Gor'kov-theory used for superconducting devices in astronomical instruments

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Lev Gor'kov's Master's diploma citation: ''engineer-physicist proficient in build-up experimental equipment and exploitation"

Dealing as a scientist with the applied world

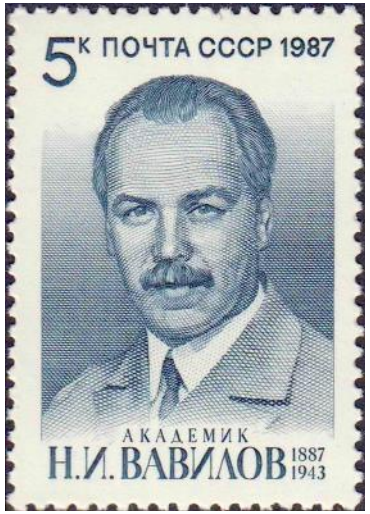
- Driven by practical use, no matter what ….. *engineer/entrepreneur*
- Driven by a scientifically correct analysis and description of functional and real behavior …. *scientist/discoverer*
- ***Man-made reality:*** Si-MOSFETs provide the *Quantum Hall effect* etc
- 'Golden eggs' are worth studying and may be a *source of new scientific developments*

Role of Lev Gor'kov or rather the Gor'kov equations?

“A theoretician is a hen that lays golden eggs”

- Ginzburg, *The physics of a lifetime (p.294)*, citing Sergey Vavilov

70th



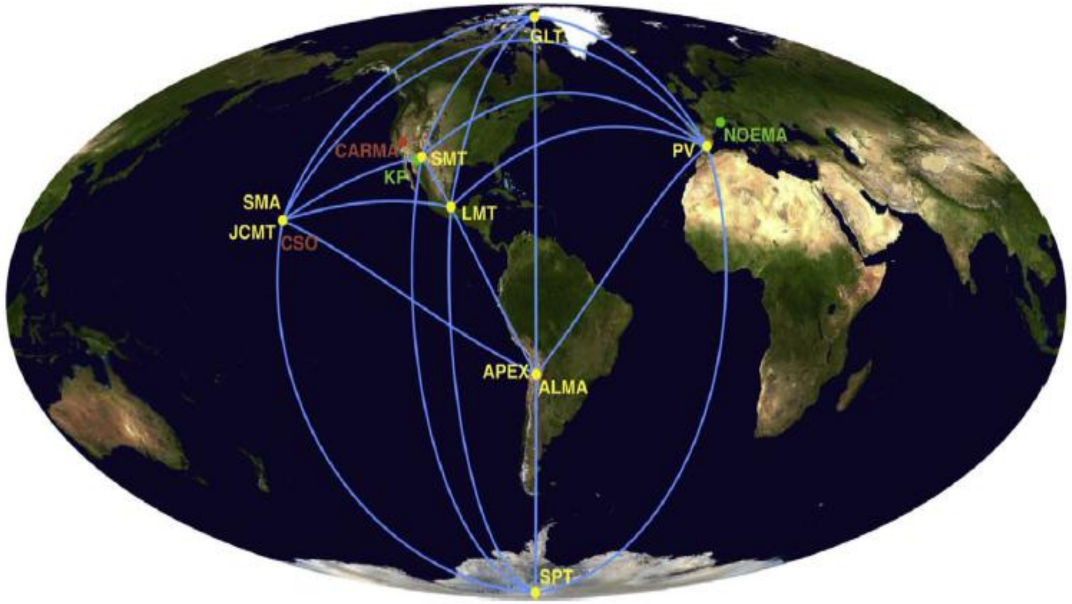
100th

Sergey Vavilov in 1947, 30 years after the revolution of 1917: ”The first three decades of Soviet rule were a period of continuous growth and development of science. The *fourth decade (1947-1957, TMK)* must and shall become a period of gigantic scientific achievement. That is our debt to the Soviet people, to our government and Party, to our great leader and teacher, …….”

Event Horizon Telescope

April 10th 2019

Picture of the edge of a black hole



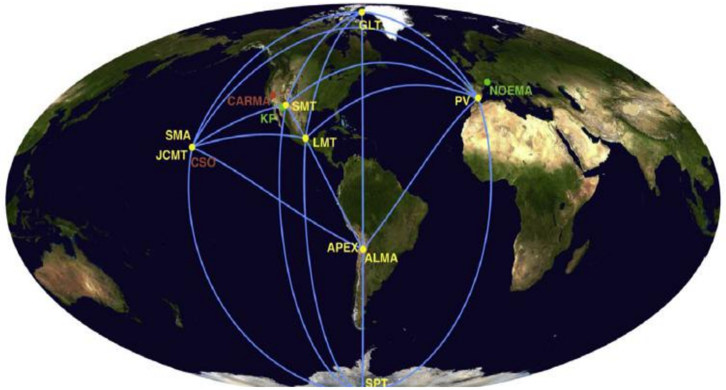
"engineer-physicist proficient in build-up experimental equipment and exploitation"

Superconductor-insulator-superconductor (SIS) junctions

3.1. Receivers

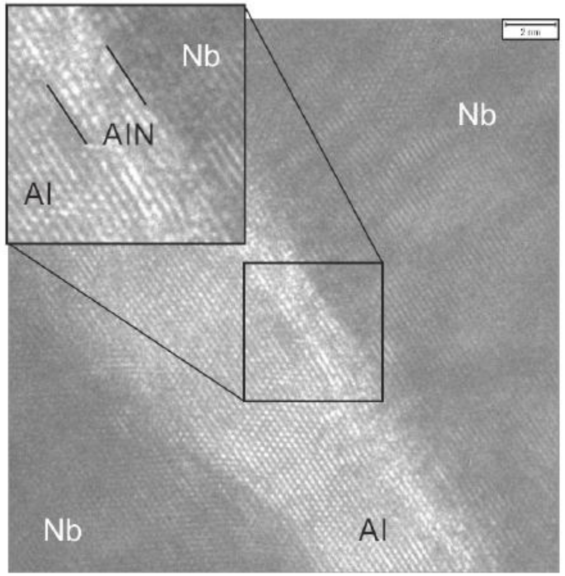
The past three decades have seen the development and widespread use of heterodyne receivers in the millimeter and submillimeter bands based on superconductor–insulator–superconductor (SIS) junctions (e.g., Phillips et al. 1981; Maier 2009; Carter et al. 2012; Tong et al. 2013; Kerr et al. 2014). Over this period, instantaneous bandwidths increased by more than a factor of 30, while noise temperatures decreased by an order of magnitude. Improvements in receiver and antenna reflector technology have combined with the increased recording rates to lay the foundations for a millimeter wavelength VLBI array that is capable of observing targets with a flux density below 1 Jy.

230 GHz



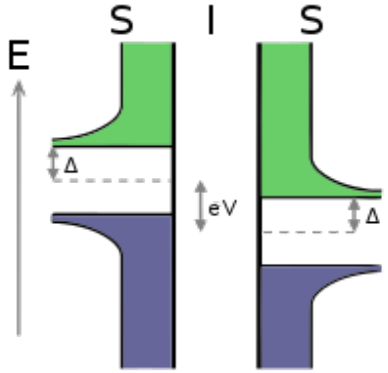
The Astrophysical Journal Letters, 875:L2 (28pp), 2019 April 10

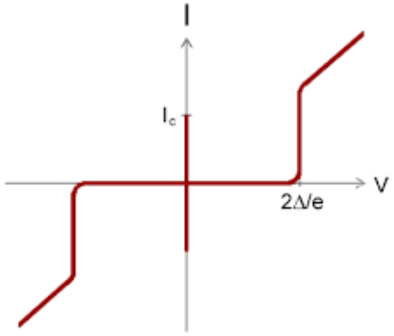
Authors: The Event Horizon Telescope Collaboration



Superconducting proximity-effect
SNIS-Junctions

Josephson-effect (1962)

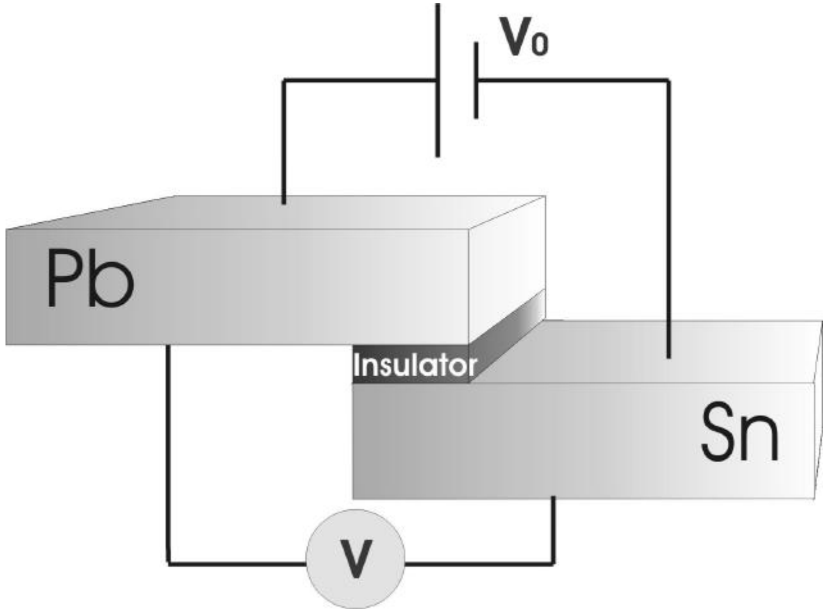




Coupled Superconductors, Rev. Modern Physics, *1964*

“Since the Ginzburg-Landau theory, microscopic theories of superconductivity have been developed, giving an explanation of its assumptions in so far as they apply (Gor’kov 1958), but as they do not add anything essentially new to the main discussion *we shall ignore them* except in Section V”

$$\mathbf{j}(\mathbf{r}) = \int \mathbf{K}(\mathbf{r},\mathbf{r}',\mathbf{r}'')\psi^*(\mathbf{r}')\psi(\mathbf{r}'')dr'dr''.$$



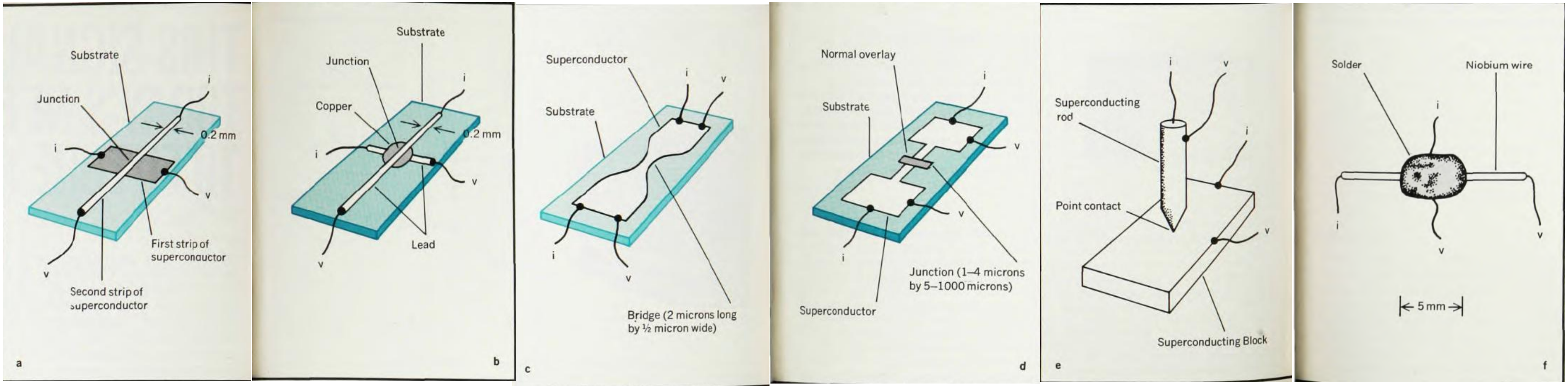
See also: V. Ambegaokar and Baratoff, Tunneling between Superconductors, PRL 10, 486 (1963)

Experimental/engineering development

- Zimmerman/Silver (Ford Motor Company), ***SQUID***, 1964 (pointcontacts, no hysteresis)
- Grimes/Richards/Shapiro (Bell), ***Far-infrared detection***, 1966 (pointcontacts,no hysteresis)
- Matisoo (IBM) ***digital switching element***,1967 (tunnel-junctions, hysteresis)
- Stewart (RCA), McCumber (Bell), Aslamazov/Larkin, ***RSJC-model***, 1968
- In Moscow (Vystavkin/Likharev,IREE) ***parametric amplification*** (1970)
- In Kharkov (Yanson/Dmitrenko, PTI Kharkov), ***experimental physics-oriented*** (1965)

Fascinated by the universality

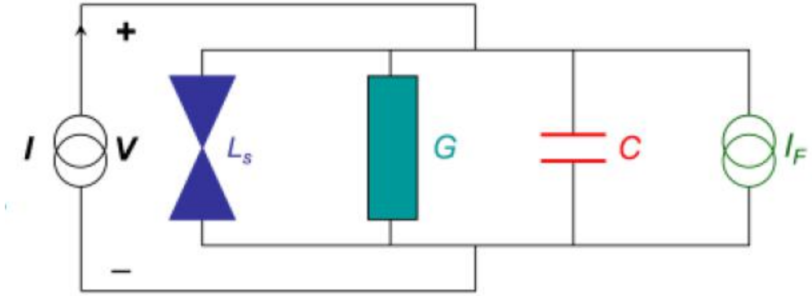
John Clarke, Physics Today, August 1971, *Electronics with superconducting junctions*



$$\frac{\partial(\phi_1 - \phi_2)}{\partial t} = \frac{2eV}{\hbar}$$

$$I_n = \frac{V}{R} = GV$$

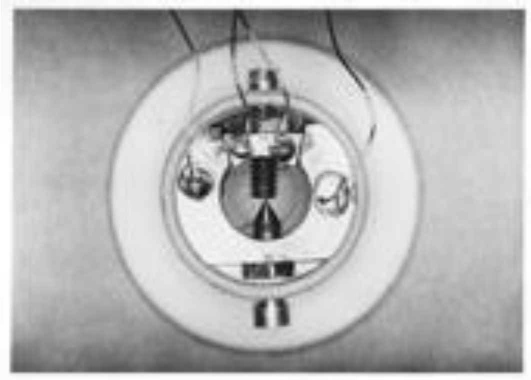
$$I_s = I_c \sin(\phi_1 - \phi_2)$$

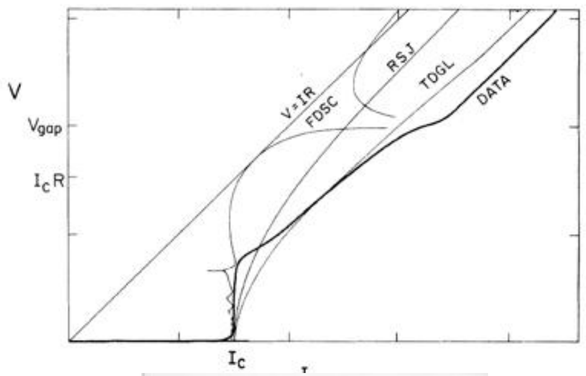


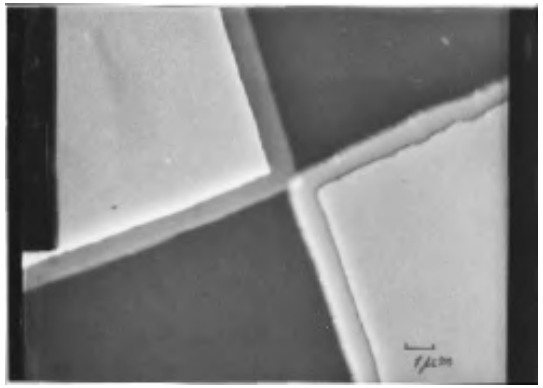
K.K.Likharev and B.T. Ulrich, *Systems with Josephson contacts*, MSU, 1978

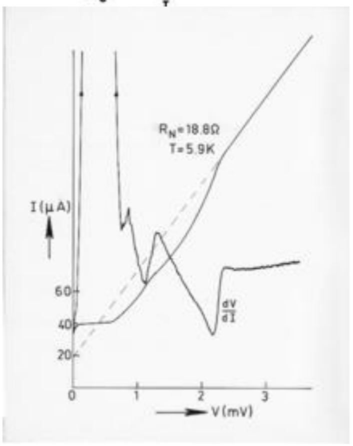
Physics fights back (1970-1982)

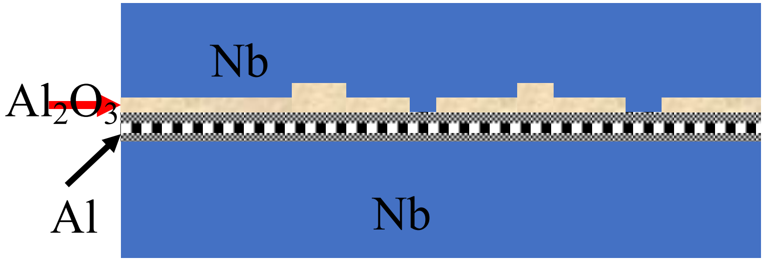
- Gor'kov-theory to *quasiclassical-theory* (Eilenberger (1968), Usadel(1970))
- Physics-relevant deviations from RSJ: *nonequilibrium superconductivity, f(E):* Gorkov, Eliashberg, Artemenko, Volkov, Zaitsev, Larkin, Ovchinnikov, Schmid, Schön, Scalapino,
- Competing theories for SNS (Gor'kov-theory or 1D *Andreev-reflection* models)











At the applications frontier around 1980?

- *Magnetometers:* DC SQUIDs are getting fabricated as shunted tunnel-junctions: *by definition in perfect agreement with RSJC-model*
- For astronomical applications the *Josephson-mixers* are 'too noisy' and drift into studies of 'chaos'
- *Digital applications* loose out on continued advances in silicon. In addition, they continue to get *bad tunnel-junctions* from the interesting materials

RSJ-model adequate (noise?)

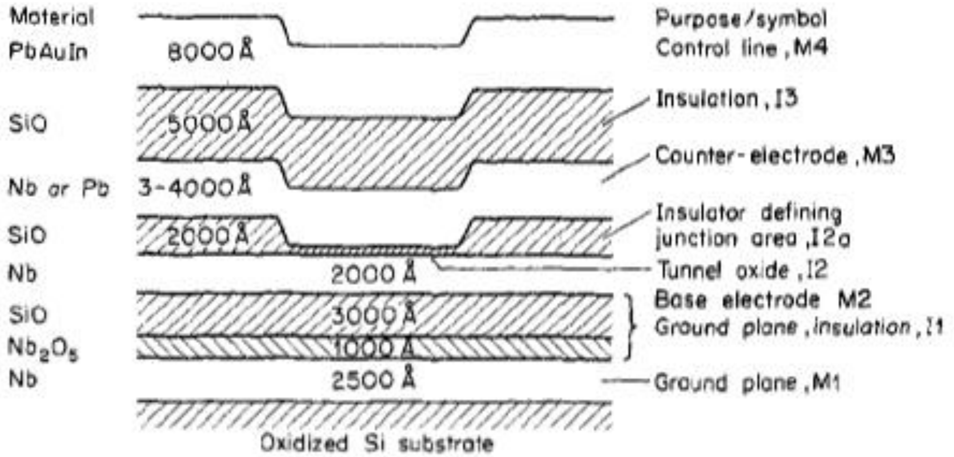
Success

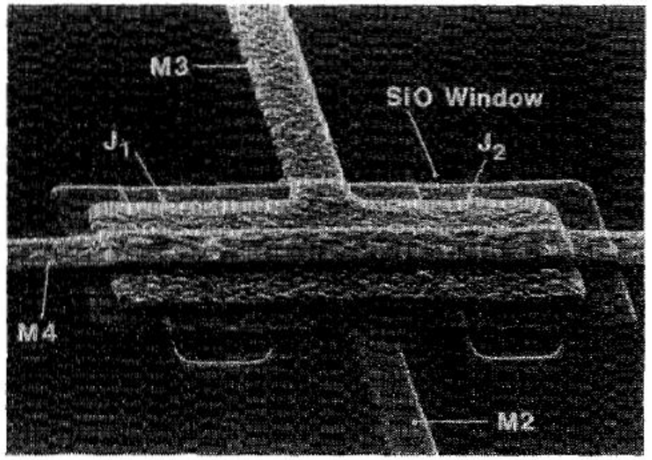
Failure

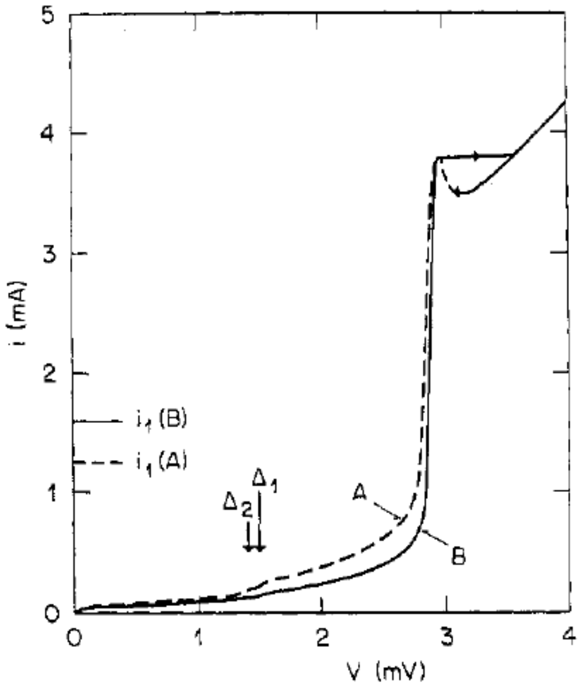
Failure

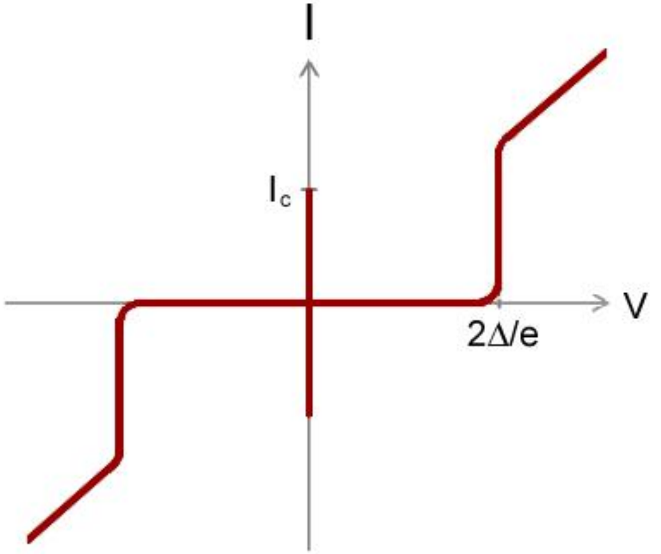
Niobium-niobiumoxide-niobium tunnel-junctions (IBM)

Broom et al, 1980





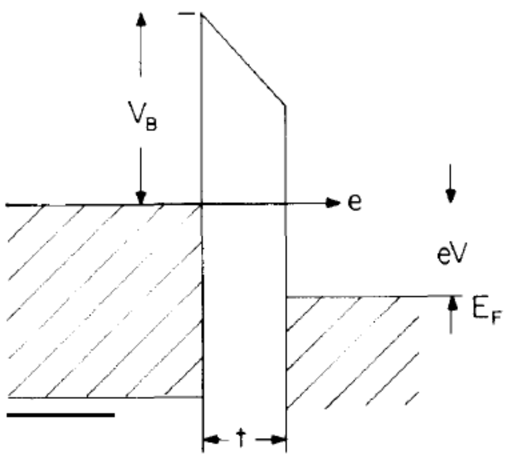




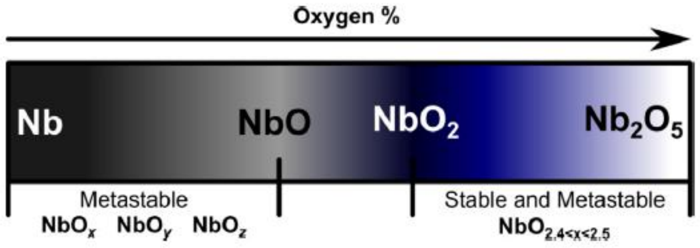
- Subgap leakage
- Knee structure
- Different gaps
- Too low critical current

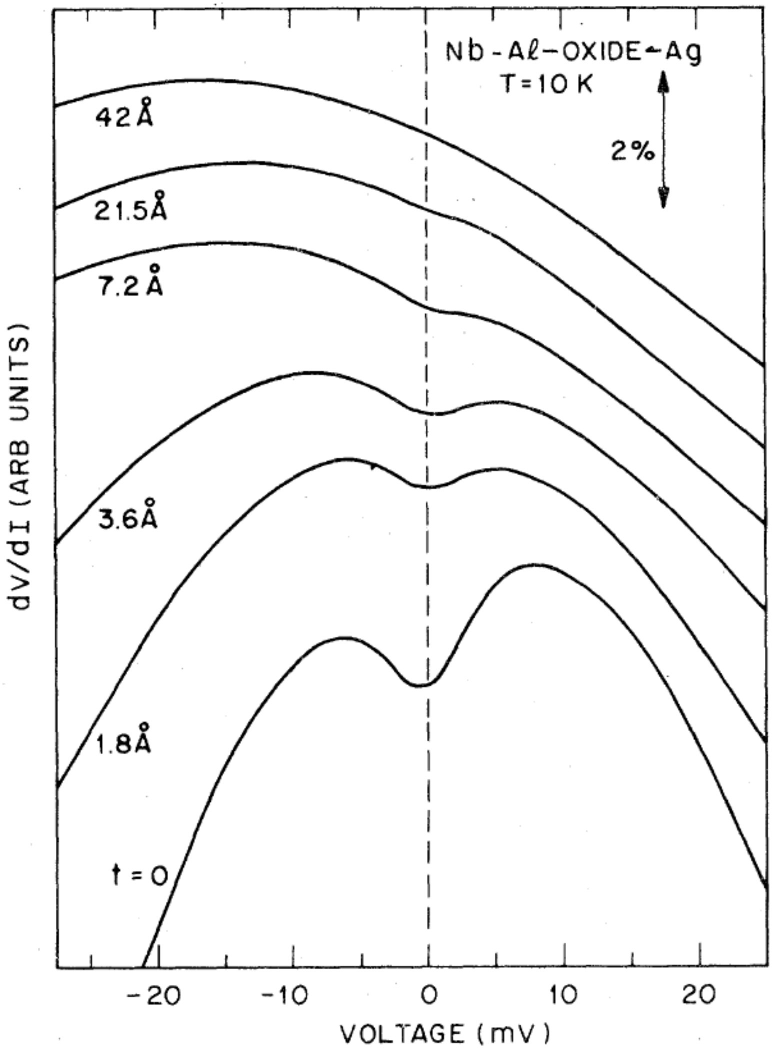
- Ideal (Al-AlOx-Al)

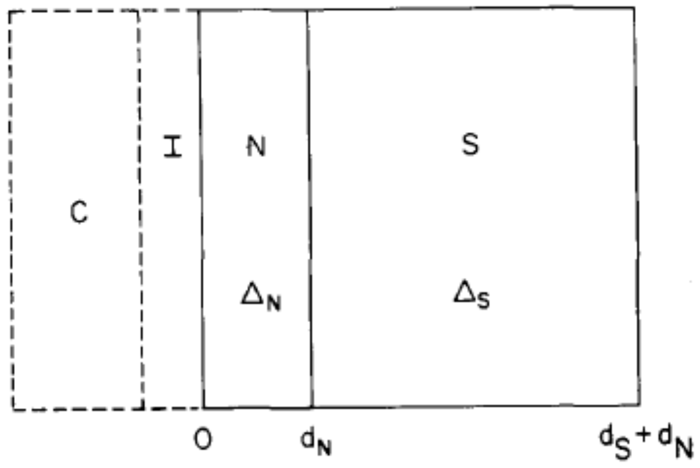
Modification of tunnel-barrier by thin aluminium (Bell)

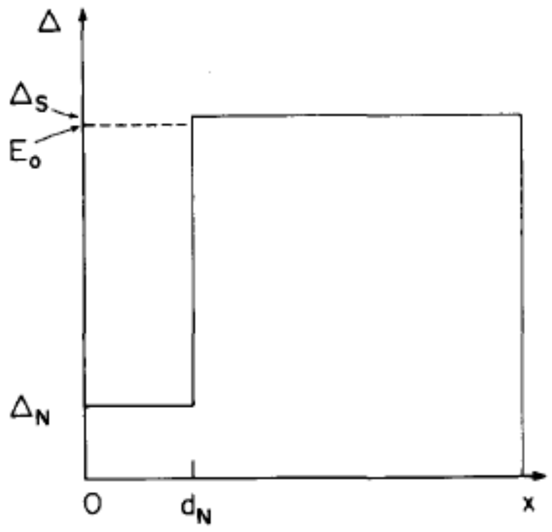


Rowell et al, Phys. Rev. B 24, 2278, 1981

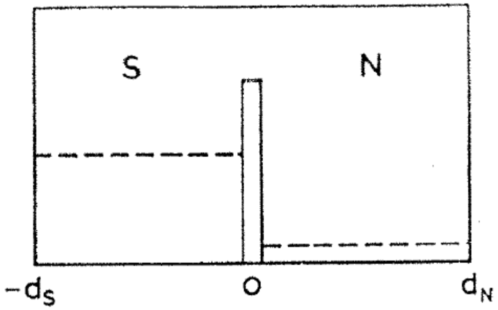


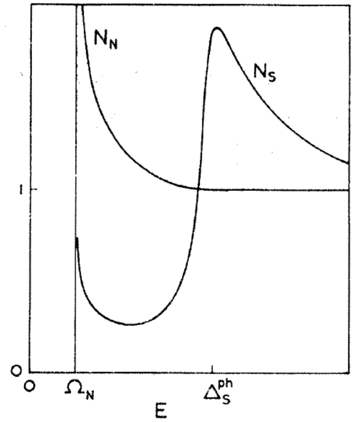






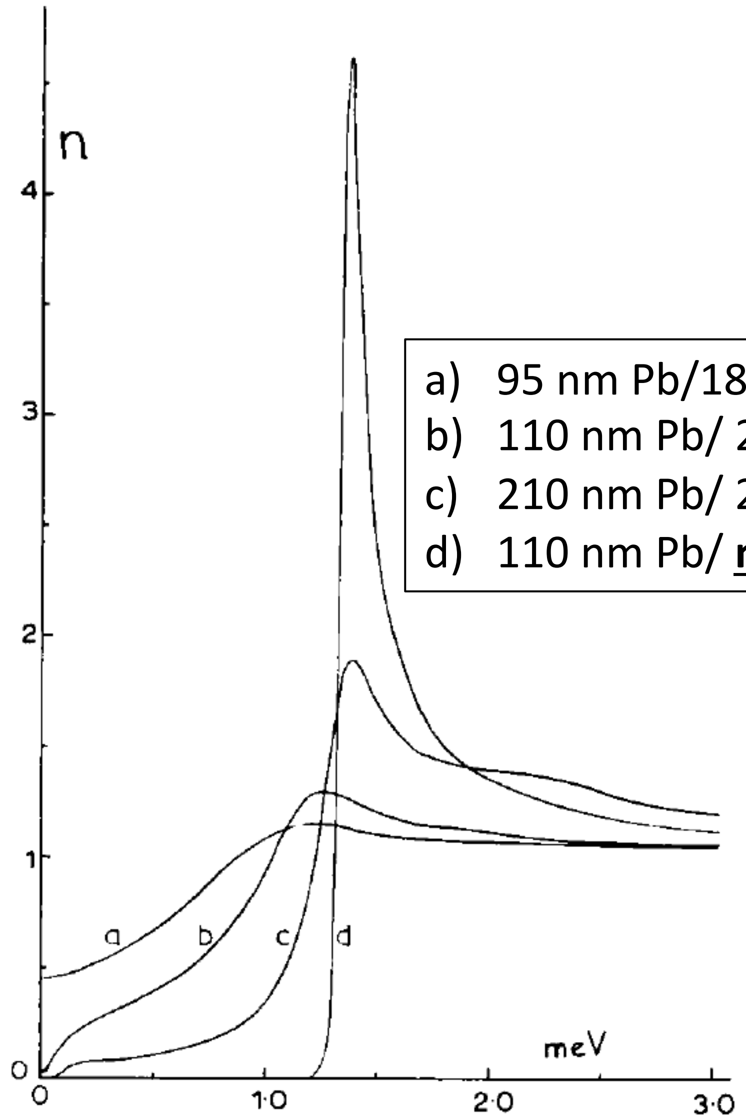
Proximity-effect





- McMillan-model (1966)
  - "One would like to be able to take the theory of superconductivity, as embodied in Gor'kov's equations, and calculate the electronic density of states for a realistic model of the SN sandwich….."
  - "…. This eliminates the difficult problems associated with true space dependence in the Gor'kov equations, and the model is now simple enough to allow a complete solution."
- Arnold-model (1978): Proximity-effect tunneling spectroscopy (PETS) (E.L. Wolf)
  - Spectroscopy of electron-phonon spectrum of materials with a difficult to make tunnel-barrier

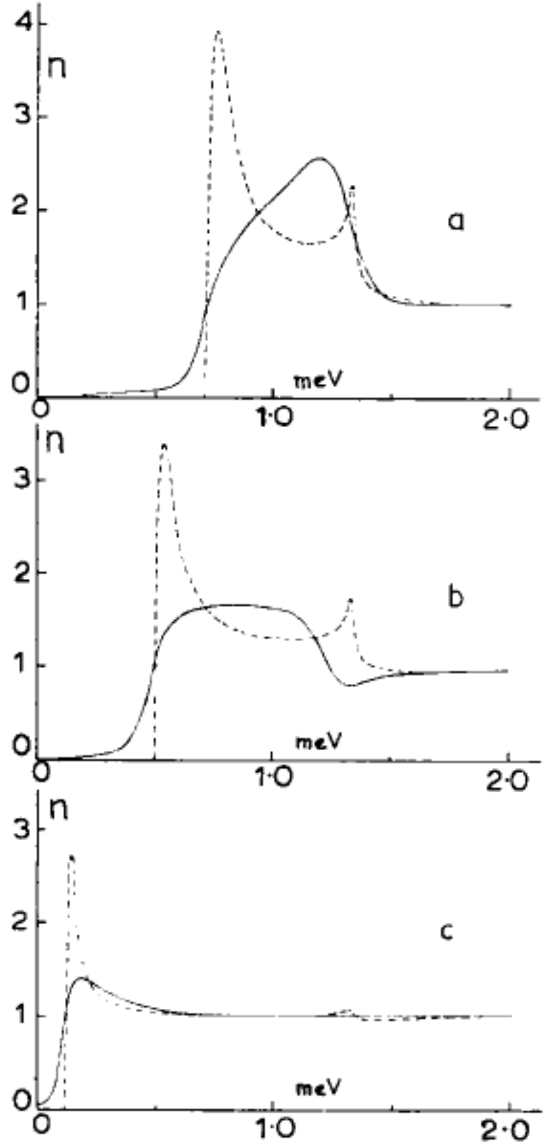
Cu/Pb sandwiches



a) 95 nm Pb/180 nm Cu
b) 110 nm Pb/ 230 nm Cu
c) 210 nm Pb/ 200 nm Cu
d) 110 nm Pb/ **no** Cu

a) 30 nm Cu
b) 55 nm Cu
c) 240 nm Cu
All 700 nm Pb

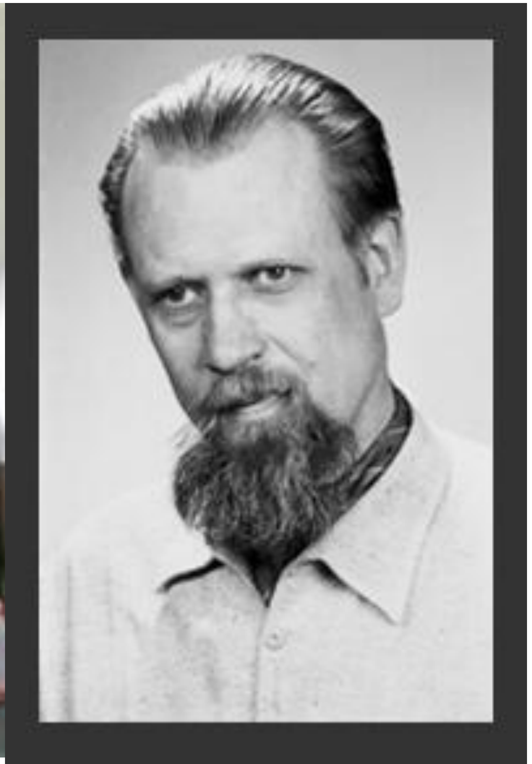
Comparison McMillan model with data



S.M.Freake, Superconducting density of states induced by the proximity-effect, Phil. Mag. **24**:188, 319-338 (1971)

Skillful ways to avoid the use of Gor’kov’s equations

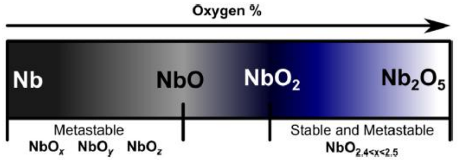
Quasi-classical approximation of the Gor’kov theory (1968-1970)

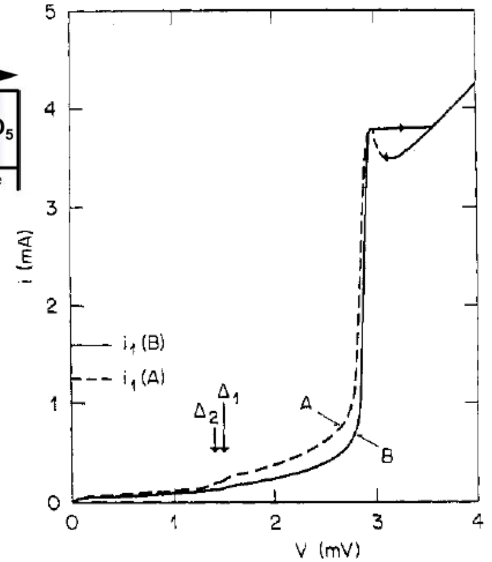



1968 Eilenberger: The fundament for almost all theoretical work on type II superconductors has been laid by Gor’kov with the formulation of a set of coupled equations for the normal and anomalous Green's functions…the new equations are discussed. They permit an easy reproduction of many known results and are considered as a good starting point for numerical calculations in those regions of parameter values, which have not been accessible to analysis so far.

1970 Usadel: Recently Eilenberger derived transportlike equations for superconductors of type II which, for a small order parameter $\Delta(r)$, reduce to the Boltzmann equation introduced and studied by Lüders. These transport-like equations are much easier to handle than the original Gor'kov' equations since the number of variables is reduced.

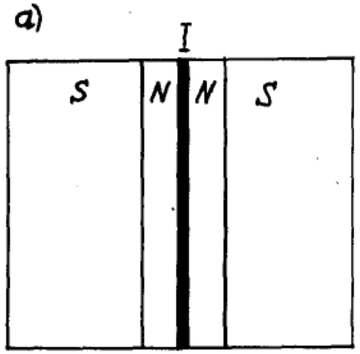
Proximity-effect; numerical computations

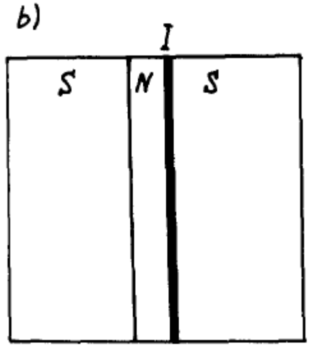




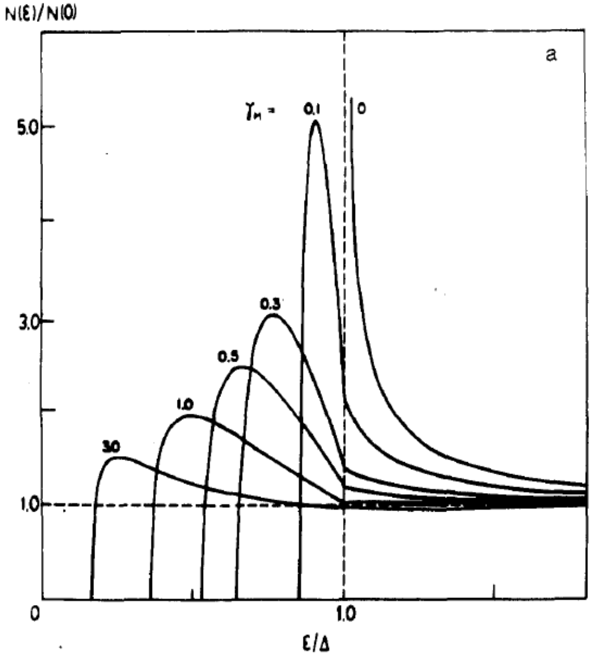
A.A.Golubov, M. Yu.Kupriyanov and V.F.Lukichev, Sov. Journal of Microelectronics 12, 342 (1983)

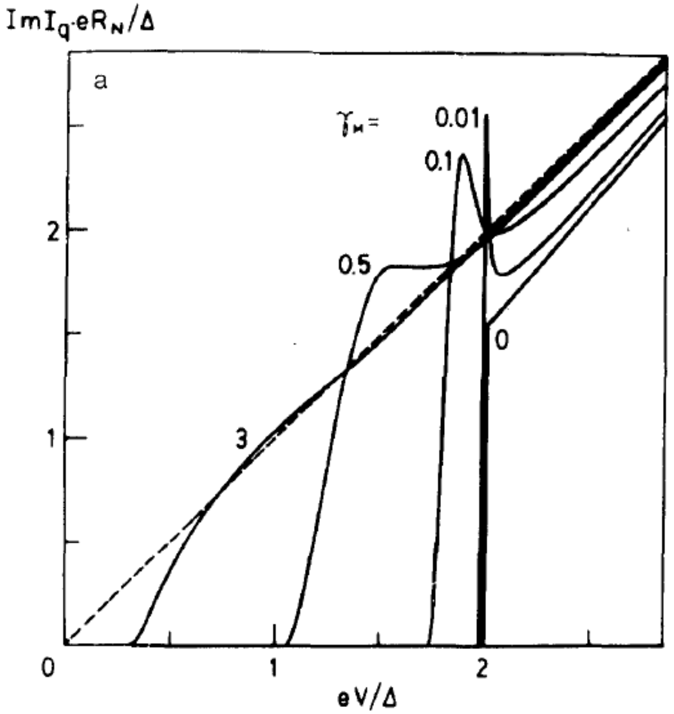
A.A.Golubov and M. Yu. Kupriyanov, J. Low Temp. Phys. 70, nrs ½, 83-130 (1988)



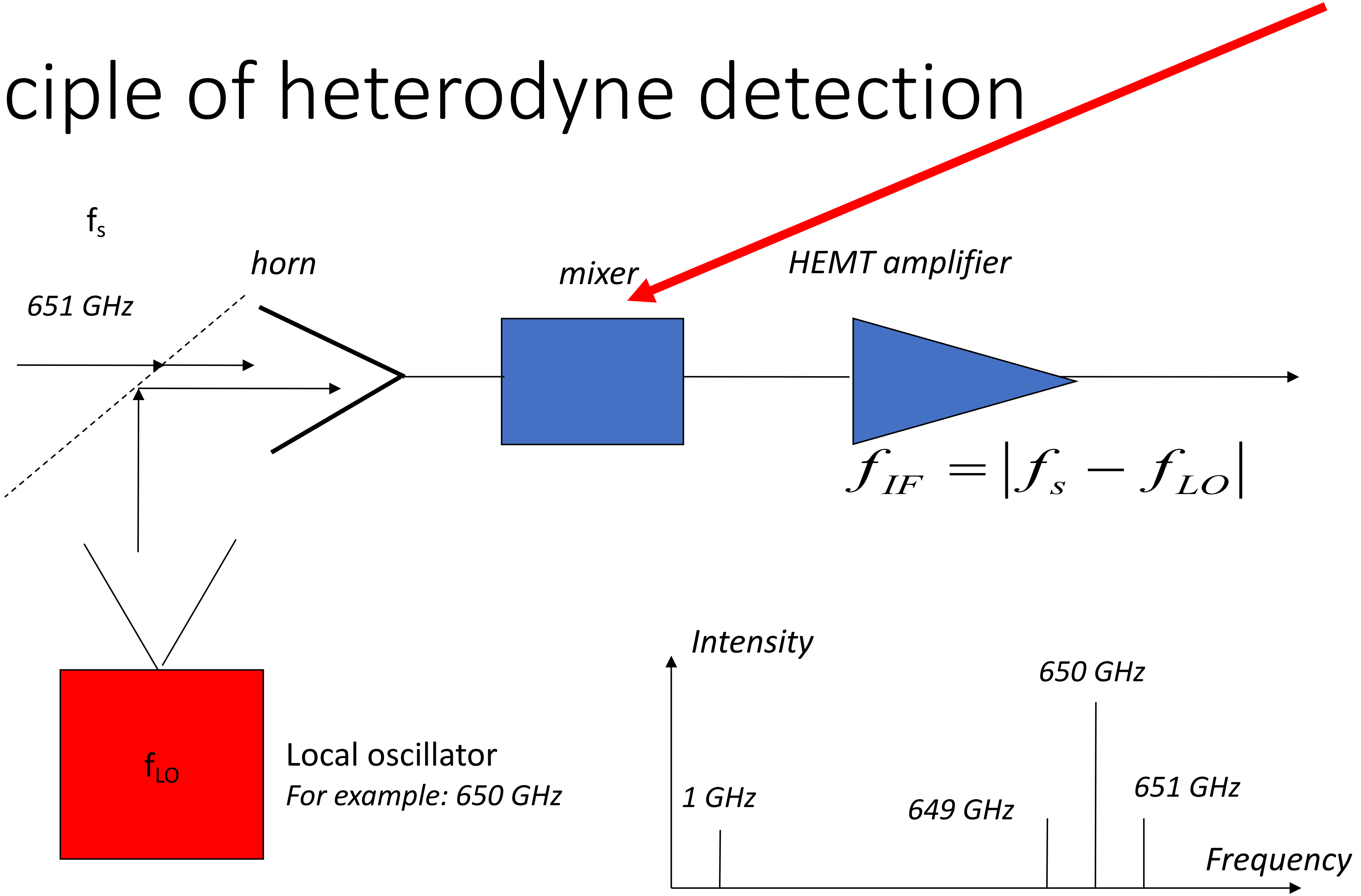


$$\gamma_M = \frac{\sigma_N}{\sigma_S}\frac{\xi_S}{\xi_N}\frac{d_N}{\xi_N}$$





Principle of heterodyne detection



Lowest order in V_ω

Quantum response when the photon energy exceeds the non-linearity

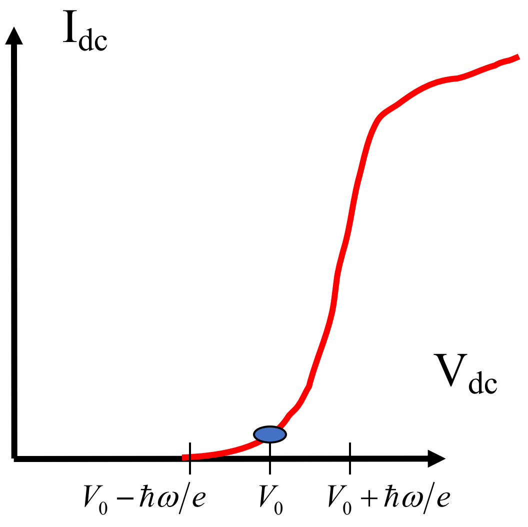
$$\Delta I_{dc}(V_0) = \frac{1}{4} V_\omega^2 \left[\frac{I_{dc}(V_0 + \hbar\omega/e) - 2I_{dc}(V_0) + I_{dc}(V_0 - \hbar\omega/e)}{(\hbar\omega/e)^2} \right]$$

$$I_\omega = V_\omega \left[\frac{I_{dc}(V_0 + \hbar\omega/e) - I_{dc}(V_0 - \hbar\omega/e)}{2(\hbar\omega/e)} \right]$$

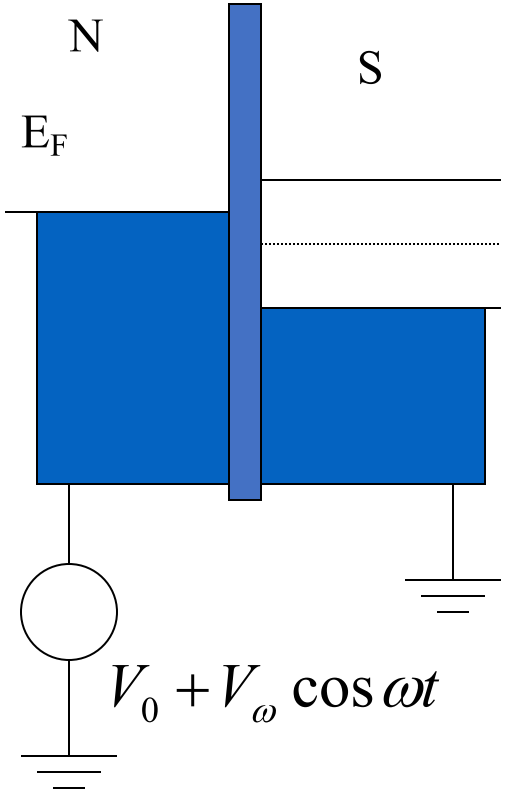
$$R_i = \frac{\Delta I_{dc}}{\frac{1}{2} V_\omega I_\omega} = \frac{e}{\hbar\omega} \left[\frac{I_{dc}(V_0 + \hbar\omega/e) - 2I_{dc}(V_0) + I_{dc}(V_0 - \hbar\omega/e)}{I_{dc}(V_0 + \hbar\omega/e) - I_{dc}(V_0 - \hbar\omega/e)} \right]$$

$$\Rightarrow \frac{1}{2} \frac{d^2 I_{dc} / dV_0^2}{dI_{dc} / dV_0}, \text{ classical limit}$$

$$\Rightarrow \frac{e}{\hbar\omega}, \text{ quantum limit}$$



Photon-assisted tunneling



40 GHz

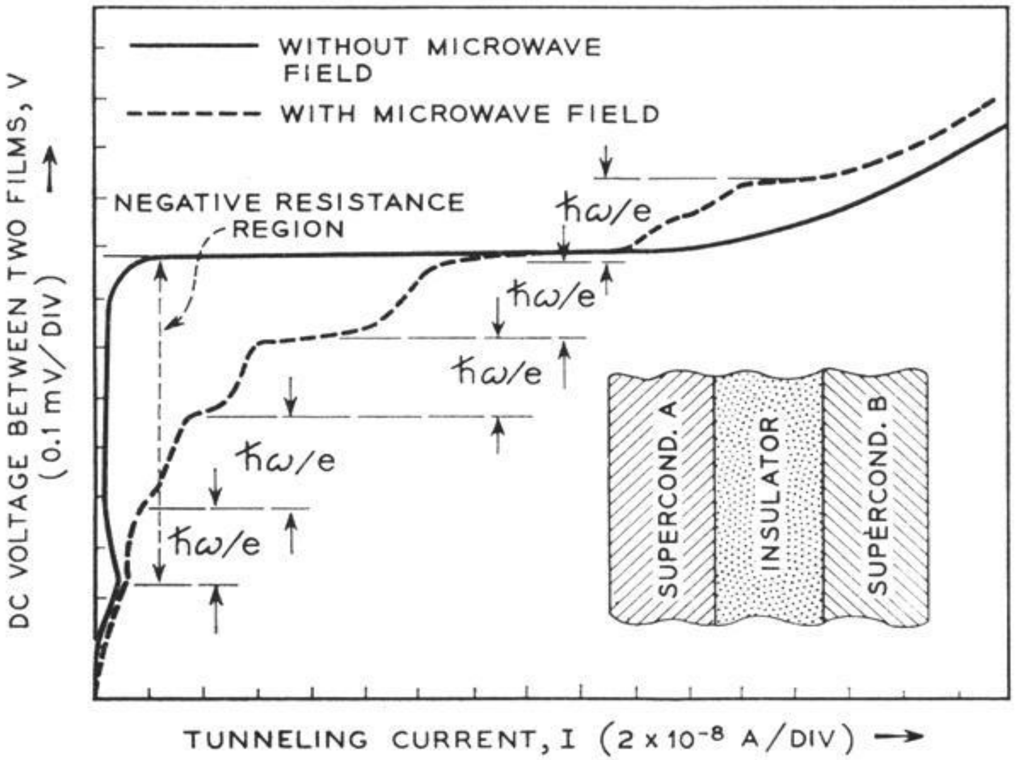


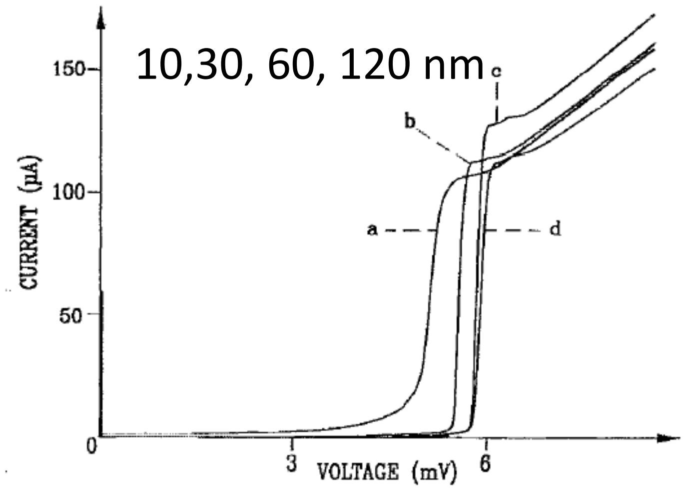
FIG. 1. Bias voltage vs tunneling current of a superconducting Al-Al_2O_3-In diode as measured by Dayem and Martin with and without the microwave field. $\hbar\omega/e = 0.16$ mV.

Tien & Gordon, Phys. Rev. **129**, 647 (1963)

Materials Choice (SNIS?)

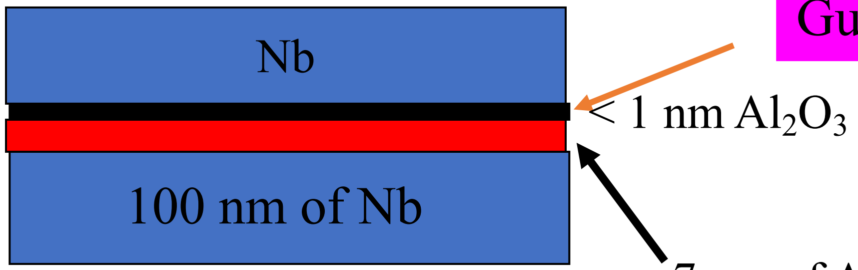
•Usable operating temperature 4.2 K
•Frequency demands gaps in excess of 2 meV

- Early (1980) work: PbInAu or PbBi technology (IBM)
- More recent work: Nb/Al-technology (since 1983)
- Recent years NbN and NbTiN-technology
- Plasma-sputter deposition techniques

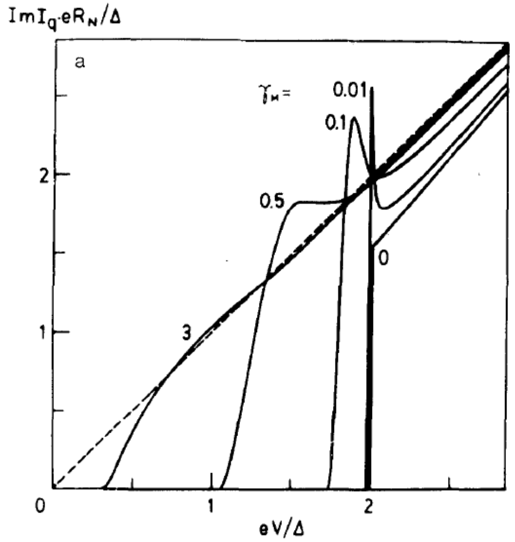


Lehnert et al,
Appl. Phys. Lett. 65, 112 (1994)

Gurvitch *et al*, APL **42**, 472 (1983)

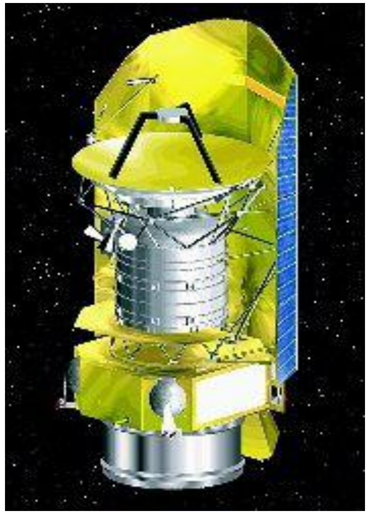


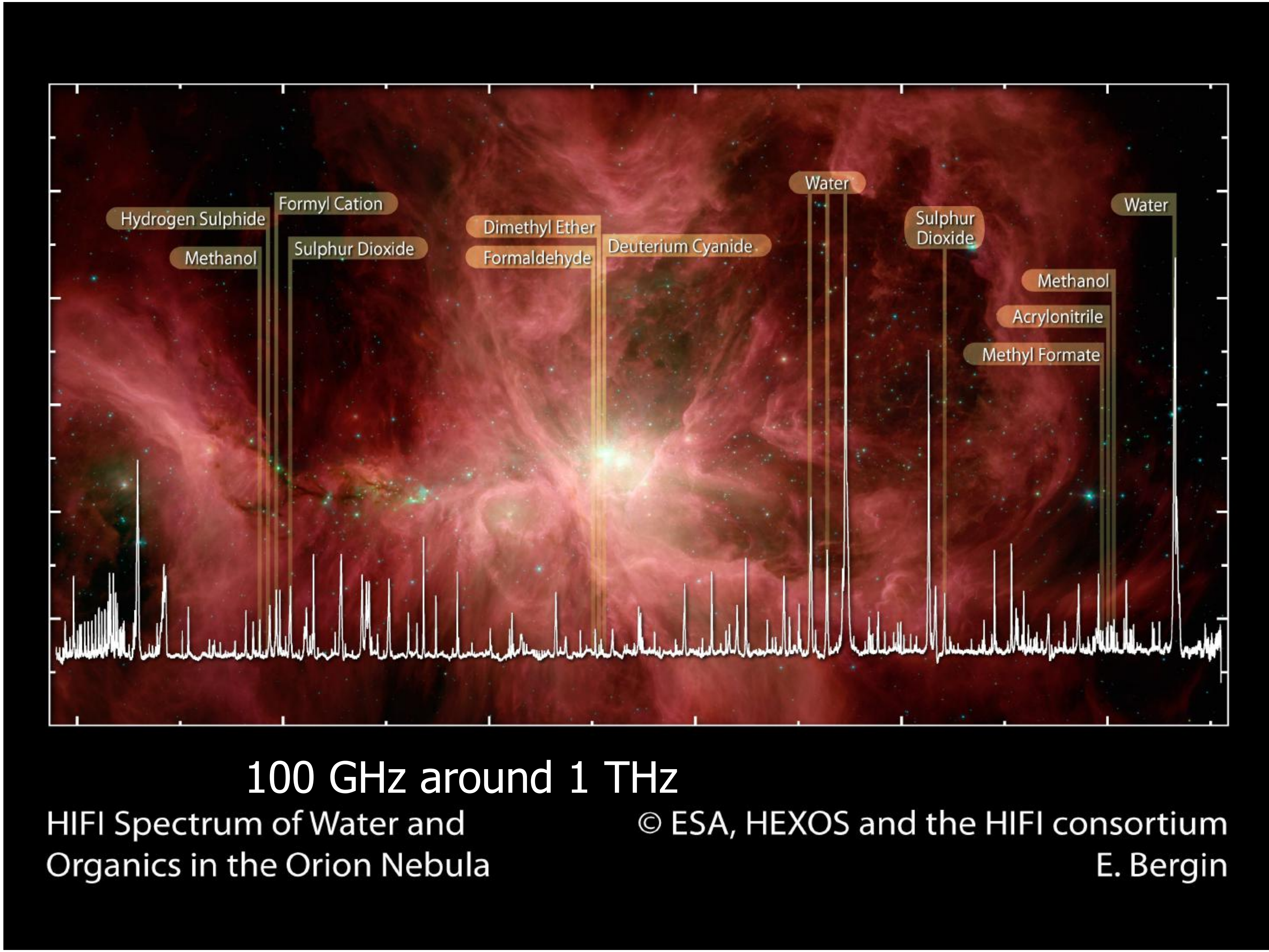
7 nm of Al (proximity-effect)

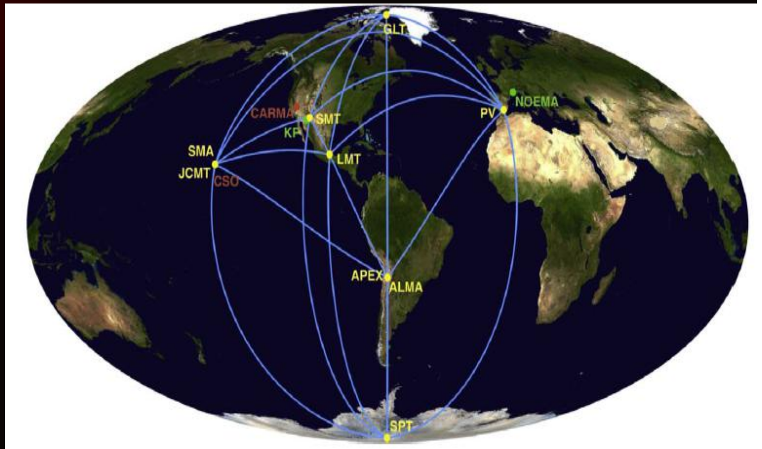


Thickness optimized by using the Gor'kov-Usadel-equations and experiments

Herschel space telescope






GLT
NOEMA
PV
CARMA
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KP
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JCMT
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LMT
APEX
ALMA
SPT

Mesoscopic physics breaks through (80-ies)

clean rooms, dilution fridges, nanoscience,
many calculational problems, many constructed research-devices

- SNS-junctions: Andreev bound states (connection with proximity-effect)
- NcN Pointcontacts: Sharvin-resistance
- ScS Pointcontacts: Artemenko-Volkov-Zaitsev (Non-equilibrium superconductivity)
- NcS Pointcontacts: BTK Andreev (spectroscopic tool)
- Ring-structure: Aharonov-Bohm oscillations in *normal metals*
- Constrictions: Quantum Point-Contacts
- Interplay between single-particle phase and superconducting phase
- Landauer-Büttiker: Quantum transport
- Ballistic transport; topological transport
- Superconducting mechanical break-junctions
- Andreev-bound state based Josephson-junctions
- Quantum computation with Al-based superconducting tunnel-junctions
- Majorana's ……….. proximity-effect

In summary

- Lev Gor’kov’s Master’s diploma citation: ‘’engineer-physicist proficient in build-up experimental equipment and exploitation”

Take home message?

If you want to do the superconducting engineering right,

use of Gor’kov’s equations