Quantum Transport FS 2015

lecture given in spring 2015 by:




Christian Schönenberger Dominik Zumbühl Andreas Baumgartner Markus Weiss

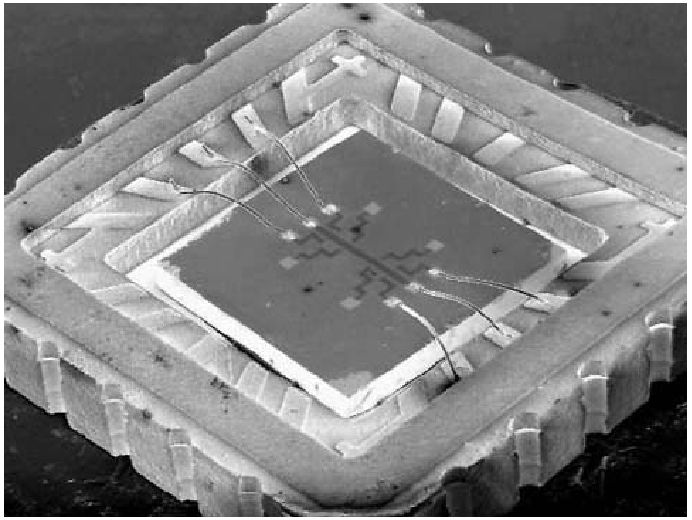
lecture is on Tuesdays 16:15 – 18:00

exercises are on Thursdays from 10:15 till 12:00

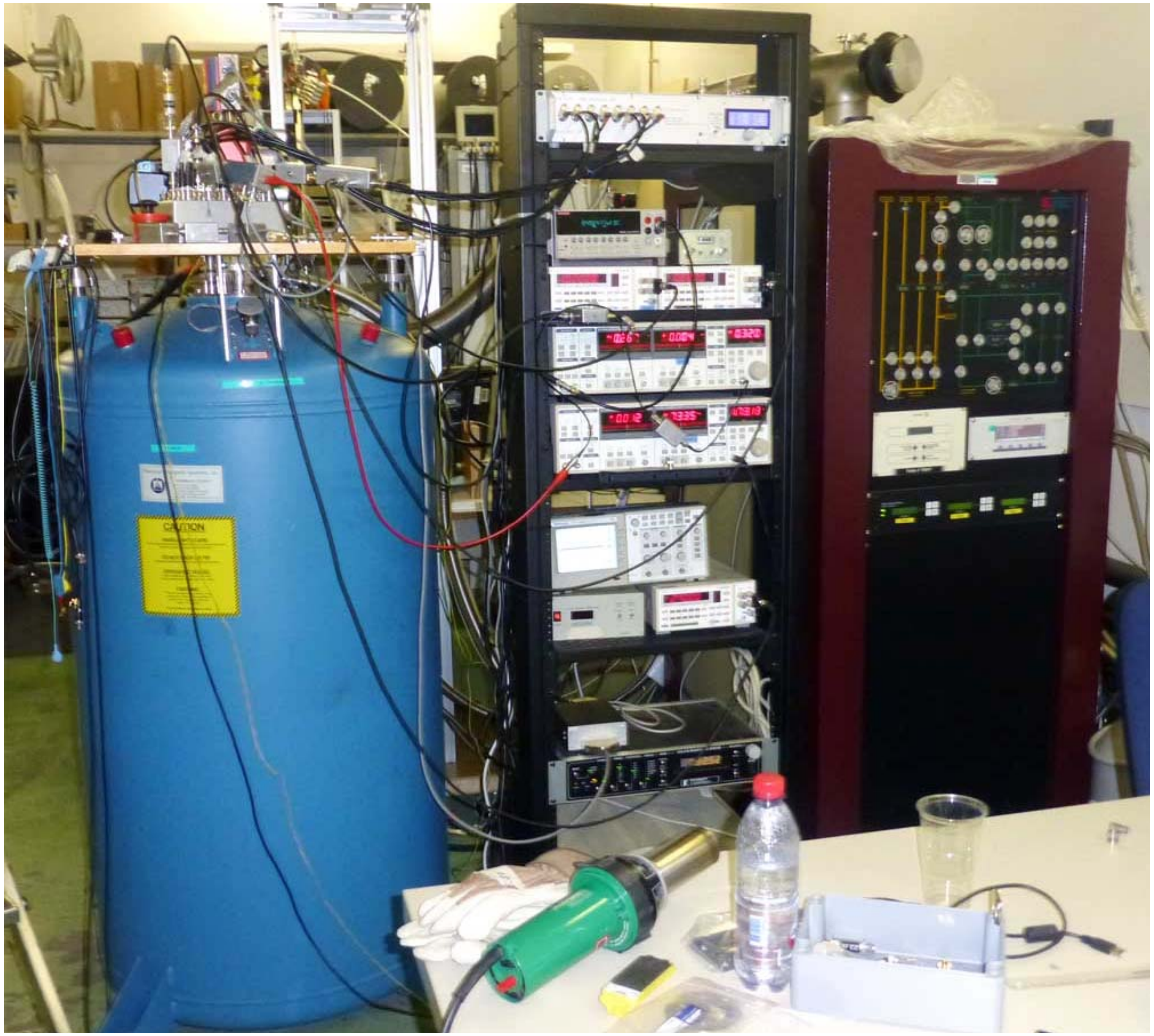
you must attend the exercises if you want to get the credit points
in the last exercise we will make a written test
condition for credits: pass the test and have attended 80% of the exercise classes

all in English

1. Quantum Transport / Introduction



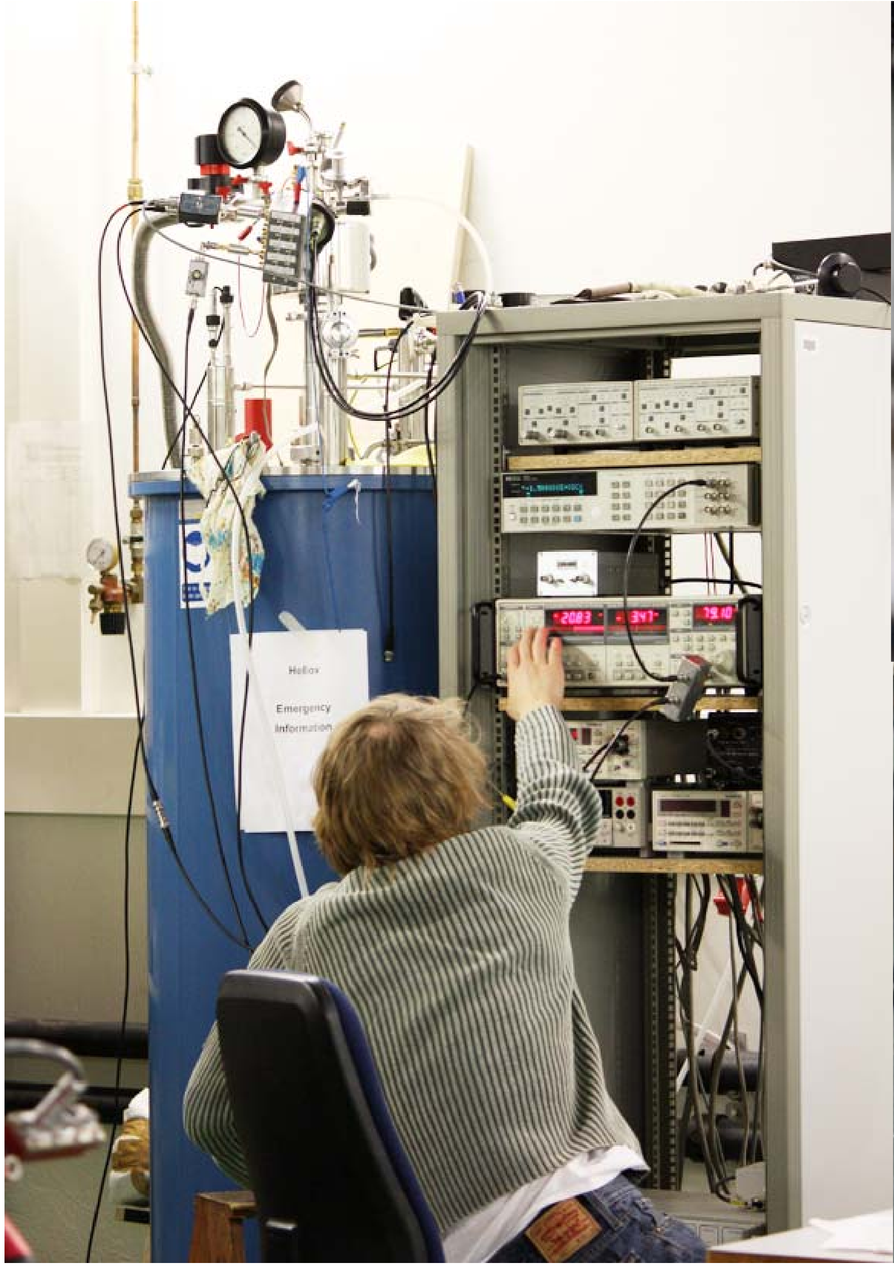
often measured in a cryostat
measurements mostly electrics, but other degrees also of interest (e.g. photons)

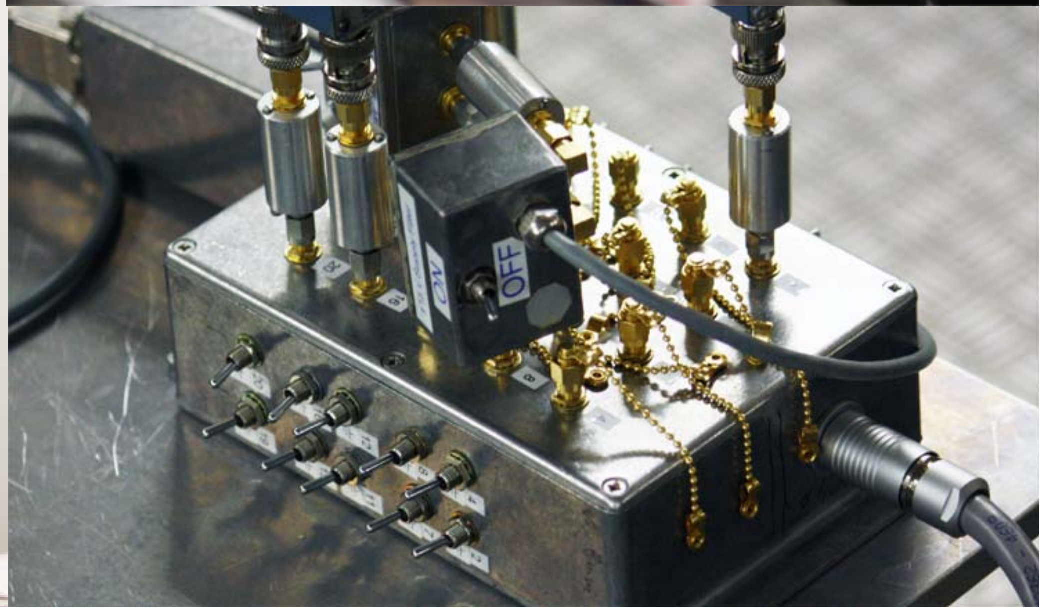


a chip carrier with a “sample” connected by bonding wires

usually fabricated by lithography methods

1. Intro / Measurement techniques



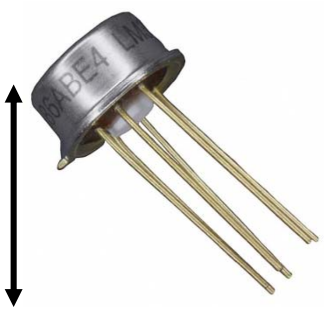


1. Intro / Motivation / history

tube

10 cm

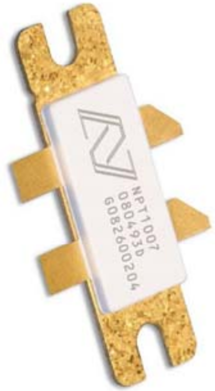
Si transistor



1 cm

„Chip“ integrated circuits

GHz
electronics



ad Blaupunkt 1959

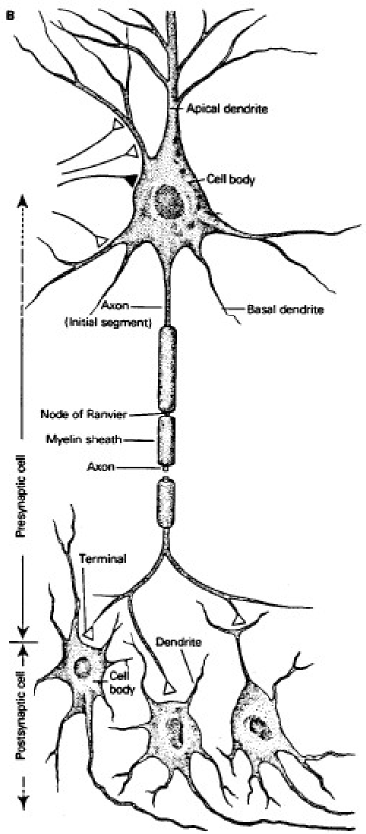
stereo and
TV for all

bits und bytes
PC / internet for all

online at
all times

1. Intro / Bioelectronics

Biochip: „brain on a chip“ **DNA memory**

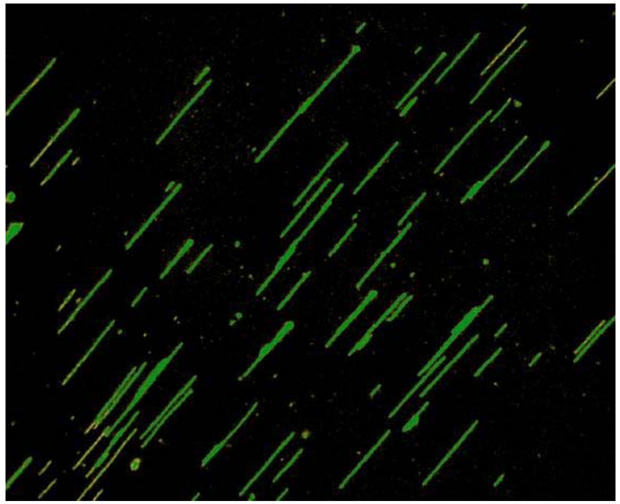


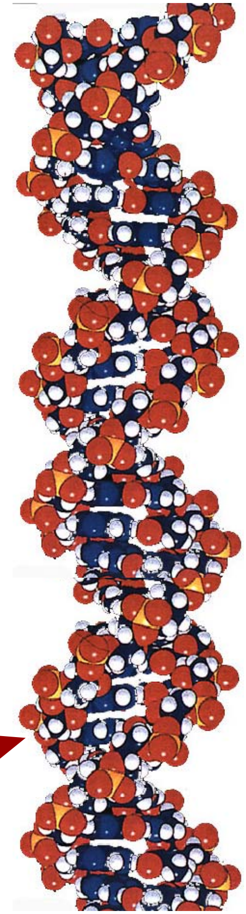
Brain, neural networks, and computation

J. J. Hopfield

neurons on a chip

image of DNA

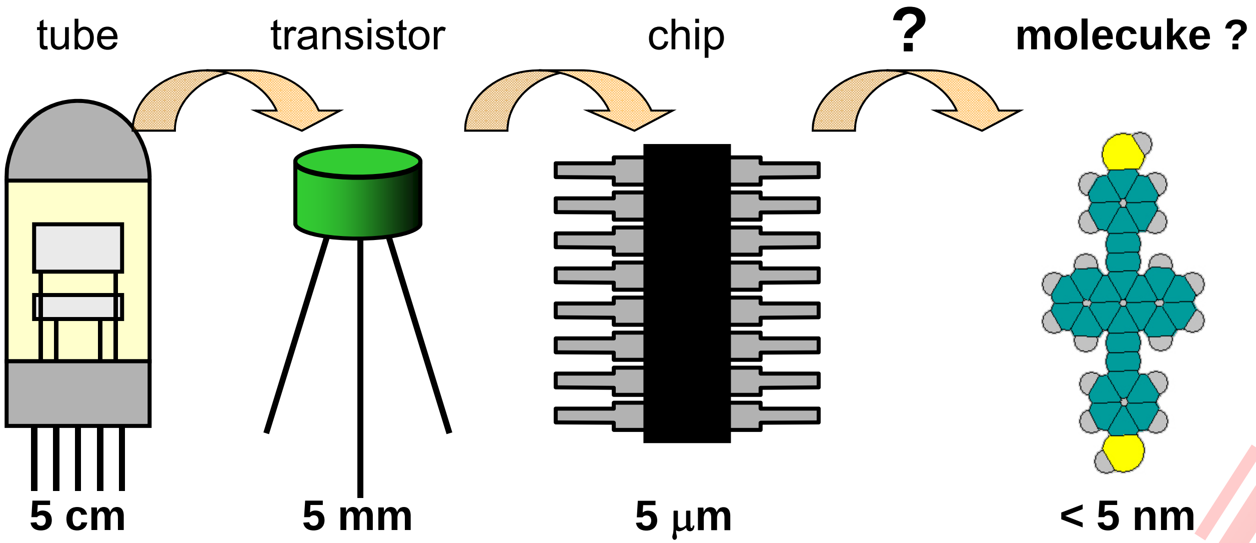


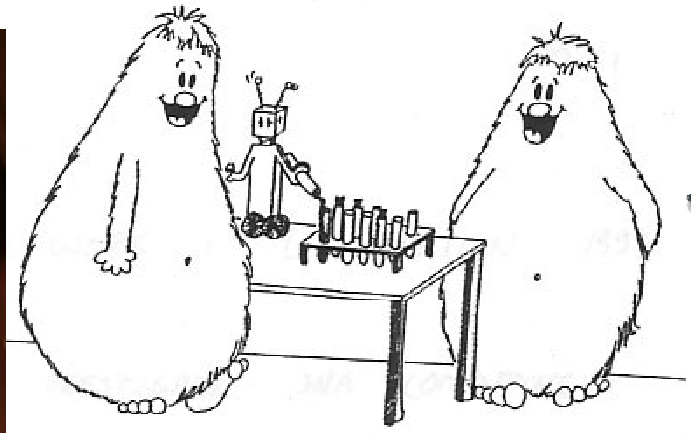


Erbsubstanzmoleküle

1. Intro / Molecular Electronics

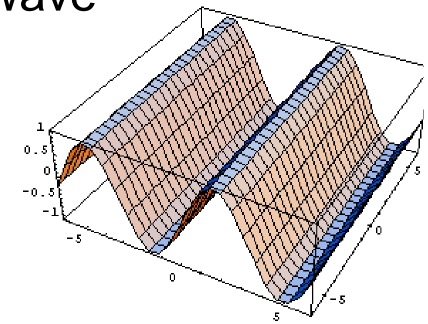
molecular electronics: the computer in a test tube

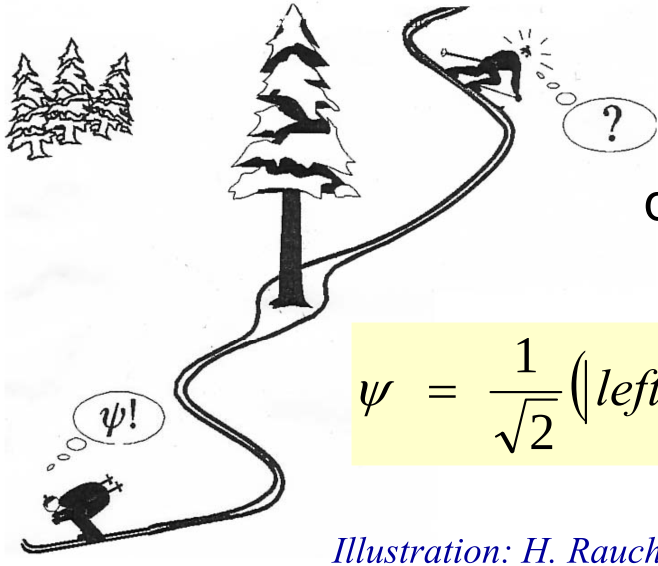




1. Intro / Quantum electronics

the electron is **a quantum particle**, it can behave as a wave and therfore interfere :



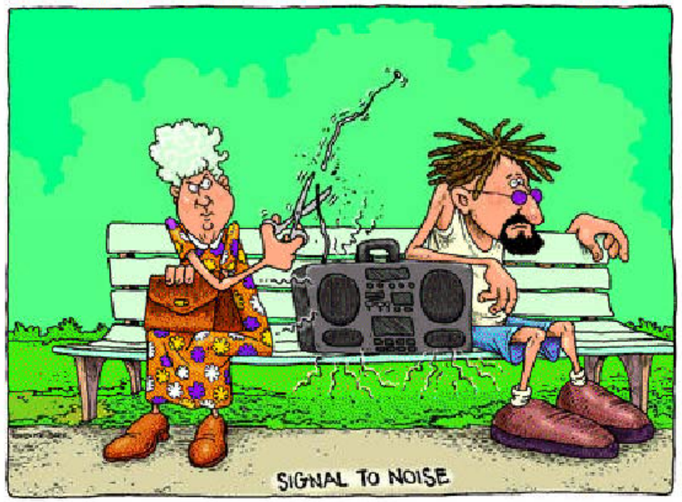


quantum effect

$$\psi = \frac{1}{\sqrt{2}}\left(|left\rangle + |right\rangle\right)$$

Illustration: H. Rauch ATI, Wien

der Stromfluss **klassischer Elektronen** rauscht wie ein tropfender Wasserhahn



quantum physics delivers concepts for a new way of computing→ **quantum computing**

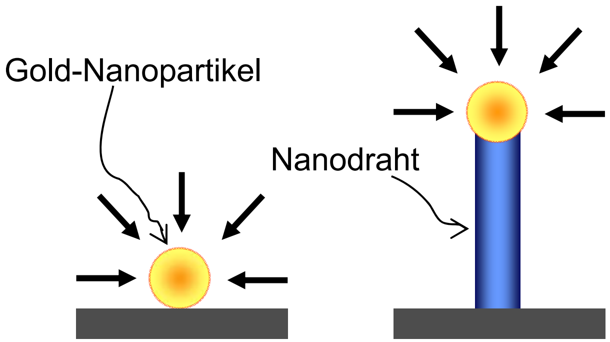
„The weirdest computer of all“ (The Economist)

1. Technology plays a crucial role (but not only)

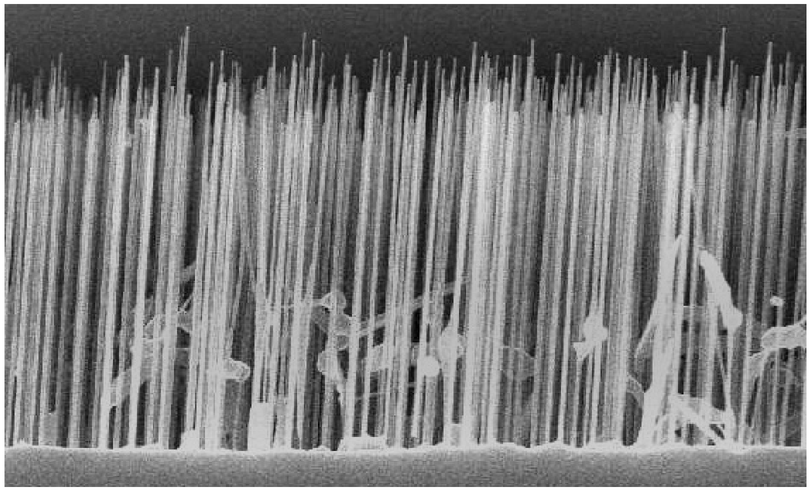
- **fabrication technology** (devices need to be made)
- devices get smaller and **smaller**
- signals get also smaller and **faster** and there is much more data
- **imaging** and analytics important
- engineering, physics, chemistry and biology may come together → **language problem**
- **new materials** may also give the field a decisive push

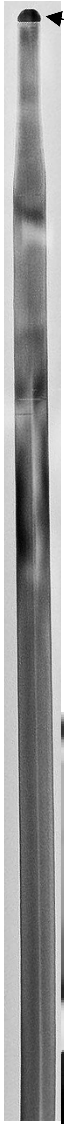
for example: nanowires

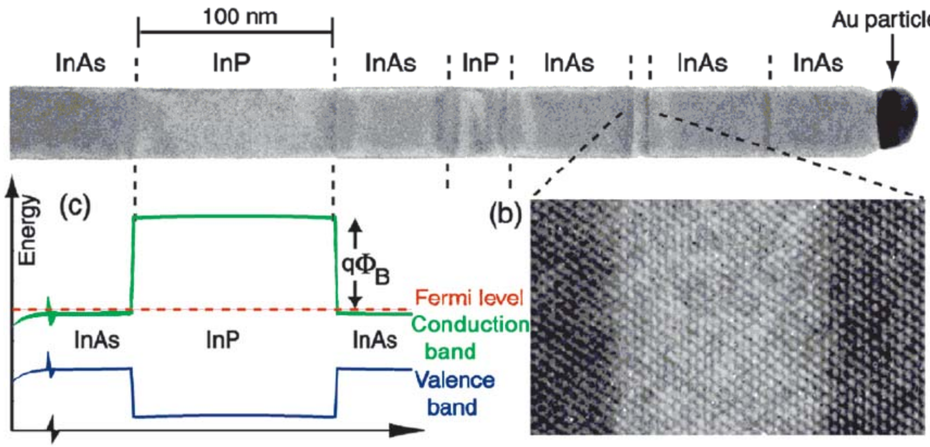
gold nanoparticles are used to catalyze the growth of nanowires



diameter ~ 10-50 nm





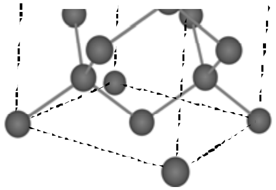


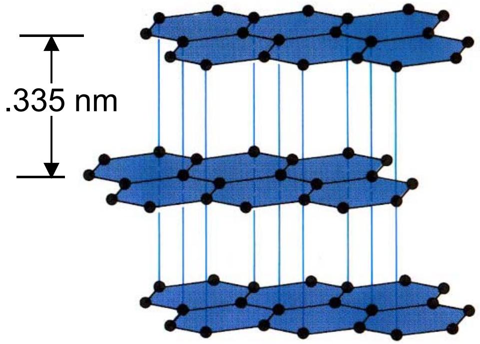
aus: M.T. Björk et al., Nano Lett. ***2****, 87 (2002)*

composition can be changed during growth

Carbon materials

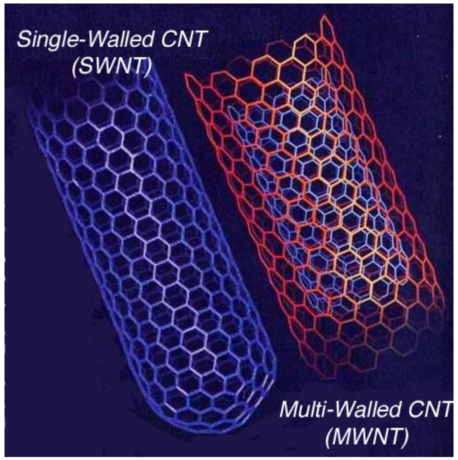
Diamond (sp^3 carbon):
- *hard material*
- *very good electrical insulator, but still a very good heat conductor (why ?)*





6 12.011
±4,2
4470
4100
2.62
C
$1s^2 2s^2 p^2$
Carbon

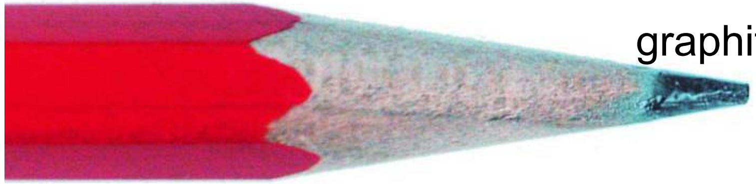
Graphite (sp^2 Carbon):
- *simple to write with (pencil)*
- *good electrical conductor*



Nanotubes:
metallic and semicondcuting ones:
diameter 0.5 - 50 nm

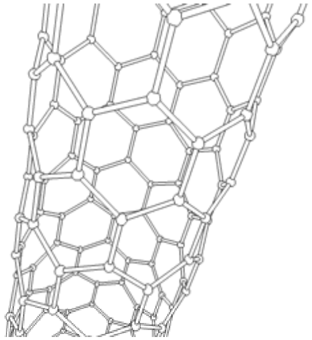
Fullerene (C_{60}):
diameter = 0.7 nm

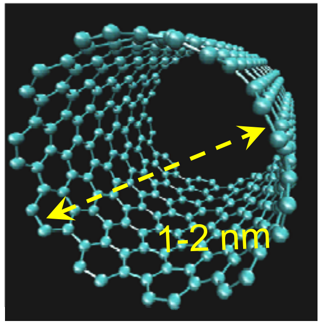
Carbon Nanotubes

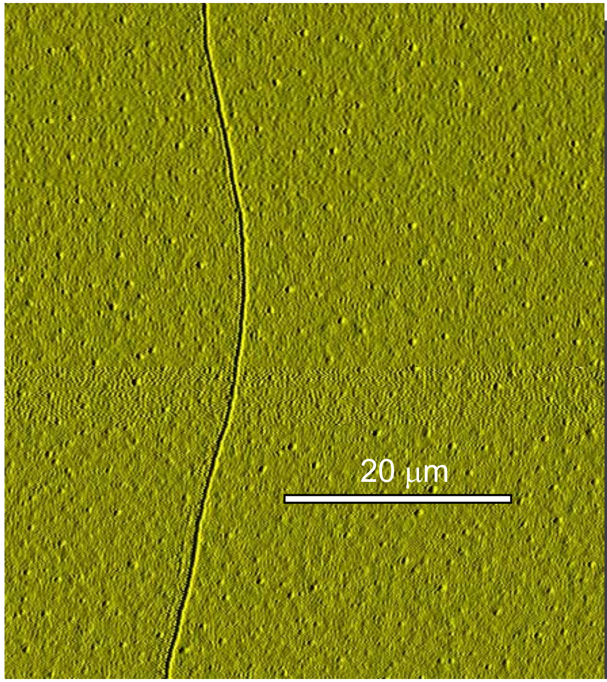


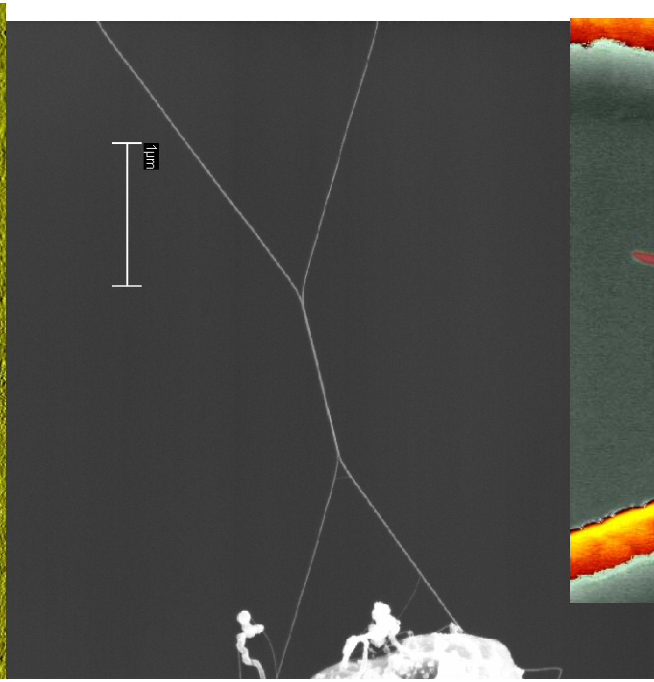
graphite

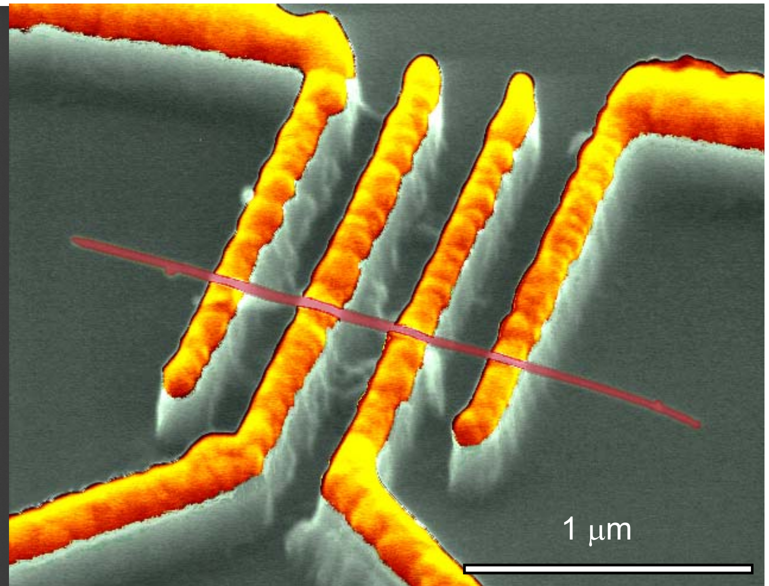
...new formsof graphite



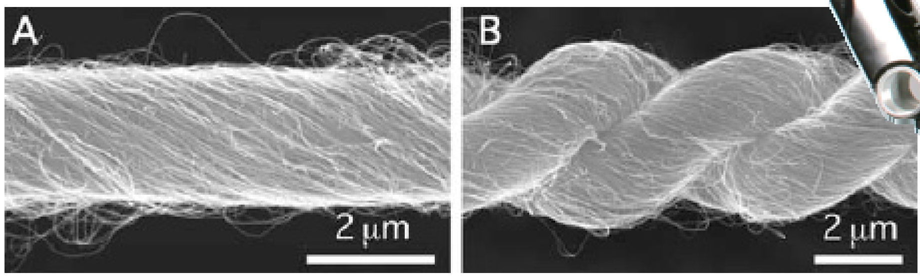






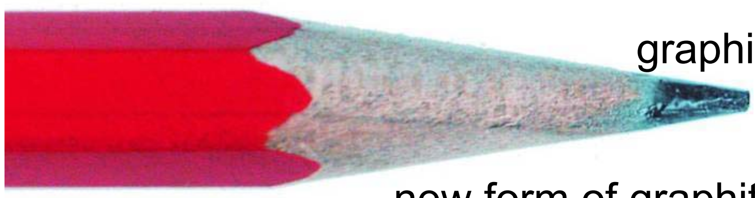


Carbon Nanotubes

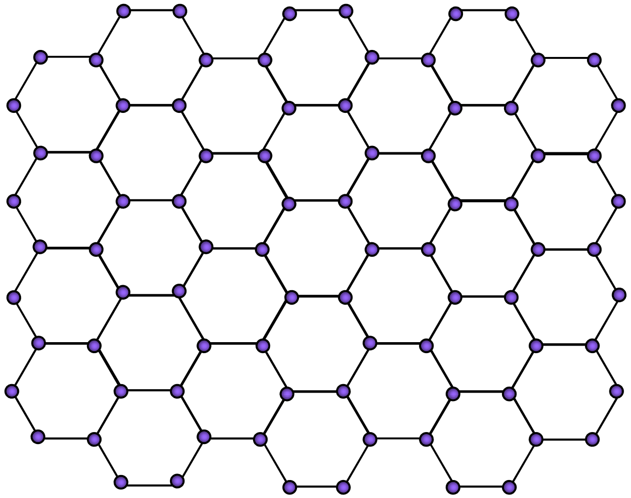


Mit Carbon Nanoröhrchen lassen sich auch ultraleichte und ultrafeste Komposite herstellen, z.B. für Fahräder, Boeing und Airbus

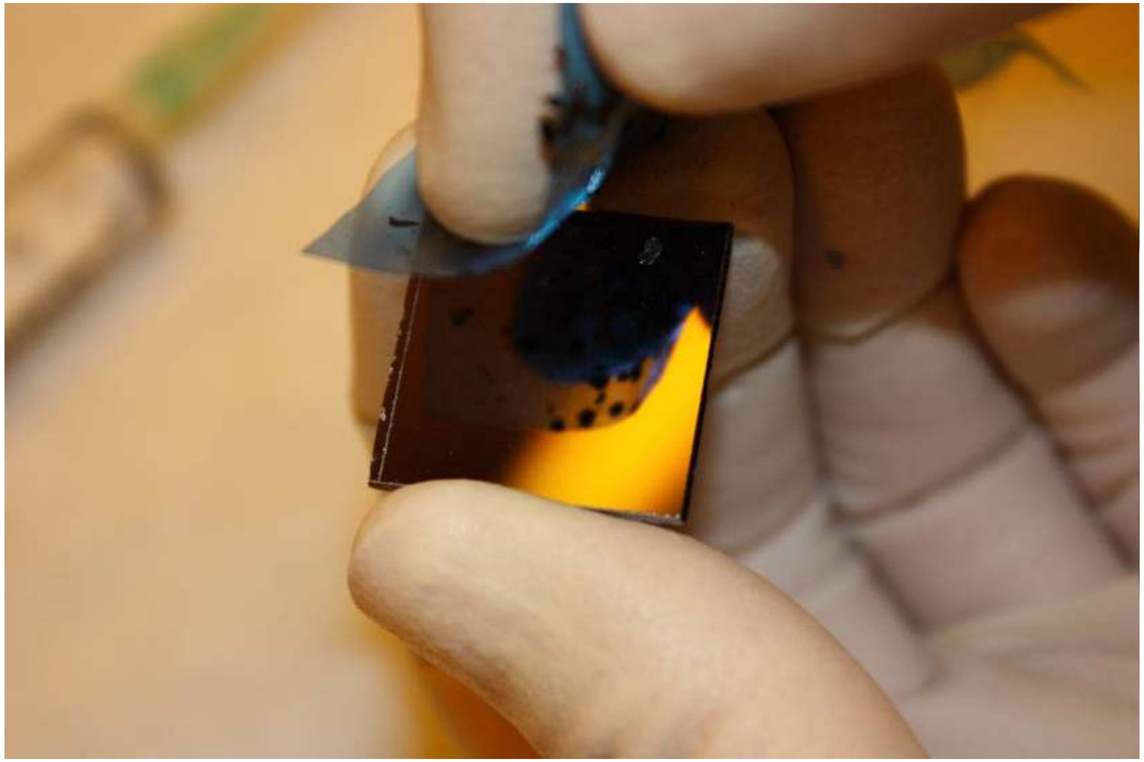
Graphene



graphite is separated with a Scotch tape into it separate thinner layers



„Graphene“ = Kohlenstoff-Monoschicht

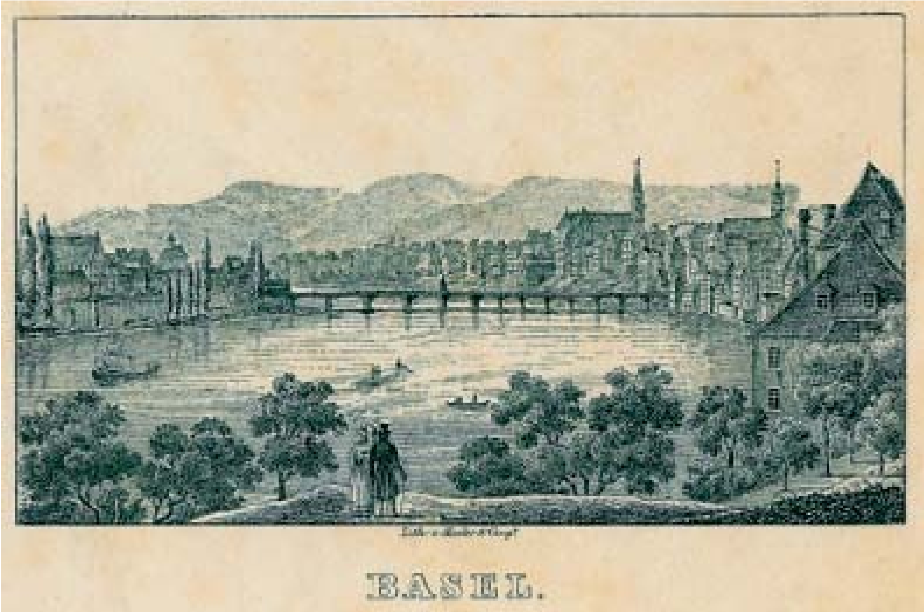


in graphene, electrons bevhave in a way like relativistic massless particles

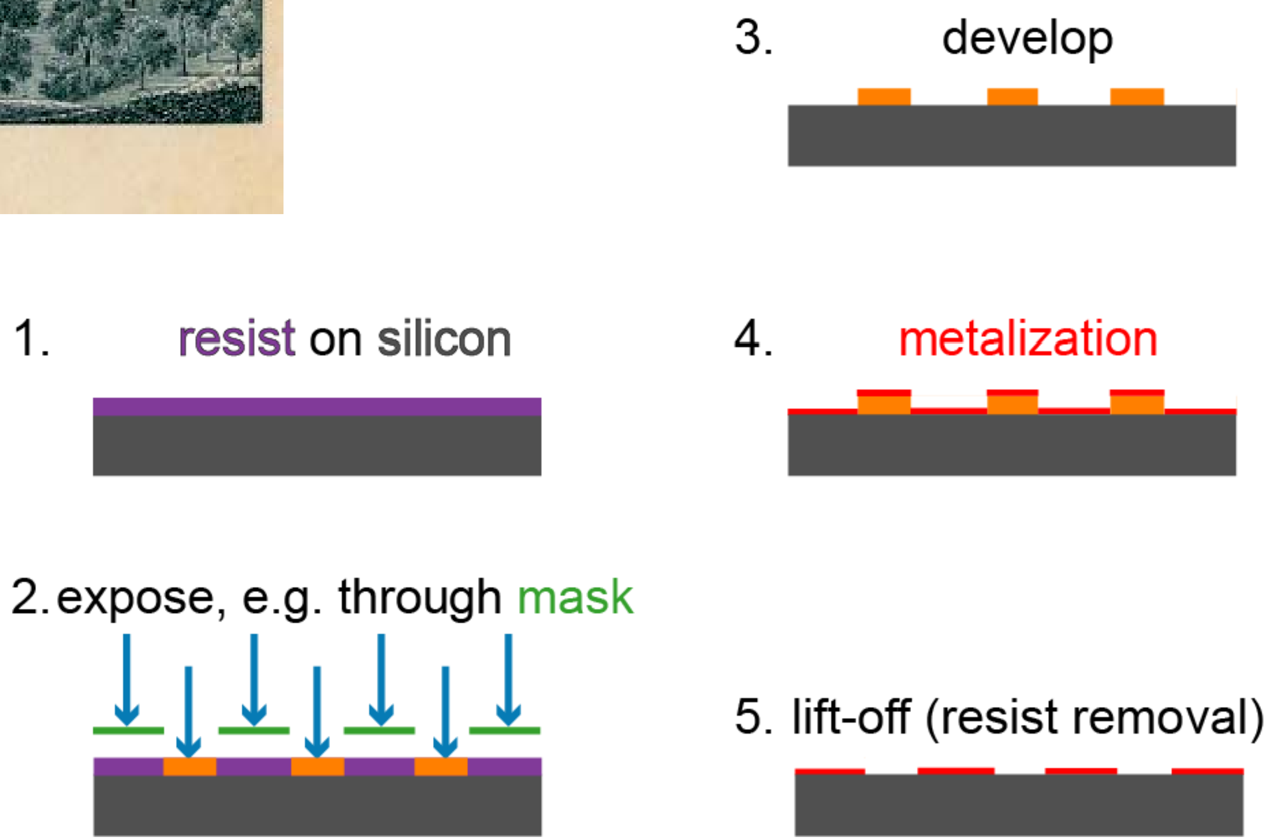
Micro- and Nanofabrication

1. Intro / Micro- and Nanofabrication Facility

How does it work: lithography

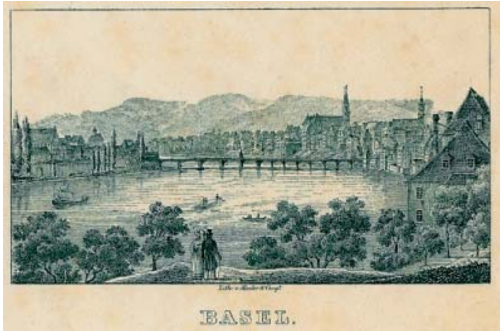


Lithographie von Basel. Druck über
eine von Hand vorgezeichnete und
danach geätzte Steinplatte



Lithography for devices

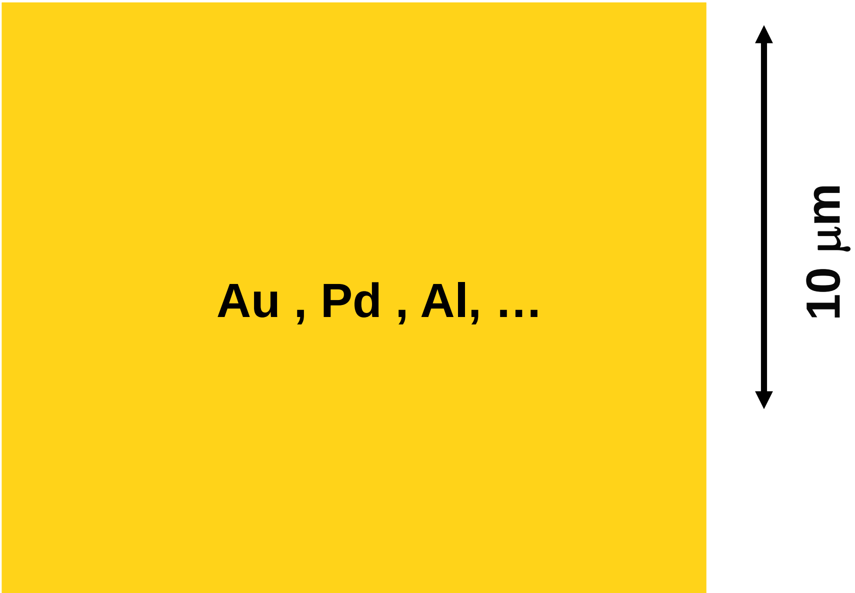
Schönenberger group www.nanoelectronics.ch



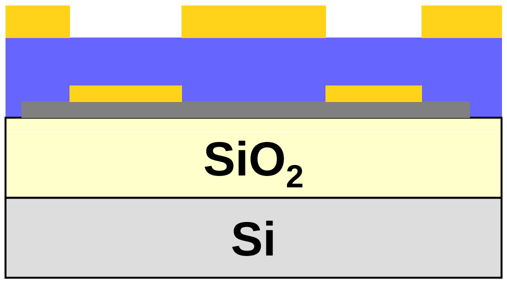
Lithographie von Basel
Druck über eine von Hand vorgezeichnete und danach geätzte Steinplatte

Lithographie mit Licht

... und mit einem Elektronenstrahl



fertig !

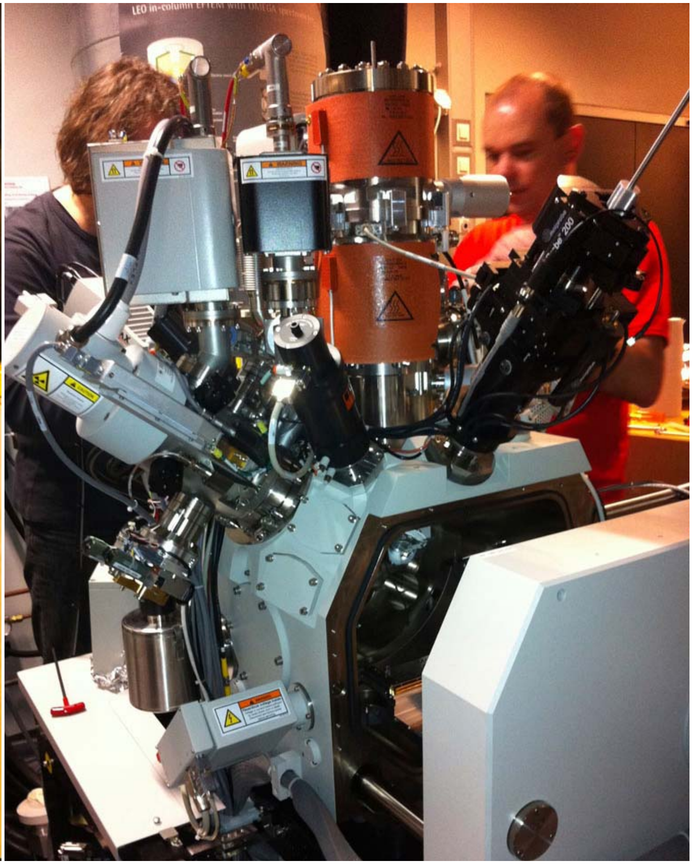


Moderen Lithographie erlaubt uns, Strukturen im Bereich **weniger Nanometer** herzustellen. Hundertfache Wiederholdung führt zu einem Pentium Chip.

Focused Ion Beam (FIB) together with ZMB

operated as a shared facility by ZMB staff and located at the ZMB

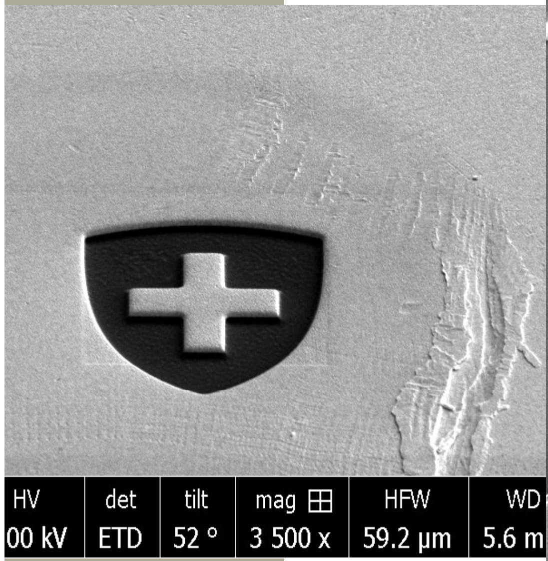
current users are: ZMB, Poggio, Schönenberger, Constable, Gerber, Stahlberg, Hierlemann (D-BSSE), Lim, Maletinsky, Meyer, Richter

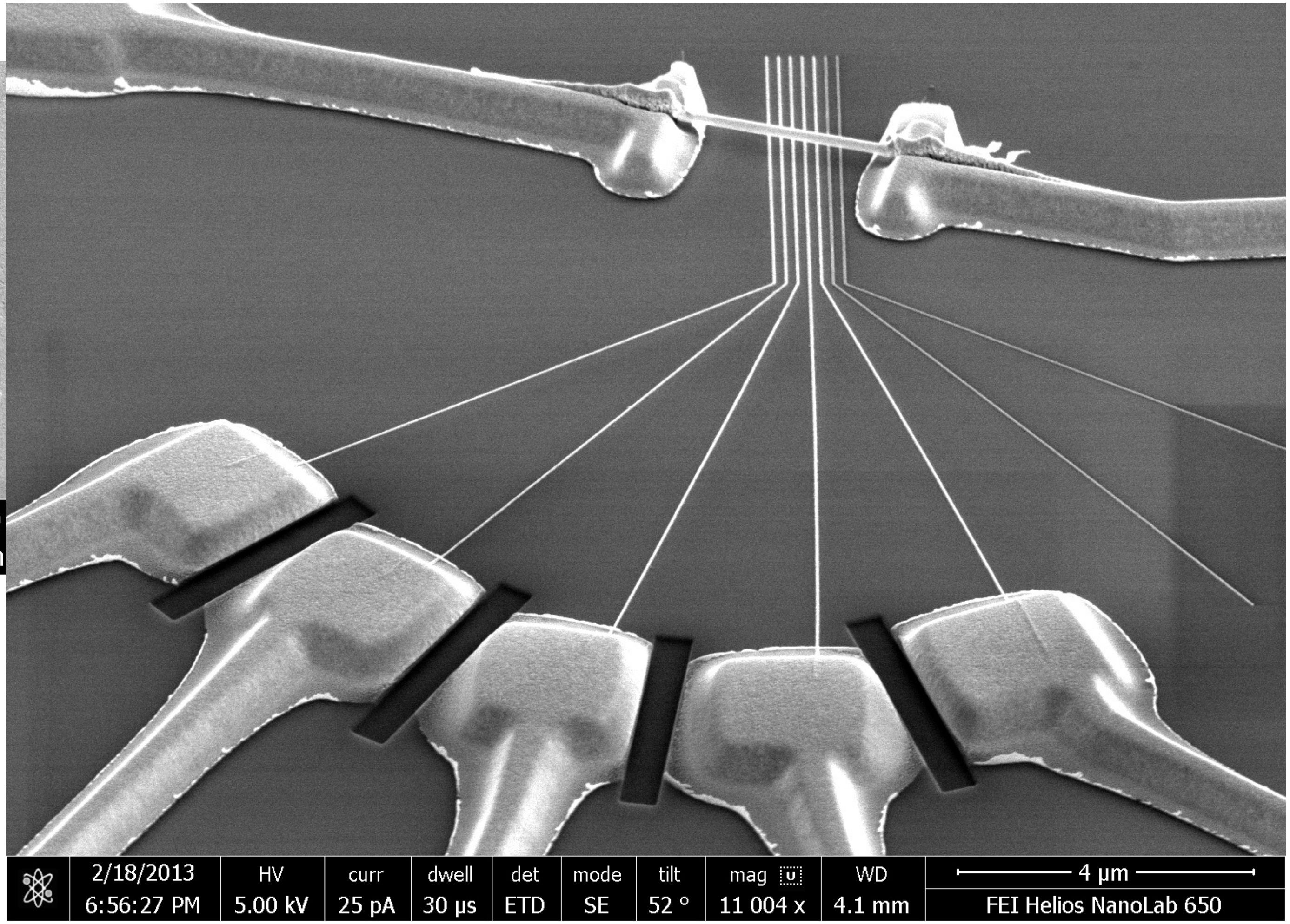


UNI BASEL

Focused Ion Beam (FIB) together with ZMB

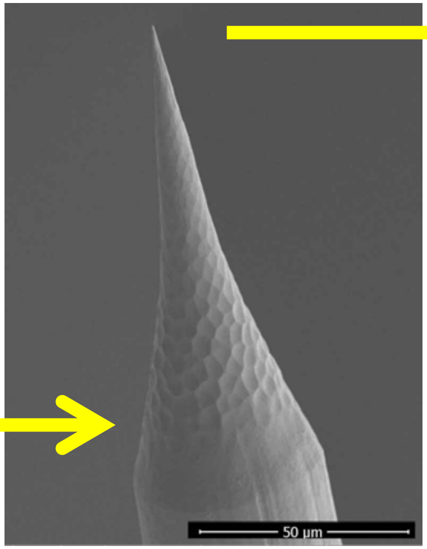
Poggio lab

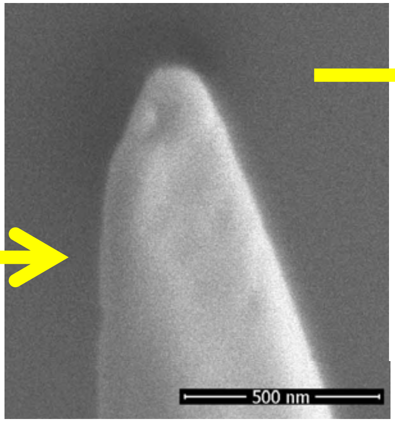




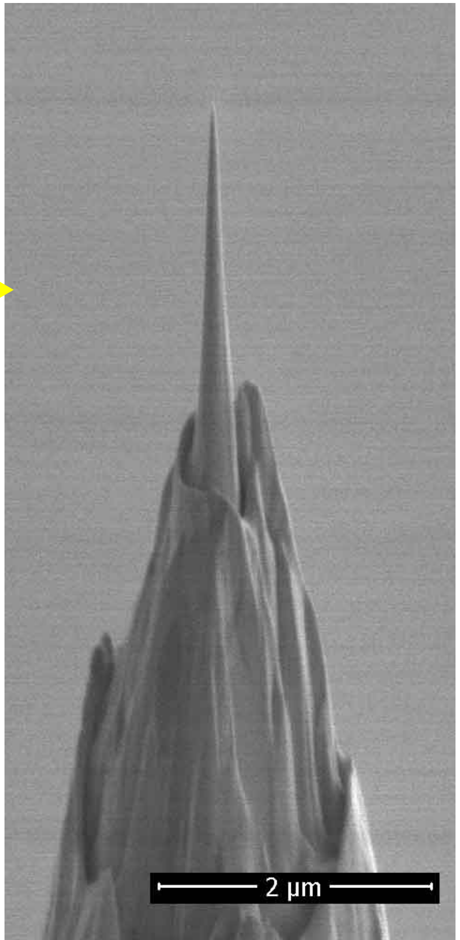
Focused Ion Beam (FIB) together with ZMB

Ernst Meyer lab





R_{tip}≈100 nm
(chemical etching)

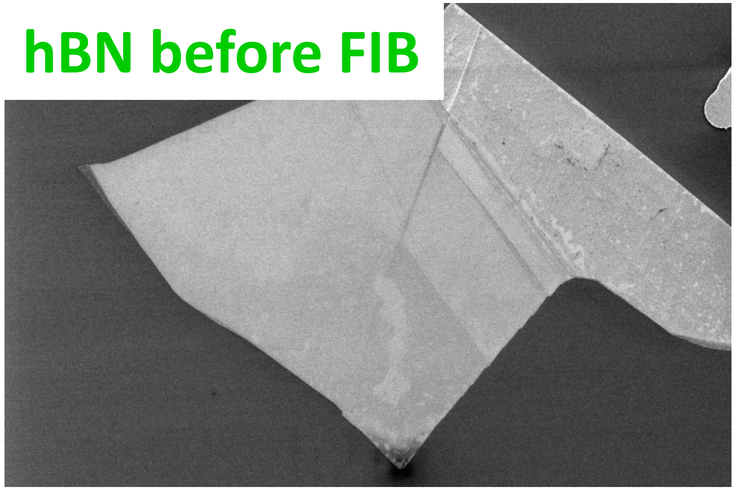


Can be sharpen by FIB milling
R_{tip}≈20 nm

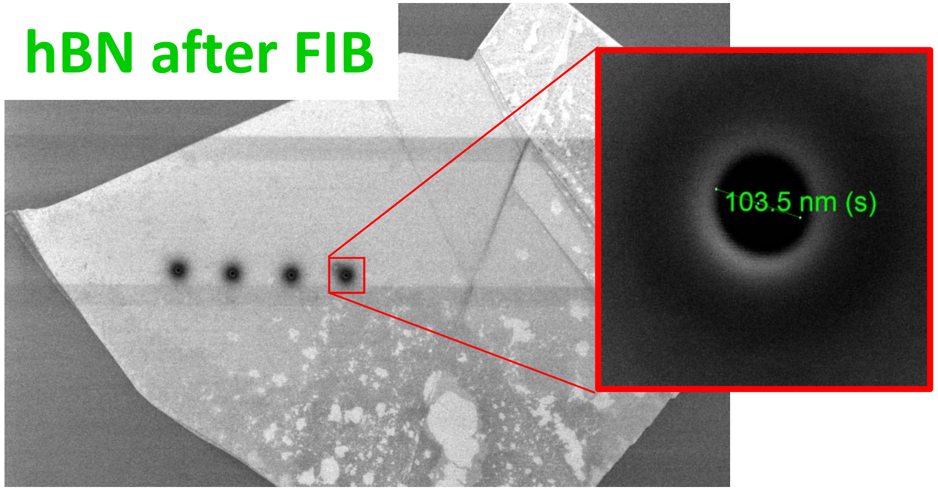
qPlus sensor: F. J. Giessibl, Appl. Phys. Lett. 73, 3956 (1998).

Inner contact to graphene

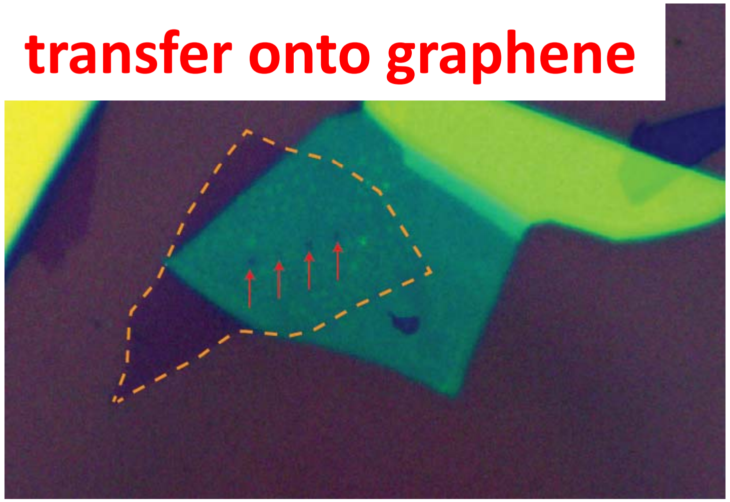
hBN before FIB



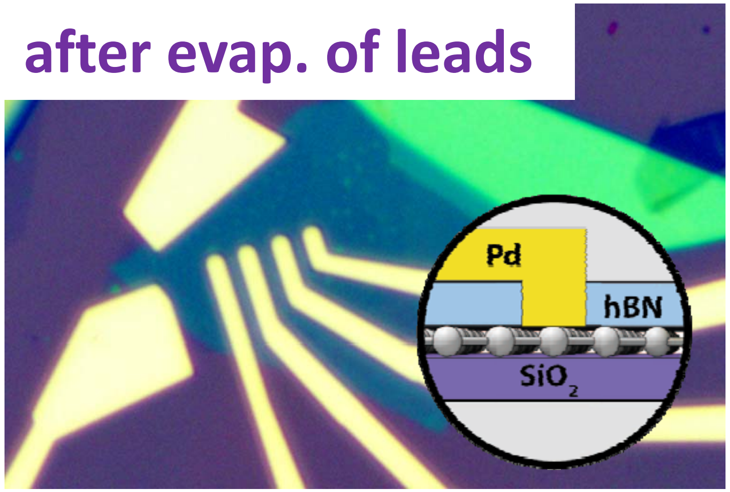
hBN after FIB



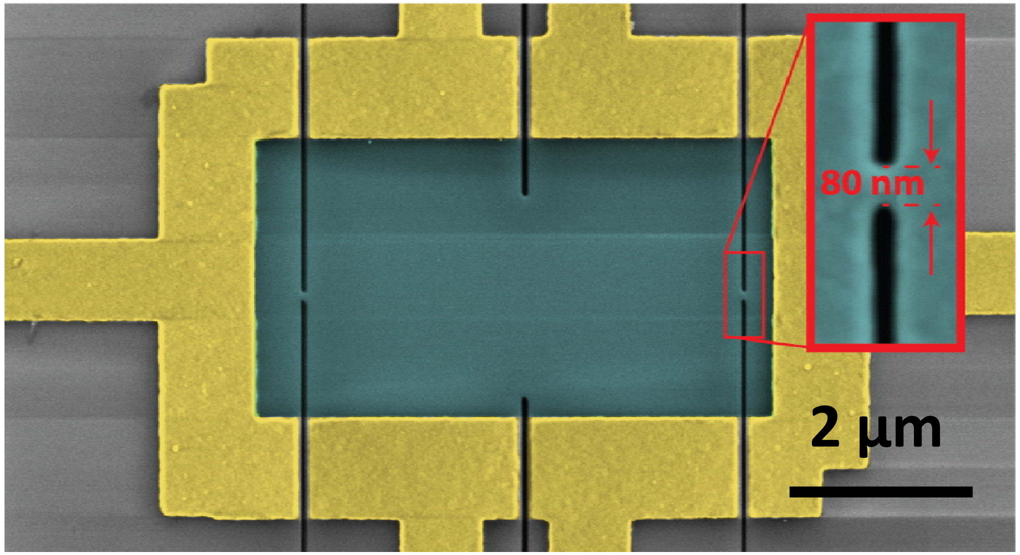
transfer onto graphene



after evap. of leads

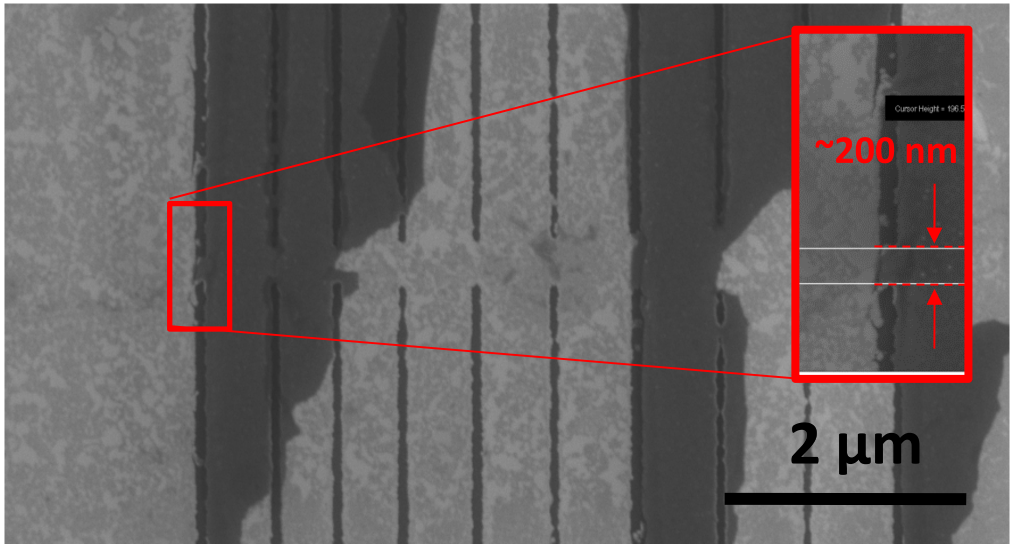


Cuts for SQUIDs



<u>Cut with FIB</u>

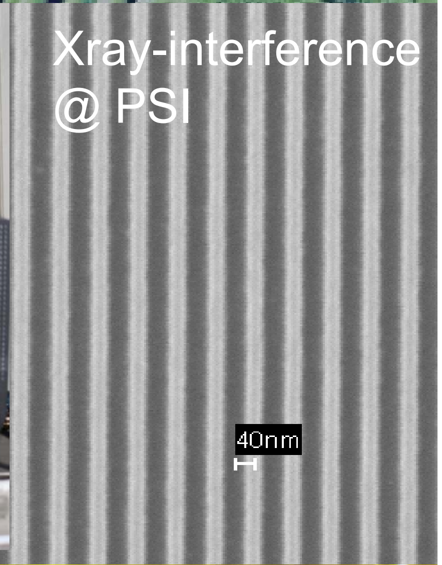
- d_{min}~ 50 nm possible
- clean cut



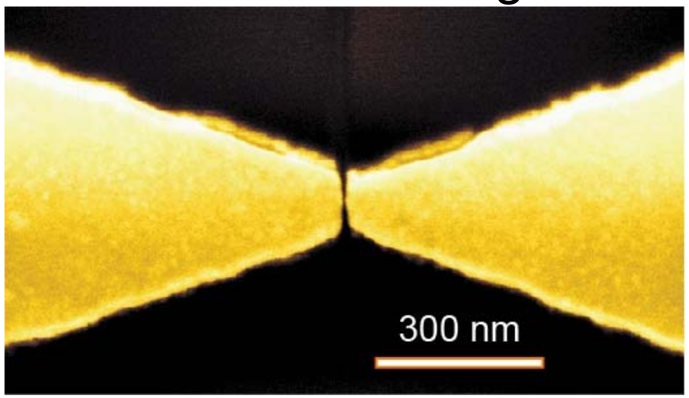
<u>Etched with SF6</u> (mask with E-beam lithography)

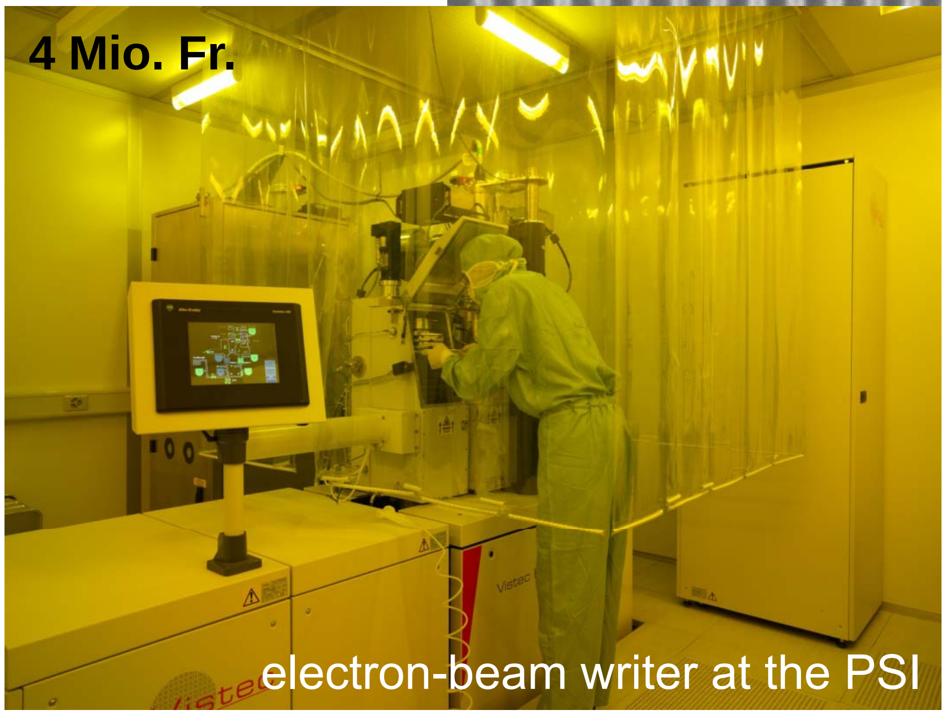
- d_{min}~150 nm
- etched cuts are not as clean as with FIB

Key equipment



- light: 1 μm down to 10 nm
- e-beam: < 10 nm demonstrated
- focused ion beam: < 10 nm
- He-beam: 2 nm range





SEM-based e-beam writer at SNI/Physics

currently run 2 of those systems (each 1 Mio), but ..

have higher demands:

a) more groups using it

b) higher resolution needed
    (< 10 nm possible)

c) better overlay accuracy

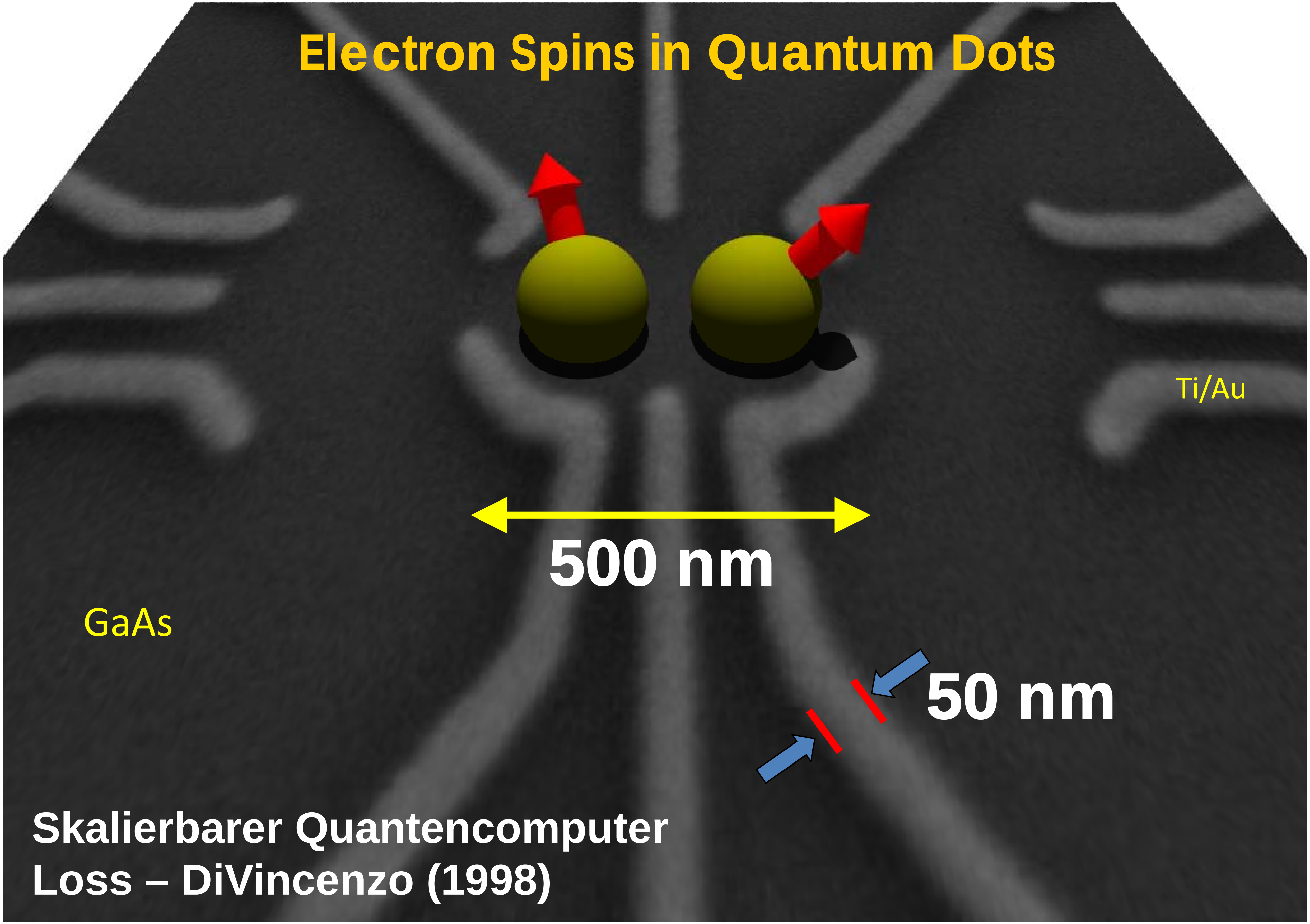
    (10nn stitching possible)

d) large area pattering

    (large field with 24 bit)


Dedicated Electron Beam Lithography
Home » Products » EBPG5200
EBPG5200
EBPG5000 Plus
VOYAGER
RAITH150 Two
eLINE Plus
PIONEER
ionLINE
ELPHY MultiBeam
ELPHY Plus
ELPHY Quantum
CHIPSCANNER
Produ
Auto
Evolut
The EBP
full 200 m
system p
and field-
solutions
making i

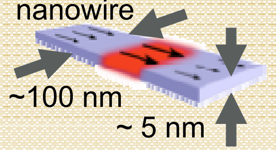
Vistec EBPG5200
Vistec
Lithography


Electron Spins in Quantum Dots
Ti/Au
500 nm
GaAs
50 nm
Skalierbarer Quantencomputer
Loss – DiVincenzo (1998)

Superconducting nanowire single-photon detectors (SNSPD)

Warburton and Schönenberger groups (Basel)

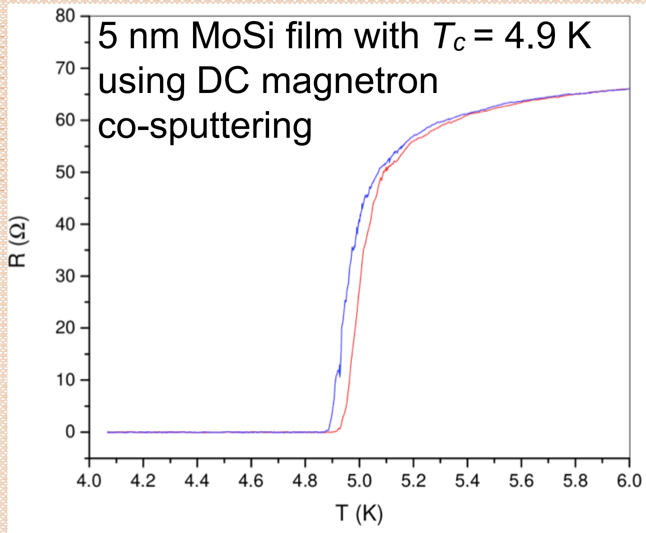
SNSPDs with amorphous materials



Amorphous material are promising candidates to yield:

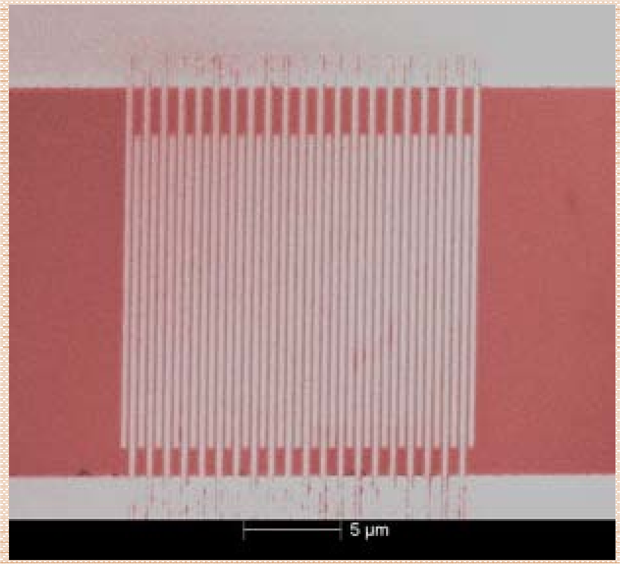
- High-efficiency (90%) from visible to telecom
- Low dark count rates (<1 kHz)
- High count rates (< 20 MHz)
- Low jitter (<100 ps)
- Closed-cycle cryo-operation

Thin-film deposition



- The large T_c of MoSi has potential for high-efficiency at 2.5 K
- T_c can be tuned for optimal performance

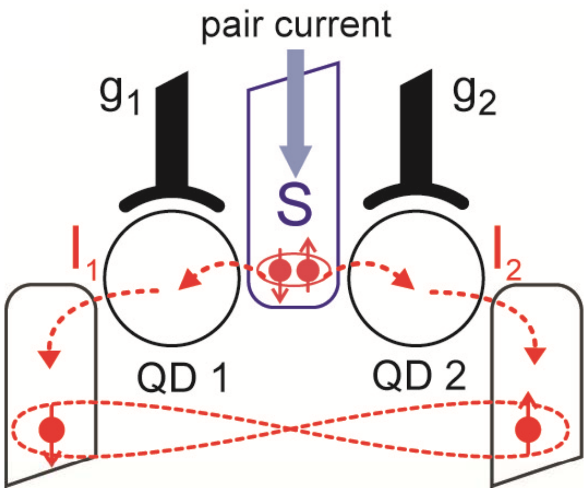
Nano-fabrication

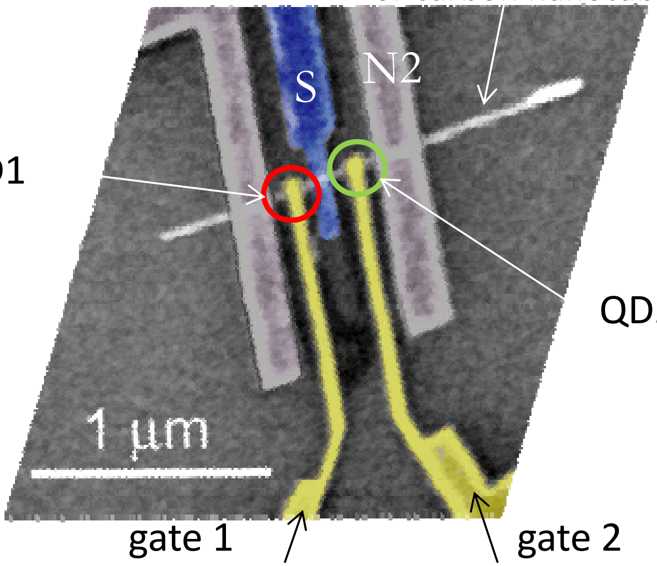


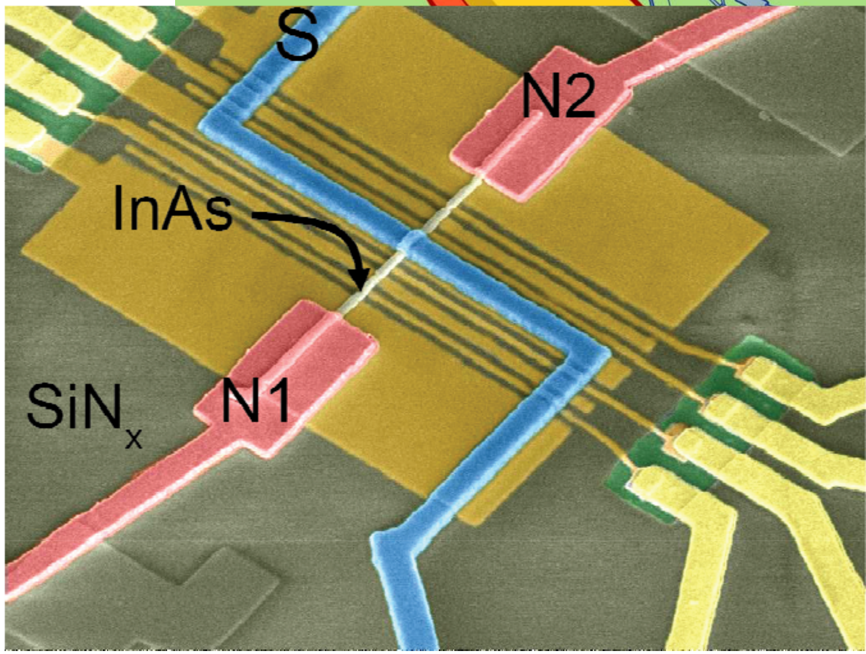
- e-beam lithography for top-down nanowire fabrication

Cooper-pair spllitter

apply quantum dots to split Cooper-pairs;
proposal by Recher, Sukhorukov and Loss

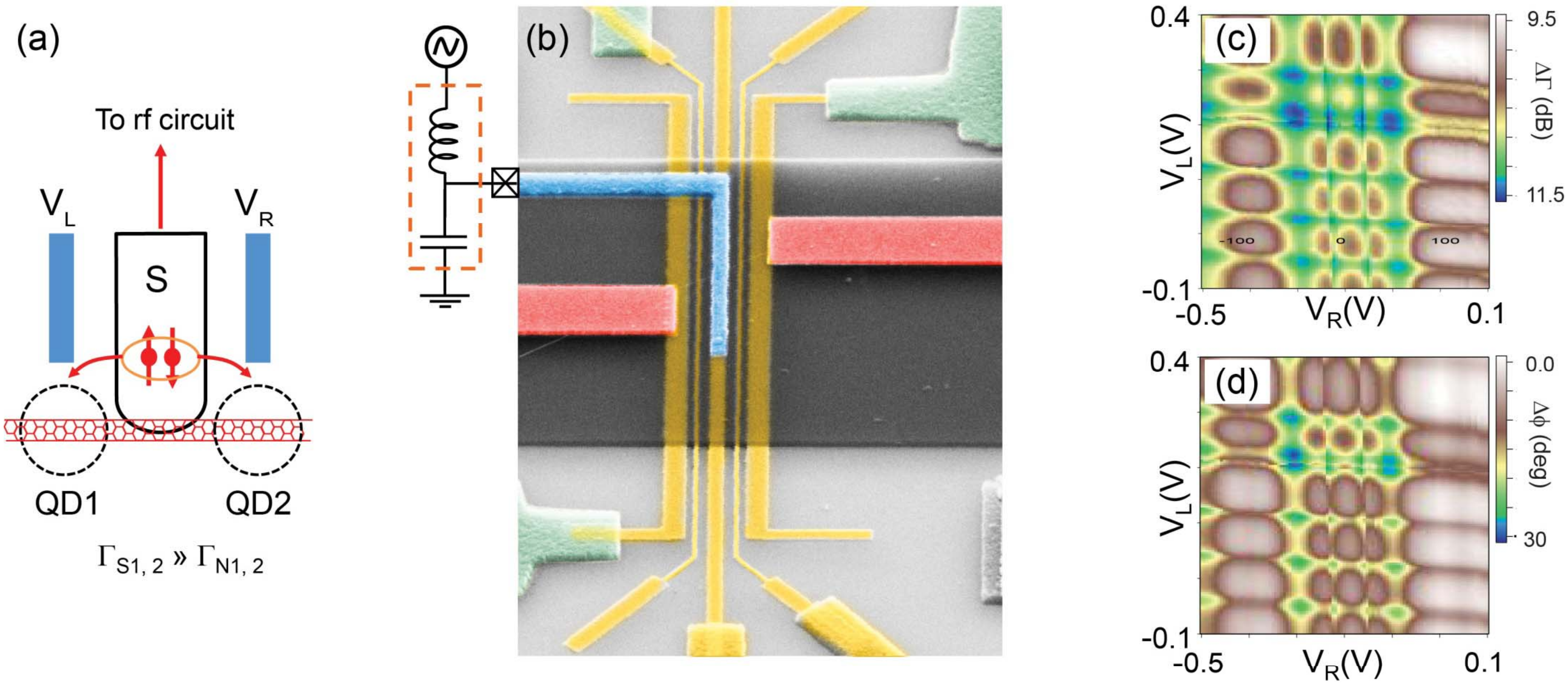






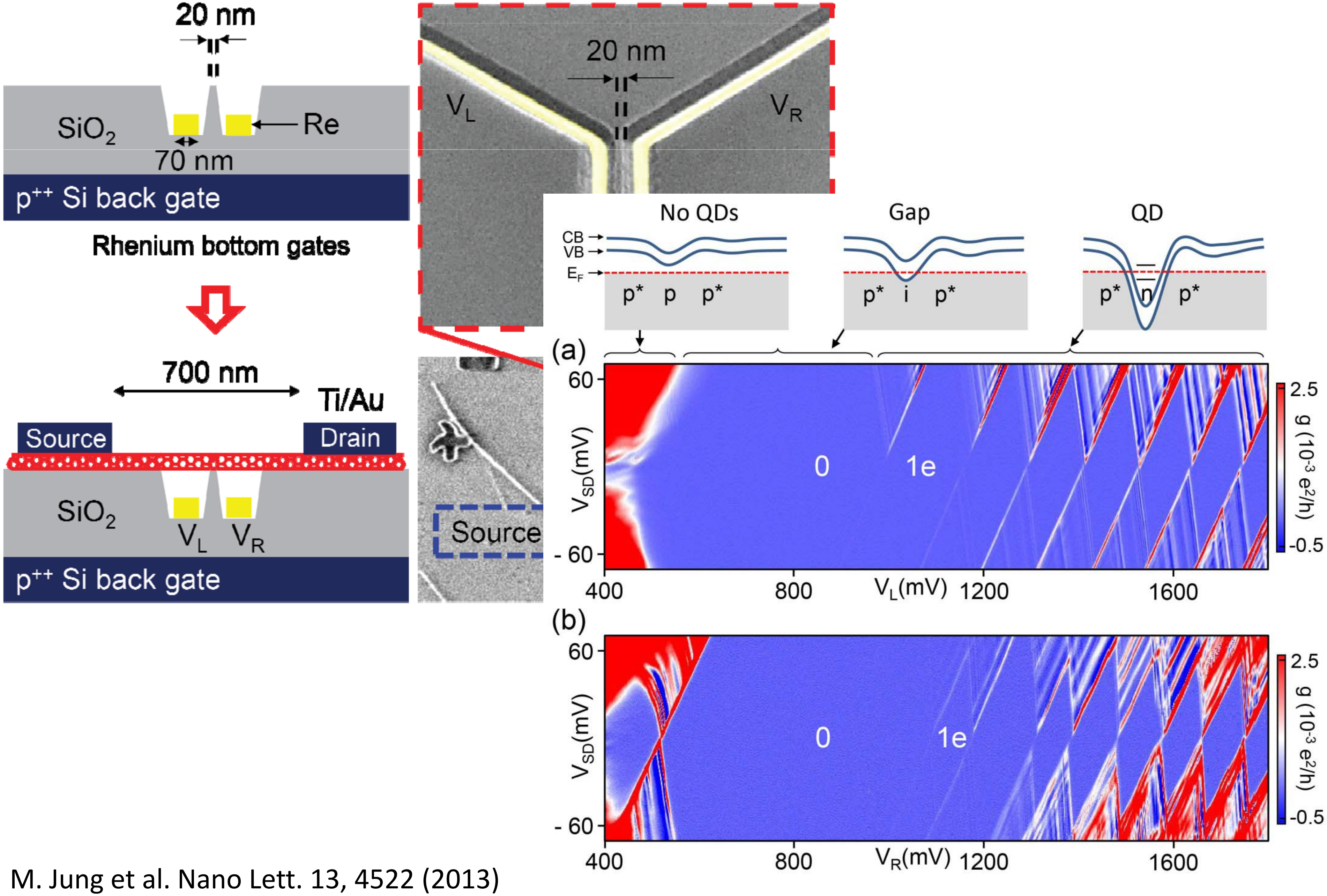
Hofstetter et al. Nature 461, 960-963 (2009)

Cooper-pair spllitter



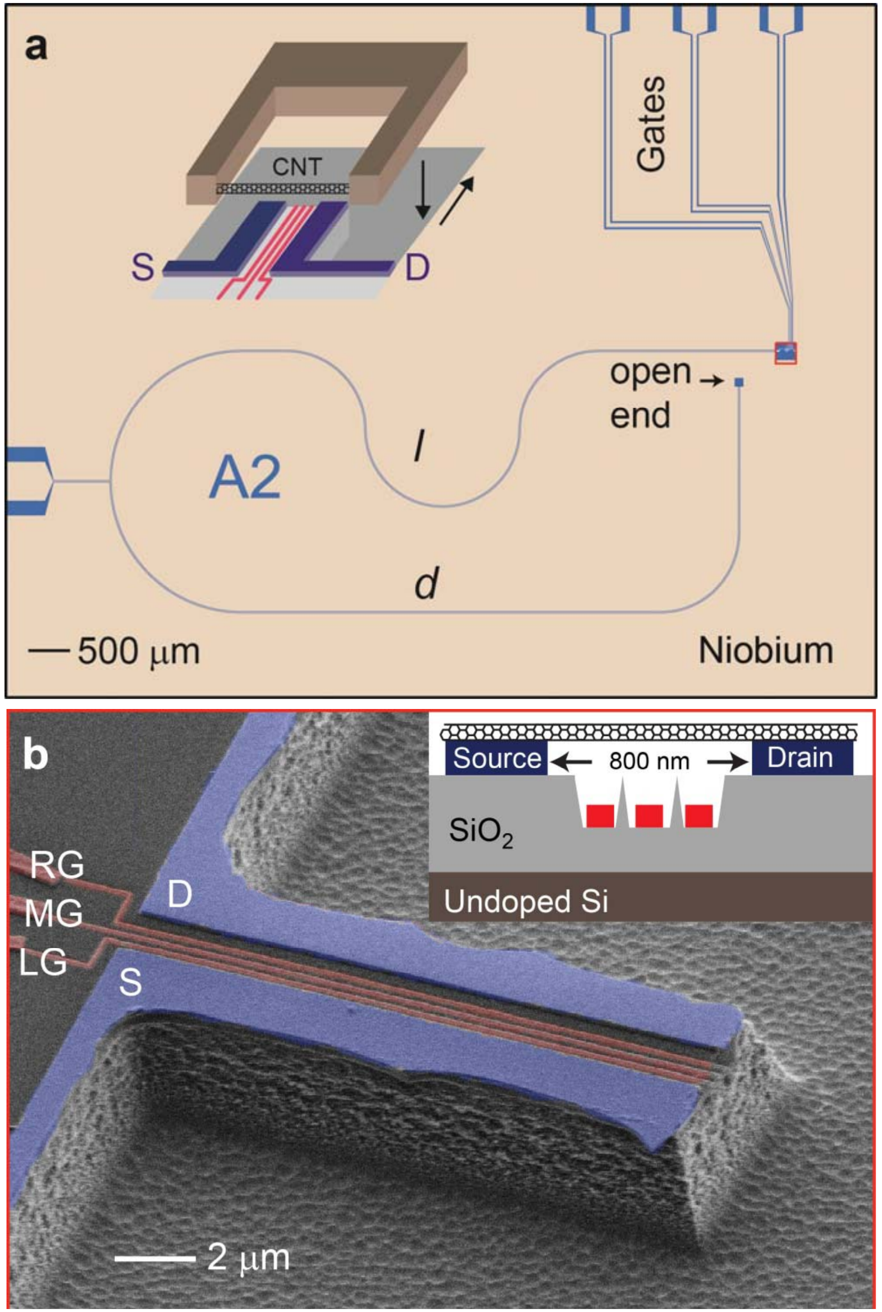
modern one with a single CNT and coupled to an rf circuit
work in progress

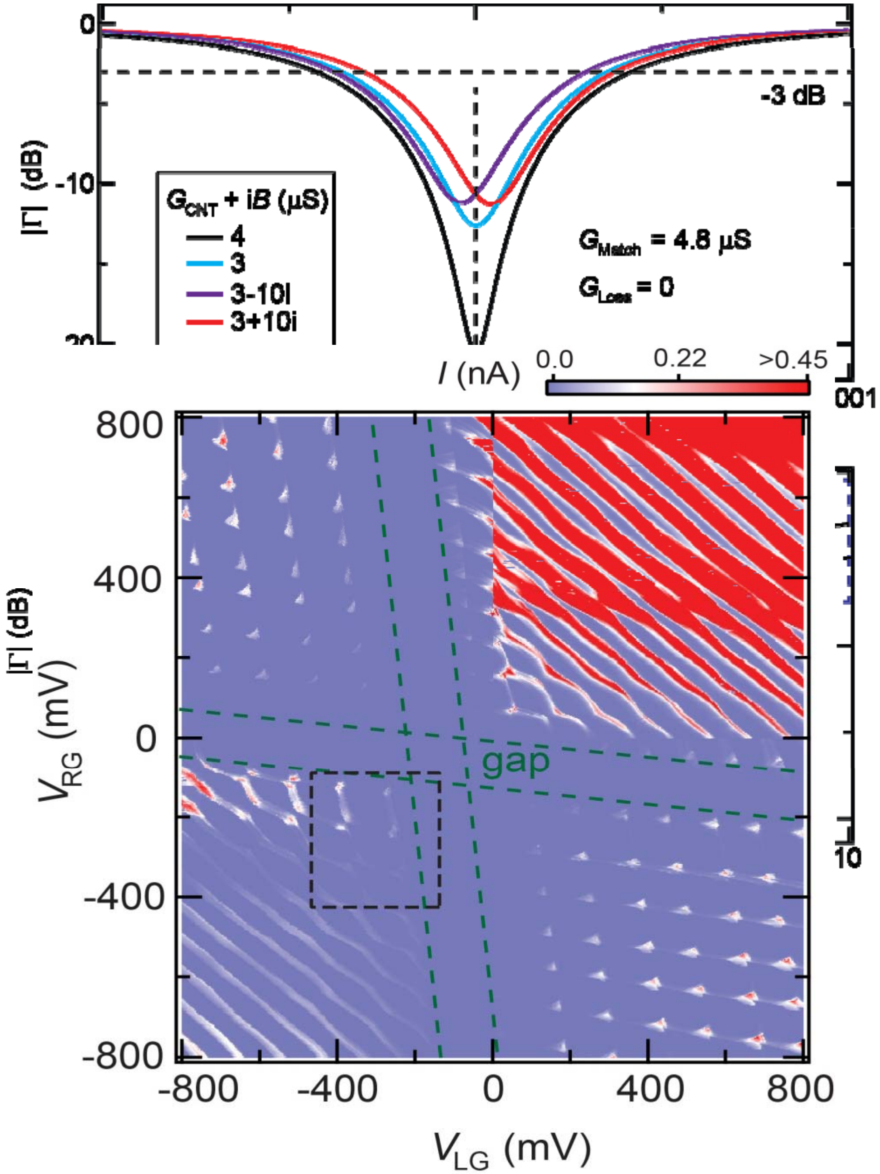
Carbon Nanotube (CNT) Quantum Dots (qdots)



M. Jung et al. Nano Lett. 13, 4522 (2013)

CNT Qdots coupled to rf cavities

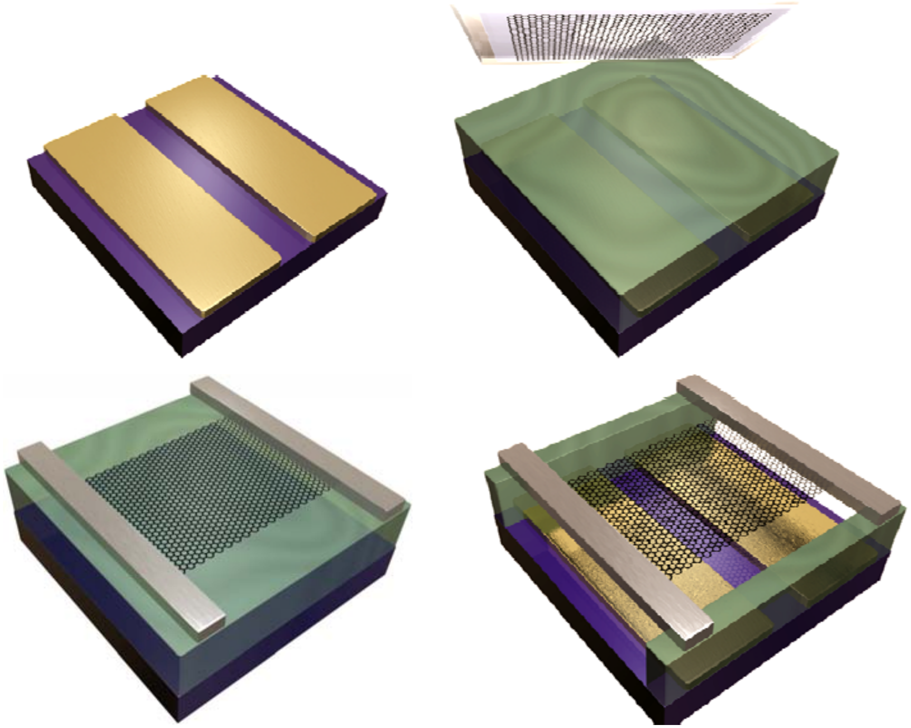


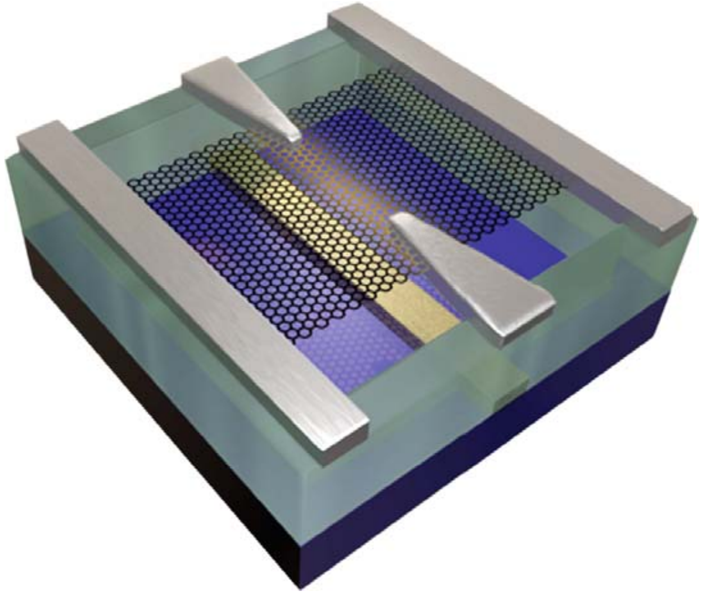


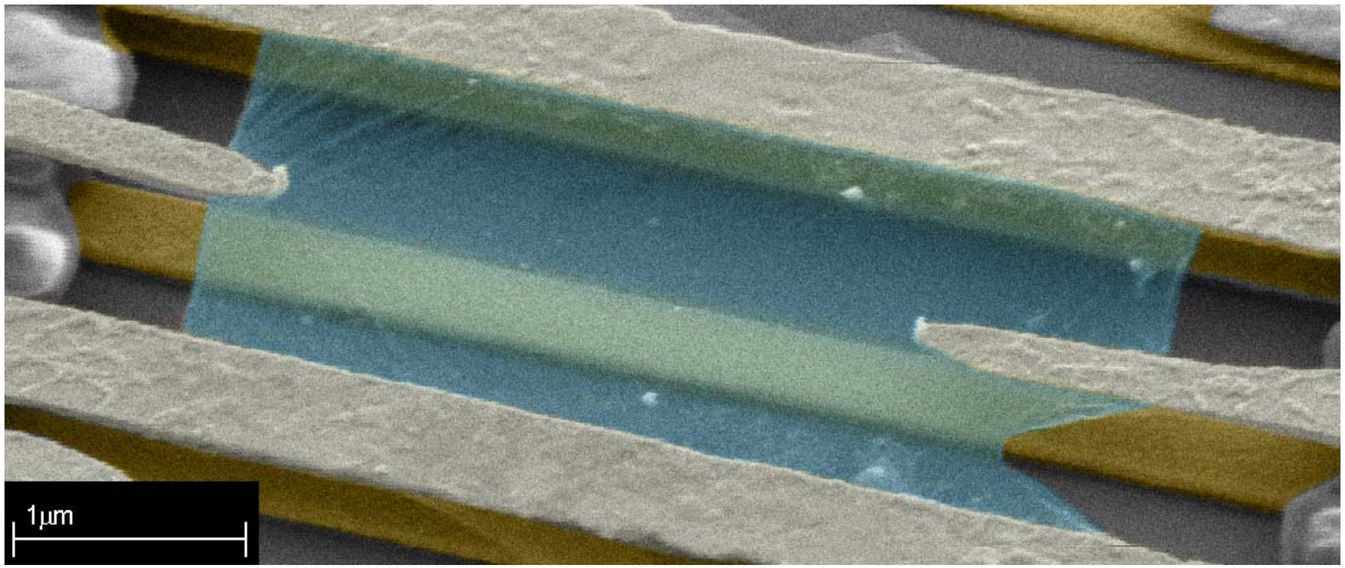
V. Ranjan et al. Nature Comm. (under review)

Graphene devices (suspended)

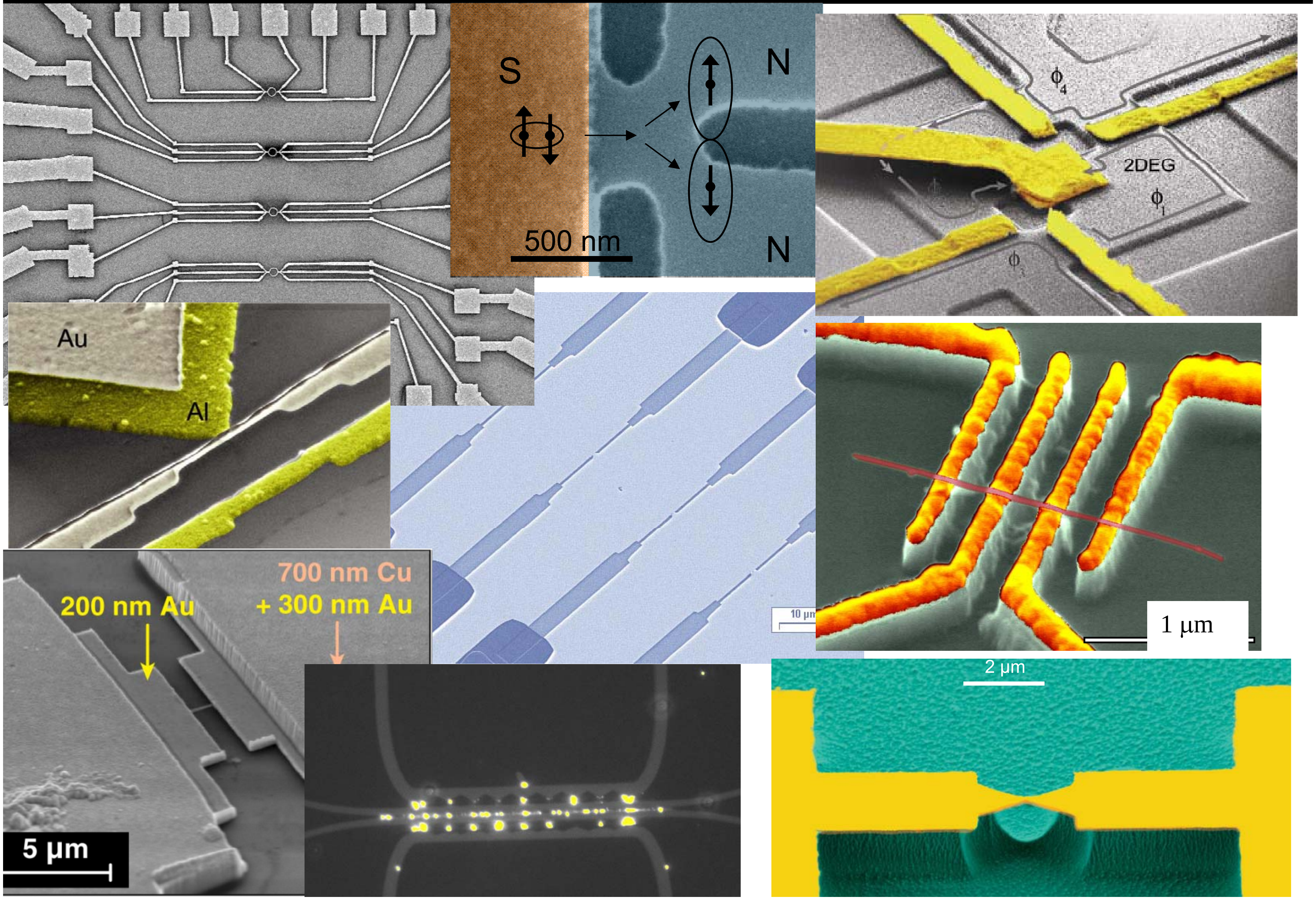
P. Rickhaus et al. Nature Comm. 4, 2342 (2013)







some more pics of devices



2. Quantum Primer

2. Quantum Primer

a) Wave-Mechanics („like“ optics, acoustics ...)

(energy E=const) **Schrödinger** **Helmholz**

$$\left\{\Delta + 2m\left(E - V\right)/\hbar^2\right\}\psi = 0 \qquad \left\{\Delta + (E/c\hbar)^2\right\}\psi = 0$$

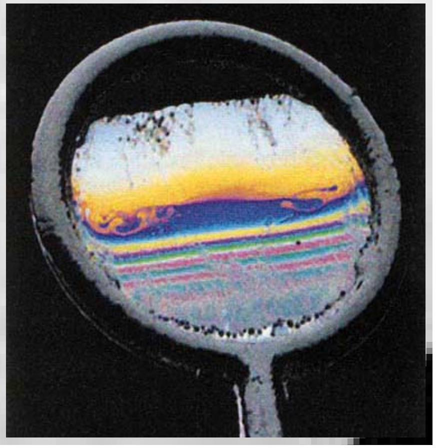
$$\left\{\Delta + k^2\right\}\psi = 0$$

waves: $\psi = A\exp(iS/\hbar)$

A: Amplitude

$\Theta = S/\hbar$ *Phase* (determined by the action **S**)

(the whole classical physics is contained in the phase)



2. Quantum Primer

b) add some weirdness

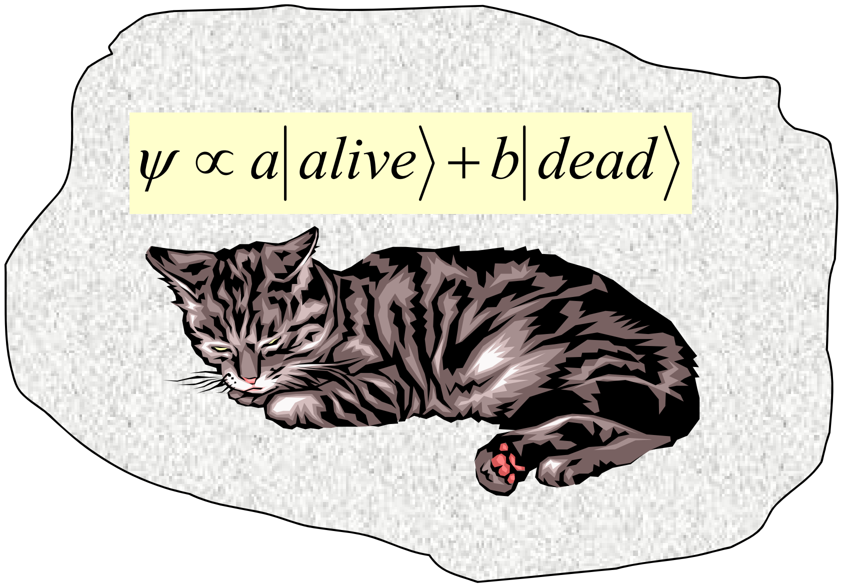
uncertainty relations: $[x, p] = i\hbar$

(not quite weird, formally a consequence of Fourier transformation)

c) some more weirdness

Copenhagen interpretation of Ψ **„collapse of wavefunction"**

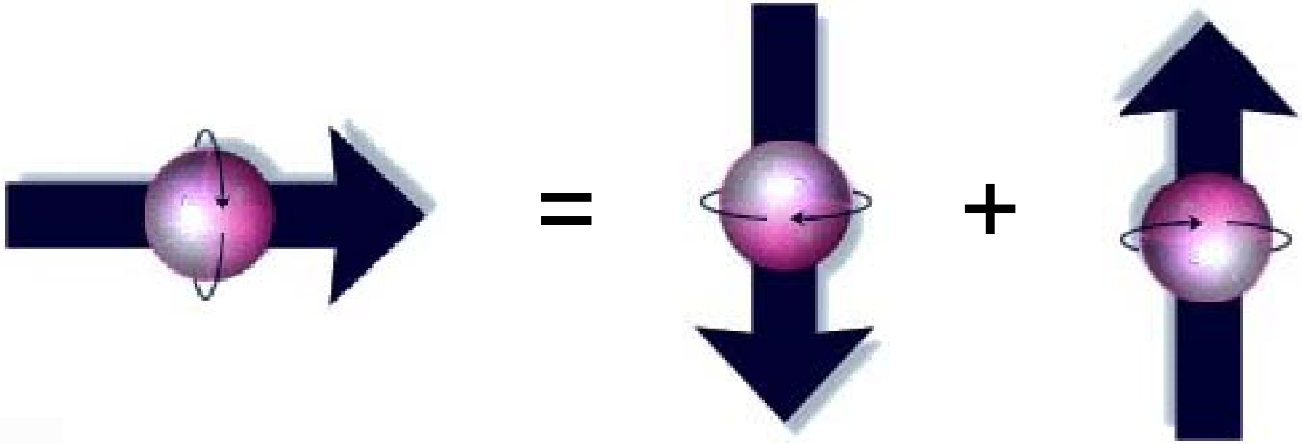
$$\psi \propto a|alive\rangle + b|dead\rangle$$

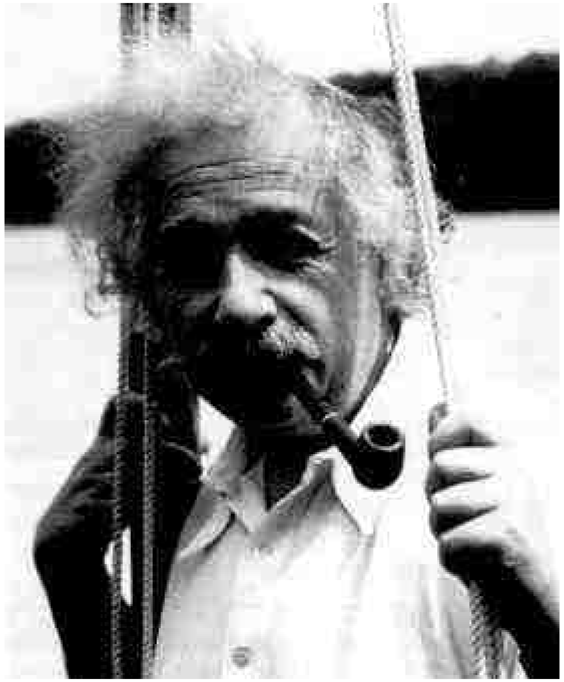


- linear superposition
- **cat is both dead and alive**
- only **if measured** is the cat **either dead or alive**!

2. Quantum Primer

superposition





„Gott würfelt nicht!“

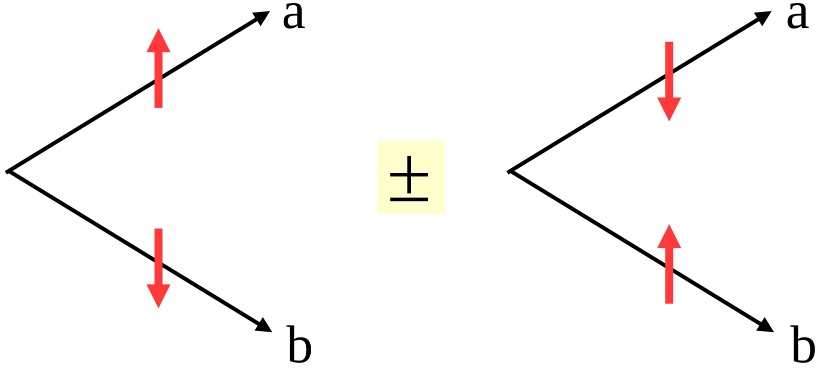
many measurements:

50% point up
50% point down

quantum physics is therefore probabilistic and not deterministic

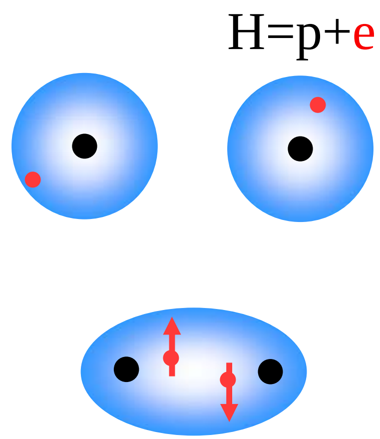
d) higher level weirdness

many-particle states, entangled states!

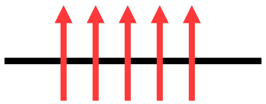


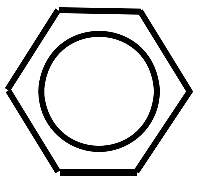
$$|a\uparrow\rangle|b\downarrow\rangle \pm |a\downarrow\rangle|b\uparrow\rangle$$

Chemistry



Magnetism

d-level  Mn ($3d^5 4s^2$)

diamagnetism 

- we all live on quantum mechanics
- we would **not exists without** QM!
- a classical world is unstable!

3. Conceptual discussions (blackboard)

- quantities yielding different energies, T, B, f, L ...
- ballistic vs diffusive
- quantum coherence
- energy conserving vs relaxation (damping)
- what is classical, which classical concepts break down
- quantum transport *“phenomenology”*

3. Conceptual discussions (blackboard)

Limit	*Length*	*Conserved quantity*
Ballistic	$L \ll \ell_{\text{el}}, \ell_{\text{e-e}}, \ell_{\text{e-ph}}$	current for each momentum state
↓ elastic scattering: randomizes momentum direction		
Diffusive, non-equilibrium	$\ell_{\text{el}} \ll L \ll \ell_{\text{e-e}}, \ell_{\text{e-ph}}$	current for each energy
↓ electron–electron scattering: mixes different energies		
Quasi-equilibrium	$\ell_{\text{el}}, \ell_{\text{e-e}} \ll L \ll \ell_{\text{e-ph}}$	charge and energy currents
↓ electron–phonon scattering: energy exchange with environment		
Local equilibrium	$\ell_{\text{el}}, \ell_{\text{e-e}}, \ell_{\text{e-ph}} \ll L$	charge current

Table 2.1 Different limits for the distribution function, defined by comparing the size L of the wire to the scattering lengths.

4. Phenomena in quantum transport

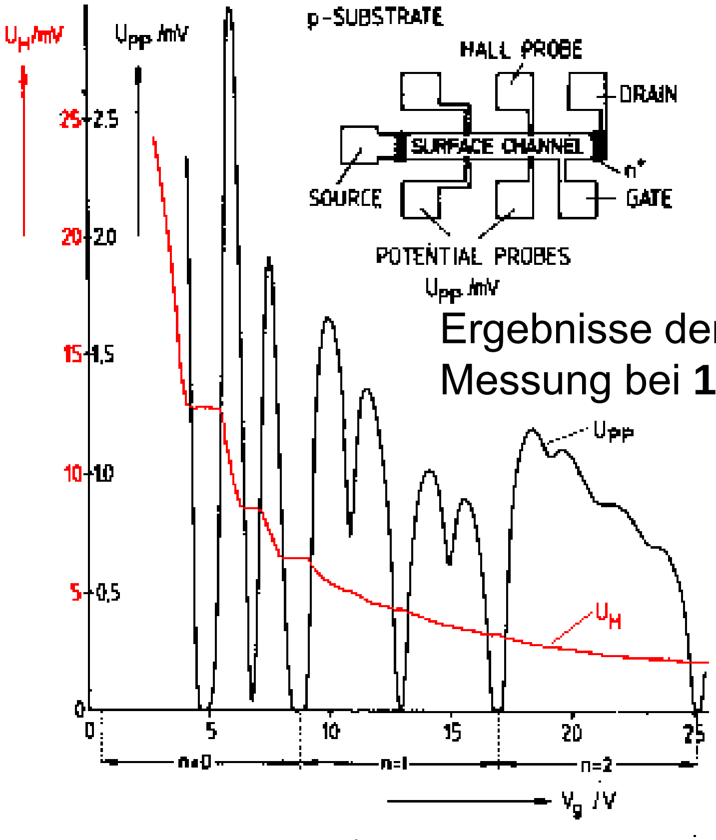
4.1 Quantum Hall Effect

1980 discovered by K. von Klaus von Klitzing in Grenoble

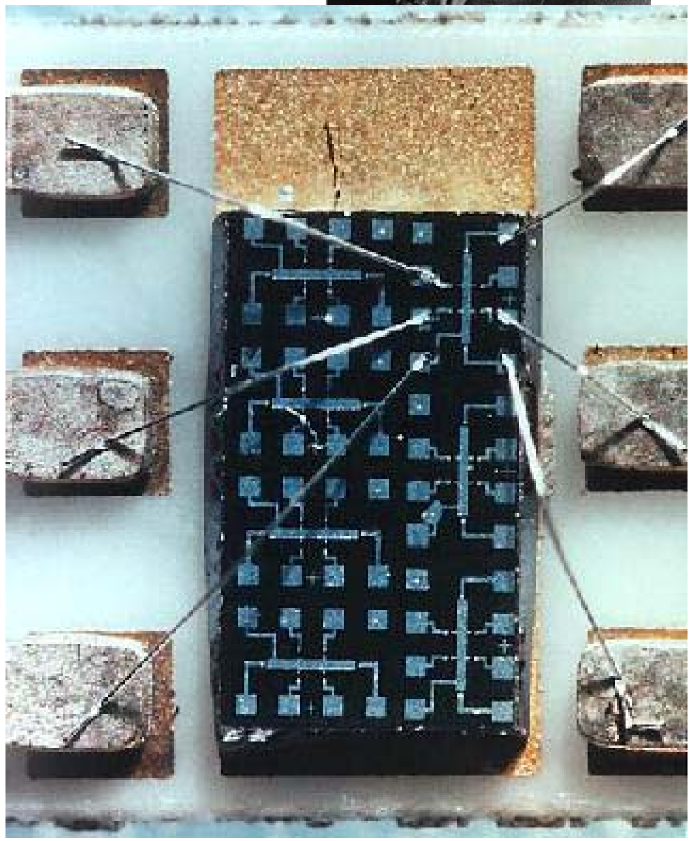
Untersuchung der Hall-Spannung von MOS-FET bei tiefen Temperaturen und starken B-Feldern

Deutung: **Quantisierung** des Hall-Widerstands

1985 Nobelpreis für Physik

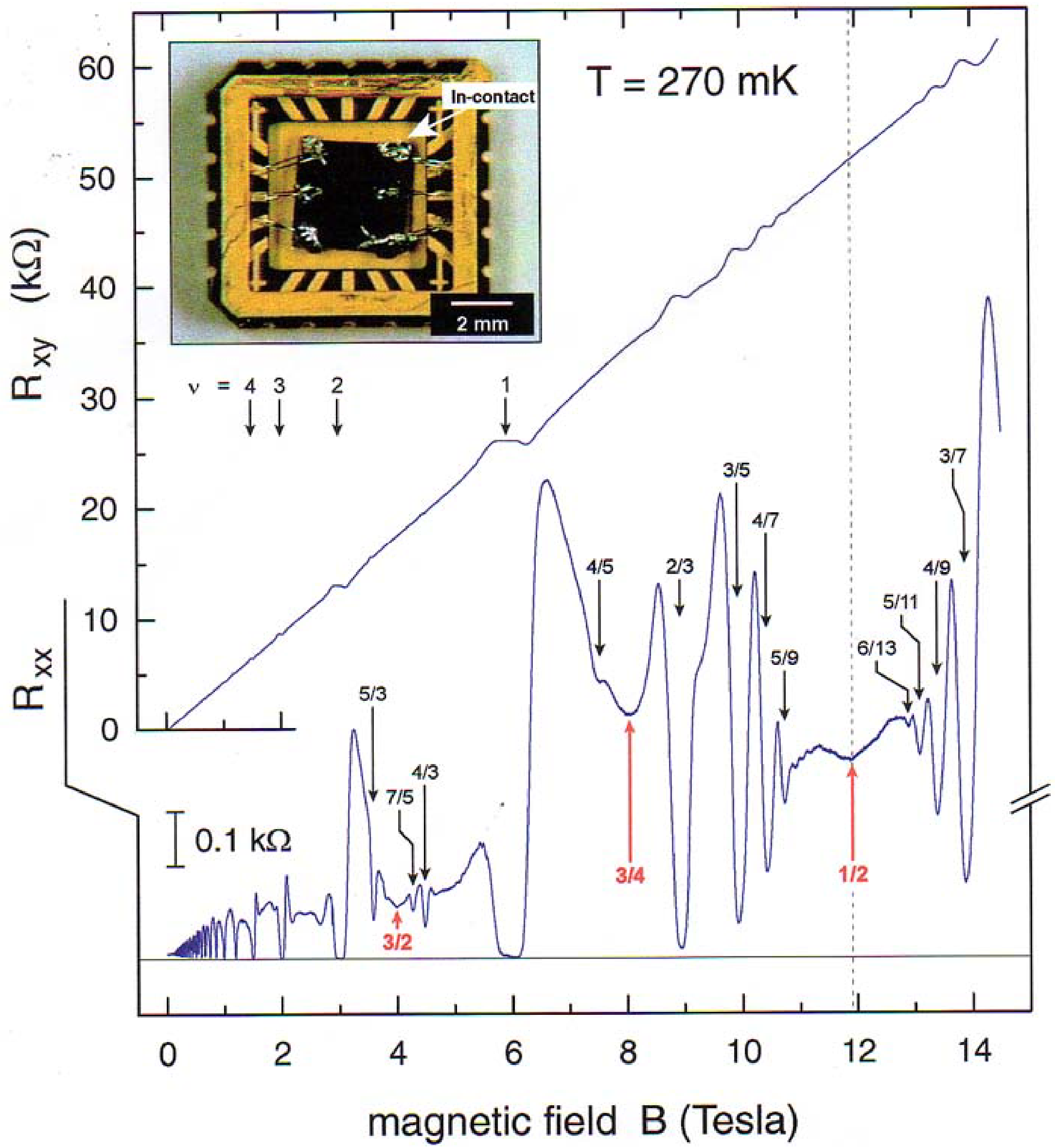


Ergebnisse der von-Klitzing-Messung bei **18 T** und **1,5 K**

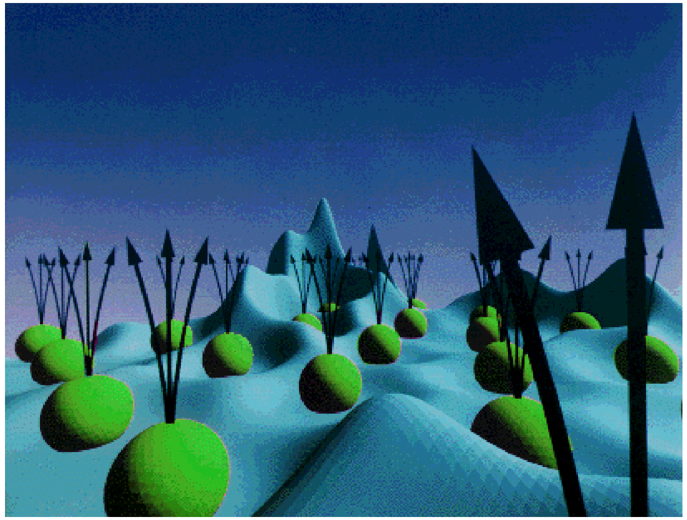


Originalprobe. Deutschen Museum Bonn

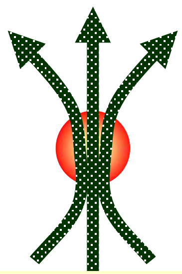
4.1 Quantum Hall Effect



Störmer, Tsui, Laughlin



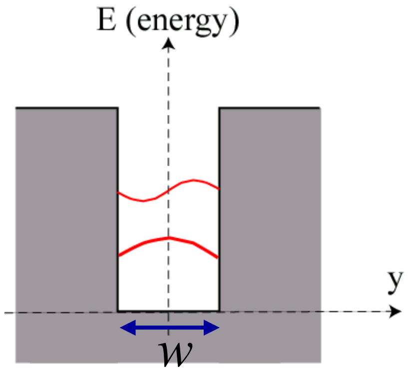
e.g. at filling 1/3

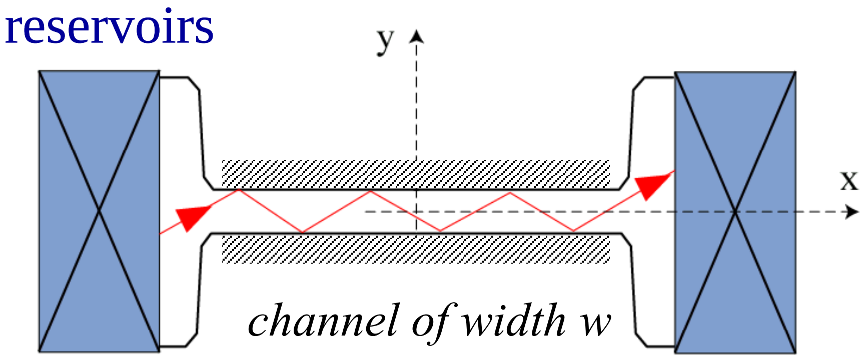


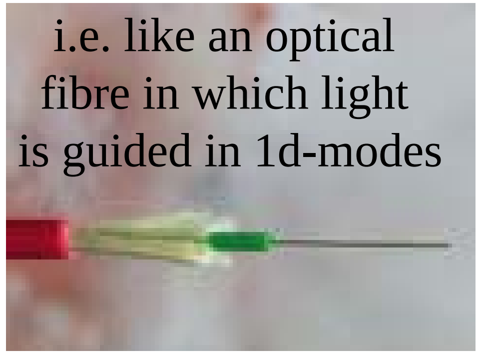
composite particle:
$1\ e\ +\ 3\ \Phi_0$

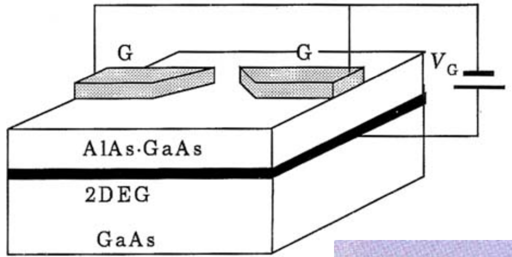
excitations (quasiparticles)
have fractional charge
(observed in experiment)

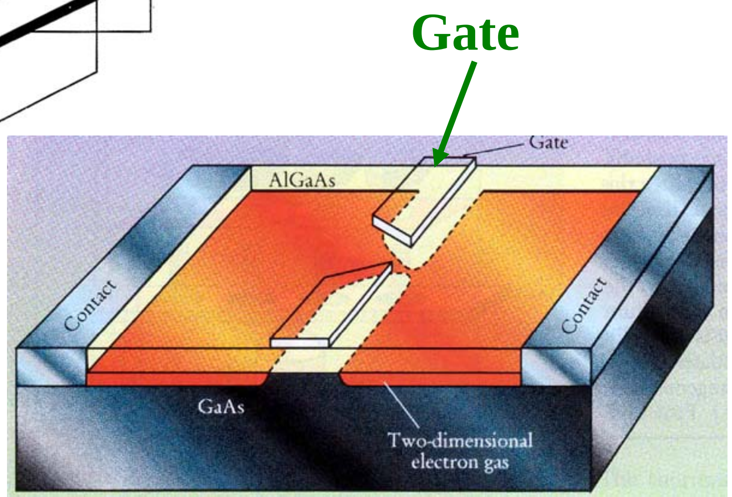
4.2 Quantum wire



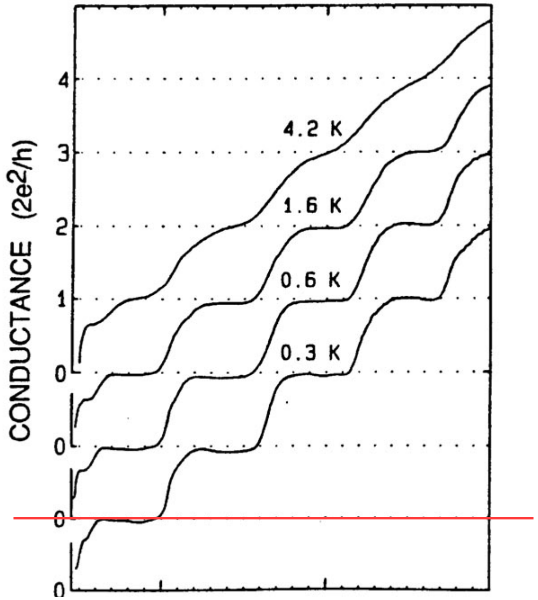








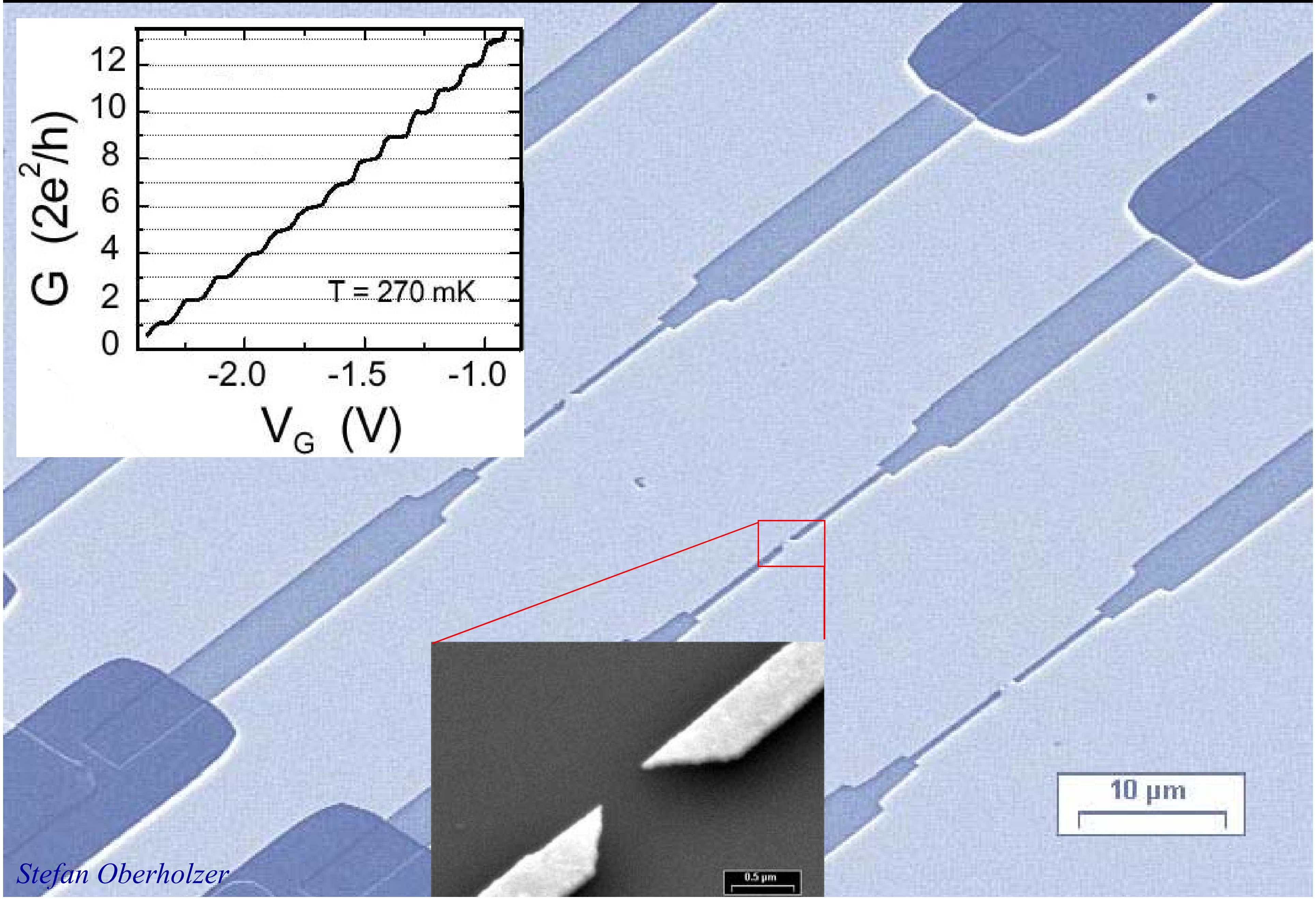
$$G_0 = \frac{2e^2}{h}$$



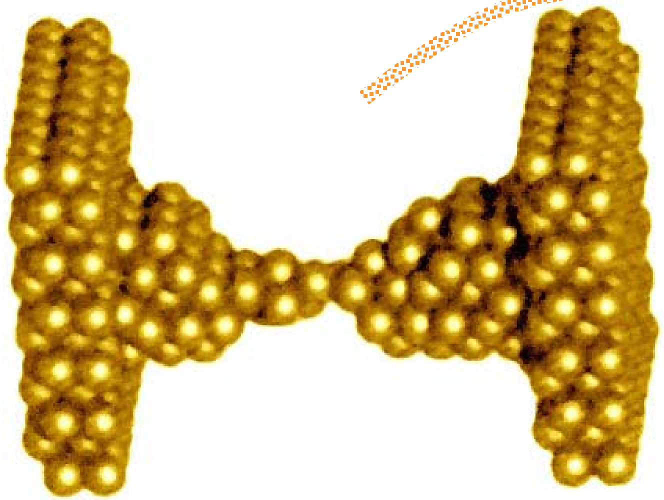
Gate Voltage ∝ width *w*

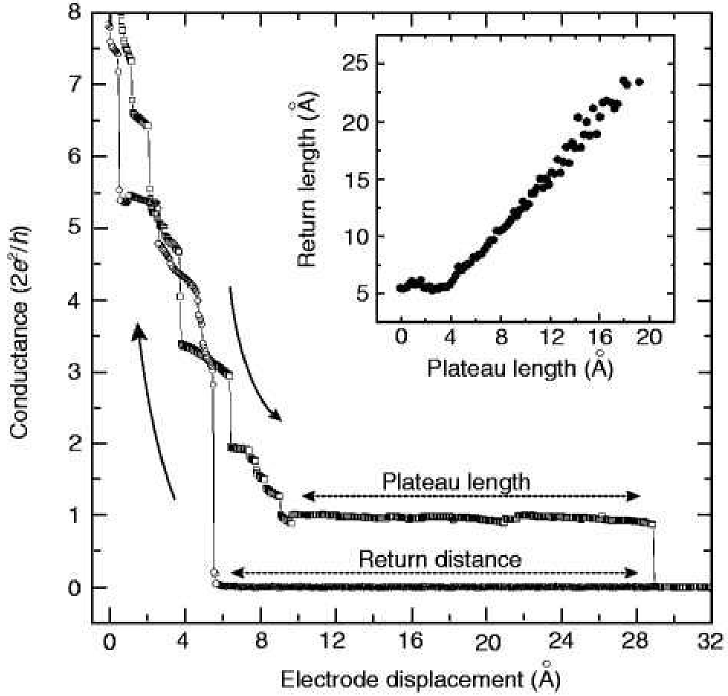
van Wees, van Houten 1988

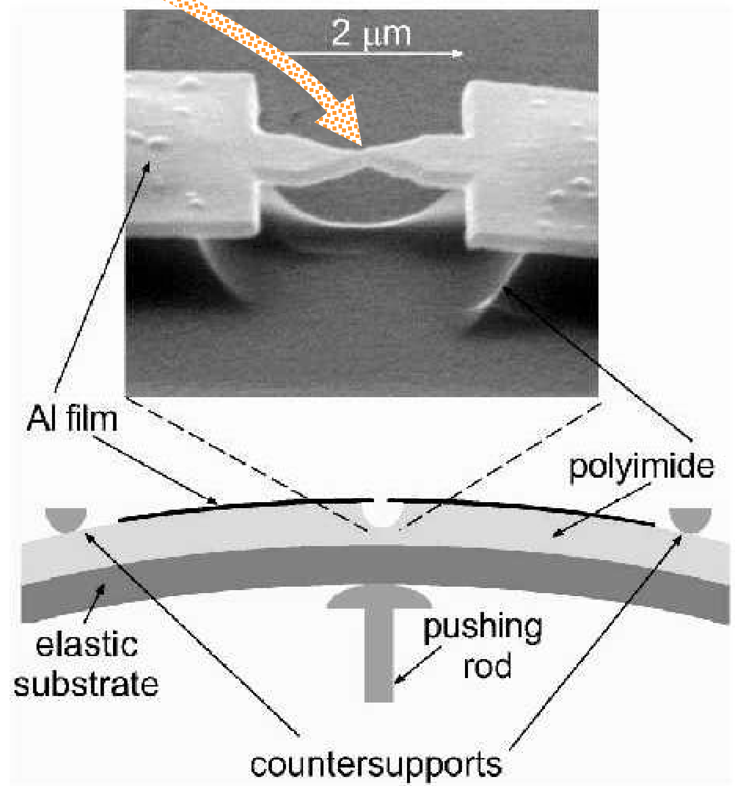
4.2 Quantum (wire) point contact (QPC)

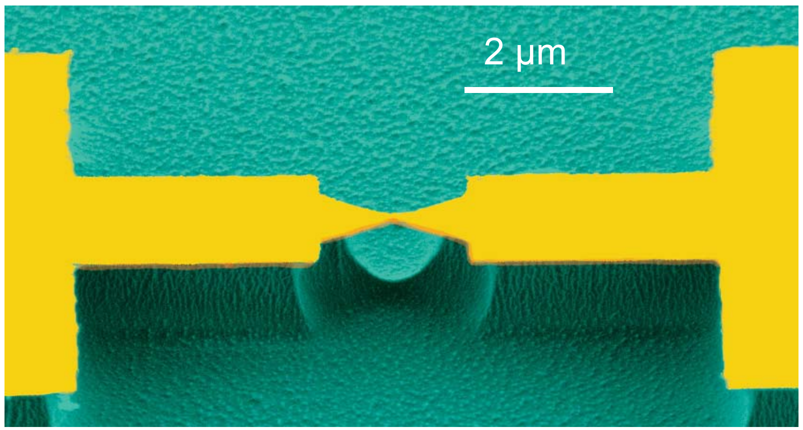


4.2 Quantum point contact (QPC)



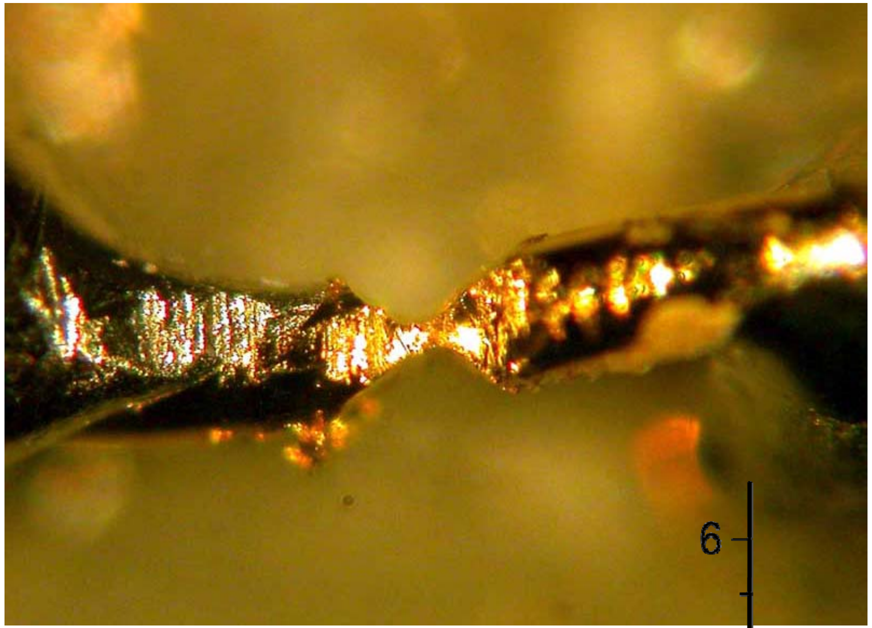


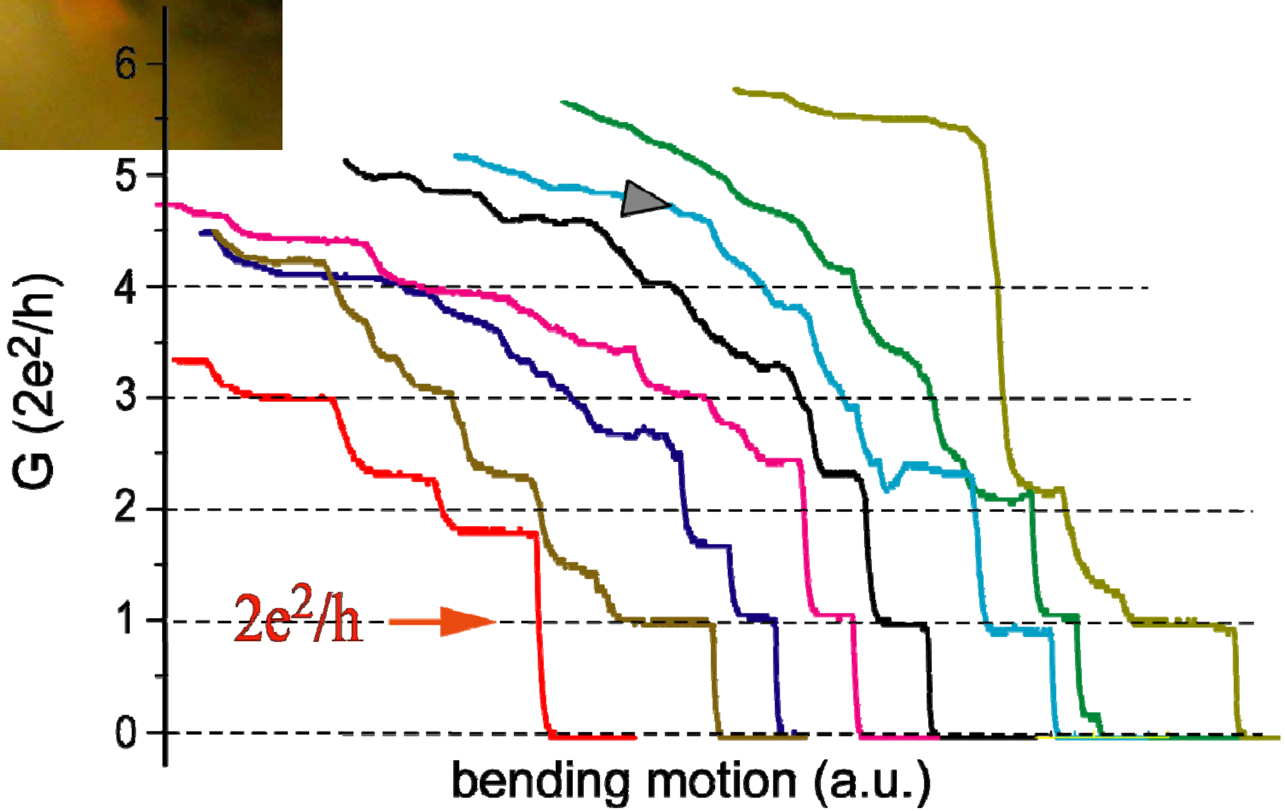




pioneered by Jan van Ruitenbeek, C. Urbina et al.

4.2 Quantum point contact (QPC)

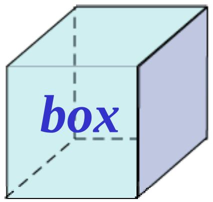




4.3 Quantized charge and flux

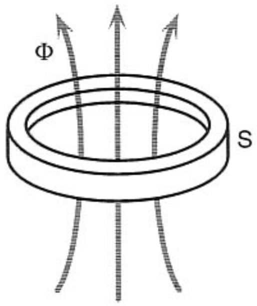
Millikan 1911

isolated piece of matter



dual

superconducting ring



charge Q is quantized

flux Φ is quantized

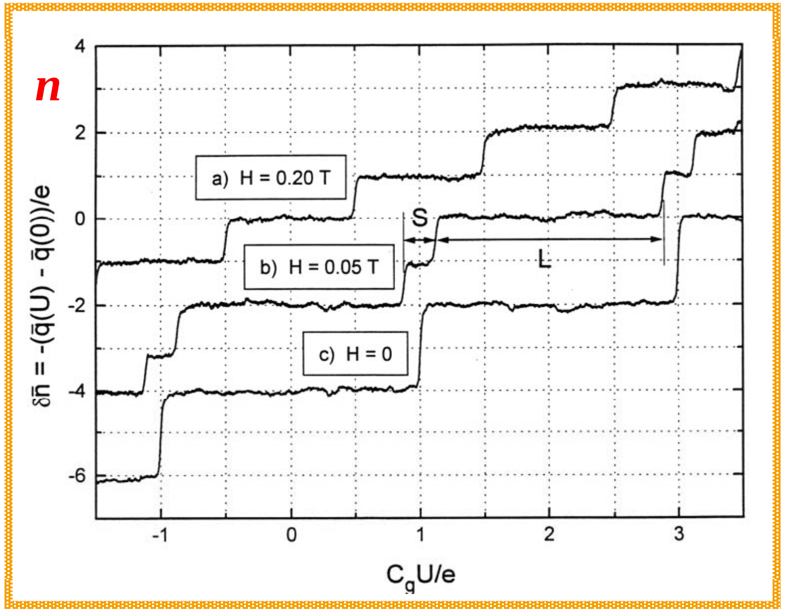
$Q = ne$

$\Phi = n(h/2e)$

(capacitor C)

(inductor L)

solid-state version of
Millikan‘s oil droplet experiment

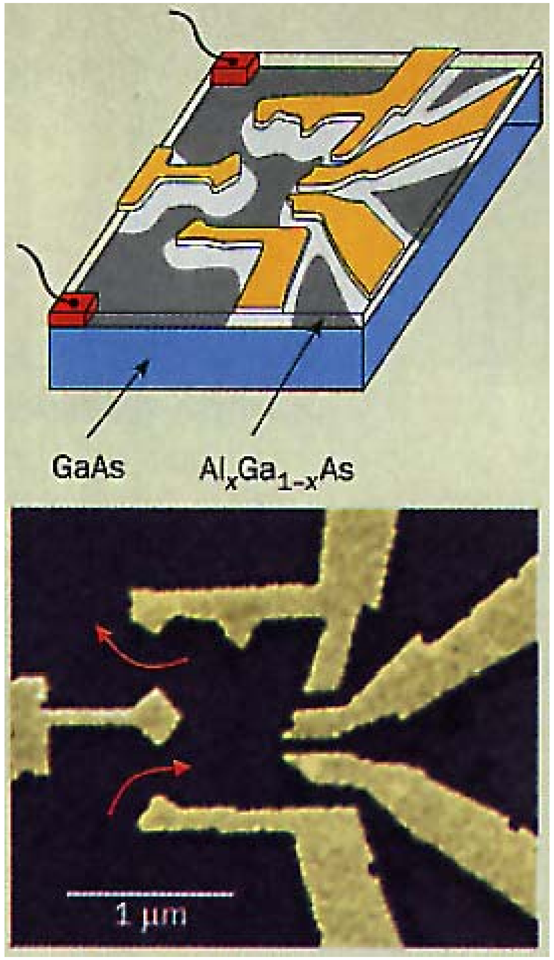


(Lafarge, Pothier, Bouchiat, Esteve, Devoret)

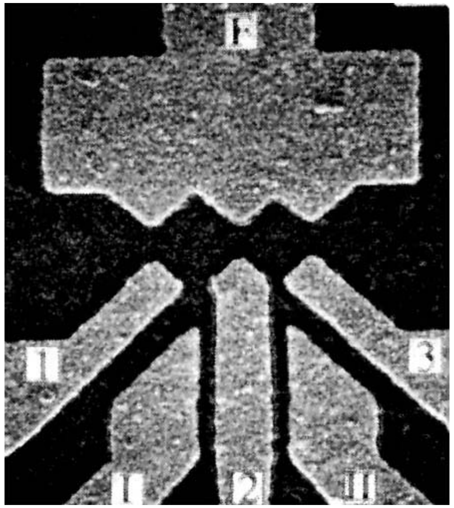
4.4 Quantum dots

“small” cavities

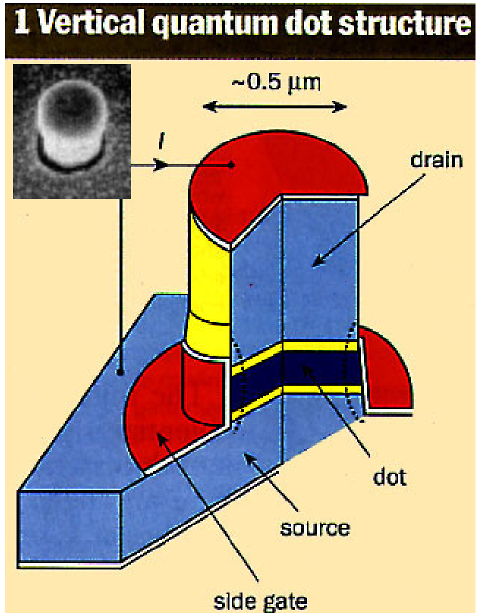
planar dot



planar double-dot



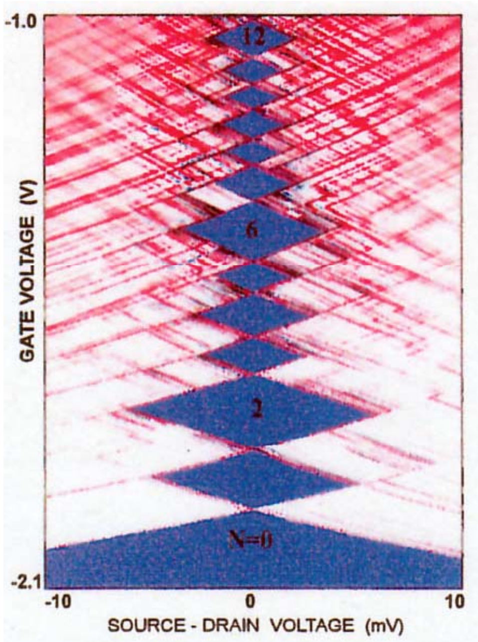
vertical dot

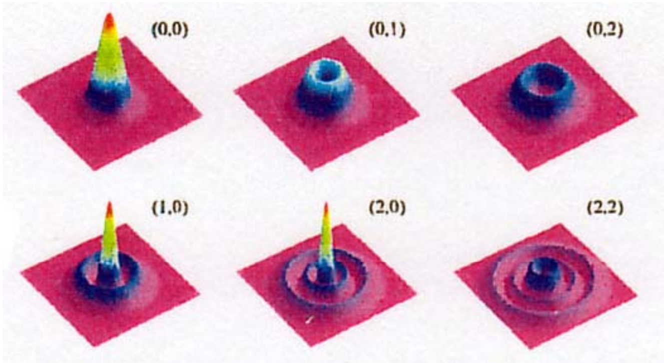


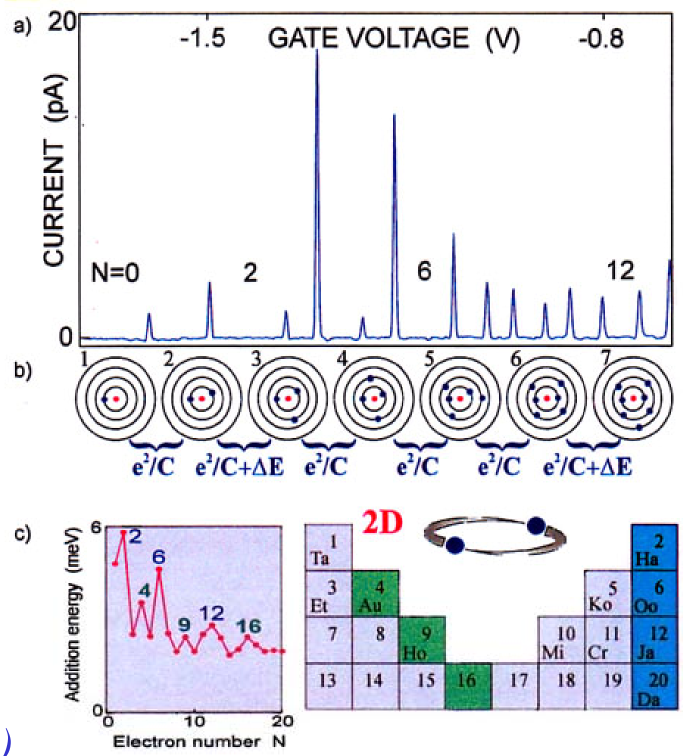
... planar multi-dot

4.4 Quantum dots

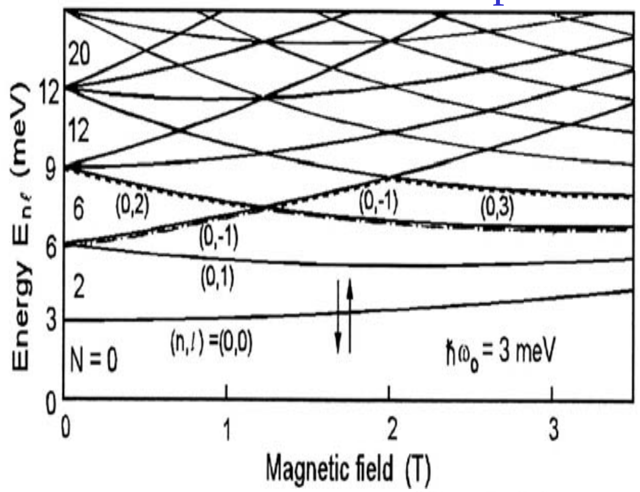
few electron quantum dots

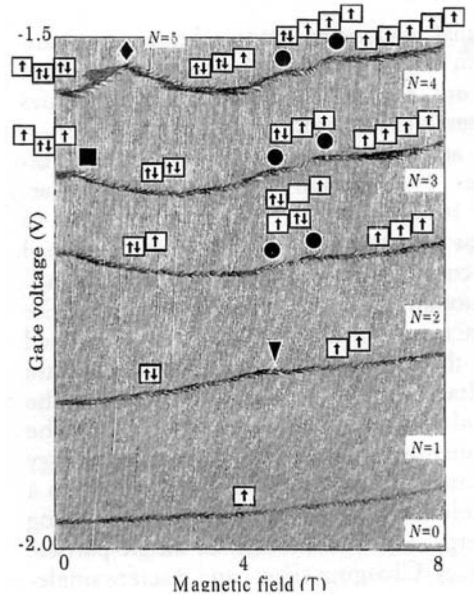






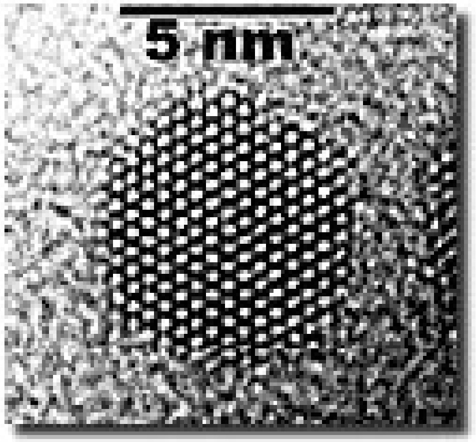
Fock-Darwin level spectra





(Kouwenhoven, Tarucha et al.)

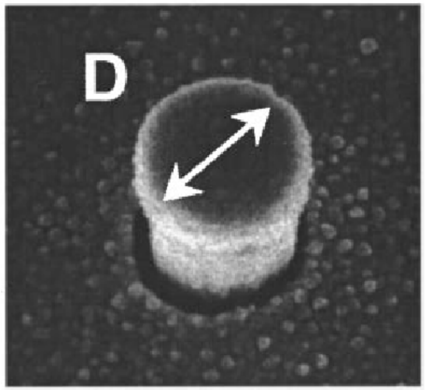
4.4 Quantum dots



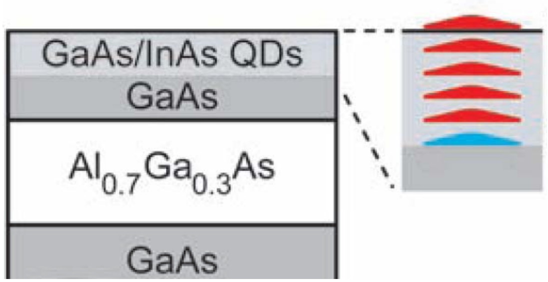
TEM by Andreas Kadavanich. Transmission electron micro-scopy shows the crystalline arrangement of atoms in a 5 nm CdSe Qdot particle.

A family of Qdot particles can be made to emit a full spectrum of colors when excited with a single excitation source.

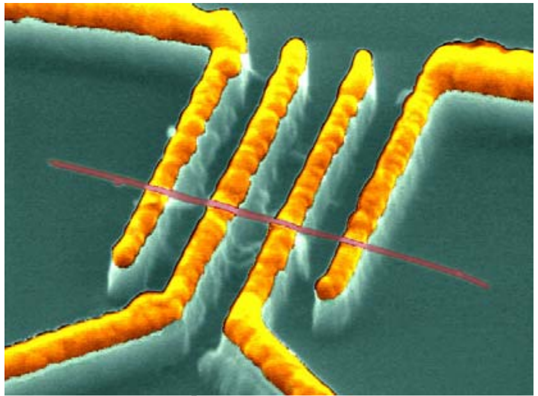
4.4 Quantum dots



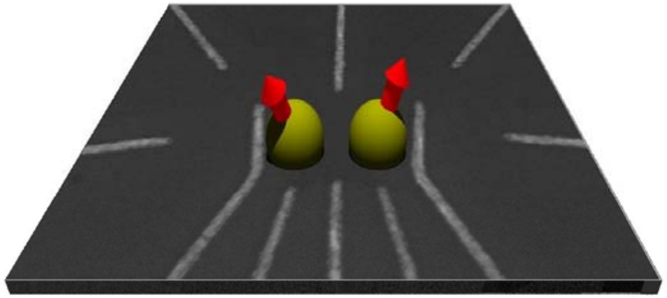
GaAs vertical



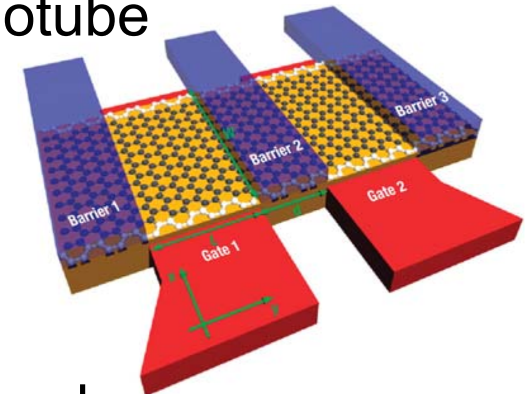
MBE grown



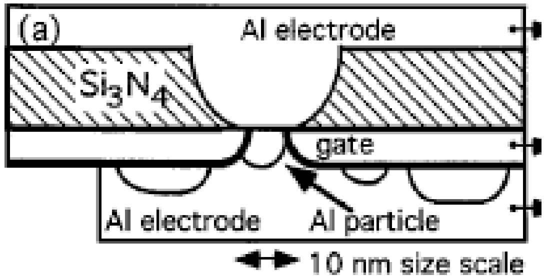
nanotube



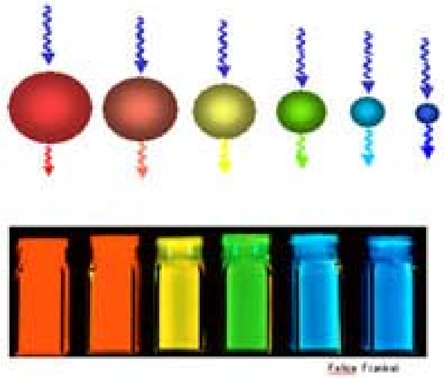
GaAs lateral



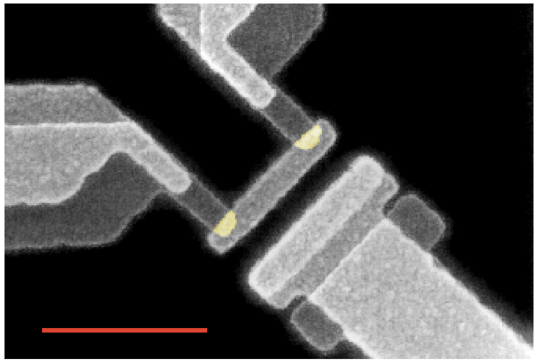
graphene



metal grain



self assembled

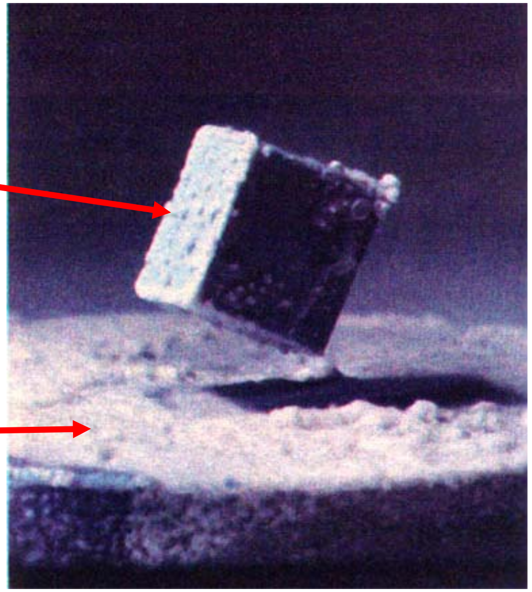


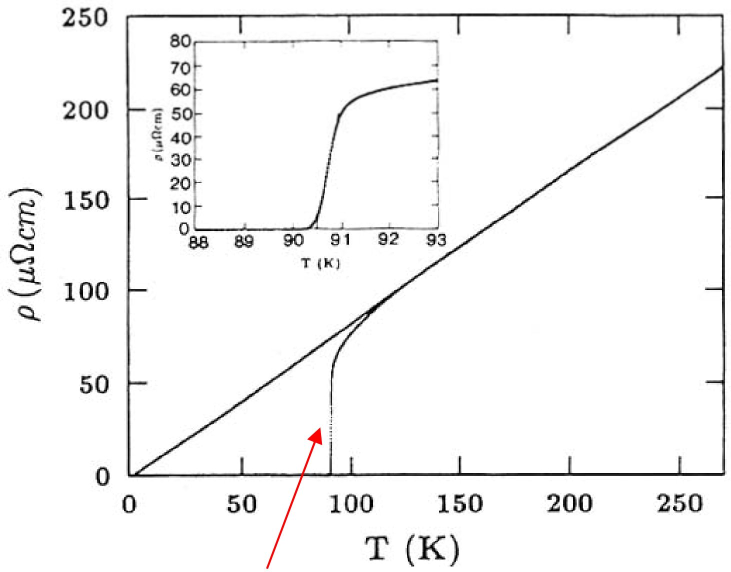
metallic SET

4.5 Intereference

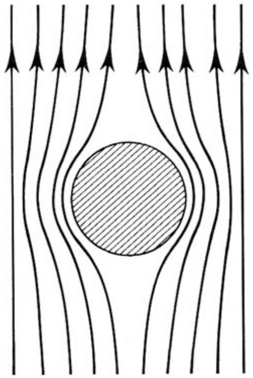
levitating magnet

high Tc superconductor





transition to zero resistance

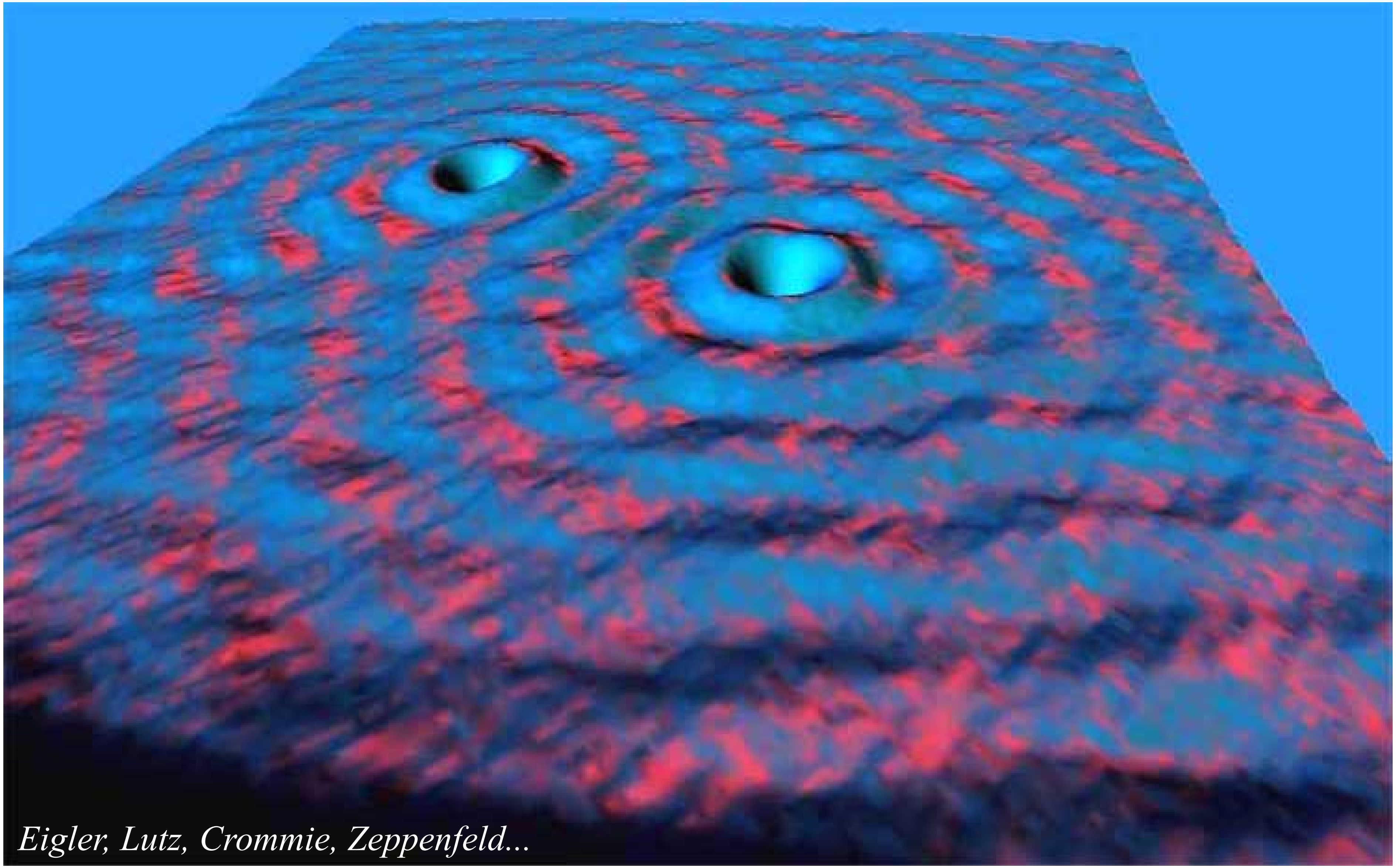


Meissner effect
(ideal diamagnetism)

$$\psi = A\exp(i\theta)$$

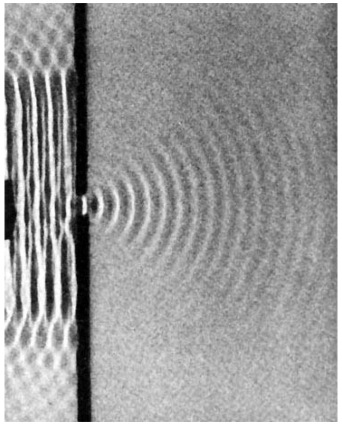
Best known **macroscopic quantum system**: both A and θ are collective „classical“ variables

4.5 Intereference

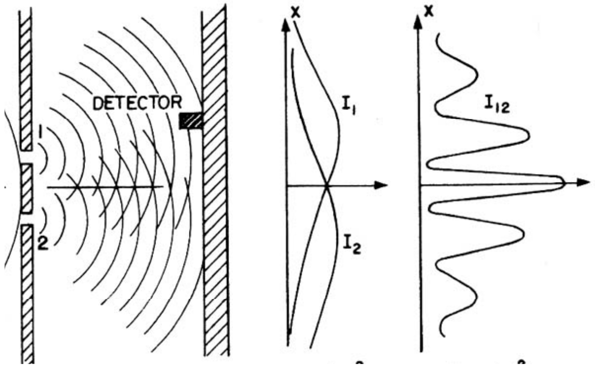


Eigler, Lutz, Crommie, Zeppenfeld...

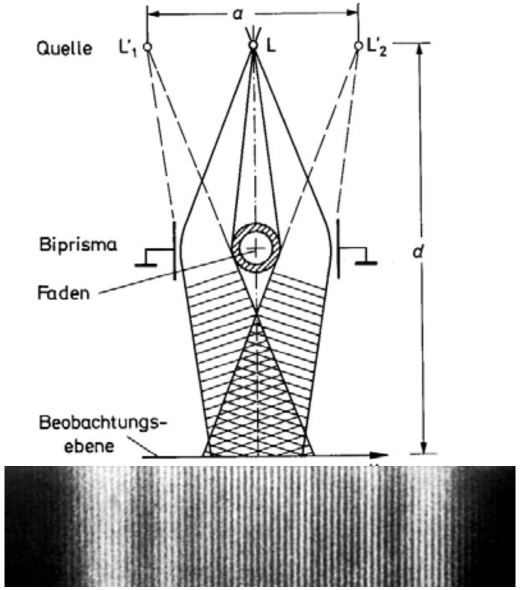
4.5 Intereference



spherical wave



interference of 2 spherical wave
Young's double slit experiment



(Moellenstedt, Tonamura)

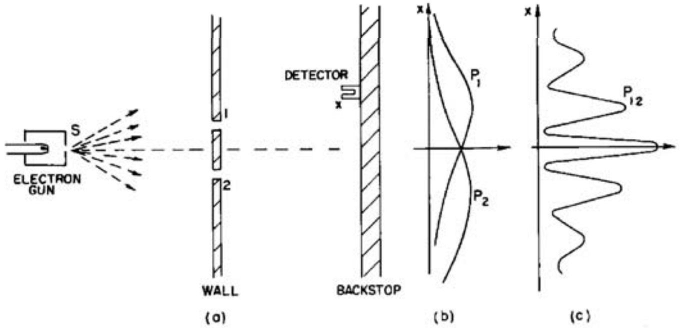
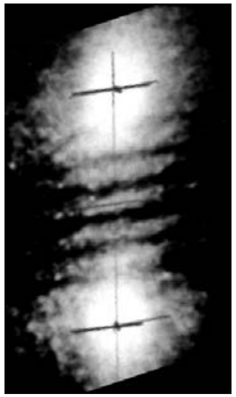
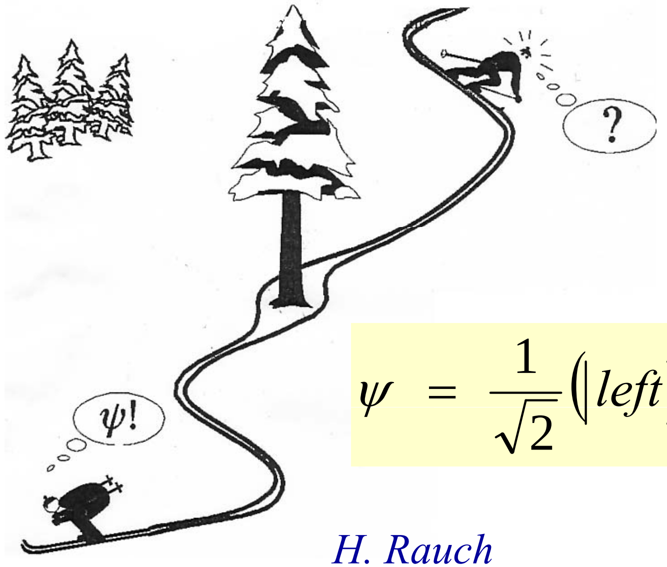


Fig 3-1. Interference experiment with electrons.



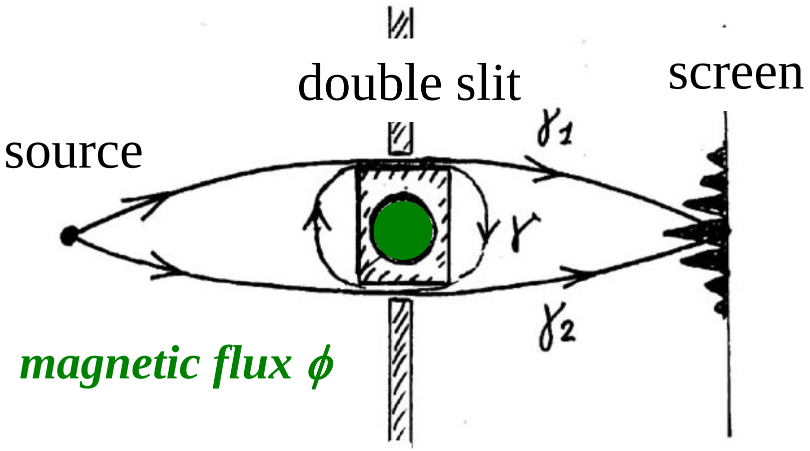
lens-less, low-energy electrons *(H.-W. Fink)*



$$\psi = \frac{1}{\sqrt{2}}\left(\left|left\right\rangle + \left|right\right\rangle\right)$$

H. Rauch

4.5 Intereference Aharonov-Bohm effect

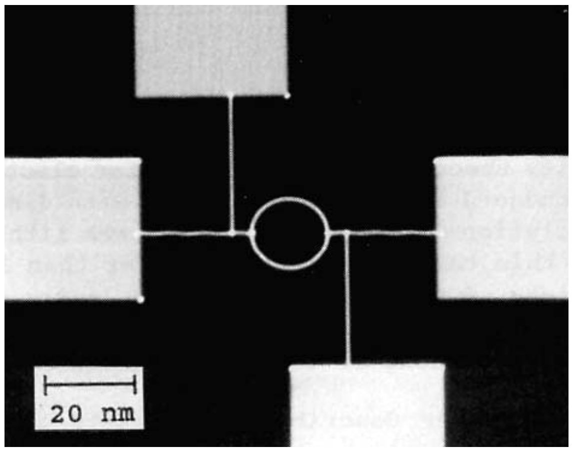


$$\psi = |\psi| \exp(i\theta)$$

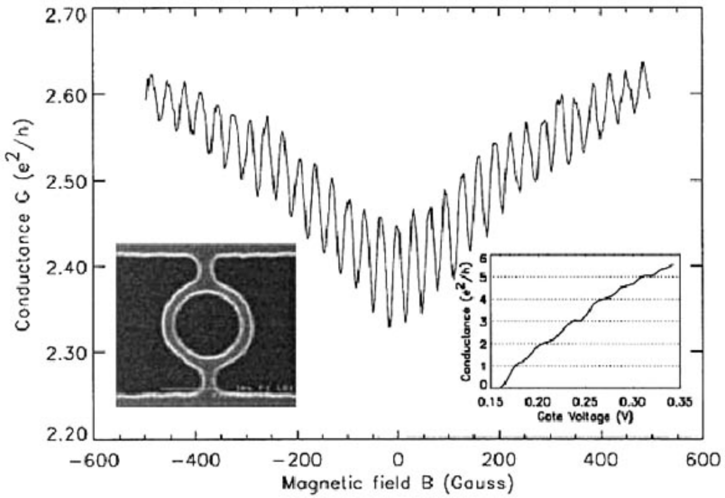
$$\theta \rightarrow \theta + \frac{e}{\hbar}\int_{\gamma i} \vec{A}\cdot d\vec{s}$$ (A = vector potential)

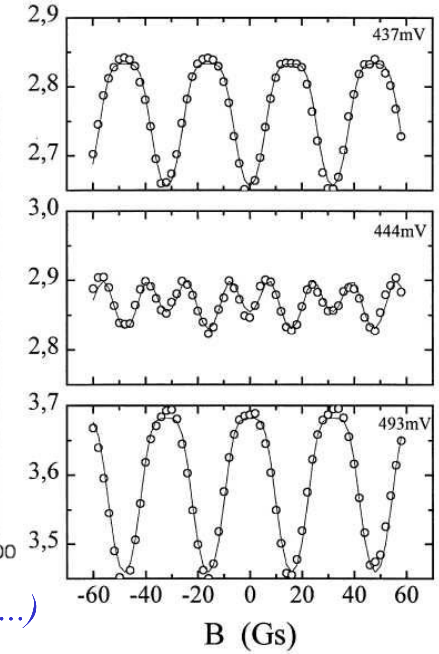
$$\Delta\theta = 2\pi \frac{\phi}{\phi_0}$$

$$\phi_0 = h/e$$ **magentic flux quantum**



(smallest men-made metallic ring)





(Pederson, Hansen...)

4.5 Intereference

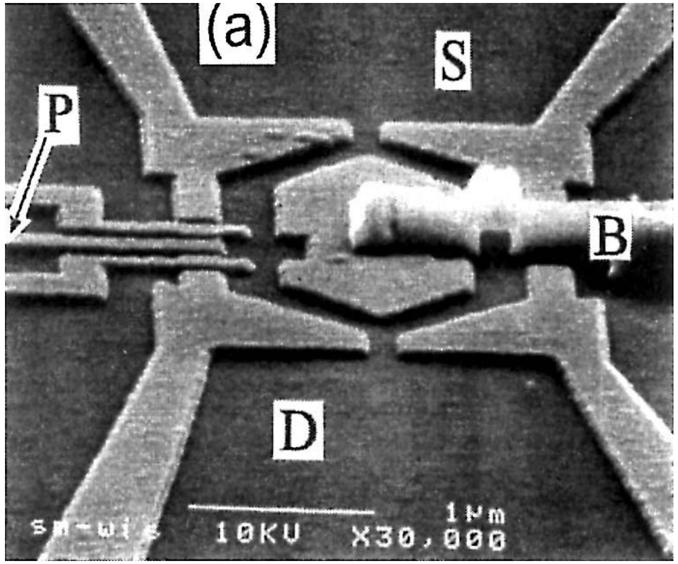
which path interferometer

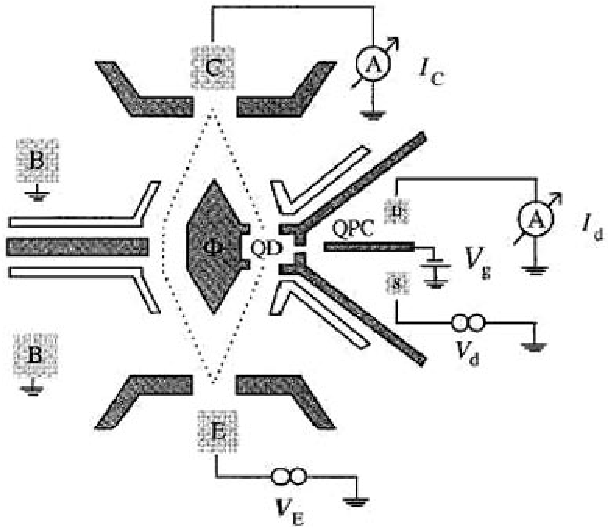
$$\psi = \frac{1}{\sqrt{2}}\left(|left\rangle + |right\rangle\right)$$

$$\psi = \frac{1}{\sqrt{2}}\left(|left\rangle \otimes |O_l\rangle + |right\rangle \otimes |O_r\rangle\right)$$

if $\langle O_r \| O_l \rangle = 0$ *=> no interference*

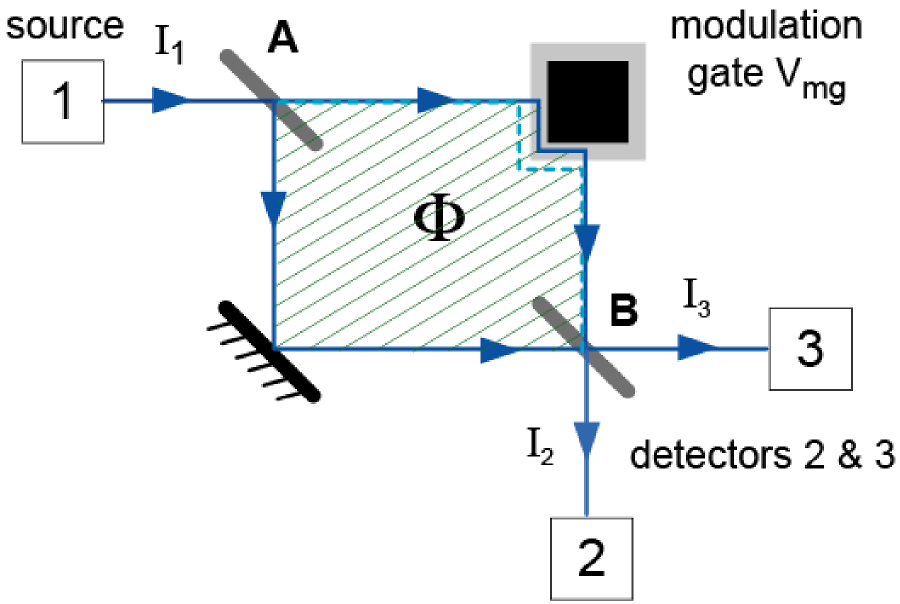
but we know which path the skier took

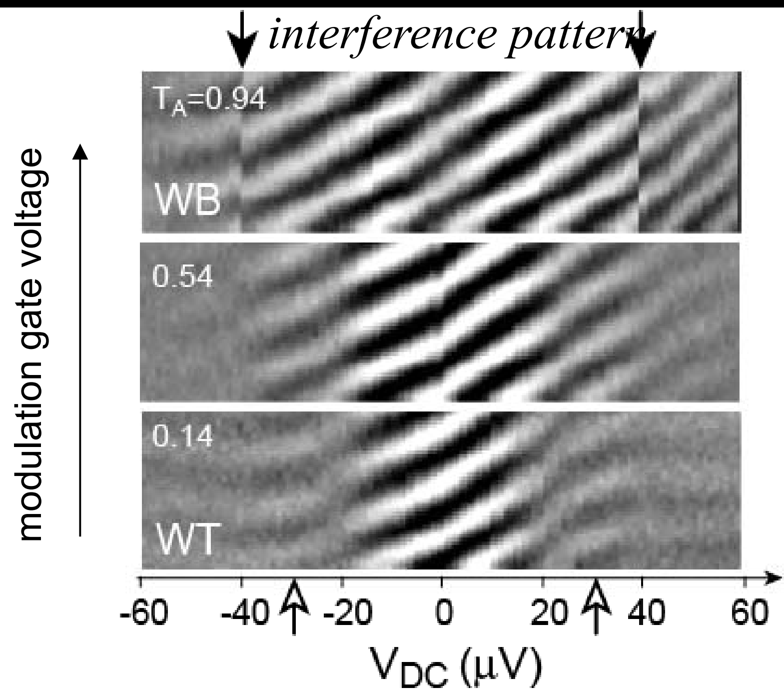


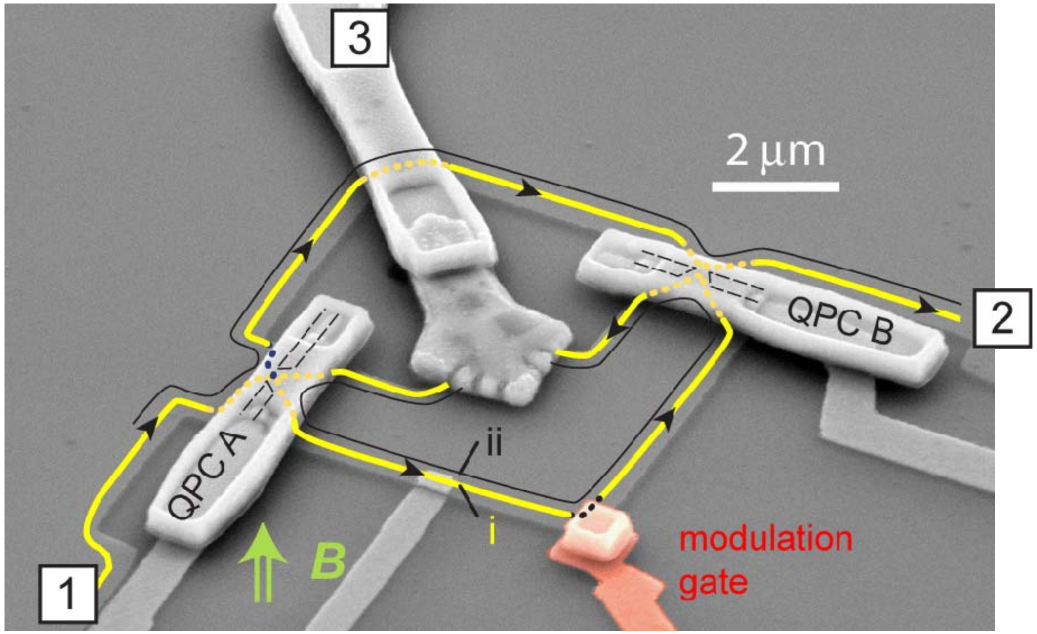


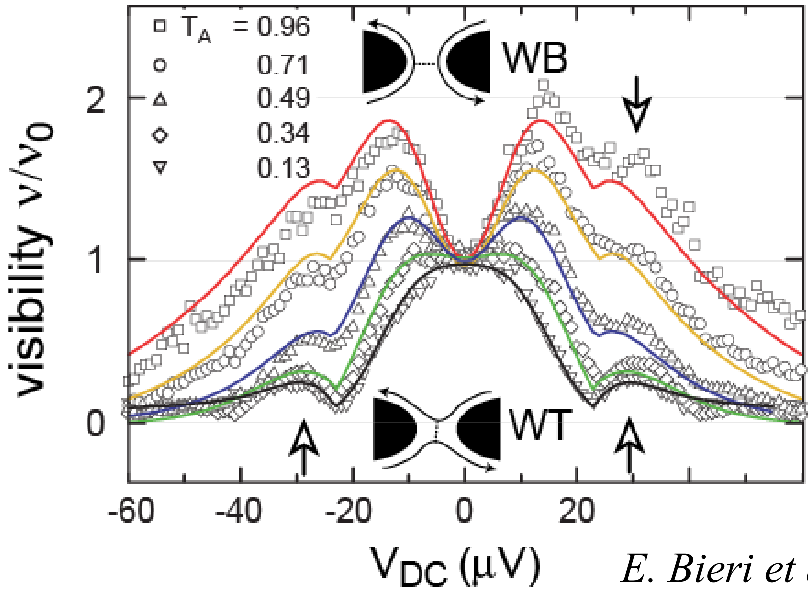
(Heiblum, Yacoby, Schuster et al. Weizmann)

4.5 Mach-Zehnder Interferometer







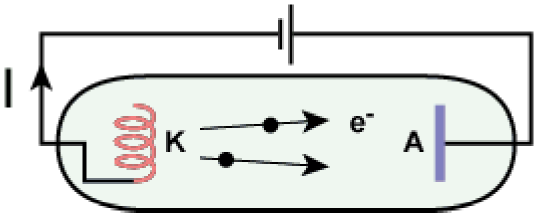


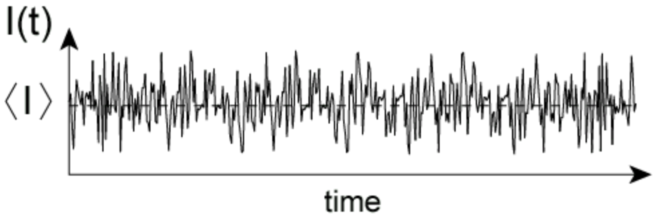
E. Bieri et al.

4.6 Noise

- A photonmultiplier makes click if a photon is absorbed.
- Such detectors are not yet available for charge transport in electronics!
- Still, the granularity of the measurement process, caused by the quantization of charge in units of e, can still be probed.

Schottky





$$S_{ij}(\omega) = 2\int dt\, e^{i\omega t} \langle \Delta I_i(t)\, \Delta I_j(0) \rangle \quad [A^2 s]$$

$$S = 2e|I|$$

(uncorrelated transfer of „quantas“, i.e. Poission statistics)

Suppression of Shot Noise caused by:

- correlations due to **interactions**
- correlations due to **statistics**
- **fractional** charged quasiparticles

4.7 Quantum computing

4.7 Quantum computing

classical bit b:

$$b \in \{0,1\}$$

b is **either** 0 **or** 1

quantum bit (qubit) q:

$$q = a|0\rangle + b|1\rangle$$

q is a coherent superposition of 0 **and** 1

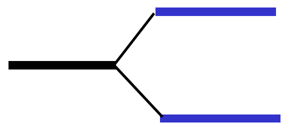
qubit:

qubit is a 2-level system

$$H = E_0|0\rangle\langle 0| + E_1|1\rangle\langle 1| + \frac{E_c}{2}\{|0\rangle\langle 1| + |1\rangle\langle 0|\}$$

coupling E_c

if $E_1 = E_2$



E.g. prepare state(s)

$$|0\rangle \Rightarrow a|0\rangle + b|1\rangle$$

through **control of interaction** (without loss of coherence..!)

INTERACTION
- charge
- current
- exchange

different realizations

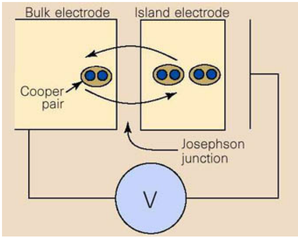
qubits =

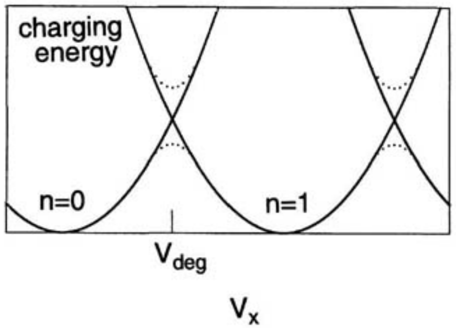
- charge qubit
- flux qubit
- phase qubit
- spin qubit
- trapped ions
- photon qubit

4.7 Quantum computing

Coherent control of macroscopic quantum states in a single-Cooper-pair box

Y. Nakamura*, Yu. A. Pashkin† & J. S. Tsai*

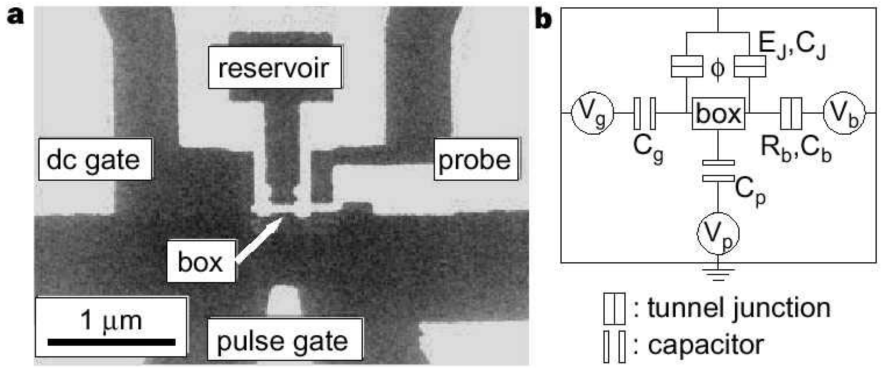


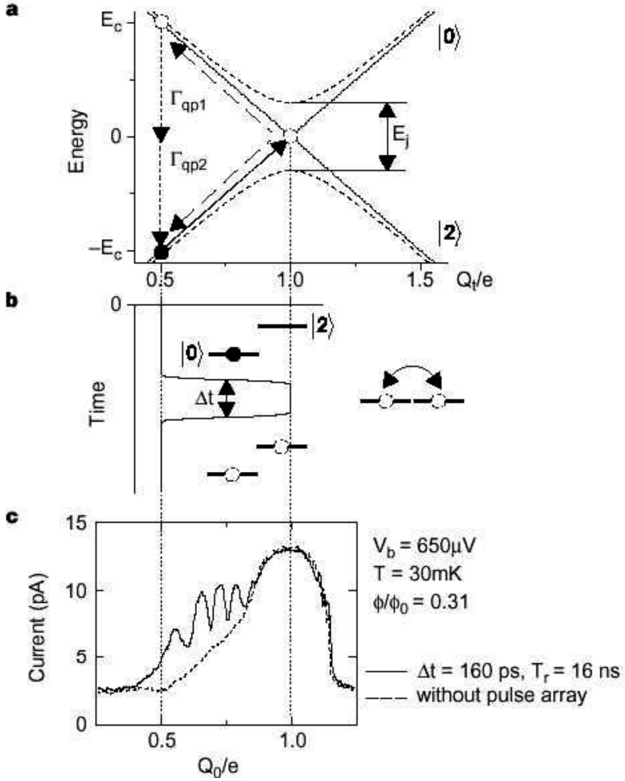


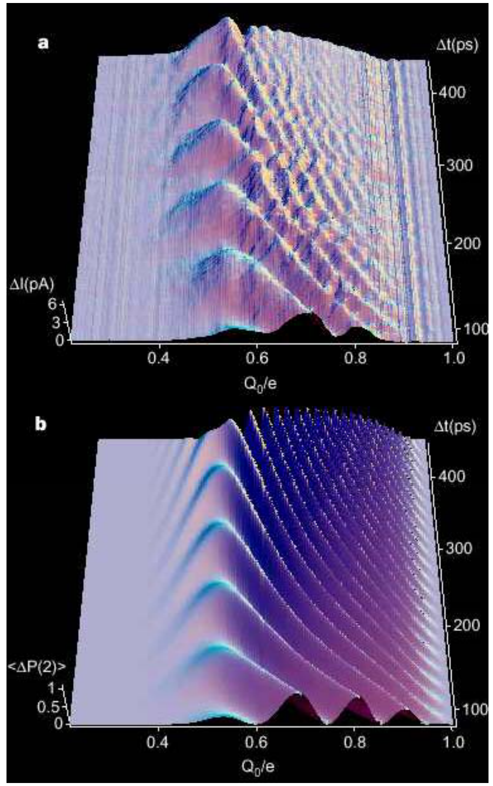
Quantum computation

Solid-state qubits under control ?

D. V. Averin







Quantum Transport FS 2015 / books

books:

- *Transport in Nanostructures*,
  M. J. Kelly, Clarendon Press, Oxford
- *Mesoscopic Physics*, Leo Kouwenhoven et al. in
  Nato ASI Series E, Vol. 345, p 1-44, Kluwer
- *Mesoscopic Electronics in Solid State Nanostructures*,
  Thomas Heinzel, Wieley-VCH
- *Electronic Transport in Mesoscopic Systems*
  S. Datta, Cambridge University Press
- *Introduction to Mesoscopic Physics*,
  Y. Imry, Oxford University Press
- *The Physics of Low Dimensional Systems*,
  J.H. Davies, Cambridge University Press
- *The Physics of Nanoelectronics*
  Tero T. Heikkilä, Oxford Master Series
- *Quantum Transport: Introduction to Nanoscience*
  Yuli Nazarov and Yaroslav Blanter, Cambridge

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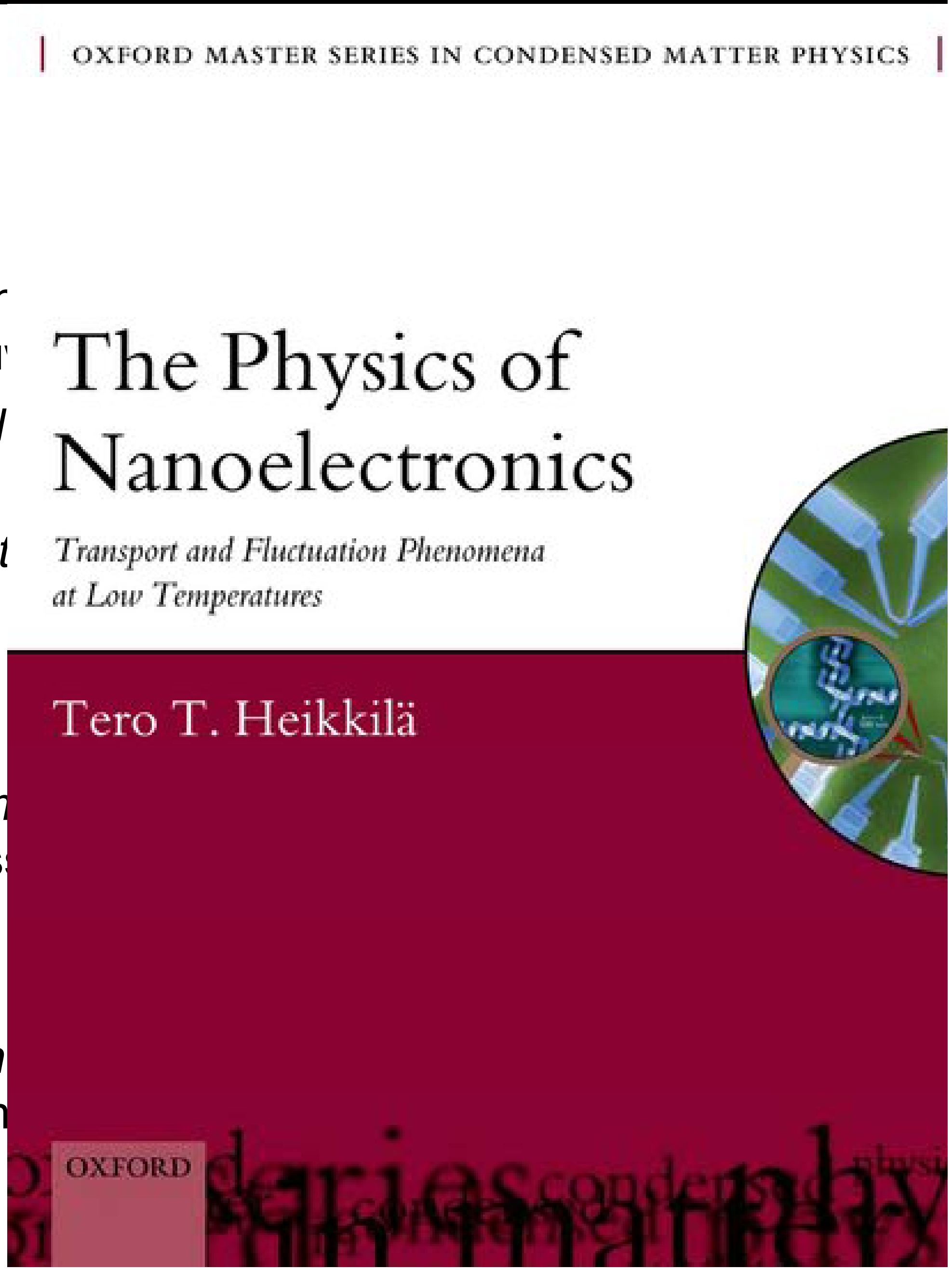

Basics and 1. exercises

all below you need to know. Repetition on Thursday, but you must prepare yourselves by studying the notes provided, i.e. *1.background_knowledge.pdf*

- Ohm's law, Kirchhof's laws
- Fermi gas, Fermi parameters like E_F, λ_F, k_F, T_F...
- band structure (metal and semiconductor, band gap)
- effective mass approximation
- density of states, DOS, $\rho(E_F)$, $N(E_F)$, chemical potential, electrochemical potential
- Schrödinger equation with confining potential in different dimensions
- density of states of Fermi gas in different dimensions
- capacitance spectroscopy (R. Ashoori 1993)
- thermodynamics, Fermi-Dirac and Bose-Einstein distribution
- generalized electron distribution function → week 2

homework 2: read "Quantum Transport in Nano-Structured Semiconductors" by B. Kramer *1.Quantum_Transport_Intro_B.Kramer.pdf*

- how to calculate a current (I do in the class right now !)