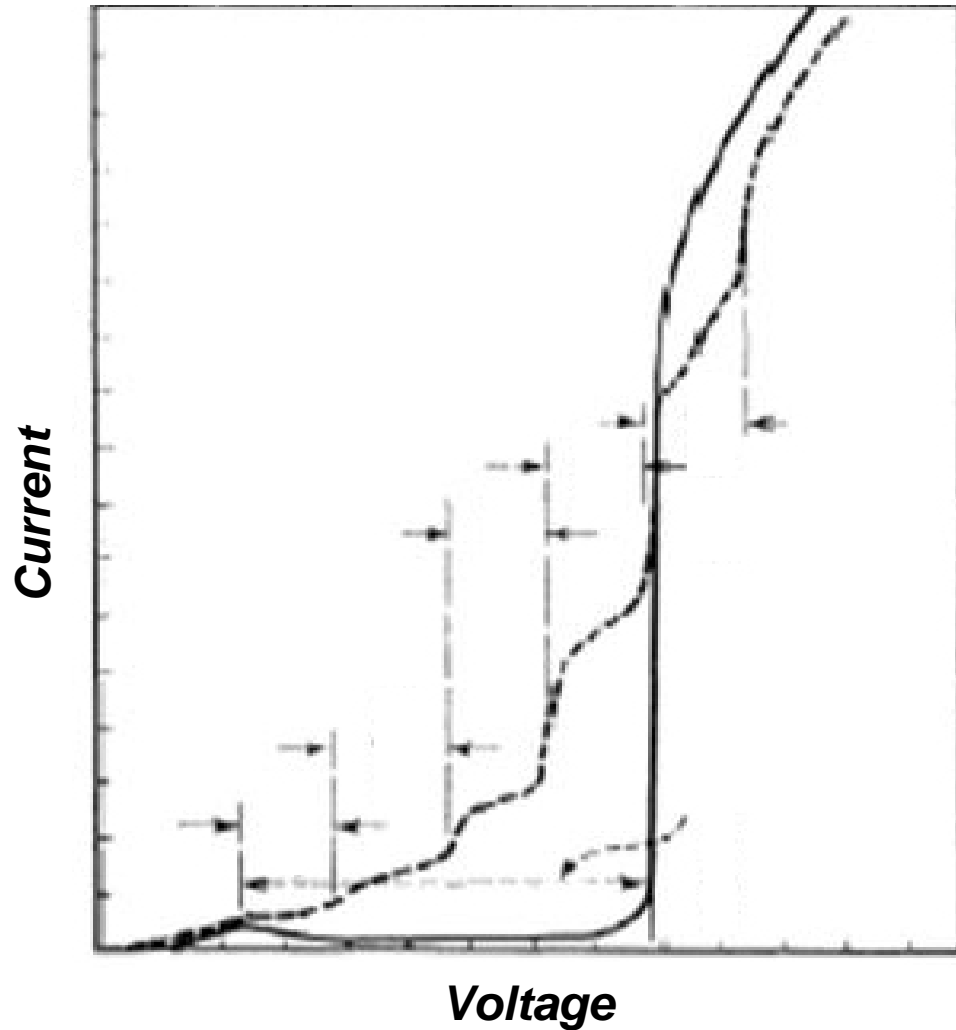


Current versus Voltage for an Al/ I /Pb junction

Giaever, General Electric, 1960.

“Suggest the M/B/S and S/B/S structures for quantum detection of microwave and submillimeter-wave radiation - - -.”

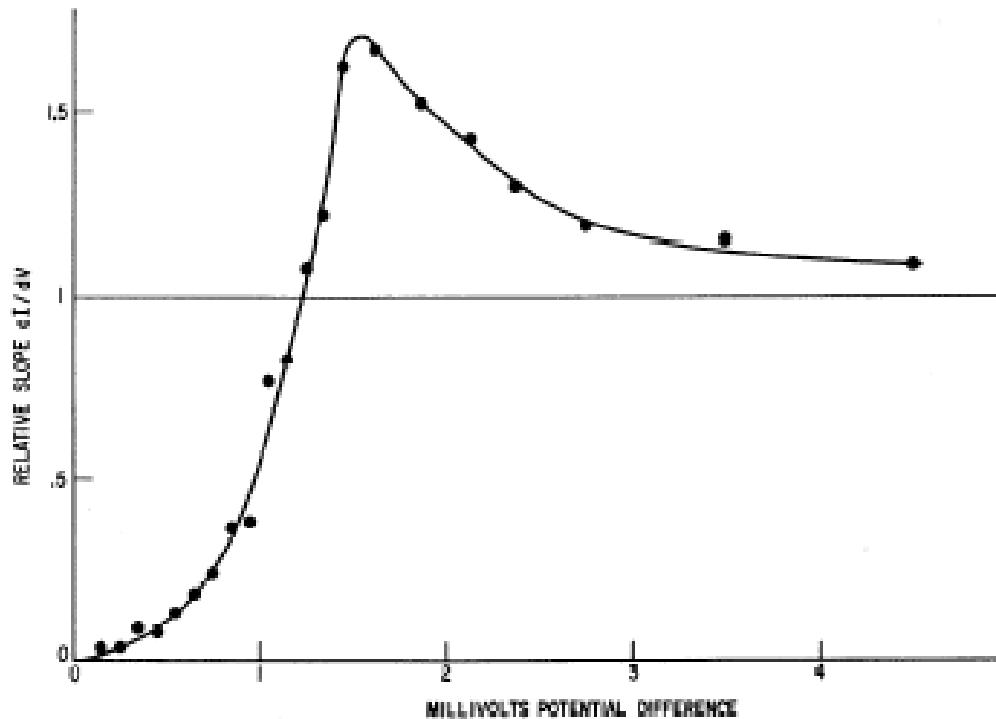
E. Burstein, D.N. Langenberg and B.N. Taylor, Univ. Pennsylvania, 1961.



Dayem and Martin, Bell Labs, 1962.



“On the naive picture that tunneling is proportional to density of states, this curve expresses the density of states in superconducting lead - - - -. The curve resembles the Bardeen-Cooper-Schrieffer density of states for quasi-particle excitations.”

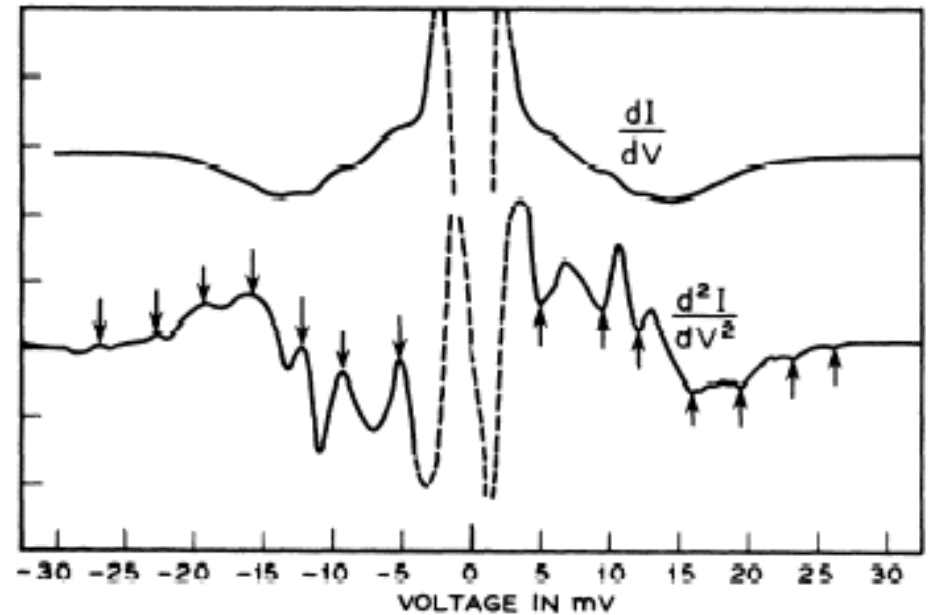
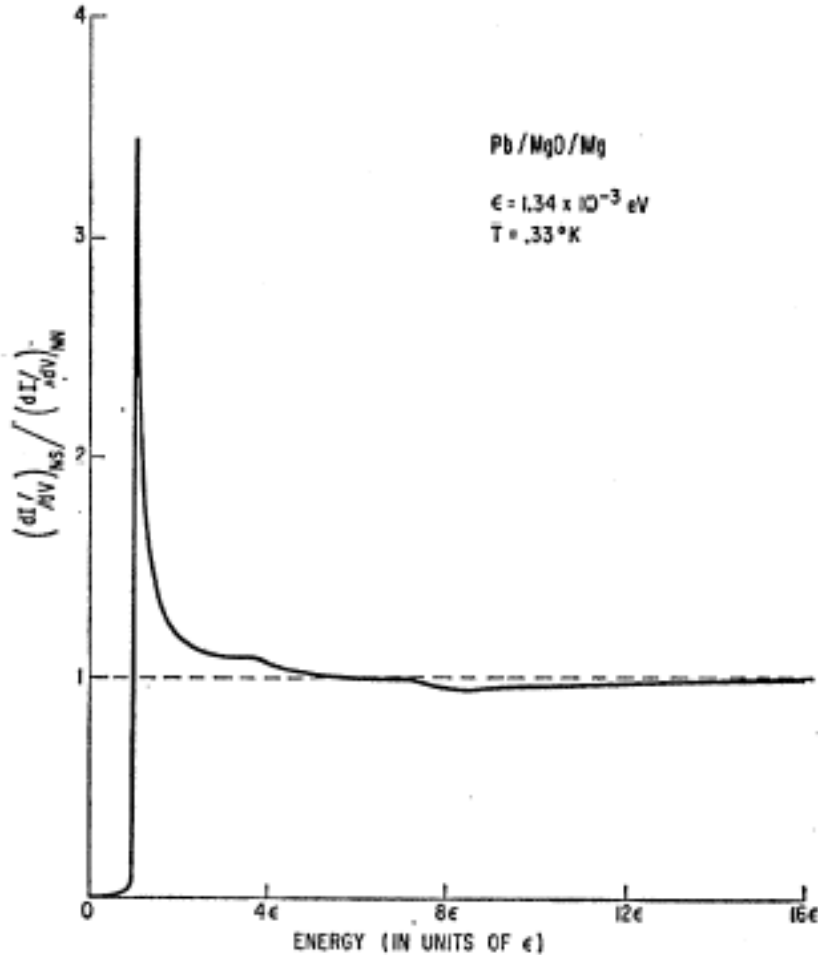


$$\frac{dI/dV \text{ with Pb superconducting}}{dI/dV \text{ with Pb normal}}$$

Giaever, General Electric, 1960.

“ At higher energies there are definite divergences from the BCS density of states ---. Note that the crossover point corresponds in energy to the Debye temperature ”

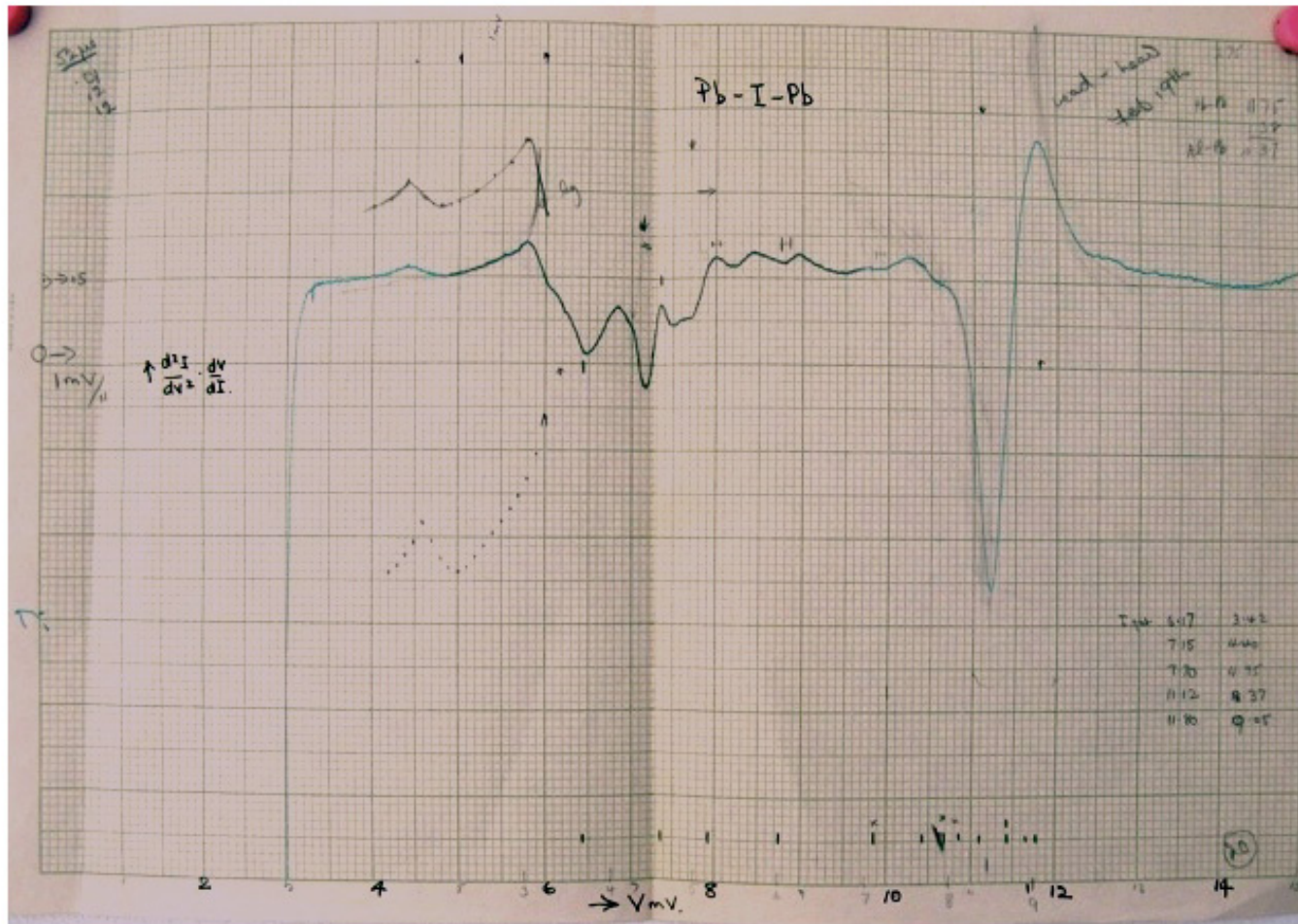
Giaever, Hart, and Megerle, General Electric, 1962.



Rowell, Chynoweth, Phillips, Bell Labs, 1962.

“ We have resolved the structure in detail and can assign much of it to specific Van Hove singularities expected from neutron measurements of the Pb phonon spectrum ”

Rowell, Anderson, and Thomas, Bell Labs, 1963.



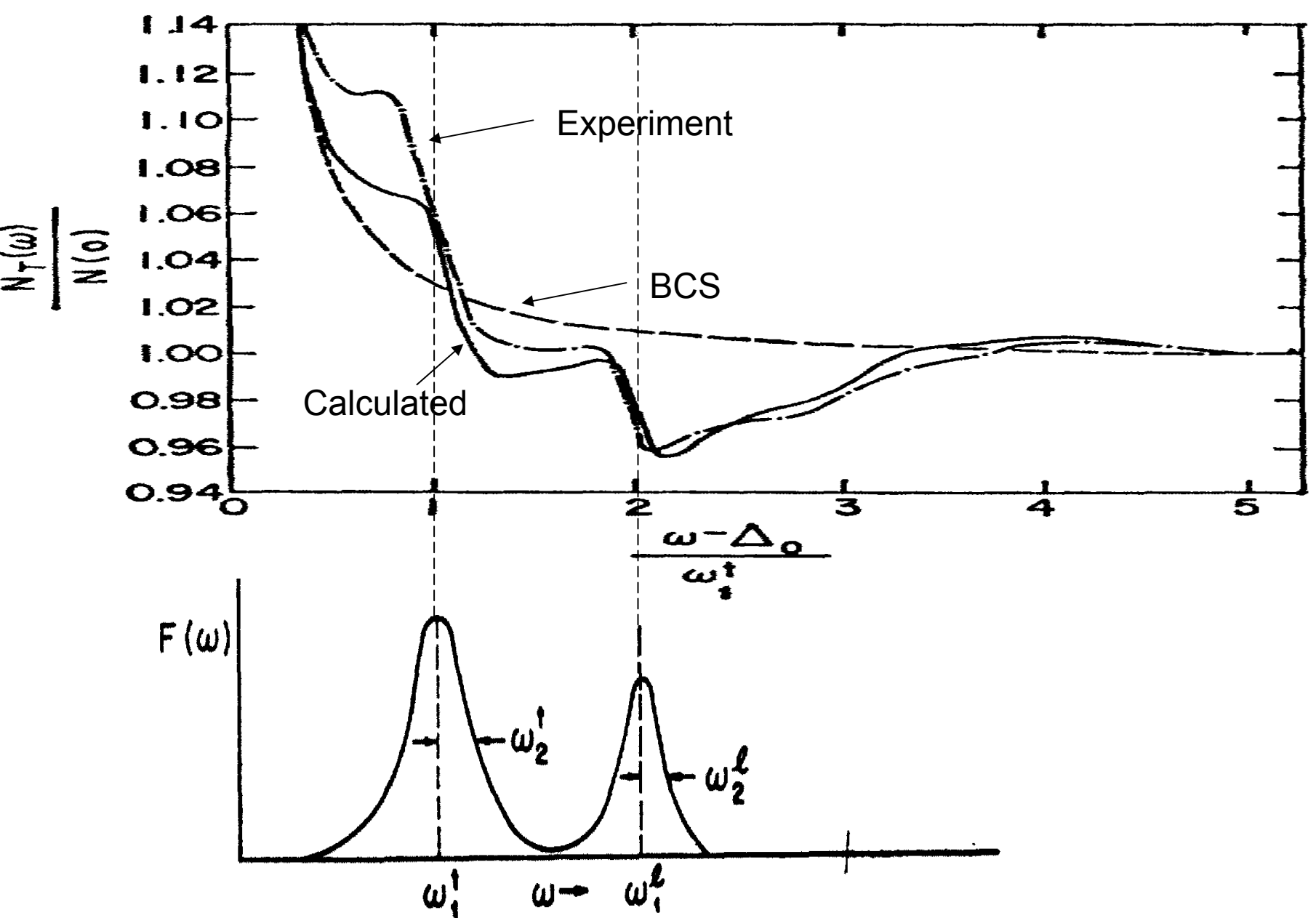
d^2I/dV^2 vs V (measured from 2Δ) for a Pb-Pb junction at 1.3K.

The “post BCS” theory of strong coupling superconductors evolved through the contributions of Bogoluibov (1958), Migdal (1958), Eliashberg (1960), Morel and Anderson (1962), Swihart (1962), and Schrieffer, Culler, and Huff, Scalapino and Wilkins (1962-3)

Tunneling into superconductors was described by Cohen, Falicov and Phillips (1962)

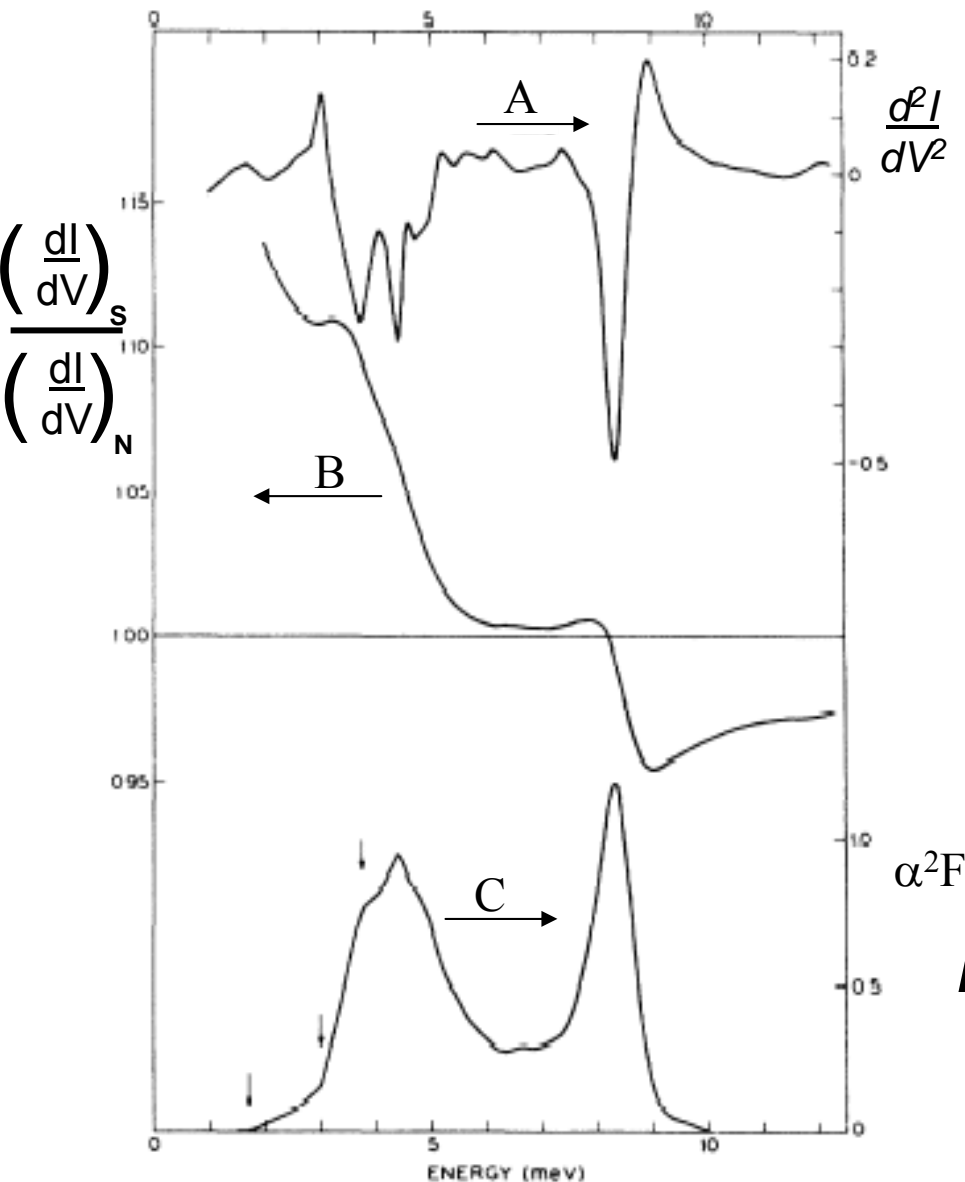
Scalapino, Schrieffer and Wilkins (1963) linked the tunneling density of states to the complex energy dependent gap parameter

$$\frac{N(w)}{N(0)} = \text{Re} \left\{ \frac{|w|}{[w^2 - \Delta^2(w)]^{1/2}} \right\}$$



Schrieffer, Scalapino, Wilkins, University of Pennsylvania, 1963.
Rowell, Anderson, Thomas, Bell Labs, 1963.

The Pairing Mechanism



The tunneling experiment is unique in probing the dynamical structure of the superconducting state and has provided a confirmation of the correctness of the strong coupling theory.”

McMillan, London Prize lecture, 1978.

McMillan and Rowell, Bell Labs, 1964.



Research student, Cambridge University, aged 22 in 1962

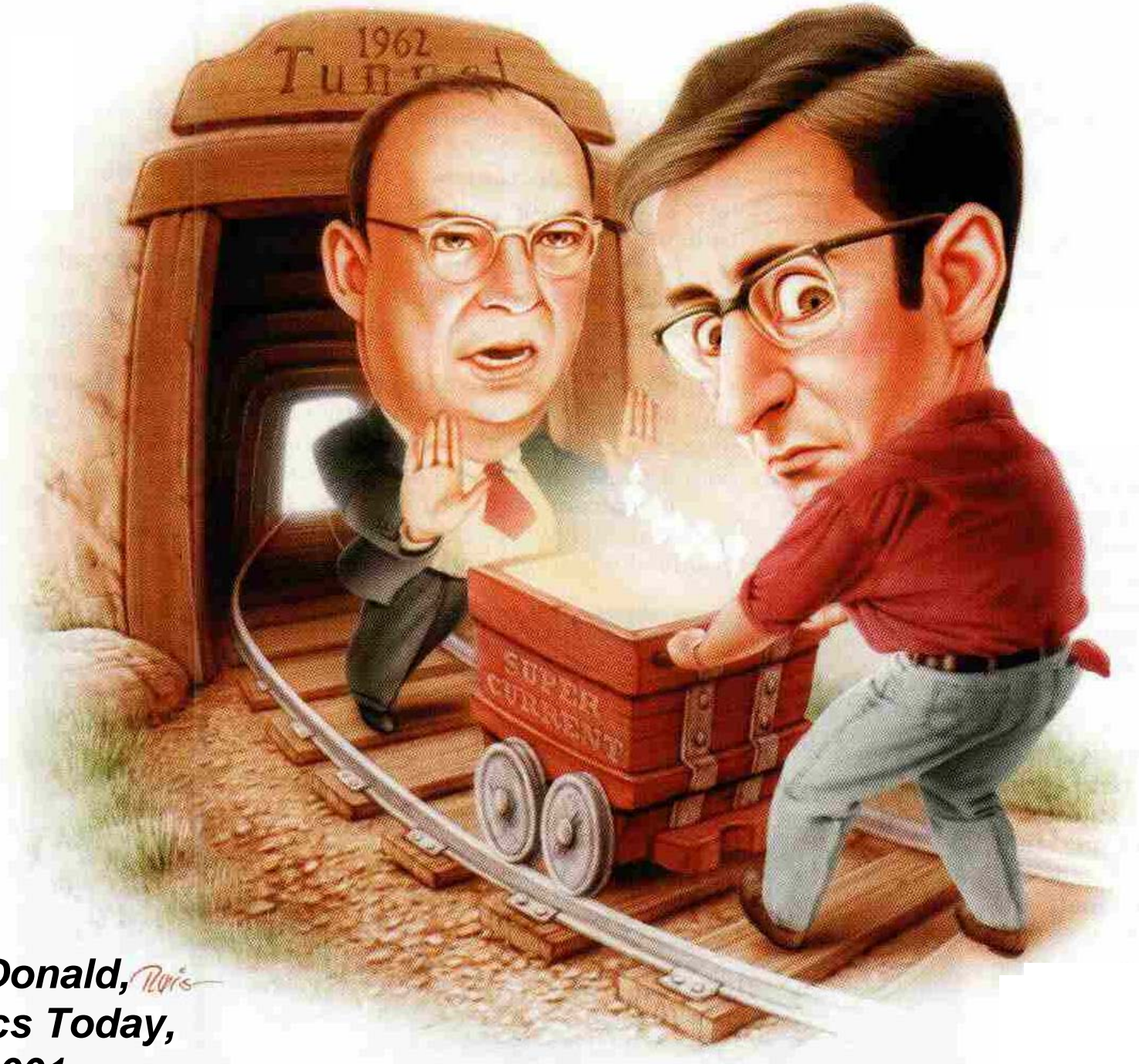
“New effects are predicted, due to the possibility that electron pairs may tunnel through the barrier.

Our theory predicts that:

i) At zero voltage, a DC supercurrent up to a maximum value can occur

ii) At finite voltages there is an AC supercurrent of frequency $2eV/\hbar$ ”

B.D. Josephson, Cambridge, 1962.



McDonald, *Paris*
Physics Today,
2001.

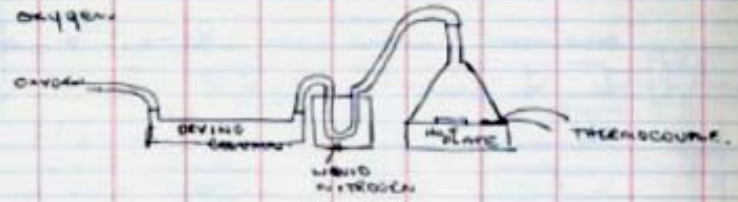
“You could hardly find two people whose minds worked on more different lines than Brian Josephson and myself, so that I was never able to understand what he was talking about.”

Pippard, Cambridge, 1966.

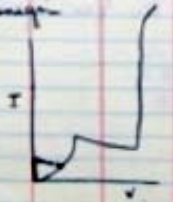
January 21, 1963

Jan 21st

Due to wide variations (starts to capacitor) of
 μ - μ in oxide-lead sandwiches made by exposure
 to air for a few days we will try testing
 μ in films (2,000 Å) thick were evaporated
 on a sapphire substrate at a temperature
 of 3mV on chromel-chromel thermocouple attached
 to the cooled block supporting the sapphire. The
 slides were taken from the evaporator & placed
 on a hot plate at 50°C in a stream of
 dry oxygen.



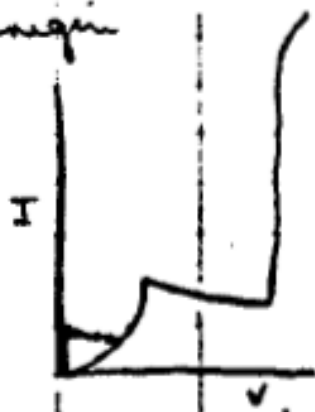
As shown in the notebook of Jan Kopf (notebook 37566)
 the slides were exposed for 7 & 15 minutes, replaced
 in the evaporator and a crossing lead films (2,000 Å)
 evaporated. The usual marks were used with pattern
 areas 1.5×10^{-4} , 1.35×10^{-3} , 2.1×10^{-3} , 1.35×10^{-2} , 8.5×10^{-4} sq mm
 looked at with IT in helium, all good but
 low resistance (<1Ω) to show peculiar low resistance
 at the origin. To be magnet is horizontal



brought up outside the device
 destroys the effect. Failed to
 burn out by going up
 to 300 mV but characteristic

not active.

hooked at unit 17 in selenium, all good but
low resistance ($< 1 \Omega$) at the origin

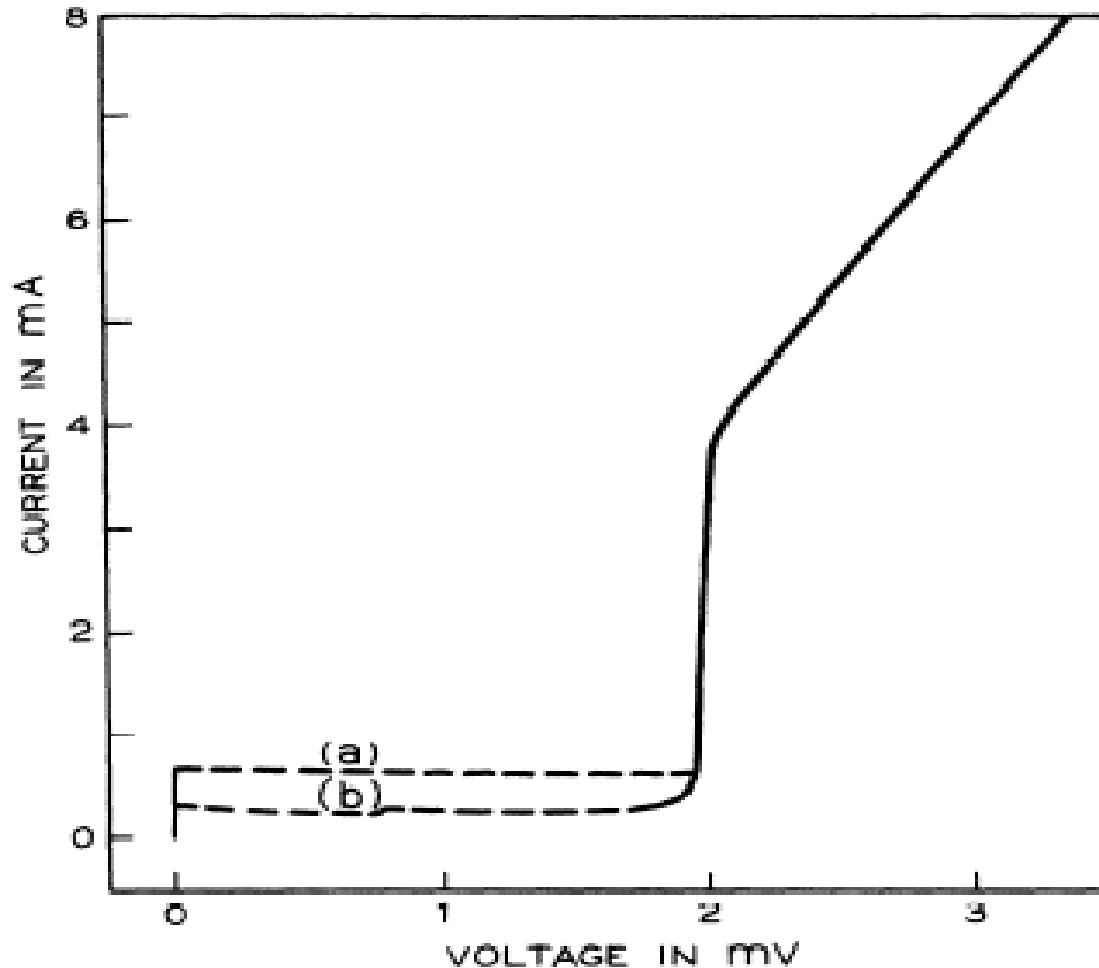


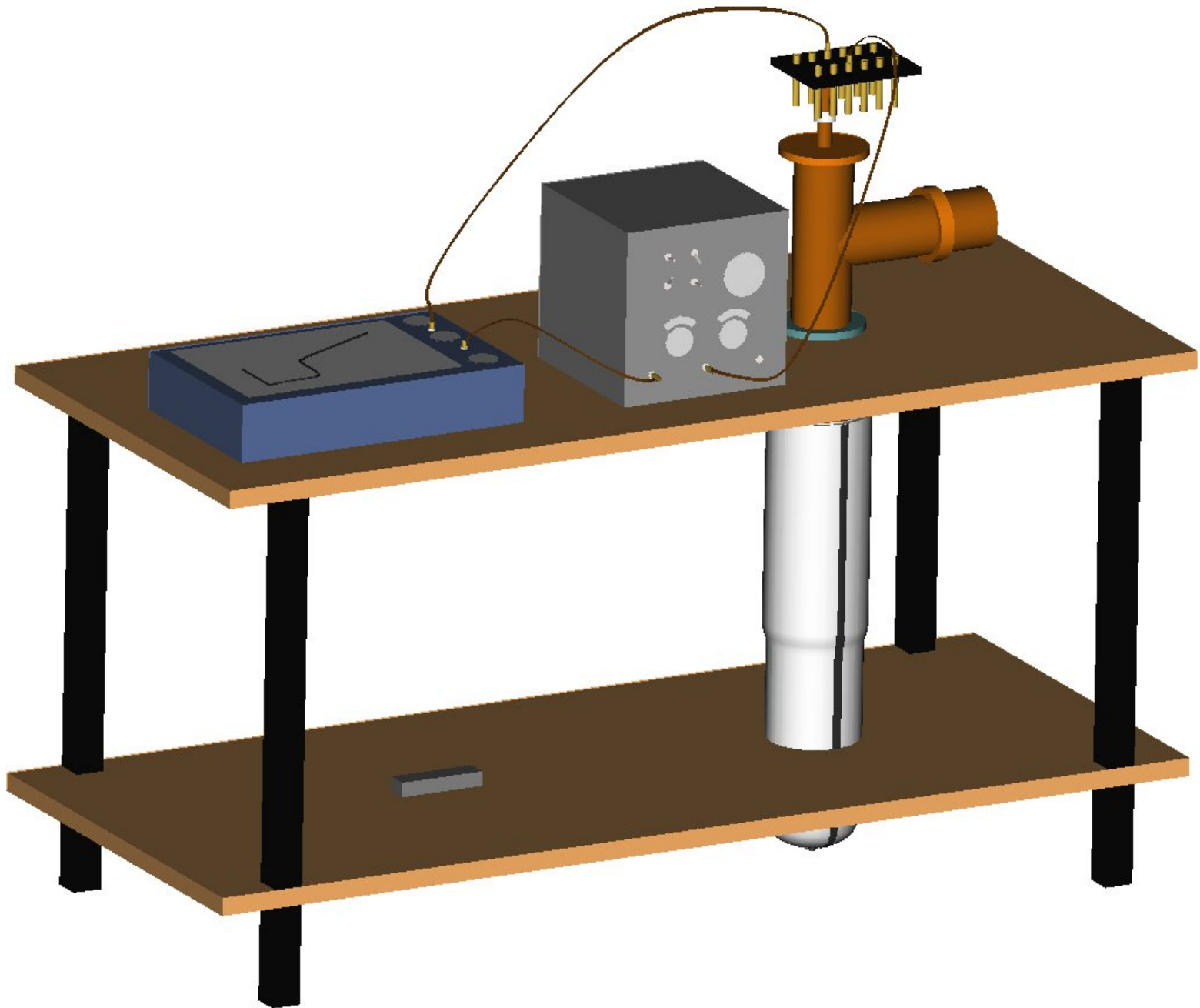
mV. altered.

All show peculiar low resistance
A bar magnet or horseshoe
brought up outside the dewar
destroys the effect. Tried to
burn out by going up
to 300 mV but characteristic

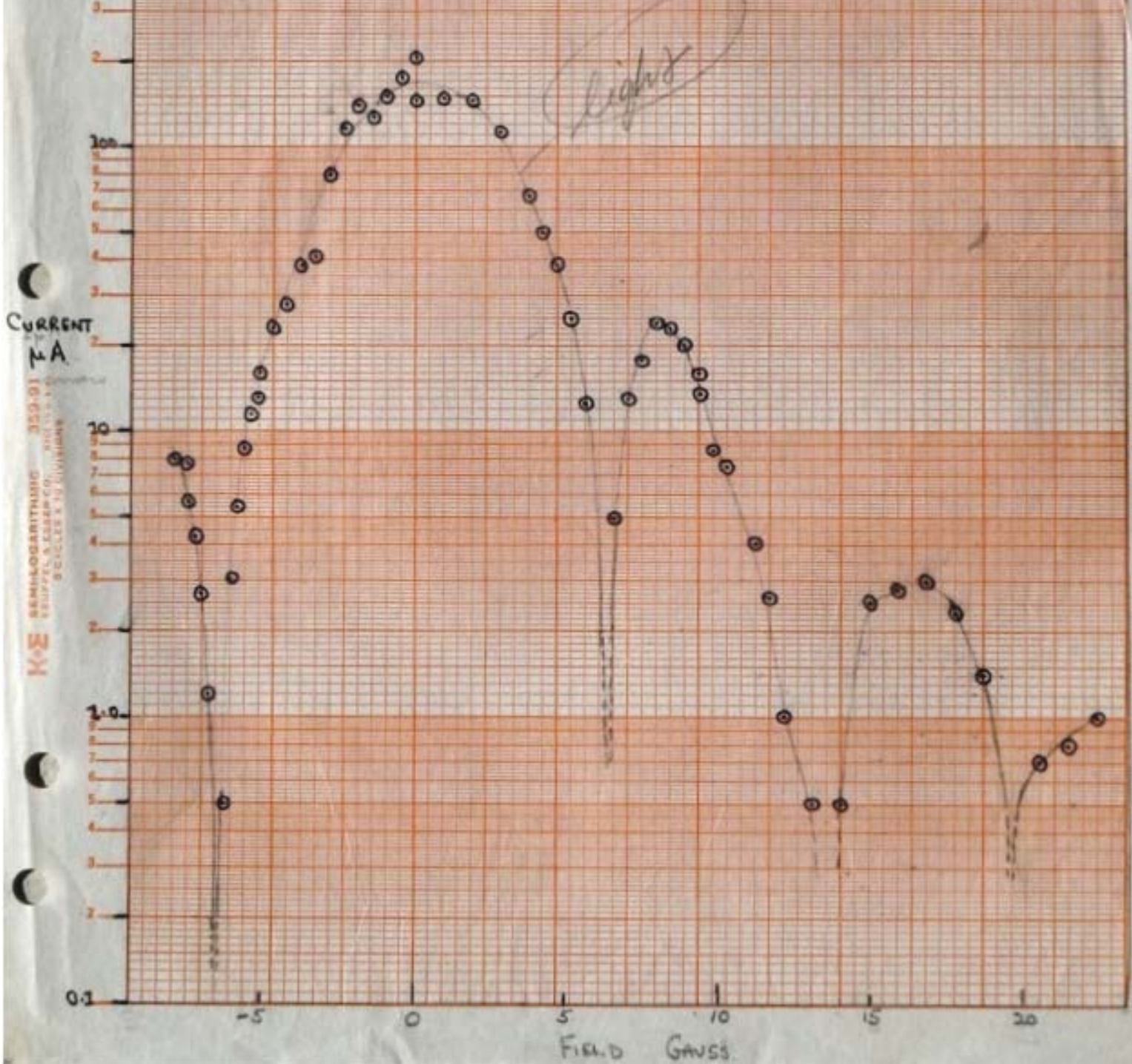
“We have observed an anomalous dc tunneling current at or near zero voltage in very thin tin oxide barriers between superconducting Sn and Pb, which we cannot ascribe to superconducting leakage paths across the barrier - - -”

Anderson and Rowell, Bell Labs, 1963.

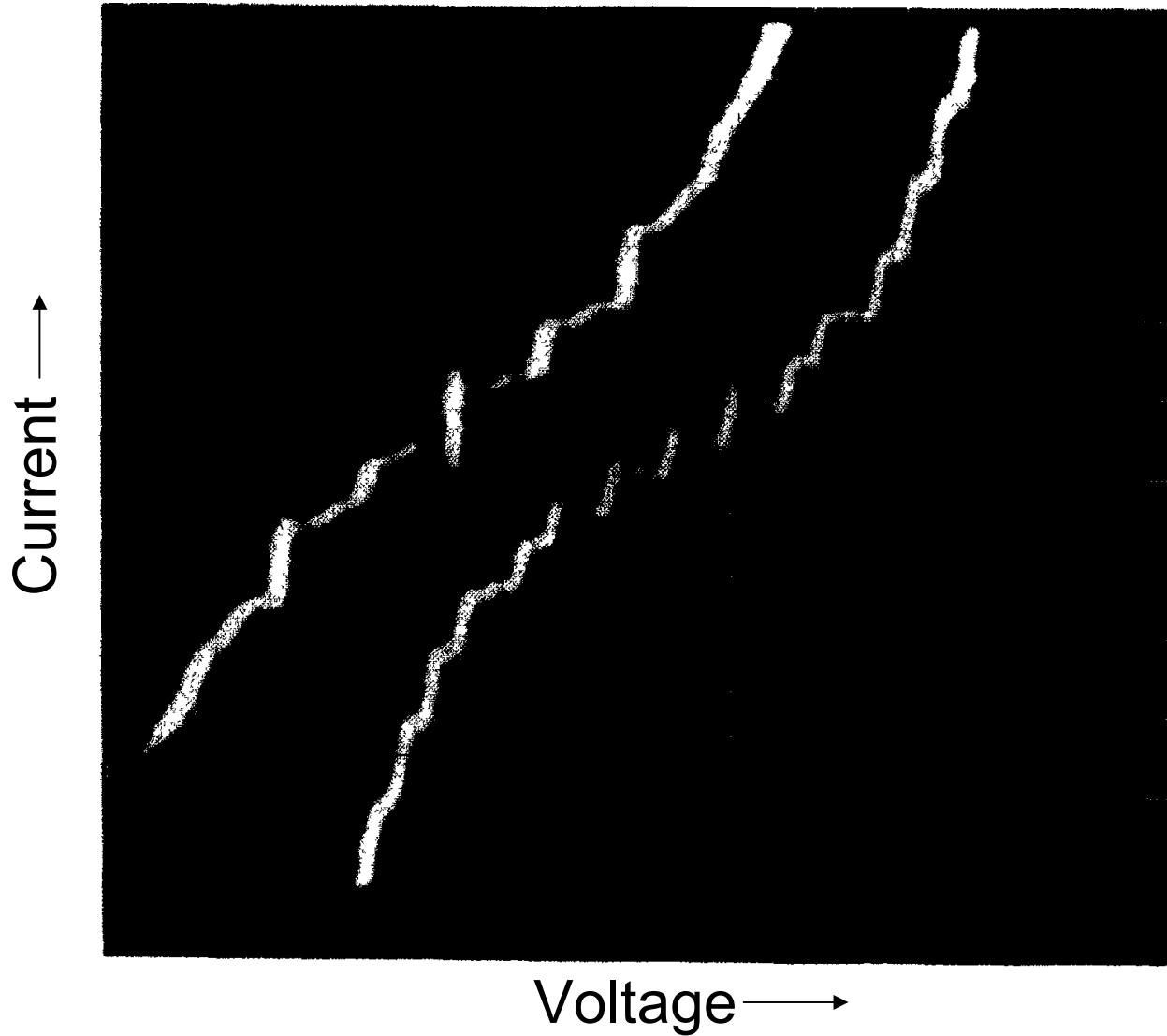








“Microwave steps” in I-V of Josephson junction

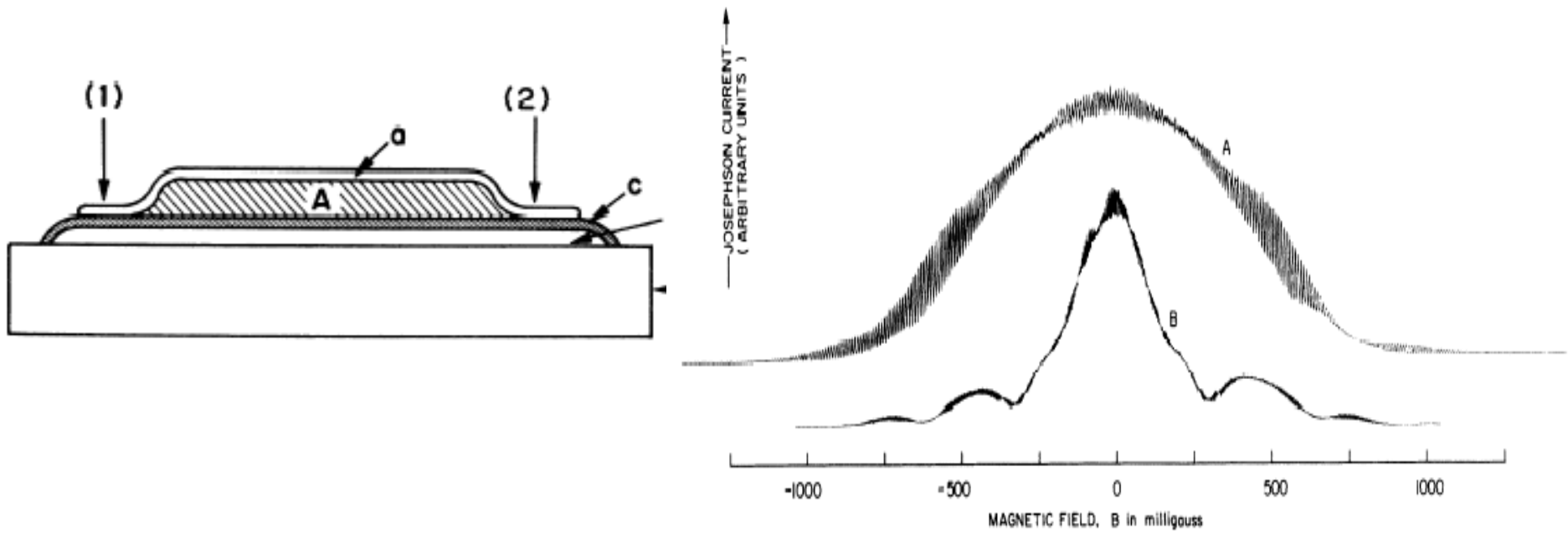


Shapiro, Arthur D. Little, 1963.

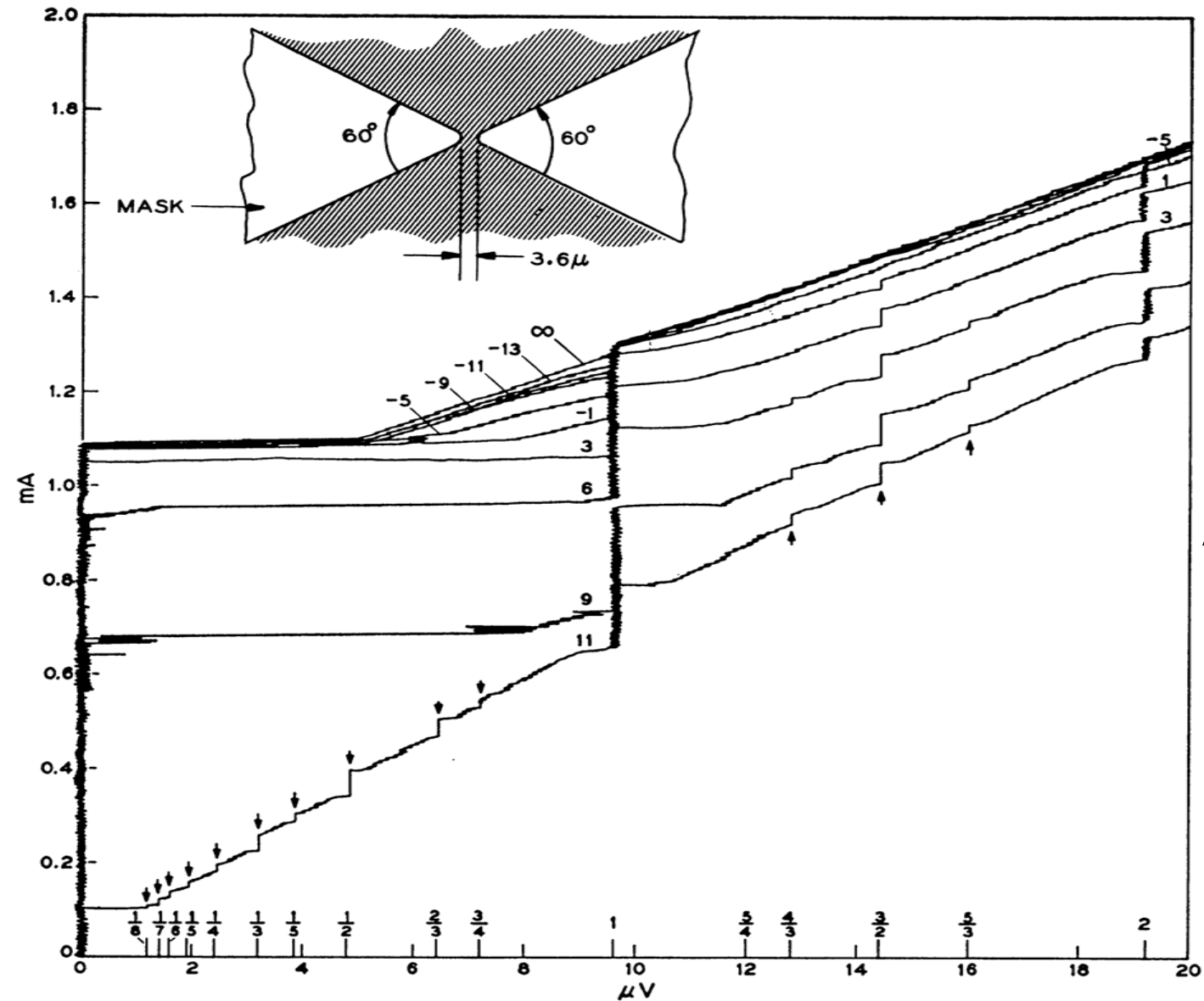
W. H. Parker, B. N. Taylor and D. N. Langenberg (Univ. of Pennsylvania) showed in 1967 that this observation of the AC Josephson Effect allowed the Standard Volt to be defined as a frequency

“This second period involves a quantum mechanical interference between the currents flowing through separate junctions in direct analogy with double-slit electron beam interference effects ”

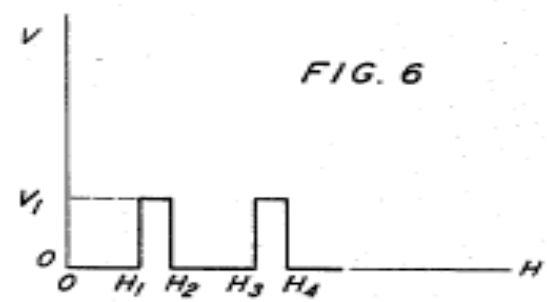
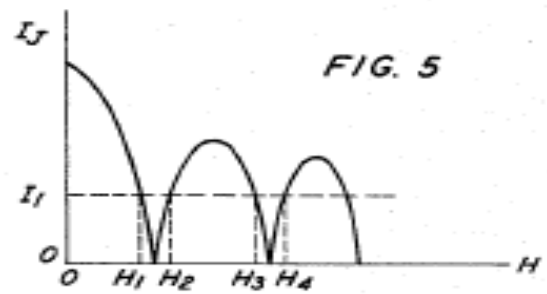
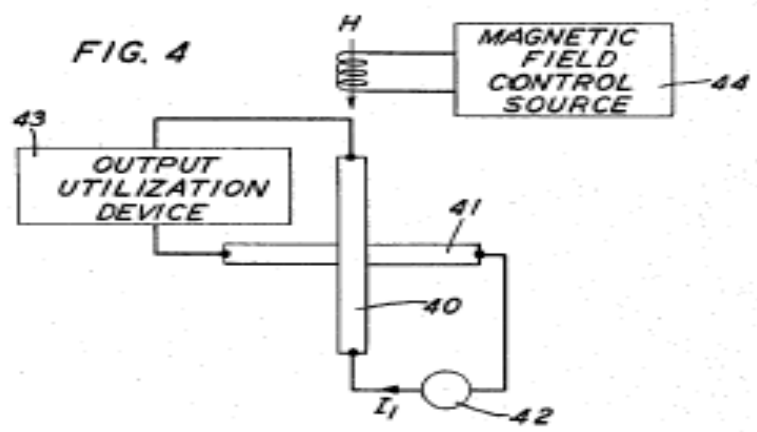
Jaklevic, Lambe, Silver, and Mercereau, Ford Lab, 1964.



Josephson Effect in Weak Links



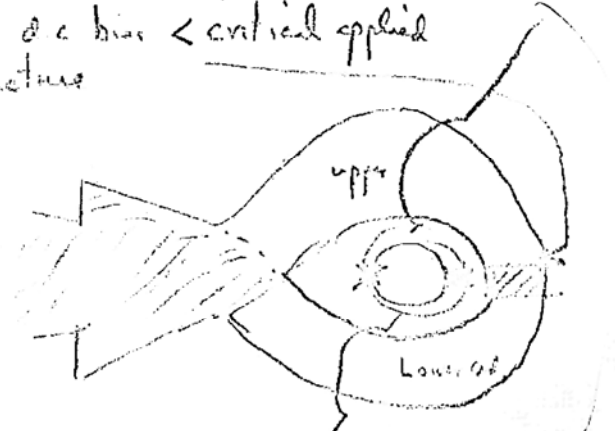
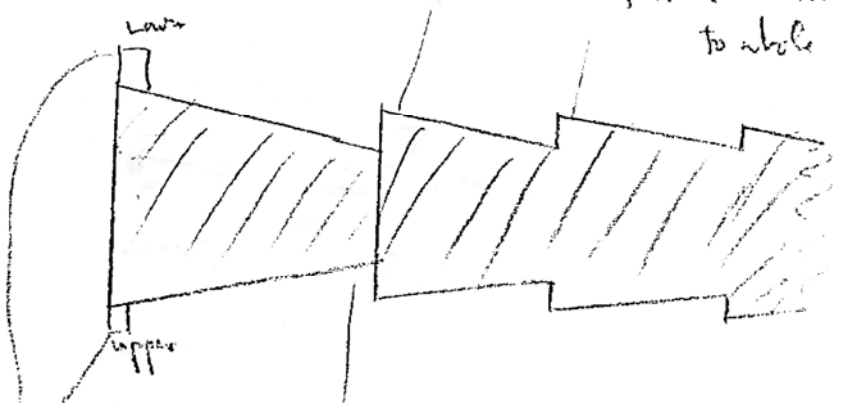
Anderson & Dayem,
Bell Labs, 1964



Can this page be such a sketch by Phil Anderson
 of a long Josephson junction of such a shape that
 it will move flux as a storage register.
 Peter Wolff

says Ali Dayer will do
 if one of you guys will. P

Steady r.f. current + d.c. bias < critical applied
 to whole structure



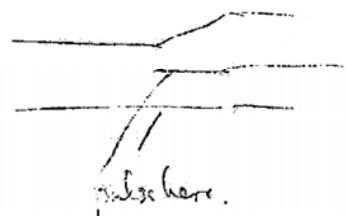
pulses in
 essentially pulse
 ($n > 1$ fluxon)

comparable
 I_p
 width to λ_J
 section about larger
 than λ_J .

/// very low r.
 /// low resistance tunnel junction
 X high " " "

reading loops: I_c
 dep. on vertex
 or not.

Can fork by



J.M. Lowell
 Sept 8 1970.

100?

On this page is such a sketch by Phil Anderson
of a long Josephson junction of such a shape that
it will move flux as a storage register.

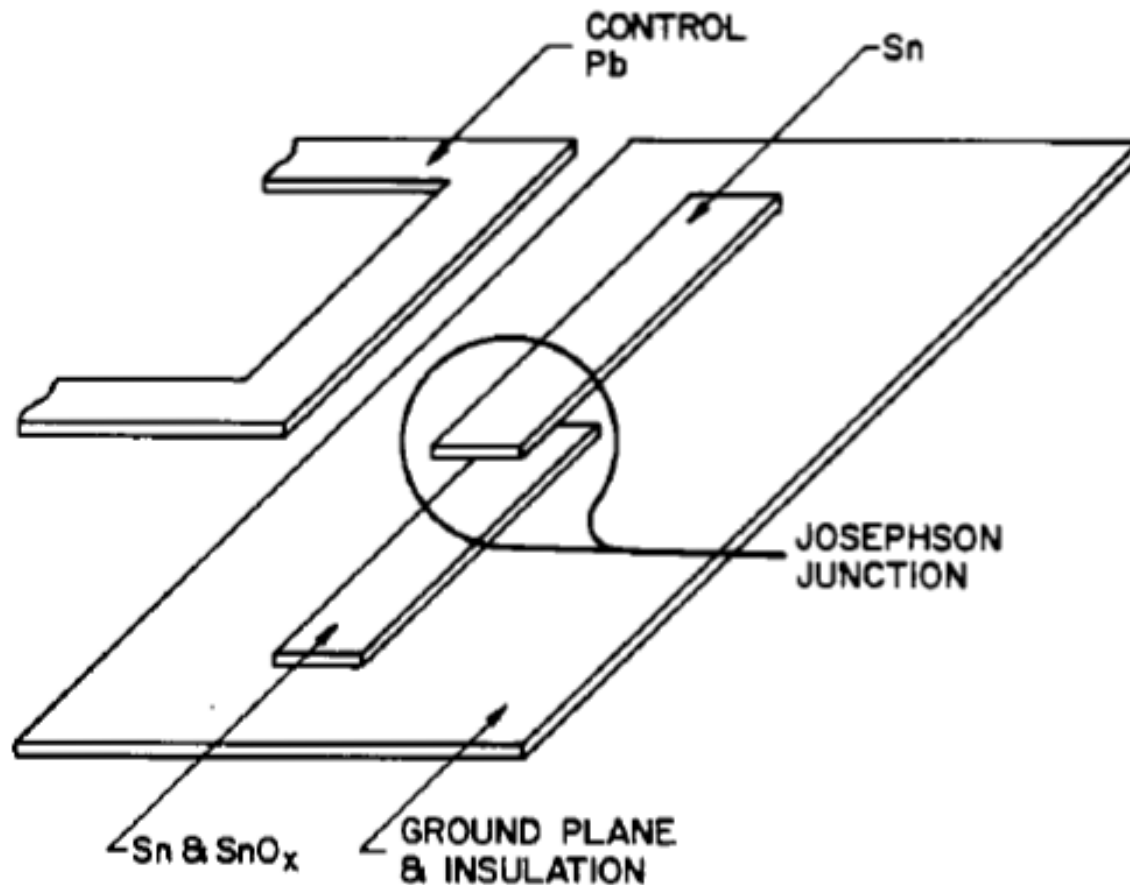
Peter Wolff

says Ali Dayem will do

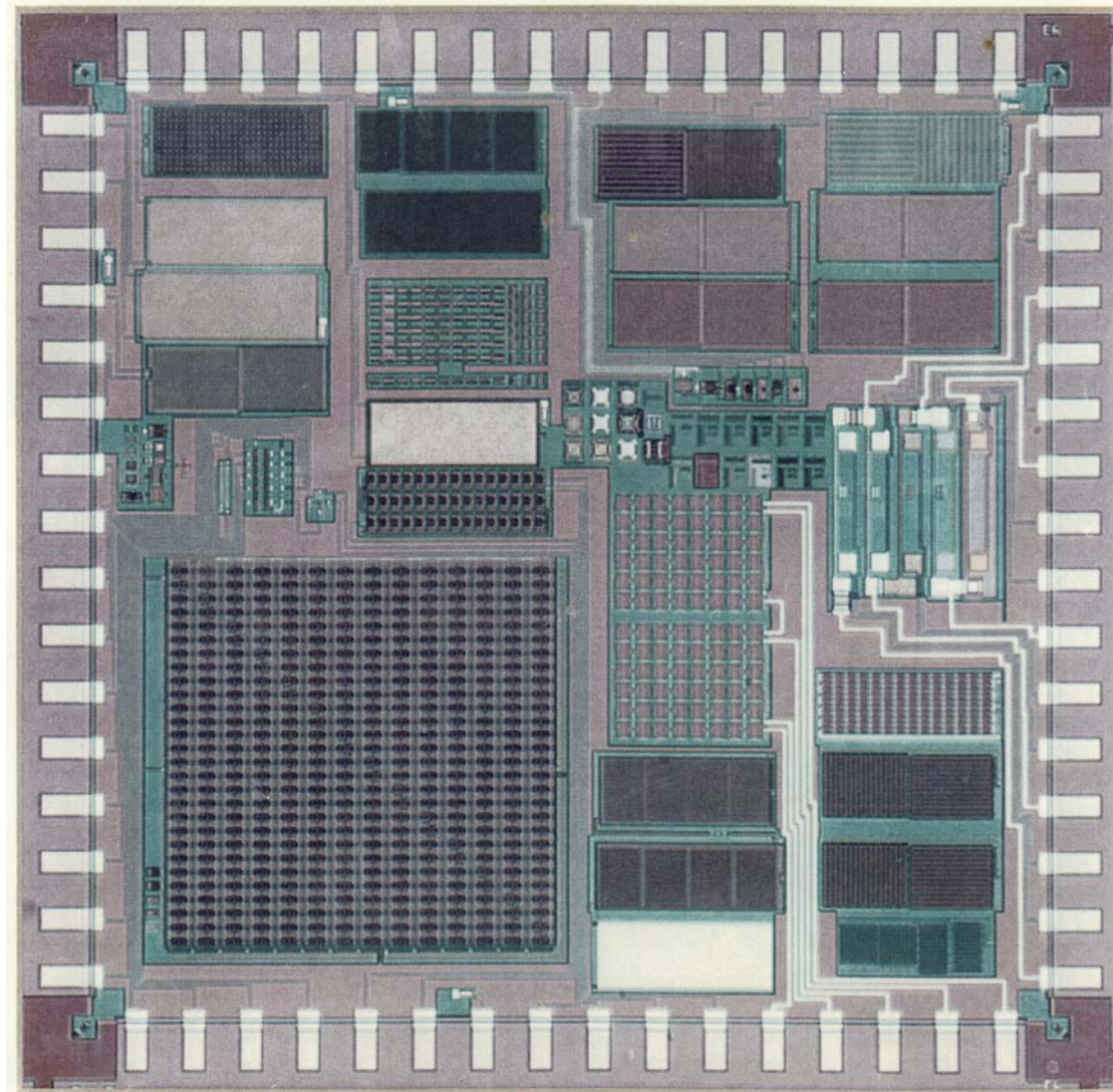
if one of your guys will, P

The Tunneling Cryotron—A Superconductive Logic Element Based on Electron Tunneling

J. Matisoo, IBM, 1967



Superconducting Digital Chip, IBM, 1970s



Conclusion

Today's superconducting electronics applications will be discussed in talks by Professors J. Clarke and K. Likharev

The technology of most of those applications is based on research of the 1950s and 60s.

- I. Giaever - Electron tunneling between superconductors.
- B. D. Josephson - Pair tunneling between superconductors.
- Also, W. L. McMillan and I measured the energy spectrum of the electron-phonon pairing mechanism

Conclusions (cont.)

My thanks to Professor N. Newman of ASU
for his help in preparing this talk.

**It was a great time to work in industrial research laboratories
A. D. Little, Atomics International, Bell, GE, Ford, IBM,
Westinghouse**

**Many thanks to all the friends I made over 50 years of work in
superconductivity**