Quantum transport in superconducting-semiconducting nanodevices

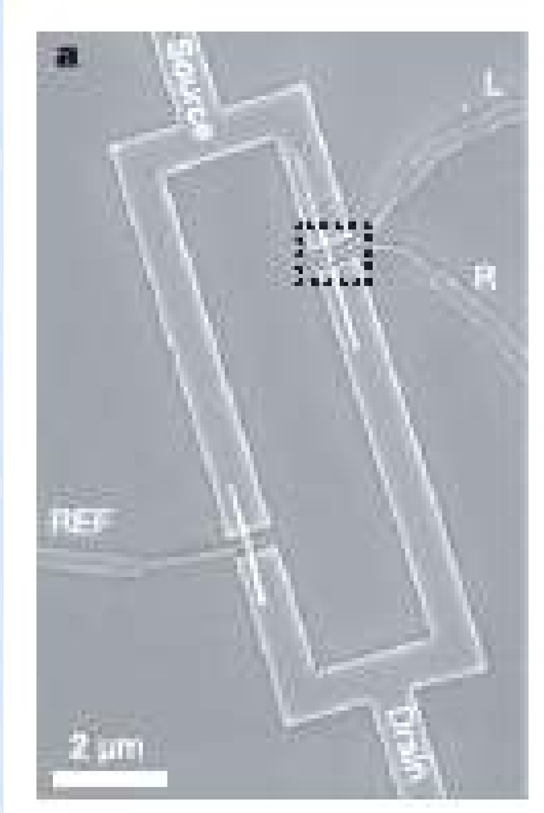
Y. V. Nazarov

Kavli Insititute of NanoScience

Delft University of Technology

The Netherlands

Outline



- **History**
  - Superconductors
  - Semiconductors
  - Combination of the two
- **Present**
  - Nanowires
  - Superconducting quantum dots
  - Exotic transport processes
- **Future**

L.P. Kouwenhoven

and

Nanowire Team

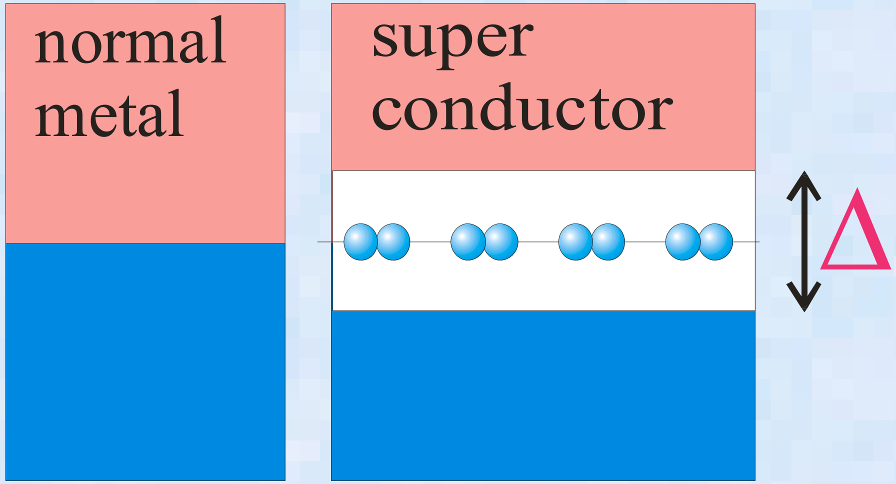
Superconductors

Discovered: Kamerlingh-Onnes, 1911
Occurs: in many metals at low temperatures
Manifestations: Zero resistance, magnetic field expulsion
Origin: unknown till 1957
Theory: Bardeen, Cooper, and Schrieffer (BCS)
Broken: Gauge symmetry
Utilized: Macroscopic quantum devices as coherence source

Spectrum and condensate

- **Electron pairs condense**
- **Gap Δ in the spectrum**

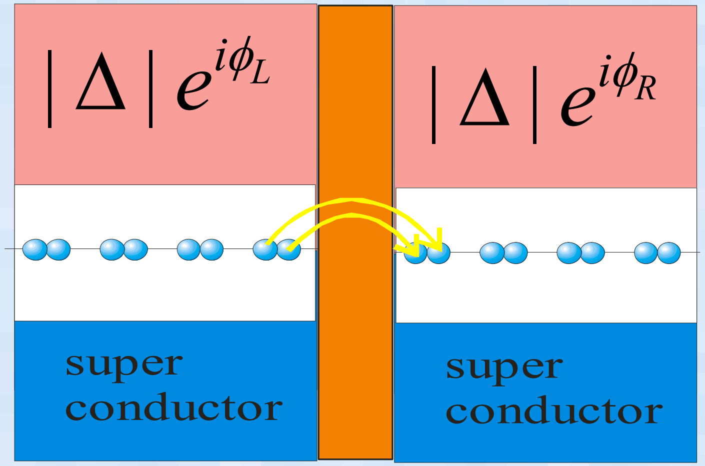
$$\Delta(r) = |\Delta| \exp(i\phi(r))$$



- **Phase differences – cost little energy**
- **Phase gradients – supercurrents**
- **Persisting, non-dissipative…**

$$\Delta \sim 1\, meV$$

Josephson junction

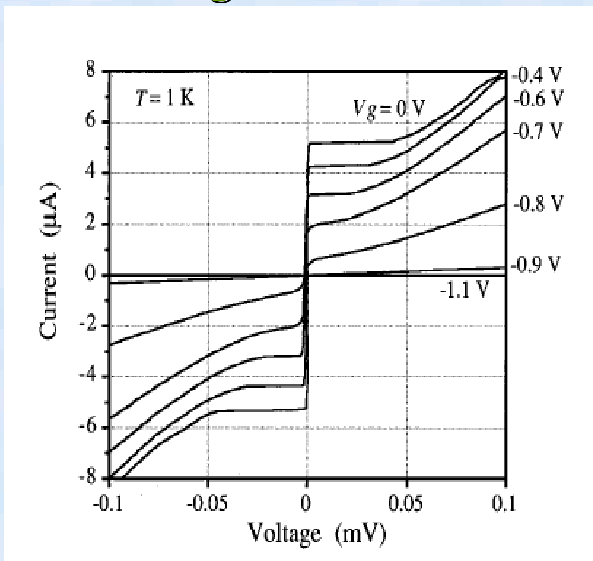


$$I = (I_c/2) e^{i(\phi_R - \phi_L)}$$
$$-(I_c/2) e^{i(\phi_L - \phi_R)}$$

- **B. Josephson,1960**
- **current = amplitude**
- **P.W. Anderson, 1962**
- **charge and phase = conjugated variables**
- **phases are shifted by magnetic fluxes**

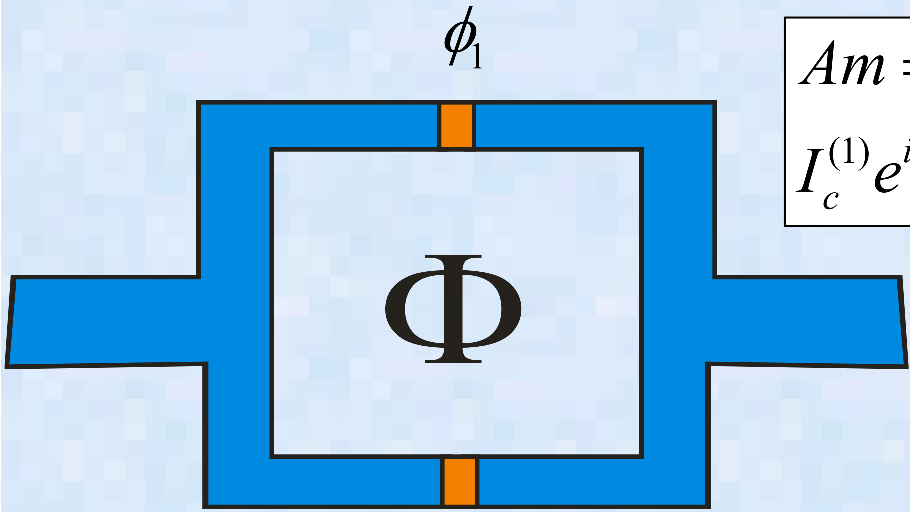
$$e^{i\phi} \to |N\rangle\langle N+2|$$

$$I = (I_c/2) \sum_N |N_R, N_L\rangle\langle N_R + 2, N_L - 2|$$
$$-(I_c/2) \sum_N |N_R, N_L\rangle\langle N_R - 2, N_L + 2|$$

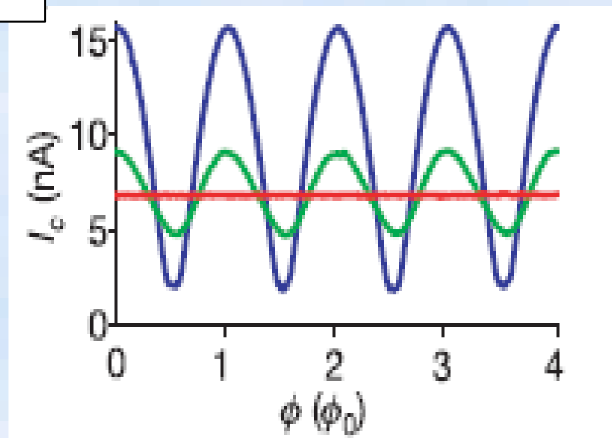


SQUID

- **Phase differences shifted by magnetic flux Φ**



$$Am = Am_1 + Am_2 = I_c^{(1)} e^{i\phi_1} + I_c^{(2)} e^{i\phi_2}$$



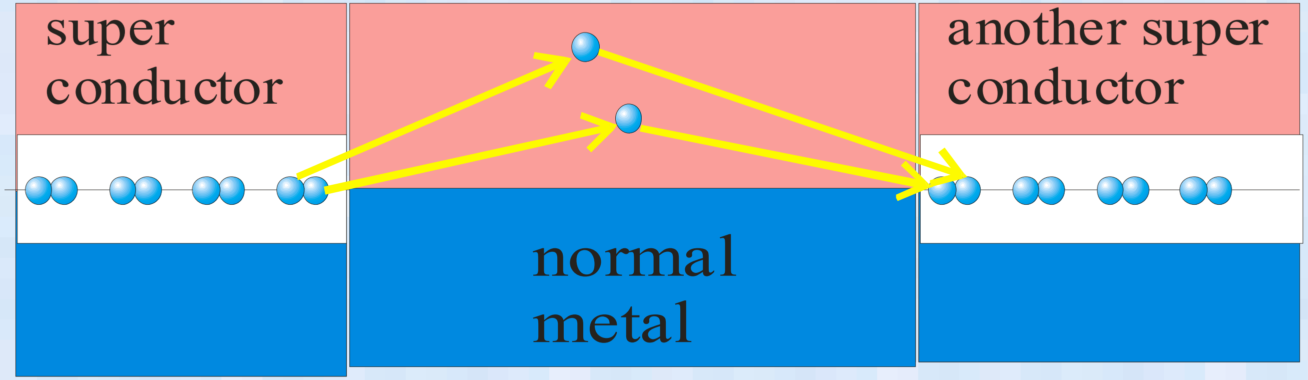
$$\phi_2 = \phi_1 + 2\pi \frac{\Phi}{\Phi_0}$$

$$\Phi_0 = \frac{\pi\hbar}{e}$$

- **Measures unbelievably small magnetic fields**

Superconducting proximity effect

- **Virtual electron propagation**



Heisenberg uncertainty

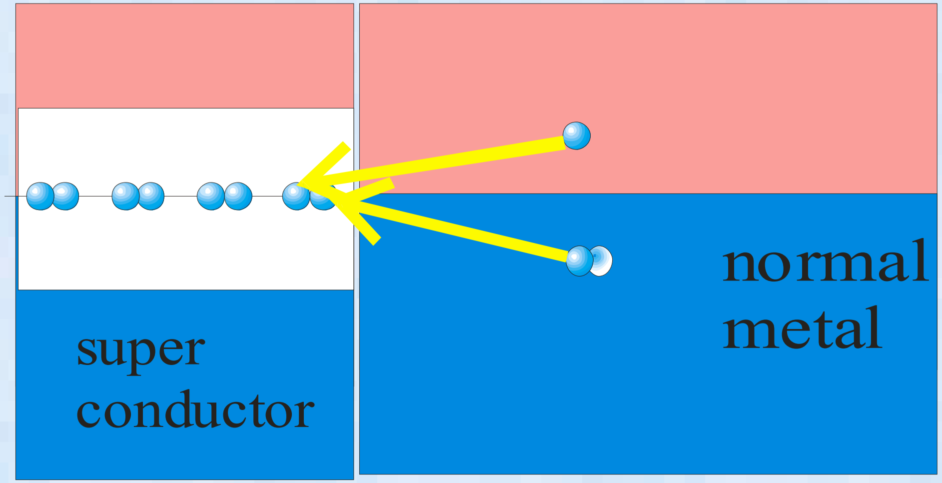
$t \sim \hbar / E$

$ballistic: \xi \sim v_F \hbar / E$

$diffusive: \xi \sim \sqrt{D\hbar / E}$

$E \sim k_B T$

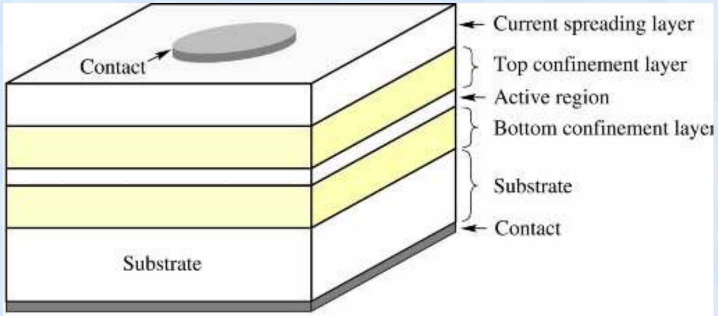
- **Two-el. Tunnelling=Andreev Reflection**



Leaving hole behind…

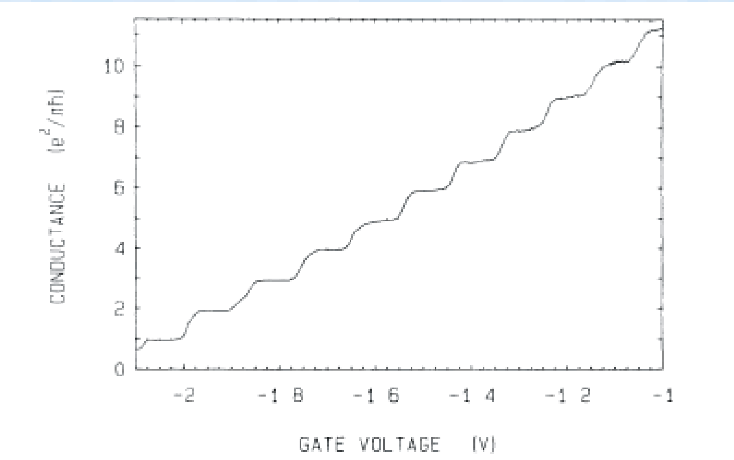
Semiconductors

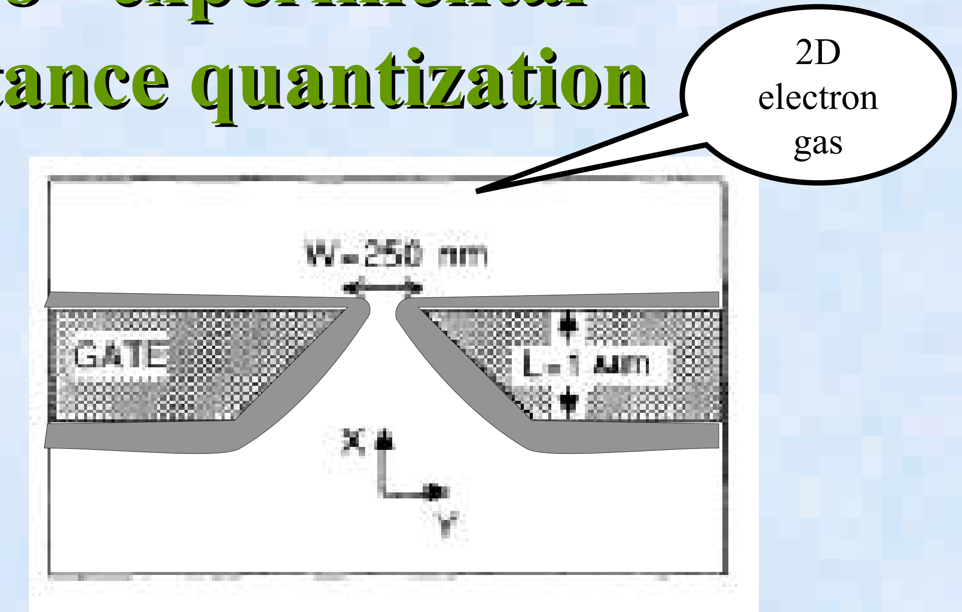
- Gap
- Doping – many materials in one
- Field effect (Transistors)
- (Easy) heterostructures and quantum wells
- 2D gas in heterostructures
- Shaping 2d gas with gate electrodes!
  - Lot of fun
  - Quantum Transport



Quantum point contact

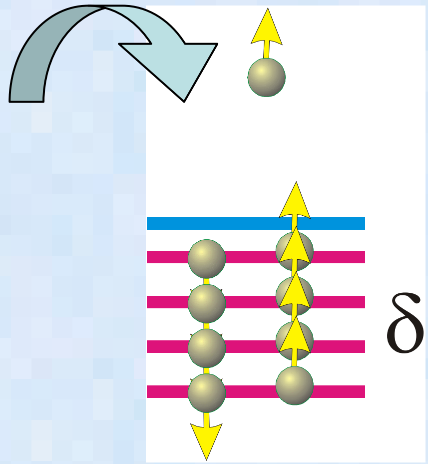
- Van Wees et al. 1988 –experimental evidence of conductance quantization



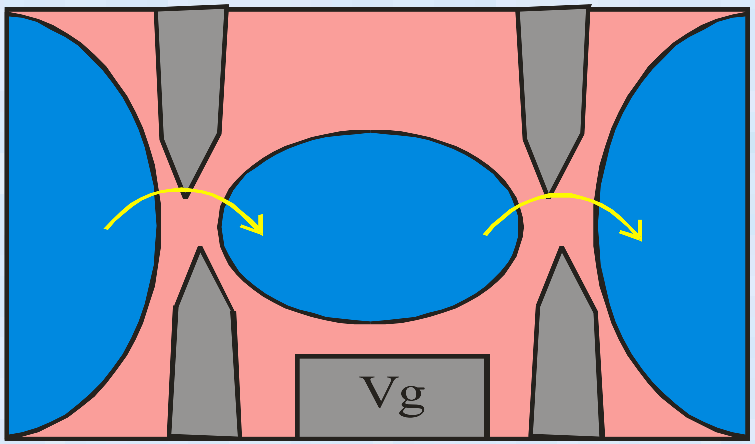


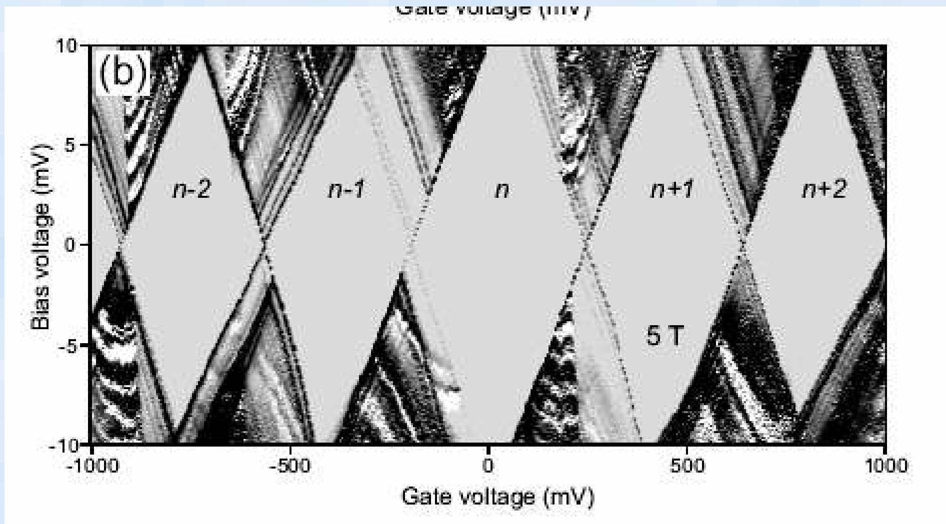
$$G_Q = \frac{e^2}{\pi \hbar}$$

Quantum dot



- **Visibly discrete spectrum**
- **Tunable number of electrons**
  - Charging energy





Combinations?

- **Josephson Field-Effect transistor**

T.D. Clark, R.J. Prance, A.D.C. Grassie, *APL 1980*

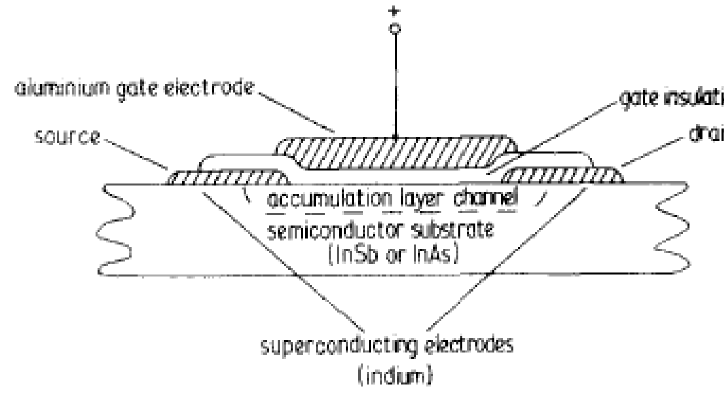


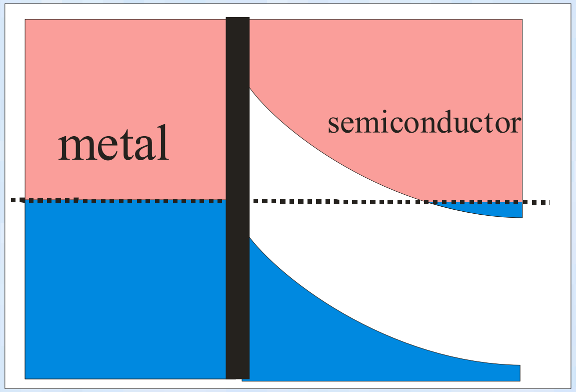
FIG. 1. Basic metal-oxide-semiconductor (MOS) JOFET configuration with Ohmic indium contacts to the source and drain; insulation 1000 Å SiO_2 or Si_3N_4.

- **90's – Contact 2D, please!**
- **Superconductivity + Quantum Point Contact**
- **Superconductivity + Quantum Dots**
- **Superconductivity+ multiterminal**

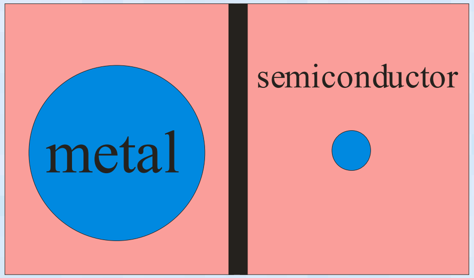
Shaping quantum devices in 2D gas
+
Using (free) quantum coherence of superconductors

Problems when combining

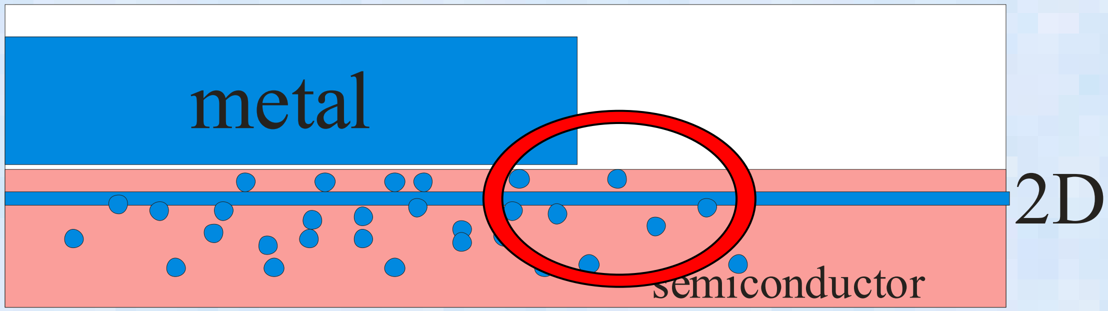
- Schottky barrier



- Fermi surface mismatch



- <u>Disorder near the interface</u>



Highlights: JoFET

- **L=350 nm, W=40 μm**

T. Akazaki. H.Takayanagi, and J. Nitta,
APL 1996

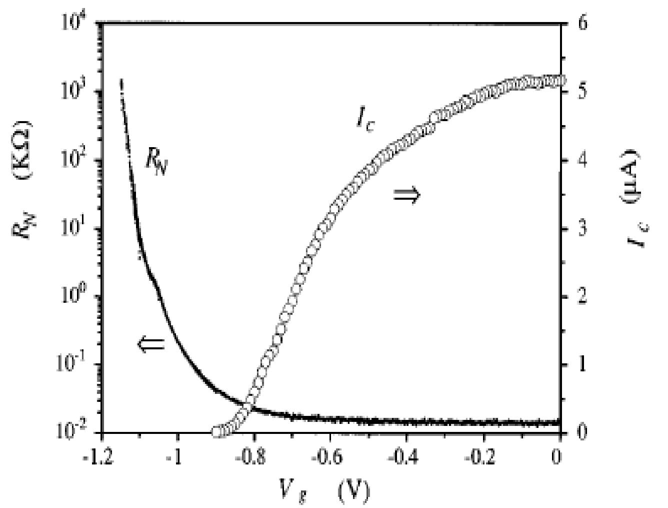
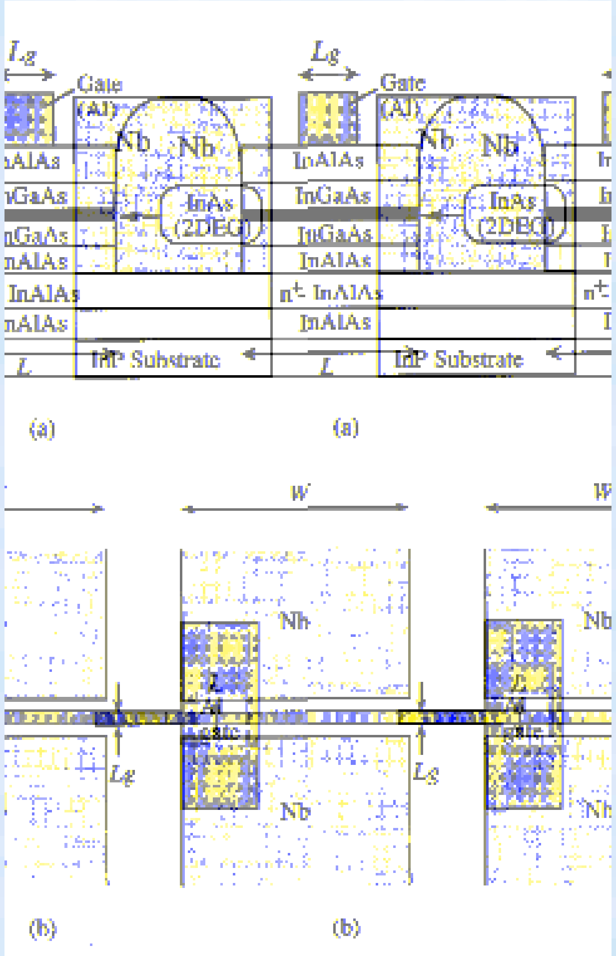


FIG. 4. Measured critical current and the junction's normal resistance at 1 K as a function of gate voltage.



HighLights: QPC

S. G. den Hartog, B. J. van Wees, Yu. V. Nazarov,T. M. Klapwijk, G. Borghs, ***PRL 1997***

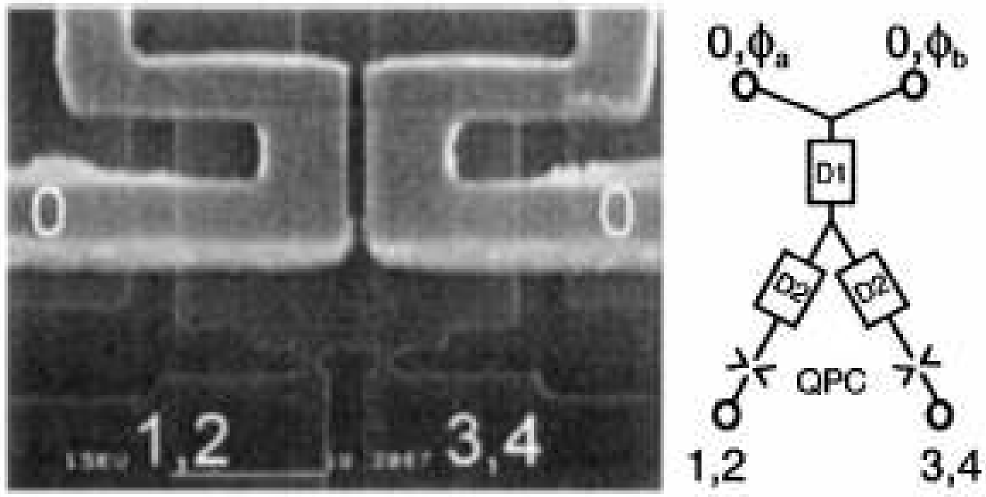
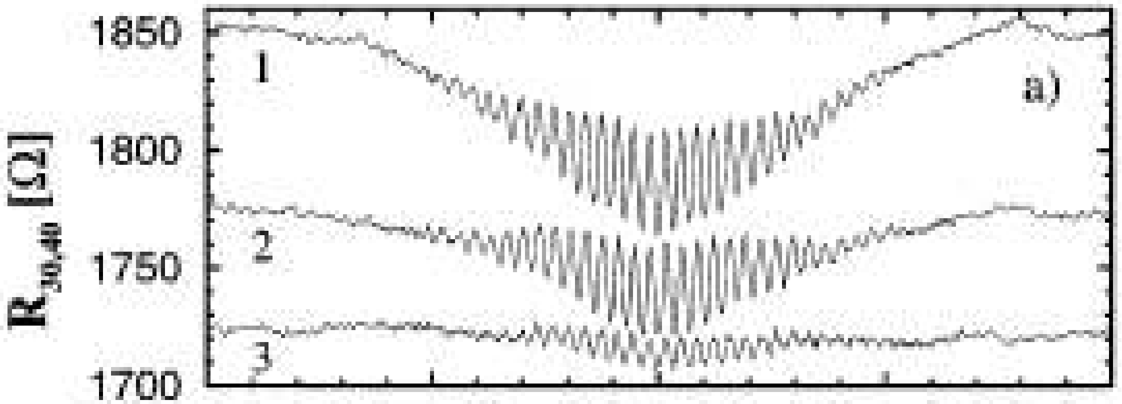


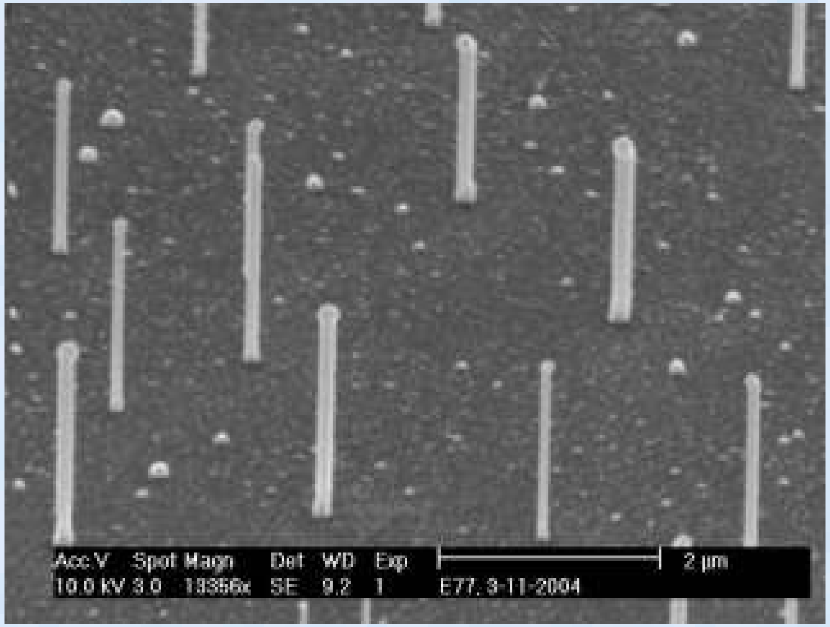
FIG. 1. Scanning electron micrograph of an interrupted super-conducting loop (0) connected via a disordered 2DEG and two ballistic QPC's to normal leads (1, 2, 3, and 4). The drawing ...ng of diffusive resistors

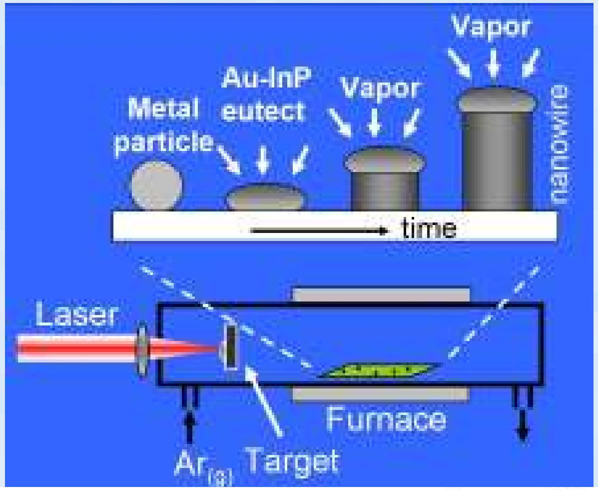


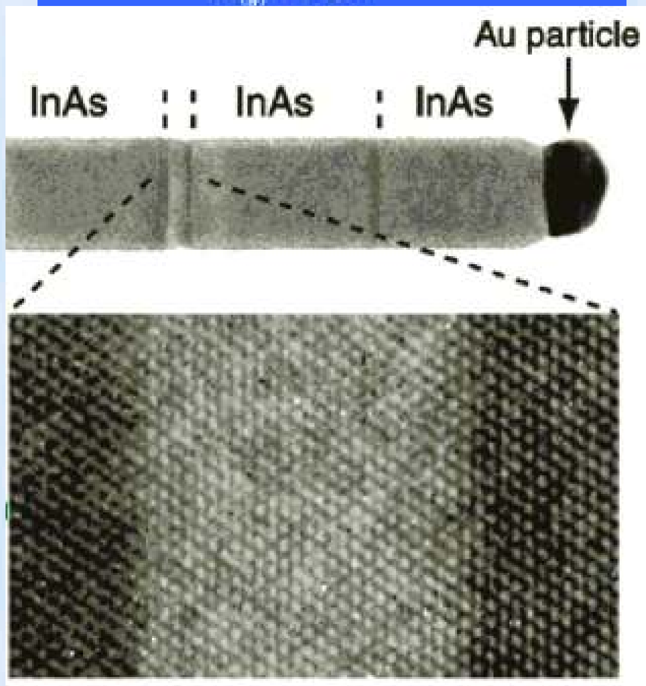
Dead end

Nanowires: optimistic

- **1d better than 2d**
- **Atomic accuracy**







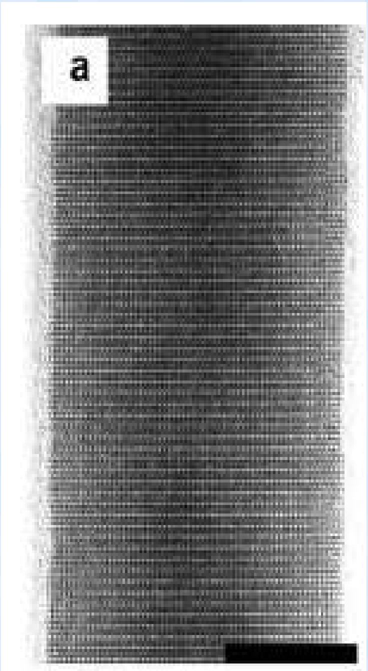
C.M. Lieber, Harward

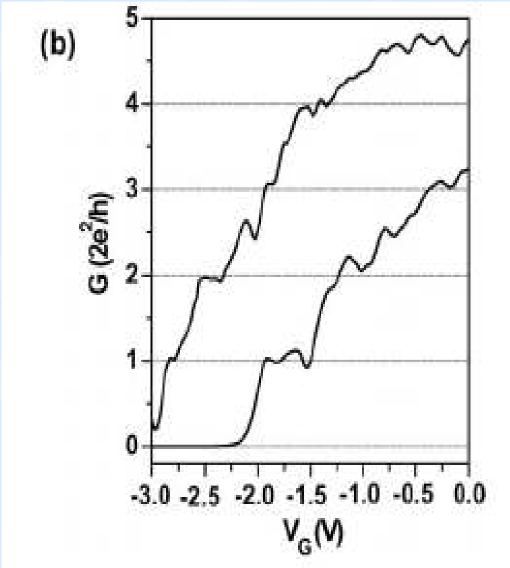
L. Samuelsson, Lund

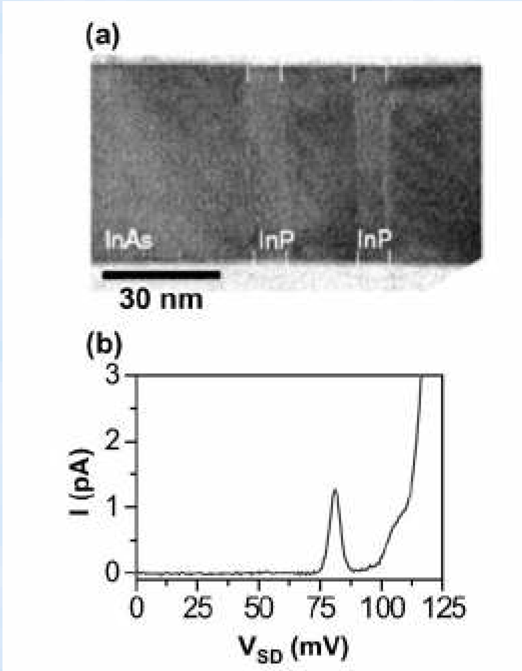
E.P.A.M. Bakkers, Eindhoven

Nanowires: pessimistic

- C. Thelander et al, *Sol. St. Comm. 2004*
- *unintentional doping*
- *short mean free path*







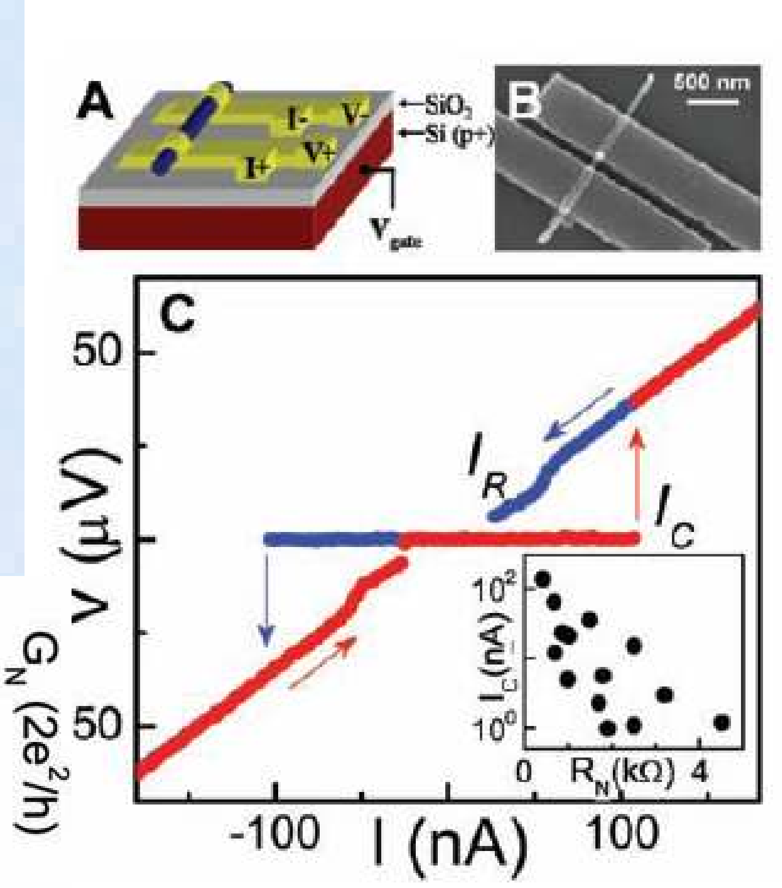
Nanowires in Delft

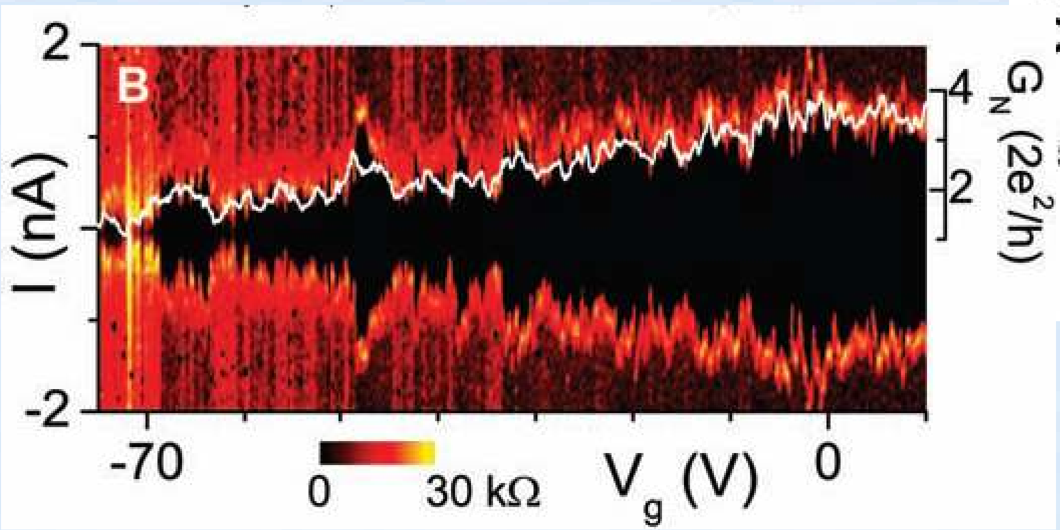
- **No growth**
- **No investigation**
- **Utilization**
  - single photons
  - single electrons
  - and holes
  - dots, turnstiles

JoFET in nanowires

Yong-Joo Doh, J. A. van Dam et. al, *Science 2005*

- supercurrent from the first try
- field-effect from the backgate



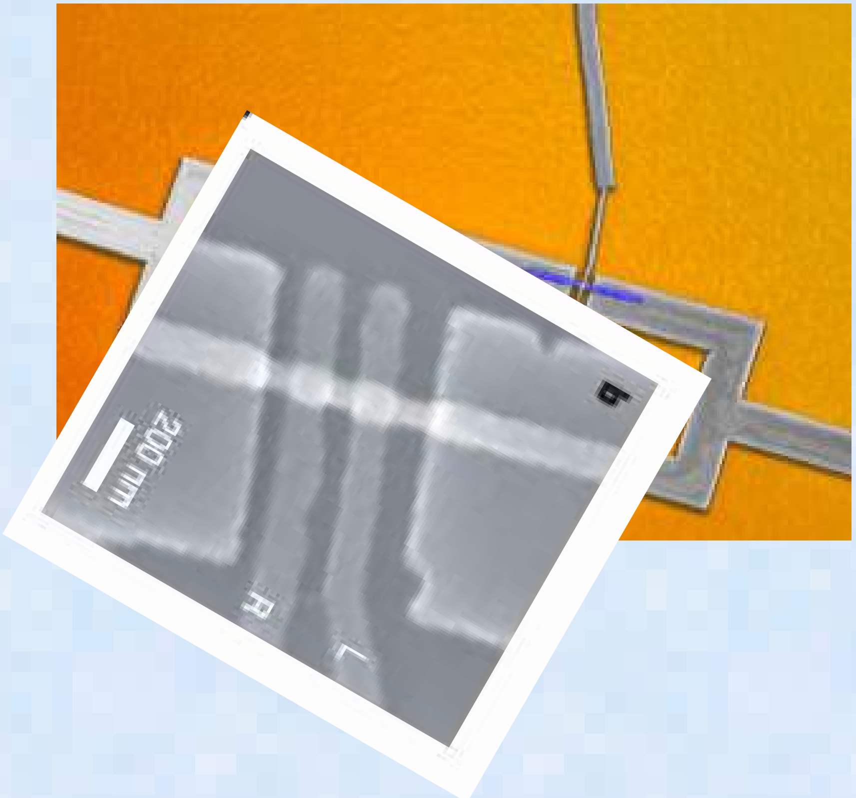


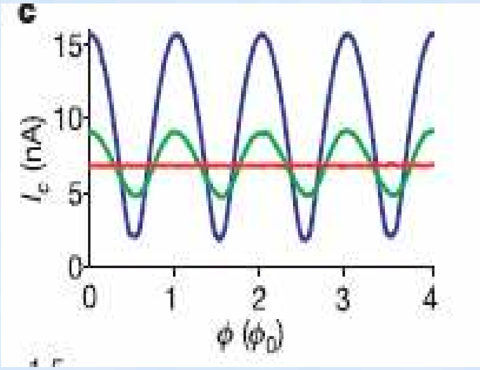
Our device

Jorden A. van Dam, Yuli V. Nazarov, Erik P. A. M. Bakkers,

Silvano De Franceschi & Leo P. Kouwenhoven, *Nature 2006*

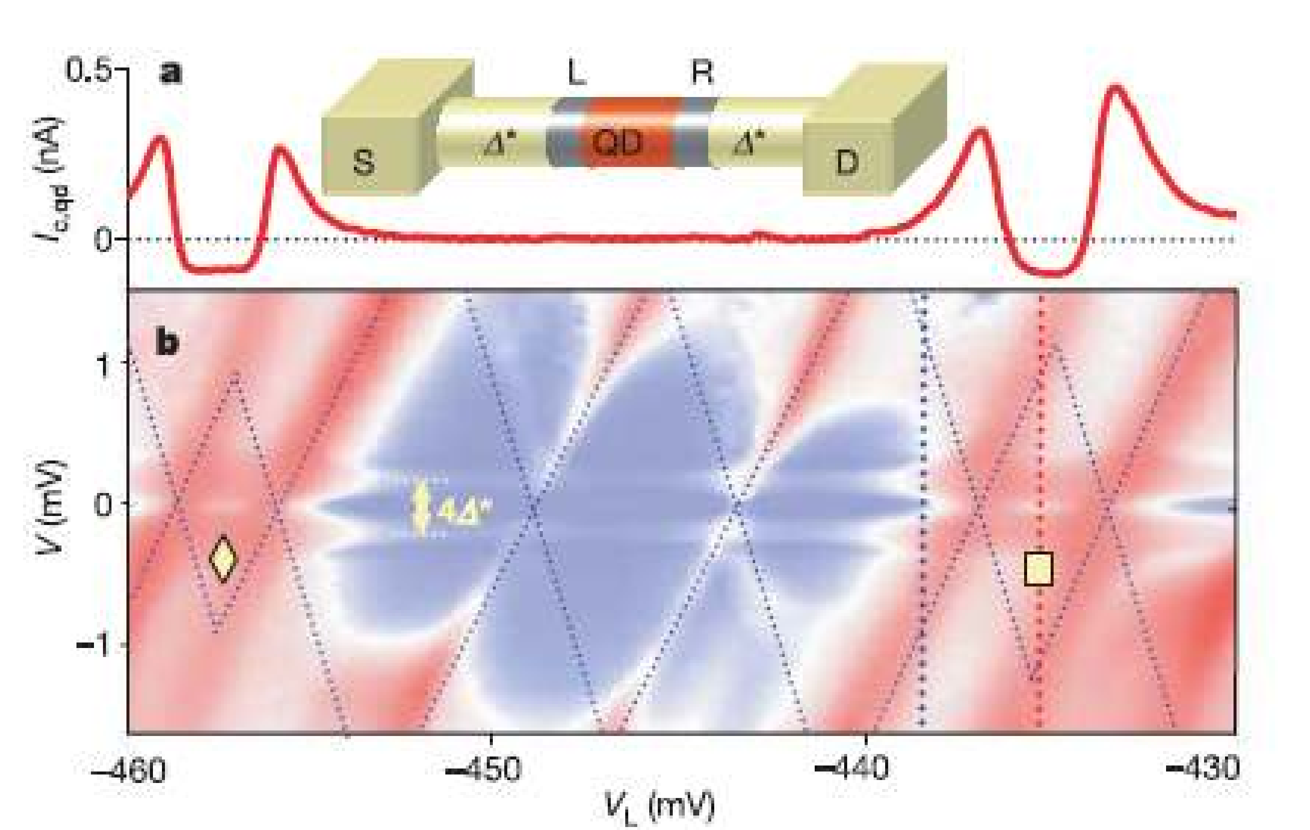
- SQUID
- measures supercurrents
- gates to junctions





To define a quantum dot

Measurement results: Supercurrent reversal



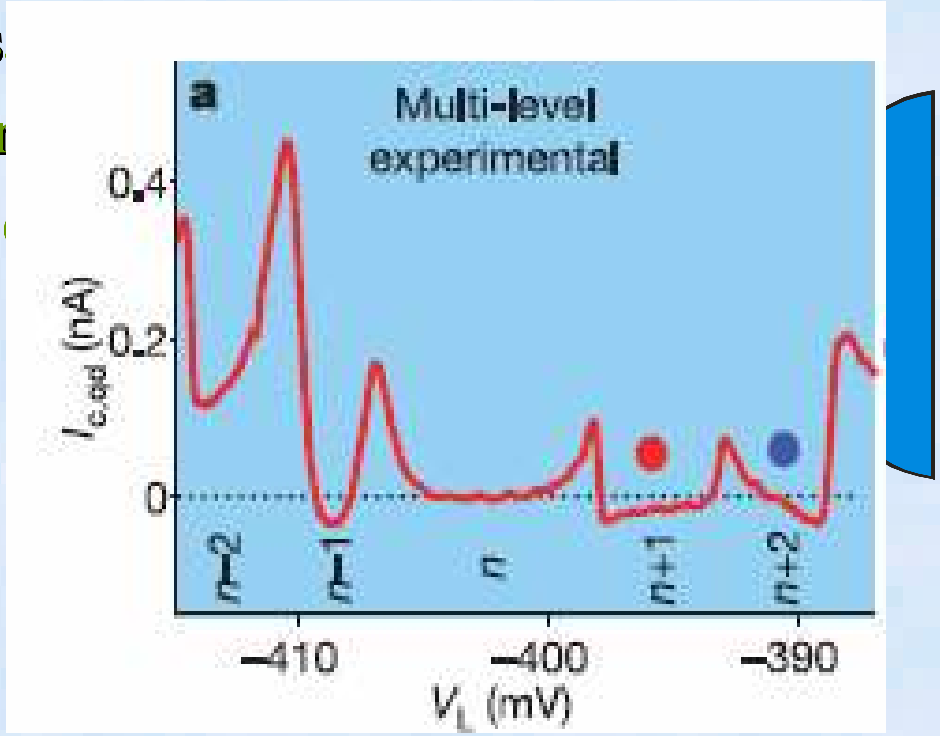
Negative supercurrent

- Negative amplitude?
- Energy balance
- π-junction(interesting,bistable)
- S-Ferromagnet-S stuctures
- A single ferromagnetic ato
- Early theories of quantum
- Superstitions in science

$$I = I_c \sin\phi$$

$$E = -\Phi_0 I_c \cos\phi$$

$$\min : \phi = 0 \; or \; \pi$$



Transport processes in superconducting q.d.

- **Tunneling Hamiltonian**

$$\hat{H}_T = \sum_n \int dk\, T_L^{(n)} (a_n^+ c_L(k) + h.c.) +$$
$$\int dk\, T_R^{(n)} (a_n^+ c_R(k) + h.c.)$$

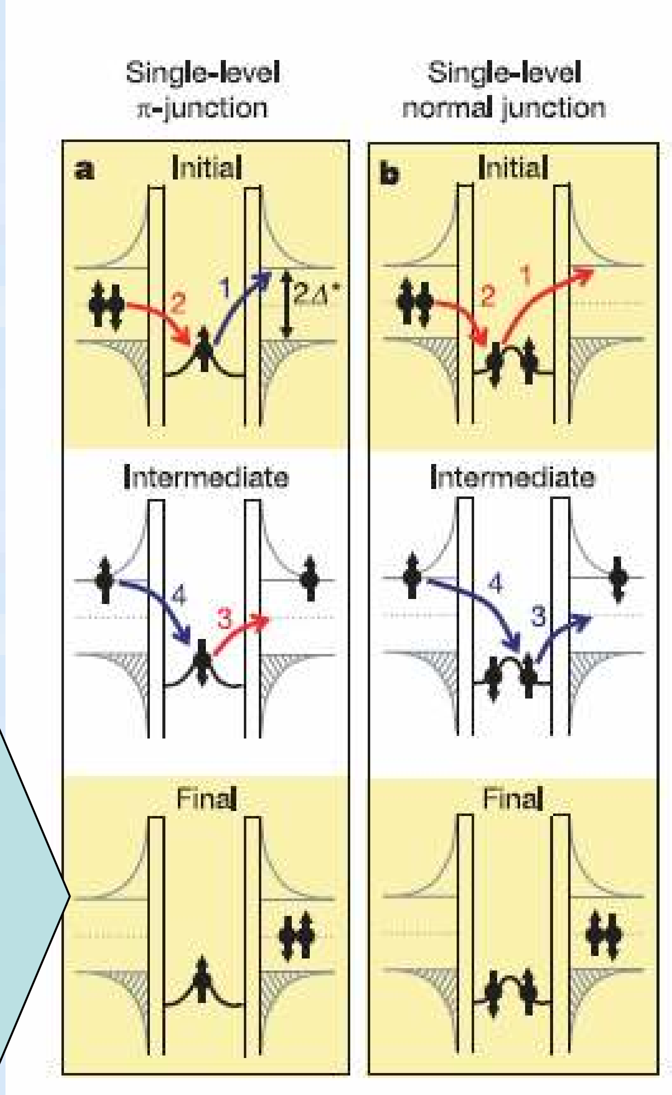
- **2 els x 2 barriers = 4 tunneling amplitudes**
- **either 1 or 2 levels involved**
- **different ordering of 4 tunnel processes: 24 possibilities**

Single-level q.d

- Cooper pair = spin singlet

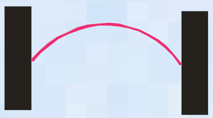
$$\frac{1}{\sqrt{2}}\left(\left|\uparrow\downarrow\right\rangle - \left|\downarrow\uparrow\right\rangle\right)$$

Spin order reversed, sign changed

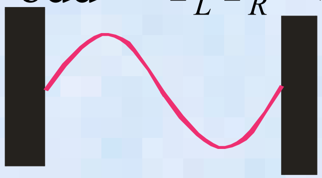


Many-level q.d.

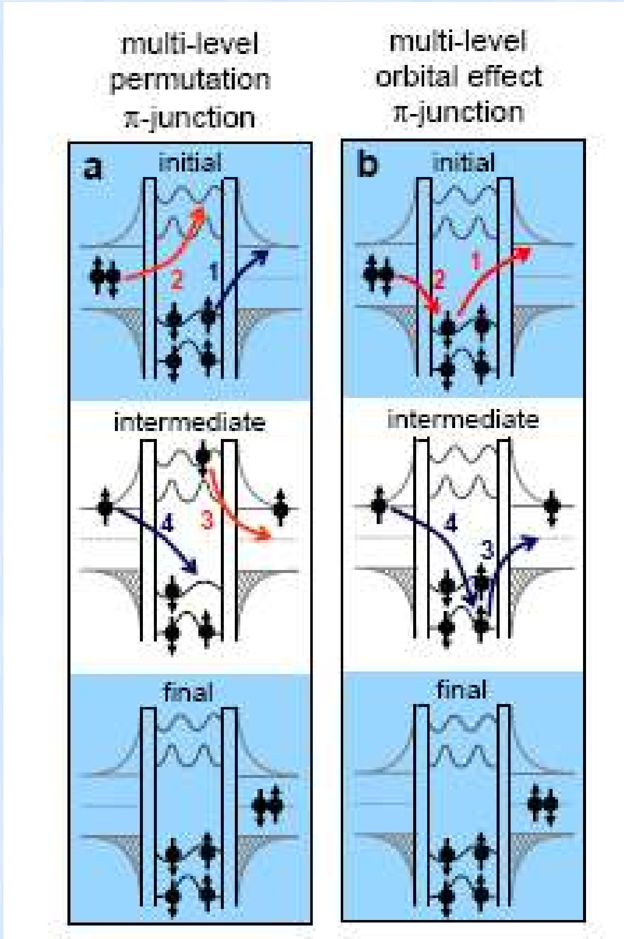
- **Levels of two kinds**
  - even $T_L^n T_R^n > 0$



  - odd $T_L^n T_R^n < 0$



- **Interference shows parity**
  - even-even or odd-odd
  - even-odd



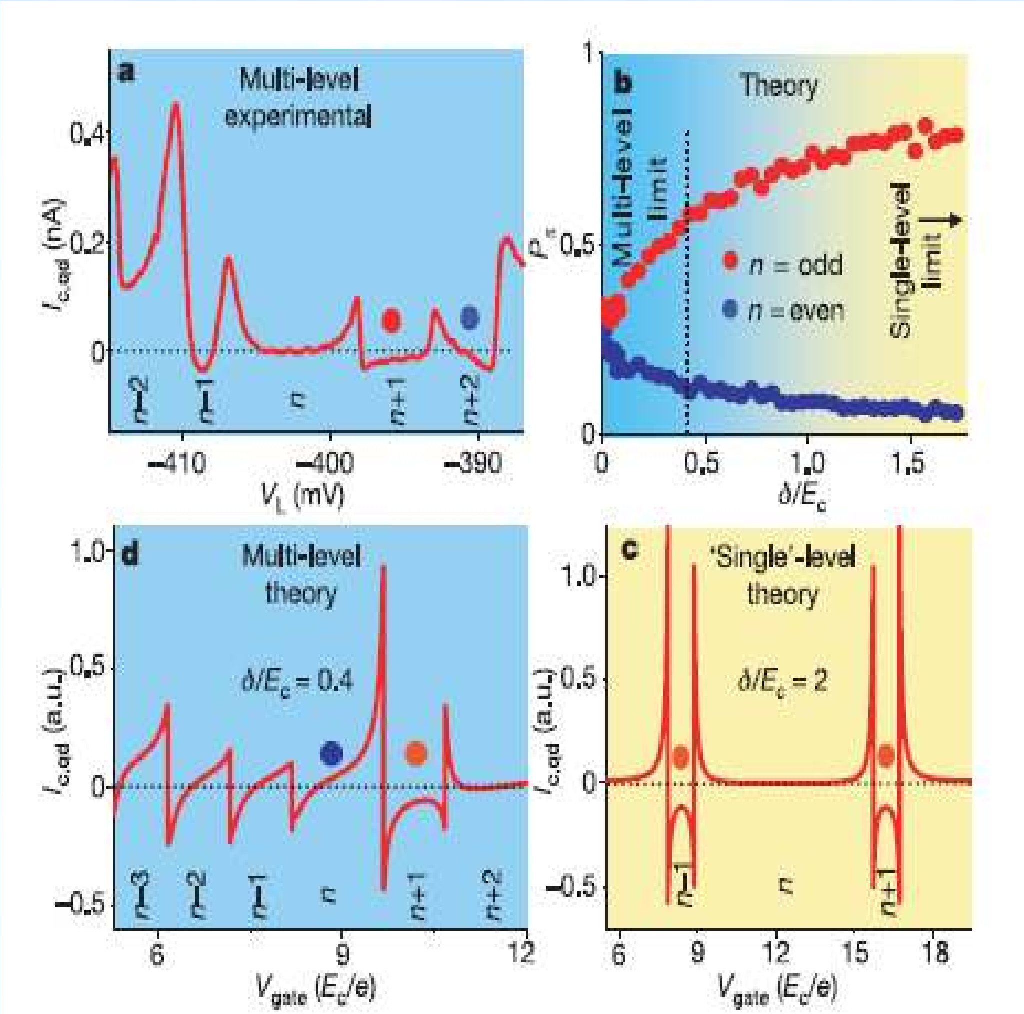
c Supercurrent sign

	even permutation	odd permutation
same parity	+	- (Fig. S3a)
opposite parity	- (Fig. S3b)	+

Results and simulations

- Chaotic dot
- δ -mean level spacing
- Effective number of levels

$\max(E_C, \Delta)/\delta$



Future

- π-bistability
- Odd-Even Bistability
- Spin-orbit effects on spin in the dot
- Spin manipulation by flux?