Metal: a box of surprises

Electrons in metallic nanostructures

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Sir Nevill Mott Lecture 2011

16 March 2011

Metal: a box of surprises

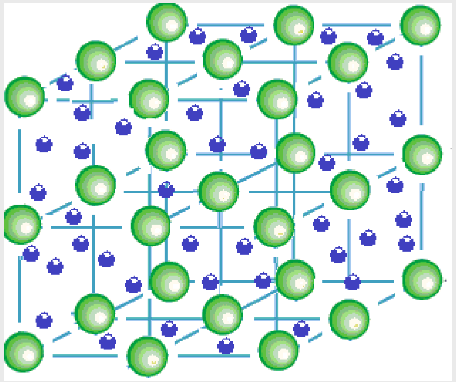
Electron transport in 2D metallic nanostructures

- Quest for the field effect in metals: from Charles Francis Mott (1902) to present
- Nanotechnology of ultra-thin metallic devices
- Room temperature quantized conductance in metallic nano-bridges
- Electric field effect in 2D metals

Hybrid metallic quantum nanostructures

- Quantum transport in disordered “Mott-Anderson” metals
- Hybrid Quantum Interference Devices with superconducting “mirrors” for continuous real time read out of Quantum Bits

Metal: a box of surprises

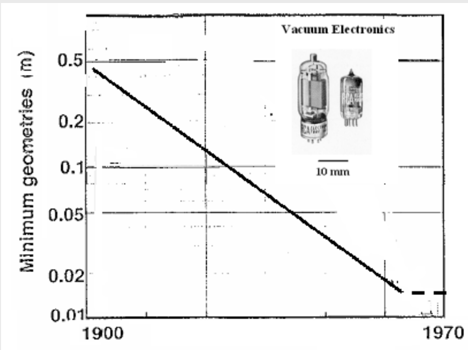


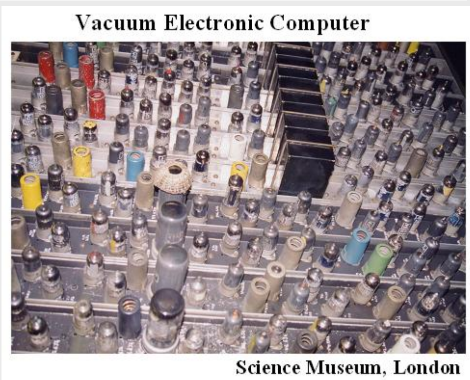
In my lecture I will focus on one of the scenarios *for nanoelectronics*, namely *the metallic scenario.*

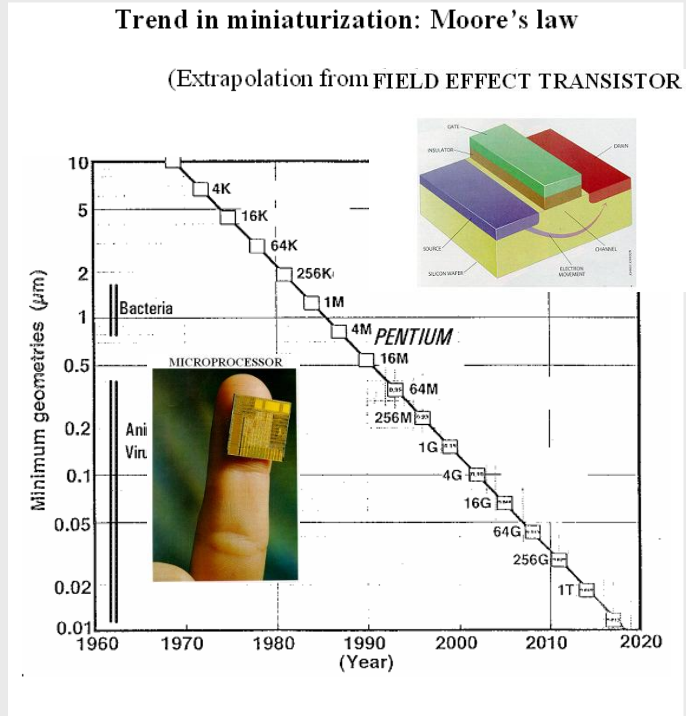
Why metals? If you consider devices made of semiconductors with *all three dimensions* at the nanometre scale you find them in the *insulating regime* because there are so few electrons. We run into a crisis similar to that with miniature vacuum electronic devices. There are too few electrons, about 10^{10} cm^{-3} can be generated in vacuum. It was the ability to control the conductance in semiconductors with much higher concentrations of n~10^{18} cm^{-3} electrons that led to a revolution in electronics.

In a metal concentration of electrons $n \leq 10^{23}$ cm^{-3}

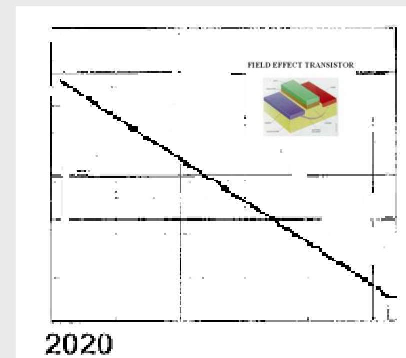
Vacuum electronics, semiconductor microelectronics ... metallic nanoelectronics?







?



Vacuum: **n ≈10^{10} cm^{-3}** Semiconductor: **n ≈10^{18} cm^{-3}** Metal: **n ≈10^{23} cm^{-3}**

If we follow "the smaller the device the higher concentration of electrons you need" trend, you have an answer to "why metals*?": in metals the concentration of electrons is up to five orders of magnitude higher than in semiconductors.* More than 80% of the Periodic Table are metals. The high electron concentration is intrinsic property of metals and does not require doping. The mean free path of up to 1 cm (!) has been achieved in metals.

Field Effect in Metals

N. F. Mott *A Life in Science*

<...> 'field effect'-which my father tried to develop in 19O2.*)

The electron was discovered about 1900, as a particle, which carried electricity <...>. It was known, too, that the electrical current in a metal wire was carried by electrons; <...>. So J. J. Thomson suggested to my father that he should make a thin film of some metal, and apply an electric field perpendicular to it, which would empty the surface area of some of its electrons and, hopefully, make the conductivity smaller in the plane of the film. But no effect was to be found. We know now that the density of electrons in a metal is much too big for the expected effect to be observable; for semiconductors, in which of course the density of electrons is much smaller, a similar effect is found and indeed used. It is now called 'the field effect'.

Re-visiting field effect in metals

V. T. Petrashov, Lancaster conference on Nanoelectronics, January 2003

http://www.lancs.ac.uk/users/esqn/nanoelectronics/talksaz.htm   Cond-mat 0910.1232

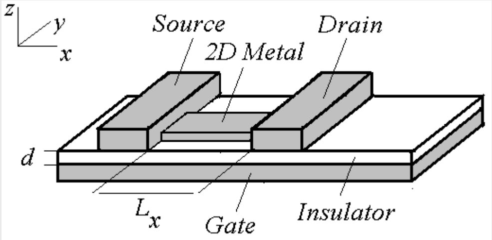


Fig. Metallic Field Effect Transistor

A device is shown in Fig. and consists of a thin metallic bridge of thickness L_z, a gate, and an insulator of thickness *d*. The extra charge that can be induced in the bridge is *limited by the breakdown electric field, E_0*:

$$\delta Q_{\max} = e\delta N_{\max} = CV_0 = \varepsilon \frac{L_x L_y}{d} V_0 = \varepsilon A E_0$$

$$\left\langle \frac{\delta n}{n} \right\rangle_{\max} = \frac{\varepsilon E_0}{e L_z n} \qquad \sigma = \frac{n e^2 \tau}{m}$$

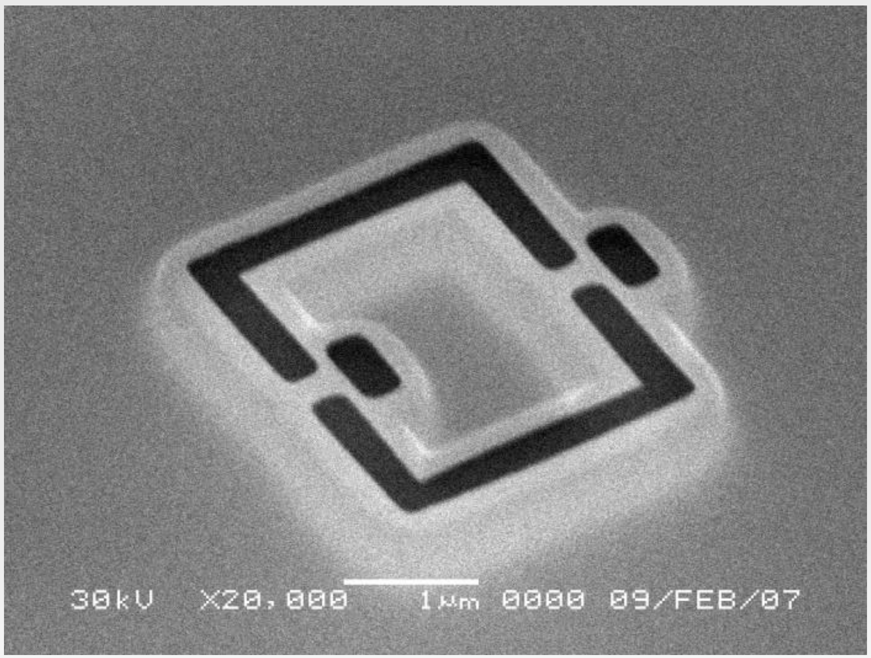
To achieve an electric field effect with realistic breakdown electric field one needs an ultra-thin film metallic bridge. The film has to be *several atomic layers thick. 2D metallic films may show completely different properties and are in essence novel materials even fabricated using elementary metals; however it is a great challenge to produce such films since they are thermodynamically unstable.*

E-Beam lithography using a mask comprised of positive resist and germanium layer

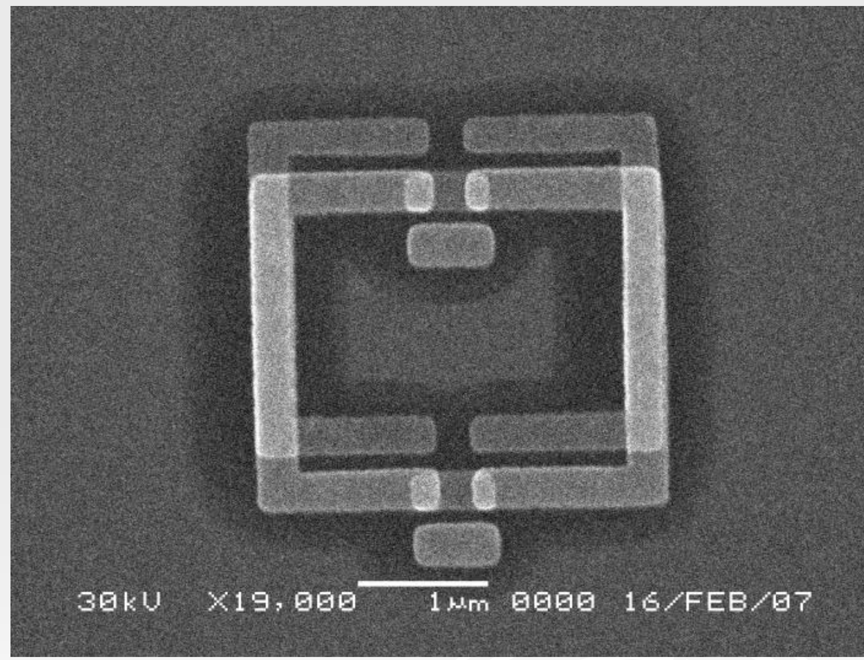
R. Shaikhaidarov and V. T. Petrashov, RHUL

Step 1 **Step 2** **Step 3** **Step 4** **Step 5** **Step 6**

Practical nanofabrication



(a)



(b)

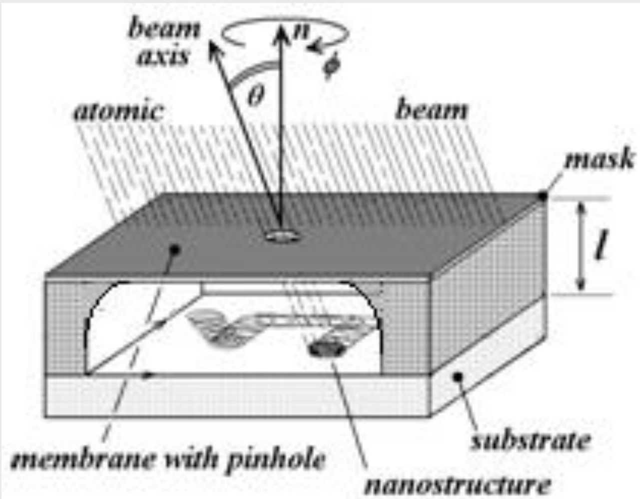
(a) Resist-Germanium system before shadow evaporation (Step 4). Pattern made using e-beam exposure, “wet” chemical etching followed by dry plasma etching

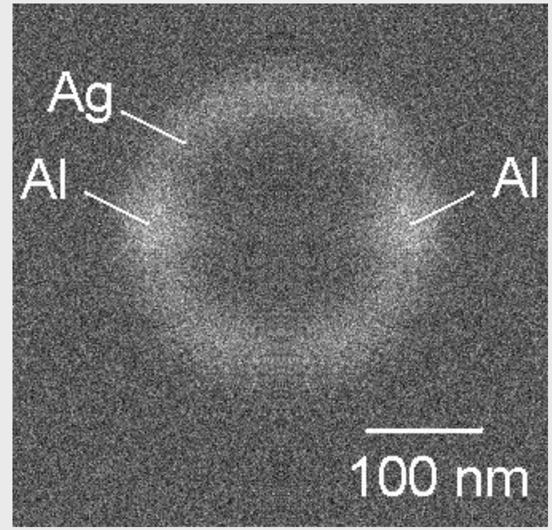
(b)

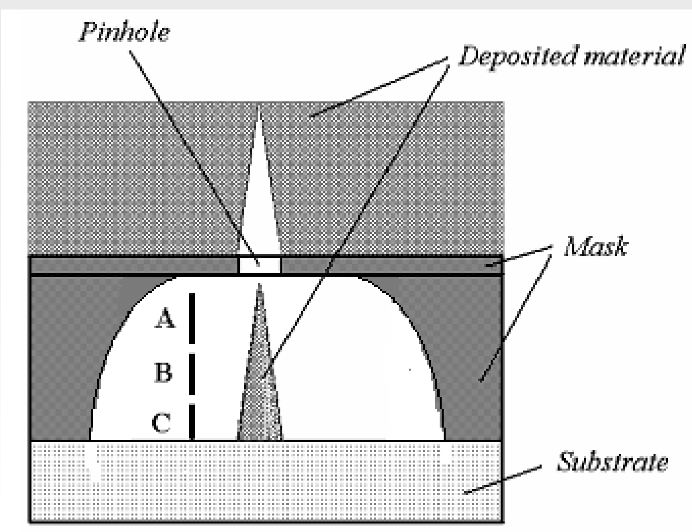
(b) Metallic nanostructure after lift-off (after step 6)

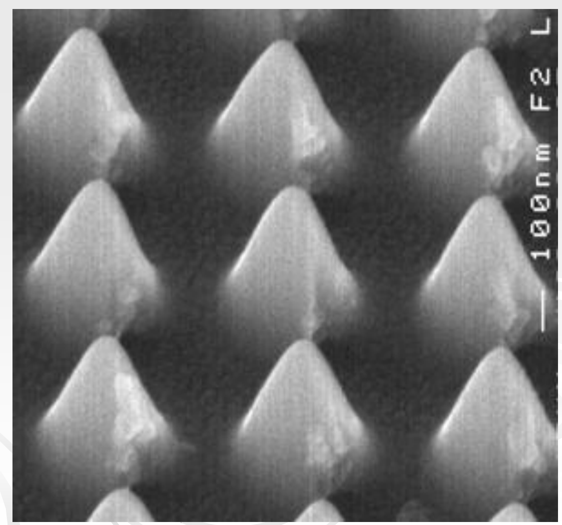
Painting with atomic nano-beams

V. T. Petrashov, *Microelectronic Engineering MNE96 (Elsevier), vol. 35, 1997*



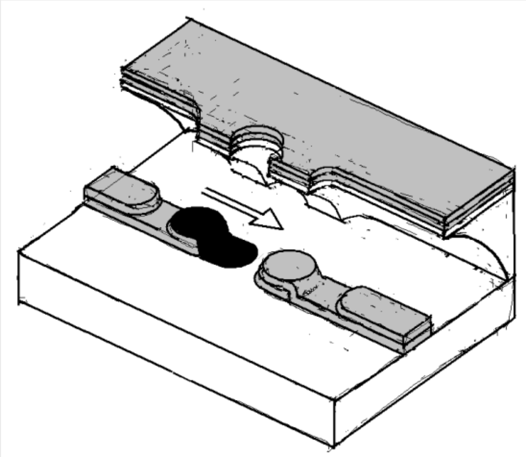


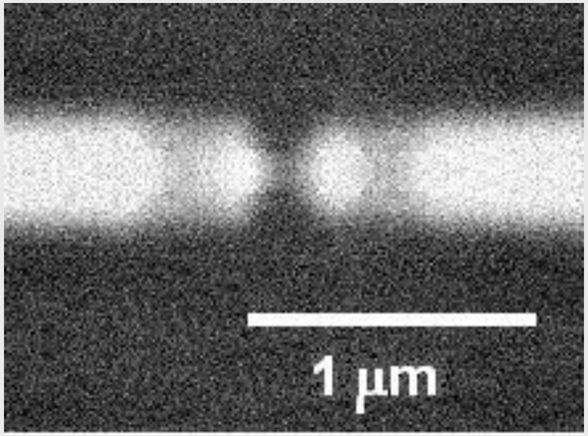


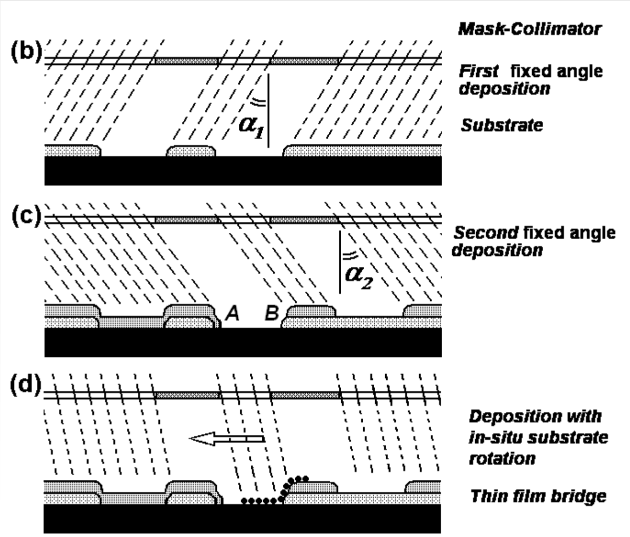


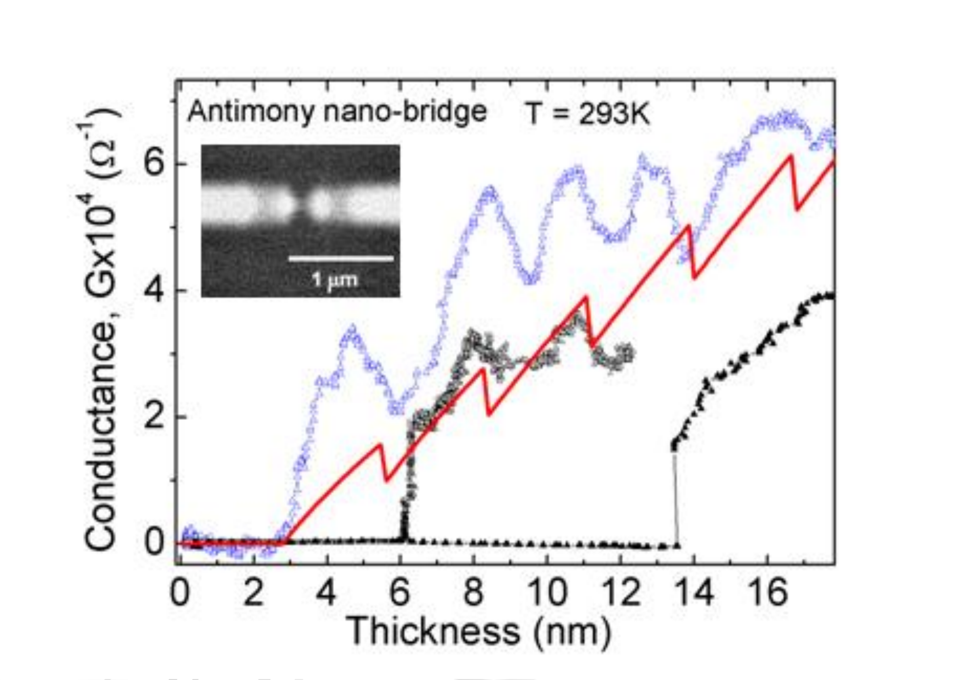
Fabrication of stable 2D metallic nanobridges
Observation of quantum conductance oscillations

I. A. Sosnin. R. Berger, V. T. Petrashov, Royal Holloway, University of London (2003)





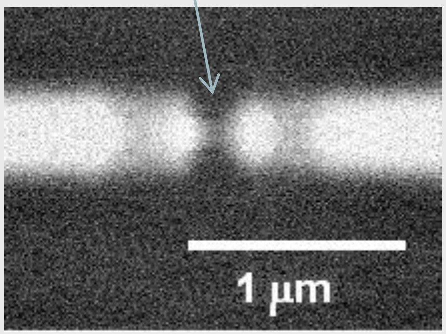


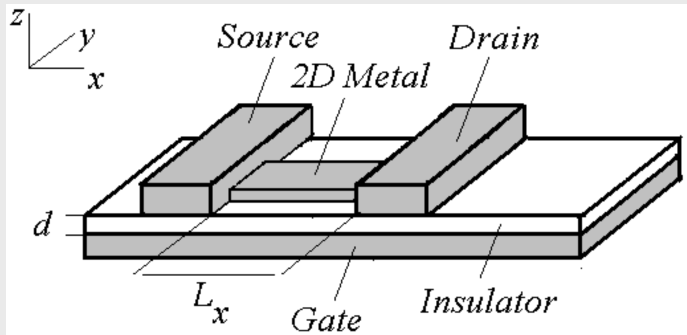


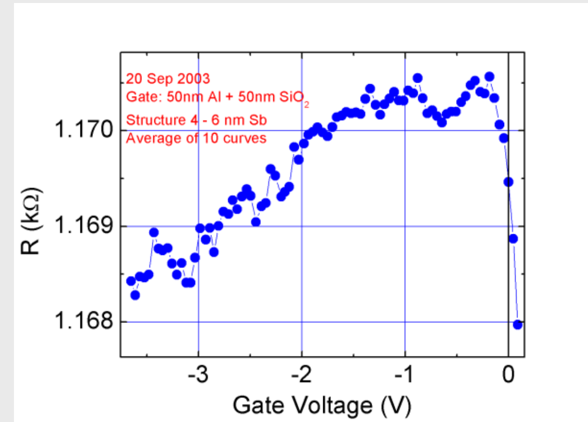
Electric field effect in antimony nano-bridges

I. A. Sosnin. R. Berger, V. T. Petrashov
Royal Holloway, University of London (2003)

2D Sb nano-bridge



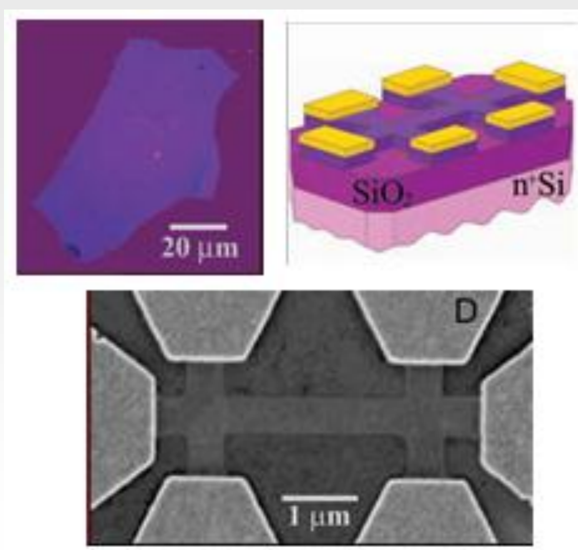


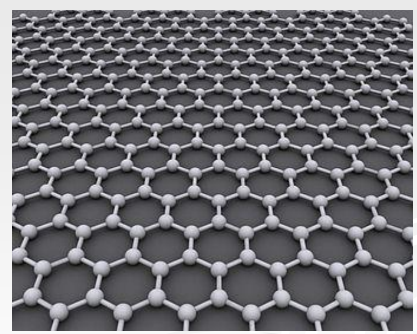


Electric Field Effect in Atomically Thin Carbon Films

K. S. Novoselov, A. K. Geim, S. V. Morozov, D. Jiang, Y. Zhang,S. V. Dubonos, I. V. Grigorieva, A. A. Firsov

SCIENCE, VOL 306, 22 OCTOBER 2004 www.sciencemag.org





UK-Russia researchers working on the physics of metallic nanostructures

Andrei Geim, VTP

VTP, Sergei Dubonos

Vladimir Antonov, VTP,
Kostya Novoselov, Rais Shaikhaidarov

Igor Sosnin VTP

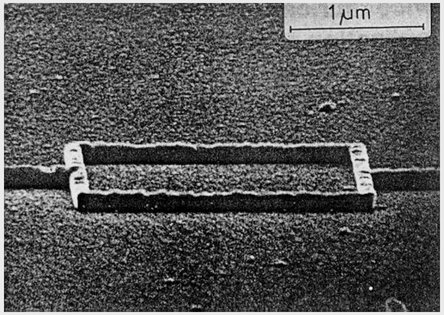
The Nobel Prize in Physics for 2010 was awarded to Andre Geim and Konstantin Novoselov

“for groundbreaking experiments regarding the two-dimensional material graphene".

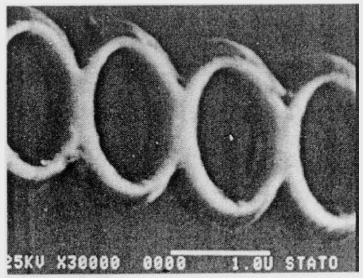
Nobel Prize Ceremonies, Stockholm, December 2010

Quantum metallic nanostructures

Single layer metallic mesoscopic devices of the “first generation”



E Krechmer, A Erko, V T Petrashov, Ha Beneking, APL (1984)



V T Petrashov, B Nilsson, J B Hansen and T Claeson, SQUID-85

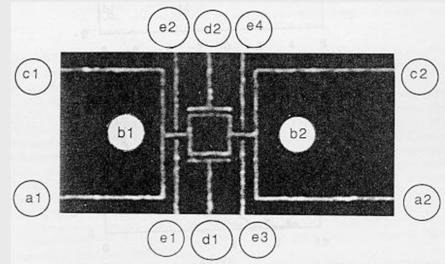
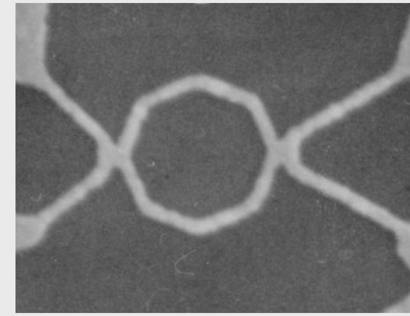


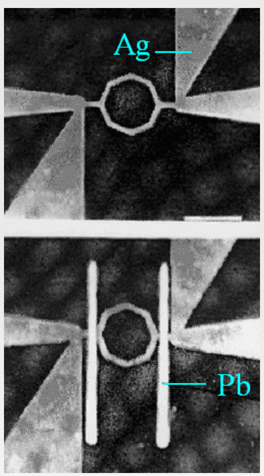
Figure 1. A SEM picture of the microstructure, in this case fabricated in Bi. The widths of the lines are about 60 nm and the thicknesses 25 nm. The lengths of the loop sides and the adjacent capacitor probes are 600 nm. Gate voltages can be supplied to d_1 and/or d_2. e_1–e_4 may be used for screening.

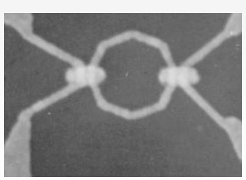
V T Petrashov, V N Antonov, and B Nilsson, (1991)



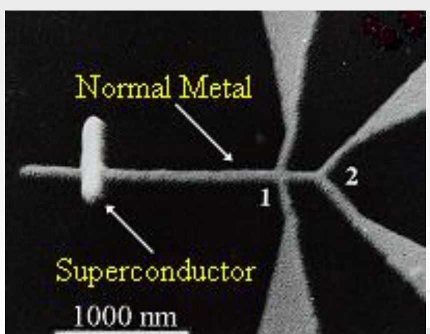
V T Petrashov, et al (1996).

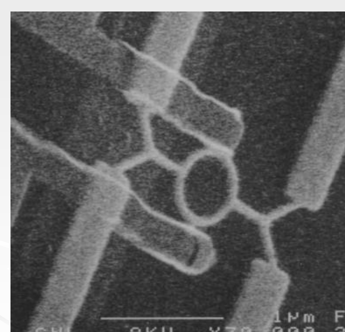
Hybrid metallic nanostructures

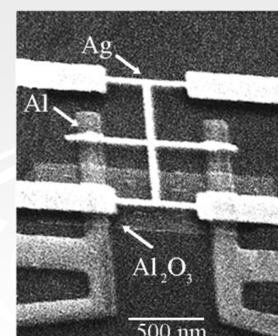




The ability to align different layers with a precision better than 50 nanometres during electron-beam lithography (V. T. Petrashov, V. N. Antonov (1990) made it possible to introduce additional elements of different materials into mesoscopic structures in a controlled way and thereby explore combinations of materials with different electronic and magnetic properties

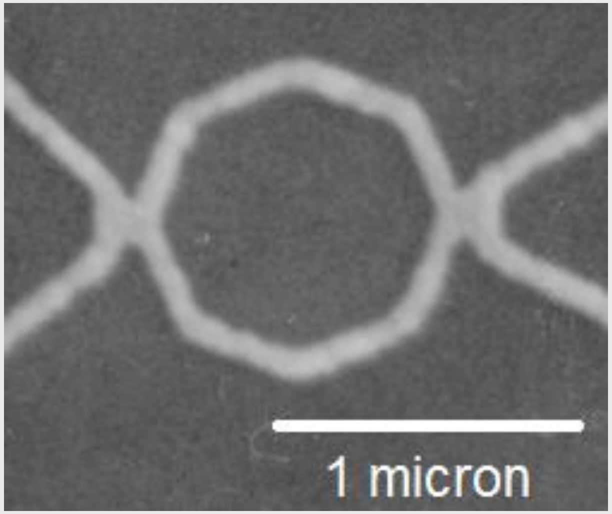


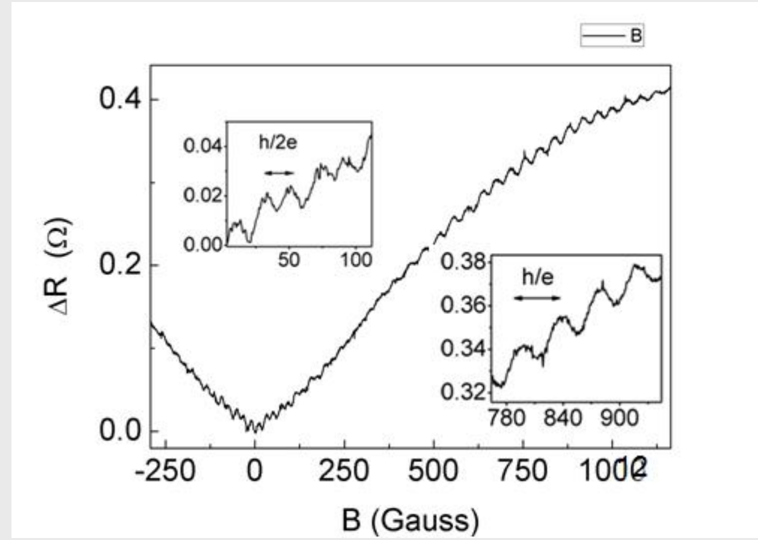




V T Petrashov, et al (1992, 1993, 1994, 1995, 1996).

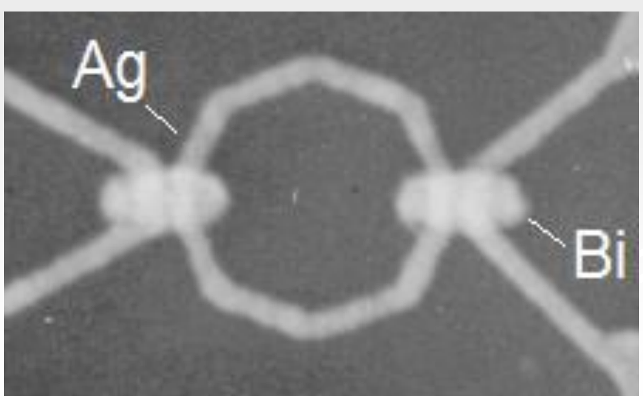
Aharonov-Bohm effect in small disordered metallic rings

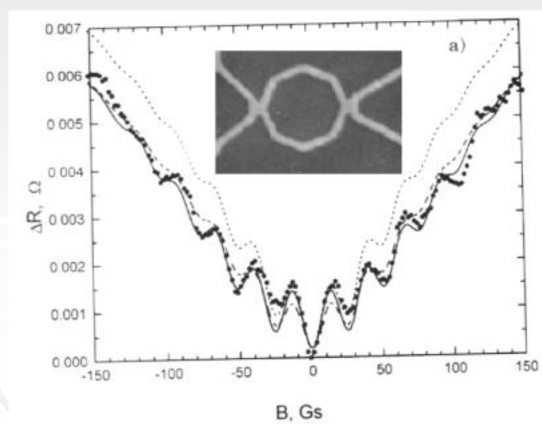


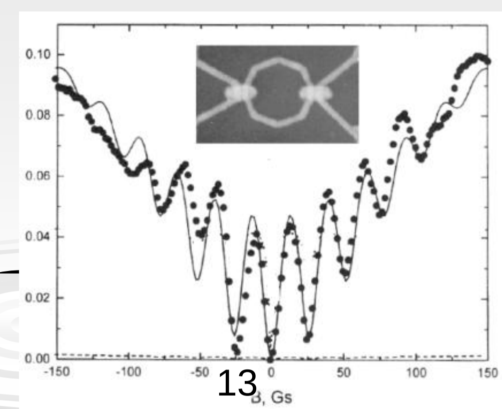


“Giant" Aharonov-Bohm effect in mesoscopic silver rings with bismuth electrodes

V. T. Petrashov, V. N. Antonov, R. Sh. Shaikhaidarov, S. V. Maksimov
P. Meeson, R. Souhami and M. Springford
Europhys. Lett., ***34 (8), pp. 593-598 (1996)***

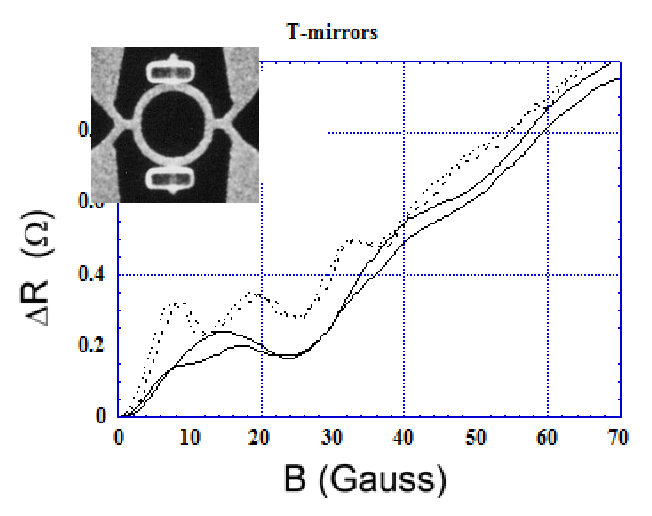




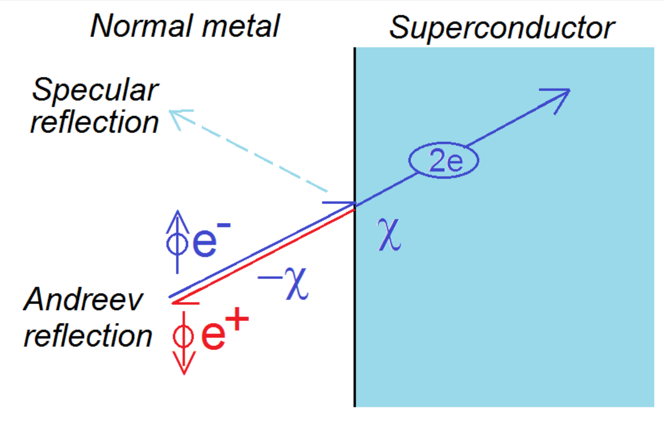


h/4e oscillations and Andreev reflection

V. T. Petrashov, V. N. Antonov, P. Delsing and T. Claeson, Phase Memory Effects in Mesoscopic Rings with Superconducting Mirrors, *Phys. Rev. Letters,* **70**, 347 (1993).



Quantum oscillations in the resistance of a silver ring with transverse superconducting "mirrors" at different measuring currents



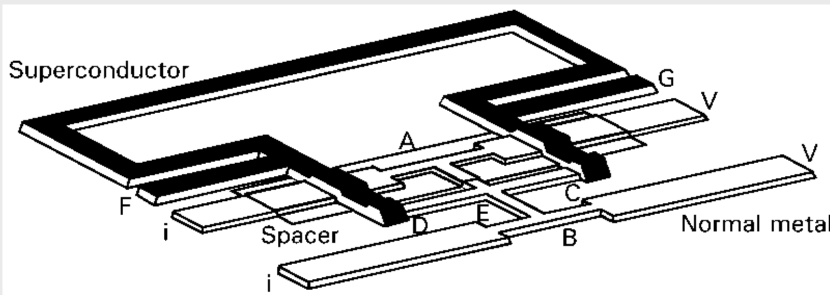
Andreev Reflection

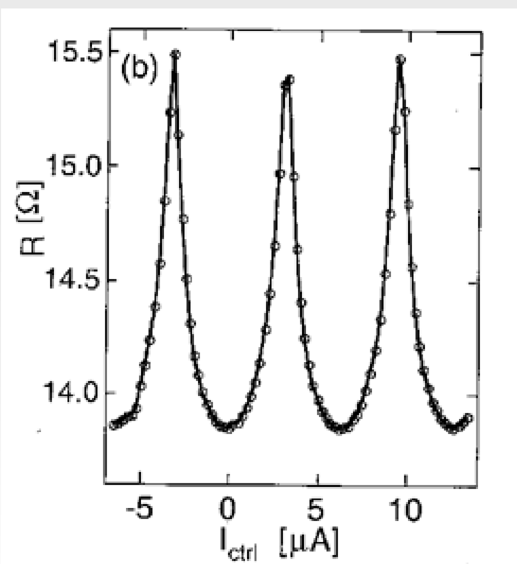
Phase transfer from superconducting condensate to quasiparticles

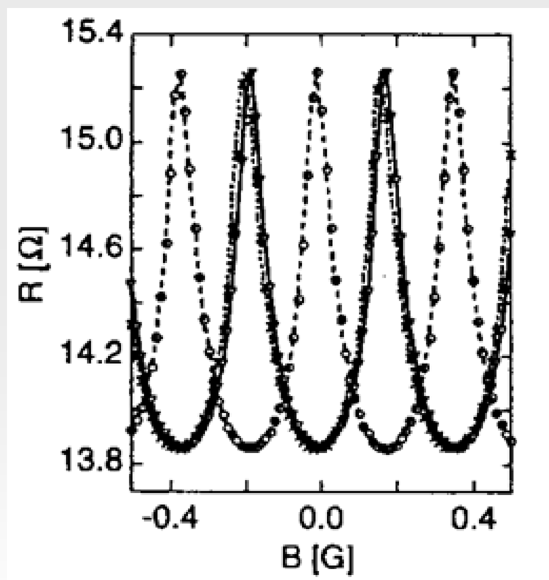
Mesoscopic interferometer with superconducting mirrors
(“Andreev interferometer”)
An alternative to Superconducting Quantum Interference Device (SQUID)

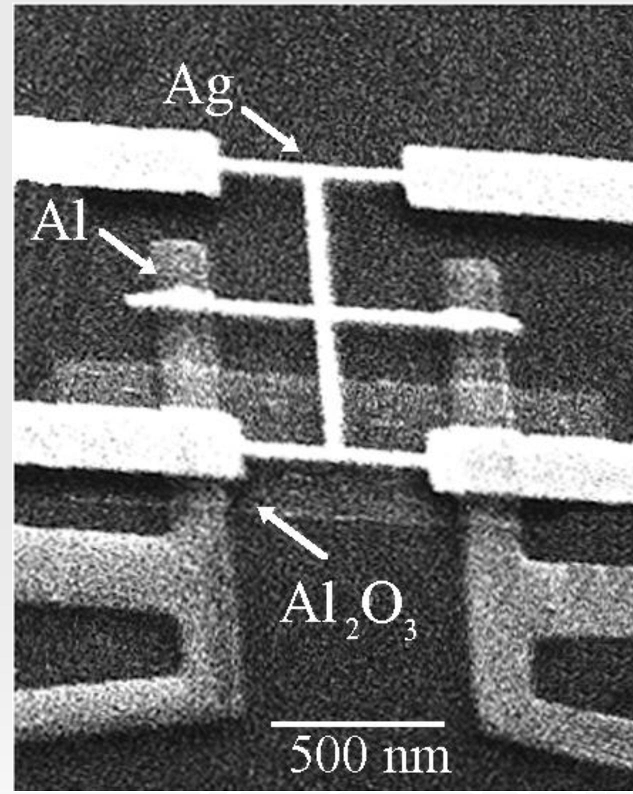
V T Petrashov, V N Antonov, P Delsing, and T Claeson; Phys Rev Letters, 74, 5268 (1995)

Phase-Controlled Conductance of Mesoscopic Structures with Superconducting Mirrors







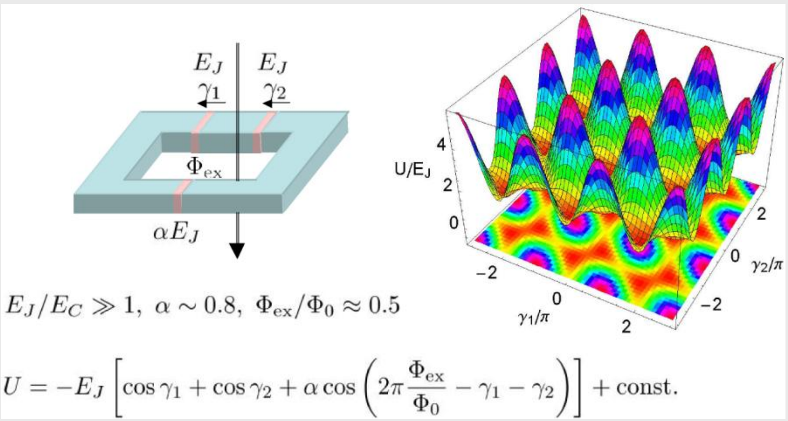


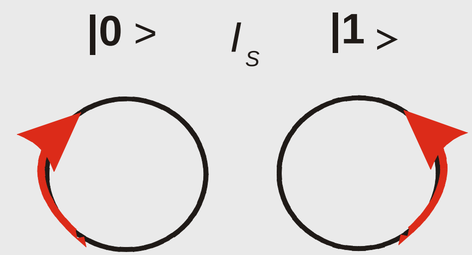
$$\varphi = 2\pi \frac{\Phi}{\Phi_0} + 2\pi \frac{LI}{\Phi_0}$$

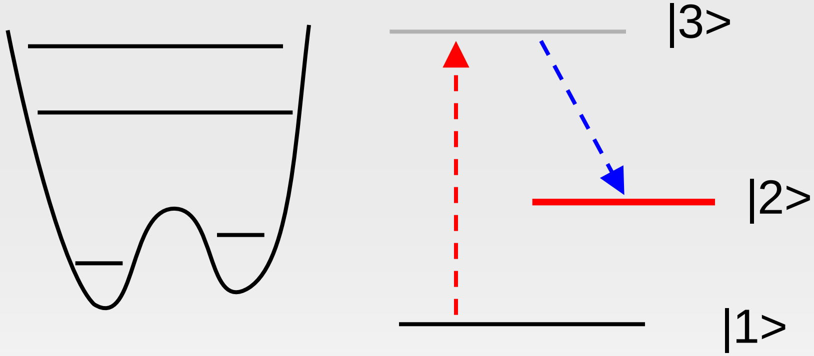
Superconducting artificial “atoms”

Josephson-junction Quantum bits (Qubits)

Flux qubits







Λ-type atom

Quantum states with clockwise and anticlockwise persistent current circulation in superconducting loops interrupted by Josephson junctions can be used for quantum computation

Low back action nondemolition read-out of persistent currents is in demand

Mooij et al. Science 285, 1036 (1999)

Andreev interferometer for read out of persistent current states in Josephson circuits

V. T. Petrashov, K. G. Chua, K. M. Marshall, R. Sh. Shaikhaidarov and J. T. Nicholls

Phys. Rev. Lett. 95 147001 (2005)

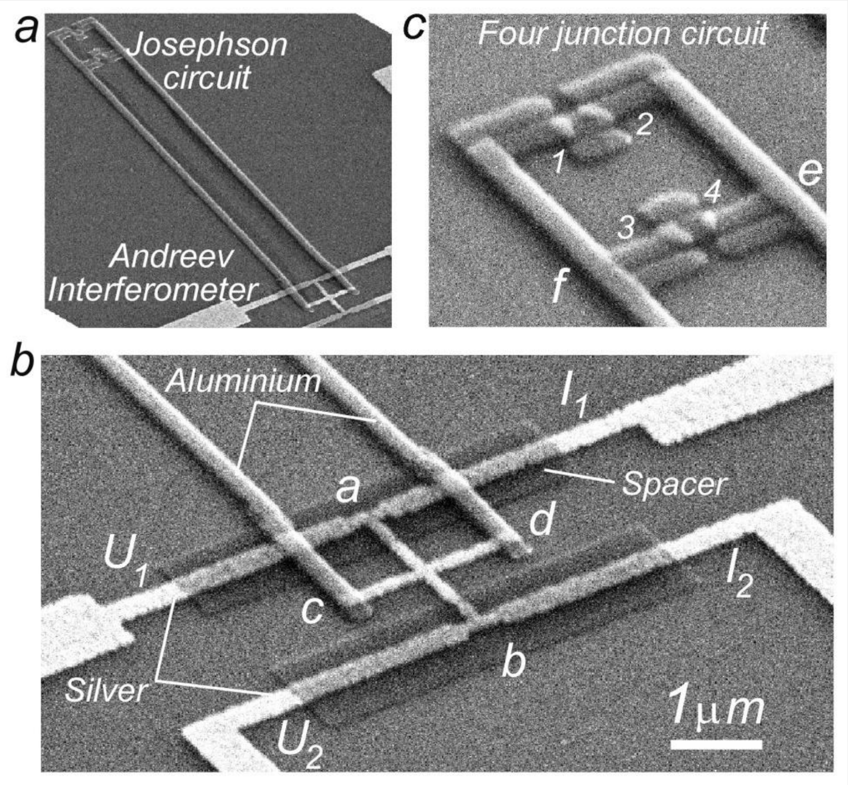


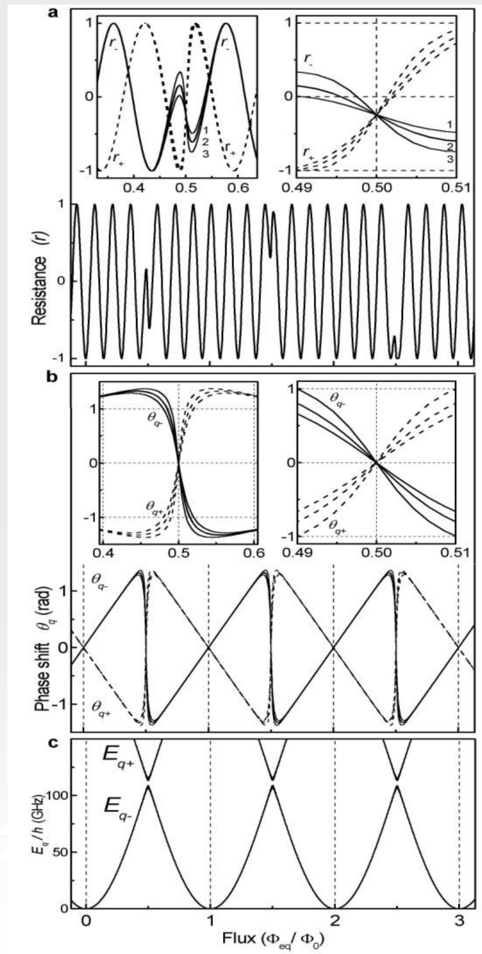
Figure a, General view. b, Andreev interferometer. The resistance *R* between *a* and *b* is measured using current (*I1, I2*) and voltage probes *(U1, U2).* c, Superconducting quantum loop interrupted by Josephson junctions. The superconducting phase difference between *e* and *f* is measured with the Andreev interferometer

Read out of persistent current states
Experimental results vs model calculations

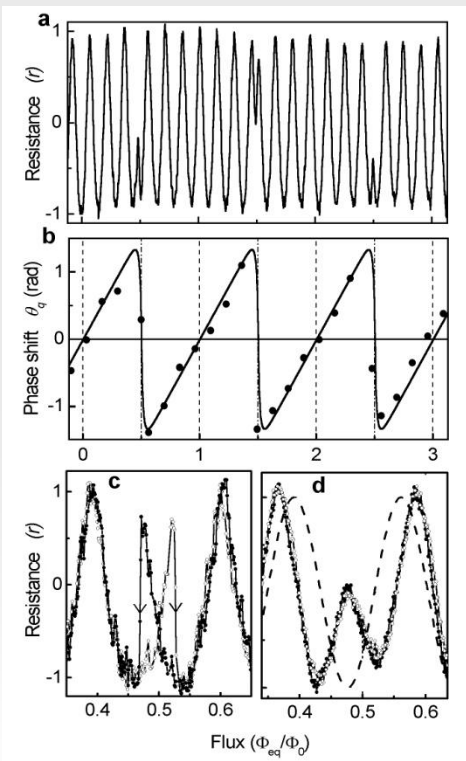
V. T. Petrashov, K. G. Chua, K. M. Marshall, R. Sh. Shaikhaidarov and J. T. Nicholls

Phys. Rev. Letters, (2005)

Model calculations



Experiment



Model calculations:

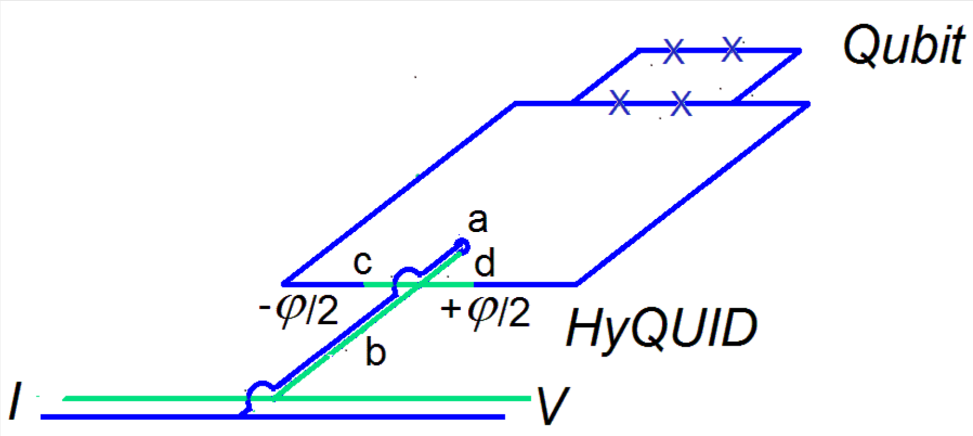
a, Oscillations of the normalised resistance in the ground energy state as a function of the normalised external flux . The insets show detail of oscillations in the ground (solid lines) and excited states (dashed lines) for different values of

b, Phase shifts in the ground and excited states; the insets show greater detail.

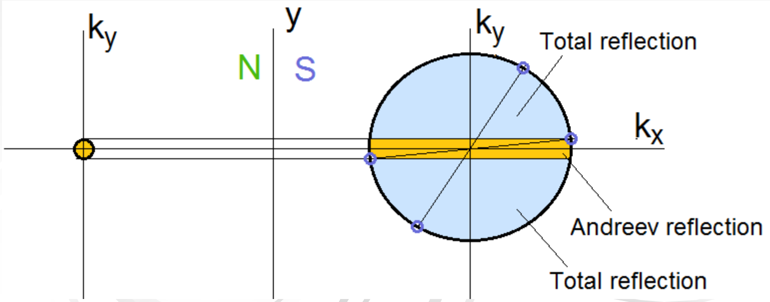
c, The energy spectrum.

Hybrid Quantum Interference Device
(HyQUID)

V. T. Petrashov
Royal Holloway, University of London, TW20 0EX UK (2009)

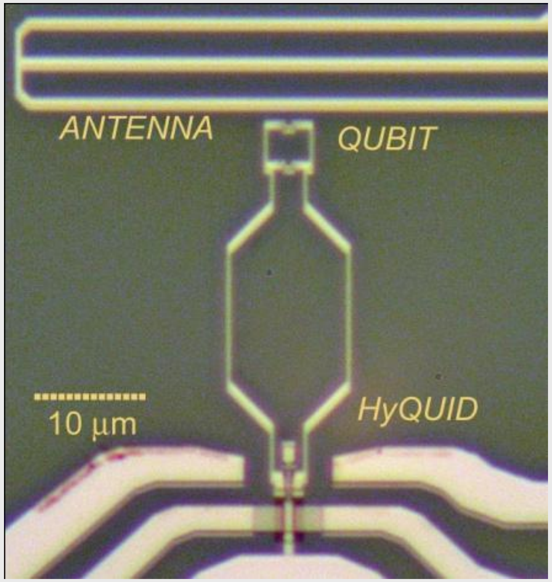


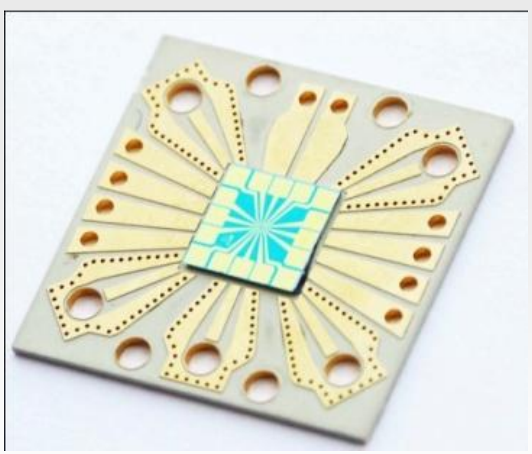
1. Negligible electromagnetic coupling to the noisy measuring circuit.
2. Suppressed Nyquist back action using
   i) Small enough normal part length to increase the mini-gap and super-current in N
   ii) One of the electrodes made of superconductor to decrease dephasing from the reservoirs
   iii) Semimetal for normal part to decrease quasiparticle concentration.
   iv) Fermi surfaces mismatch decreasing perturbation of superconducting condensate:

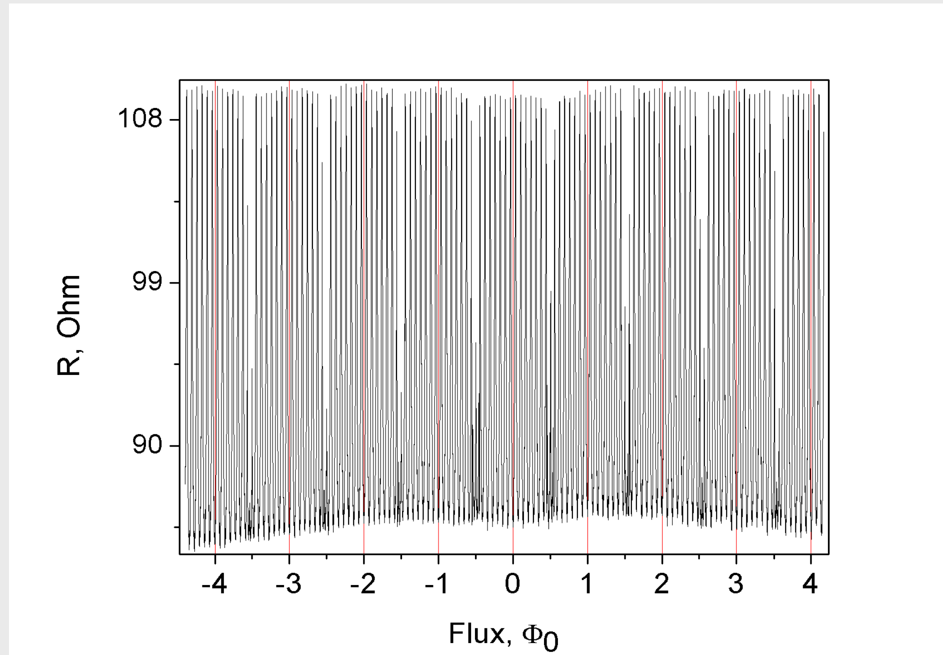


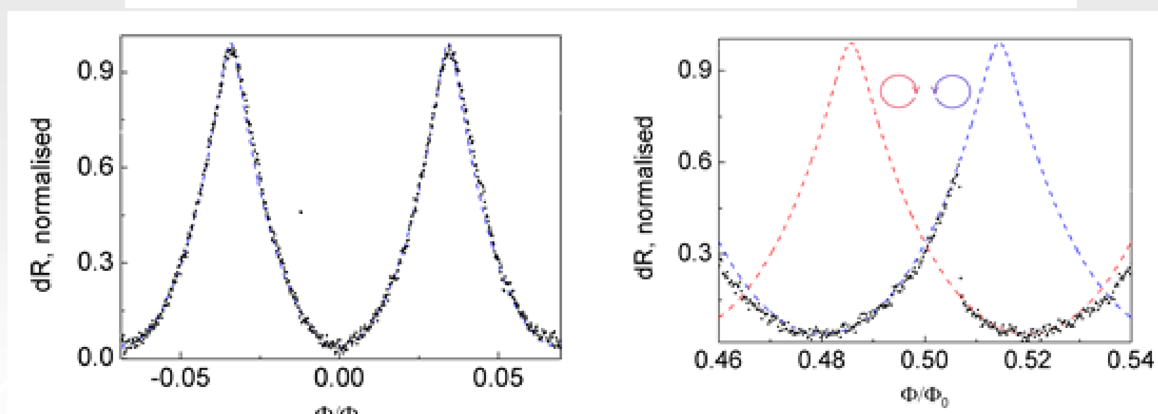
Real time continuous measurements of qubit dynamics

A. Iagallo, C. Checkley, R. Shaikhaidarov and V. T. Petrashov (2010)
Royal Holloway, University of London, TW20 0EX UK







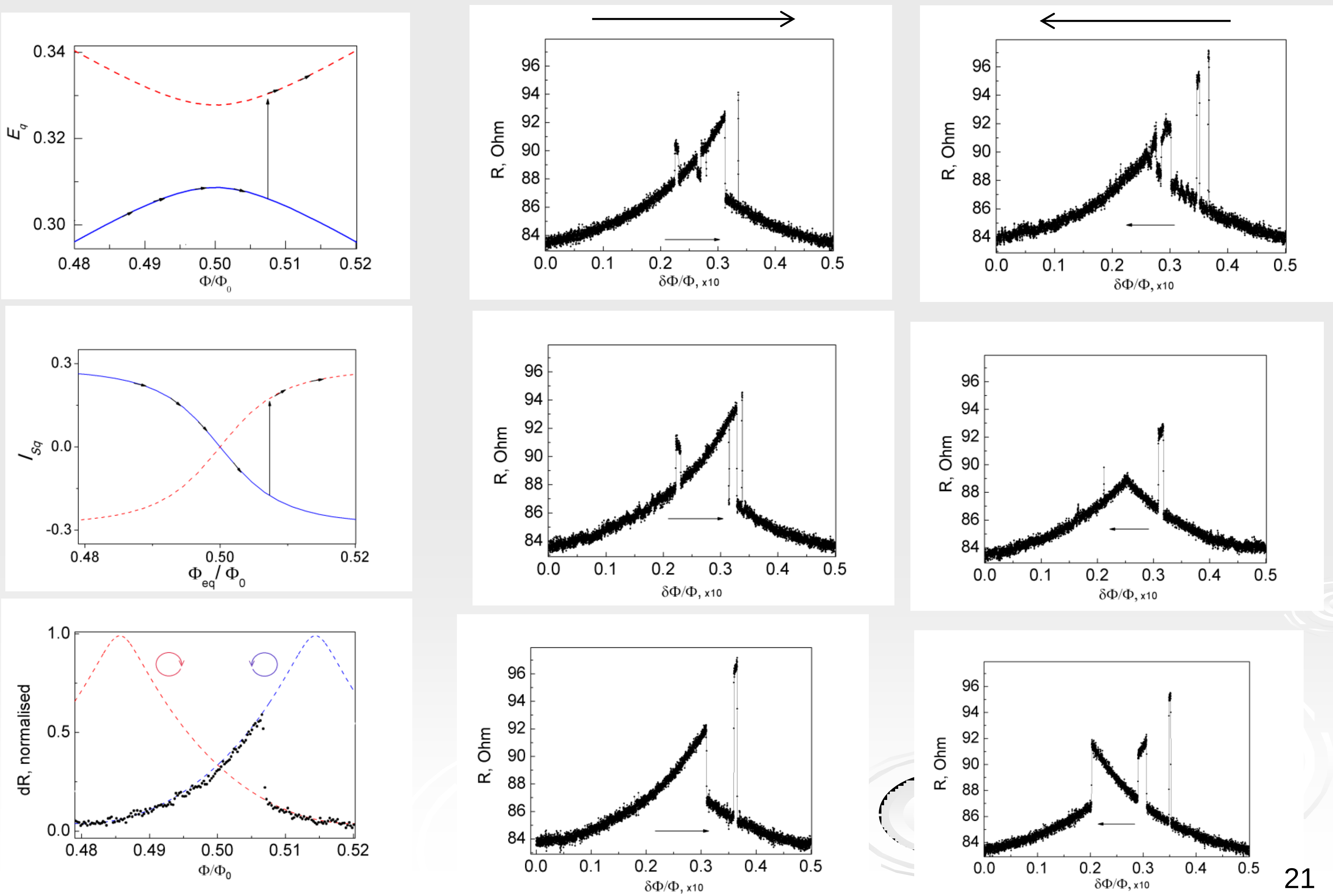


Resistance of Hybrid Quantum Interferometer vs flux

Real time continuous measurements of qubit dynamics

Transitions between metastable quantum states

V. T. Petrashov, A. Iagallo, C. Checkley and R. Shaikhaidarov, (2010)
Royal Holloway, University of London, TW20 0EX UK



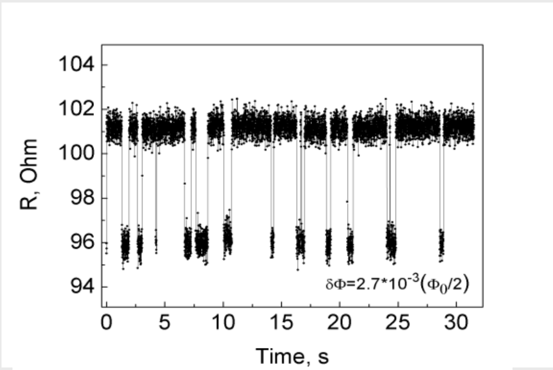
Similarity between real and artificial atoms

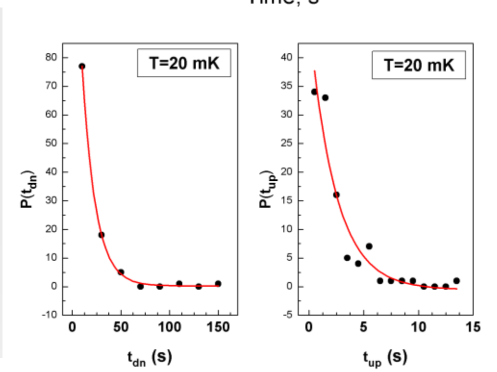
Jumps between metastable states in superconducting qubits,

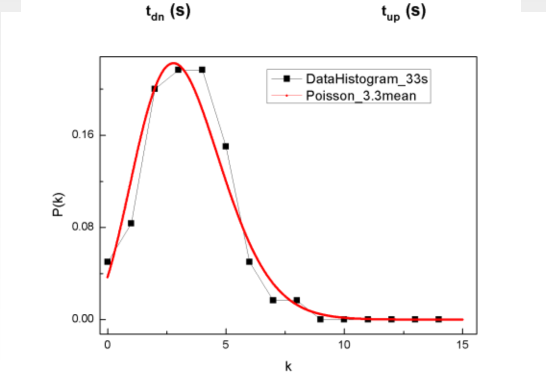
A. Iagallo, C. Checkley, R. Shaikhaidarov and V. T. Petrashov (2010)

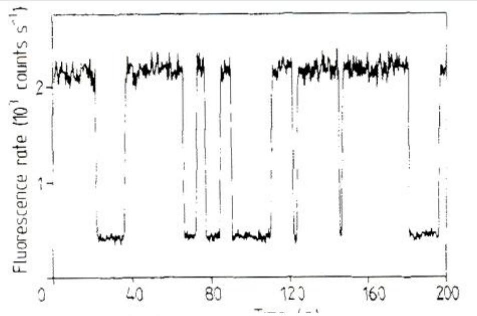
Quantum jumps in fluorescence of individual optically cooled Ba ions

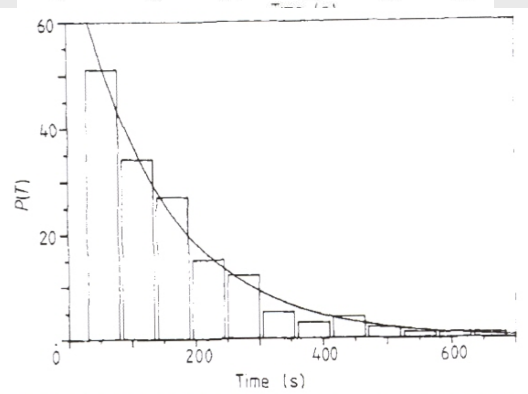
R. Blatt, and P. Zoller, Eur. J. Phys. 9 250 (1988)

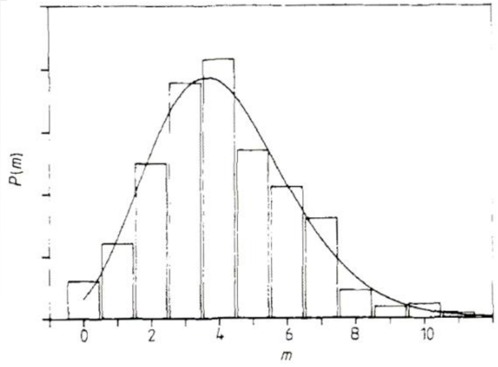












‘Metal: a box of surprises’

The general properties of metals are well known, but at the nanoscale they show spectacular new phenomena that provide many opportunities for the exploration of fundamental physics and for potential practical applications for nanoelectronics. These properties are rooted in quantum mechanics, providing insights and new physics fitting to the lifework of Sir Nevill Mott.