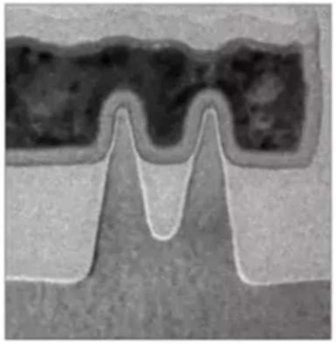
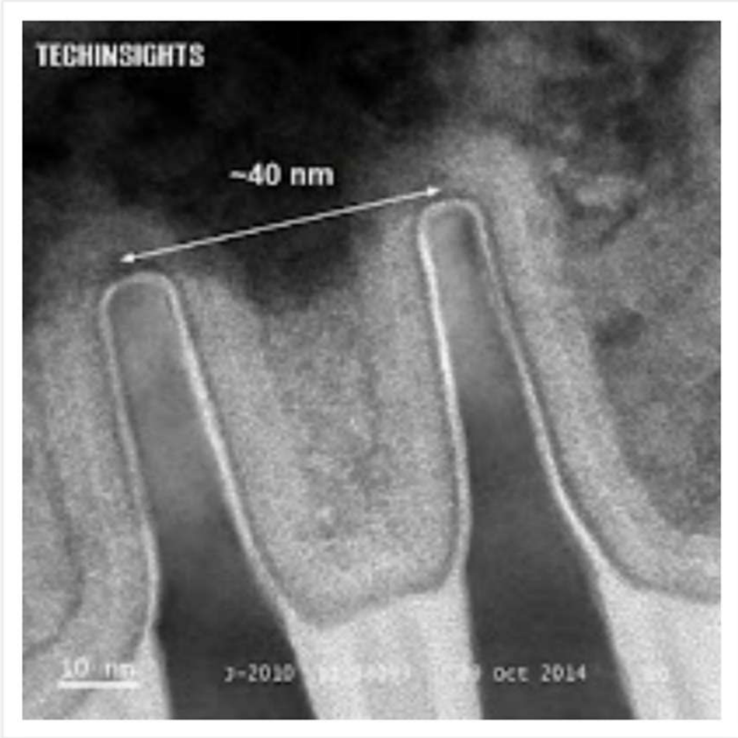
Nanofizika ‘26

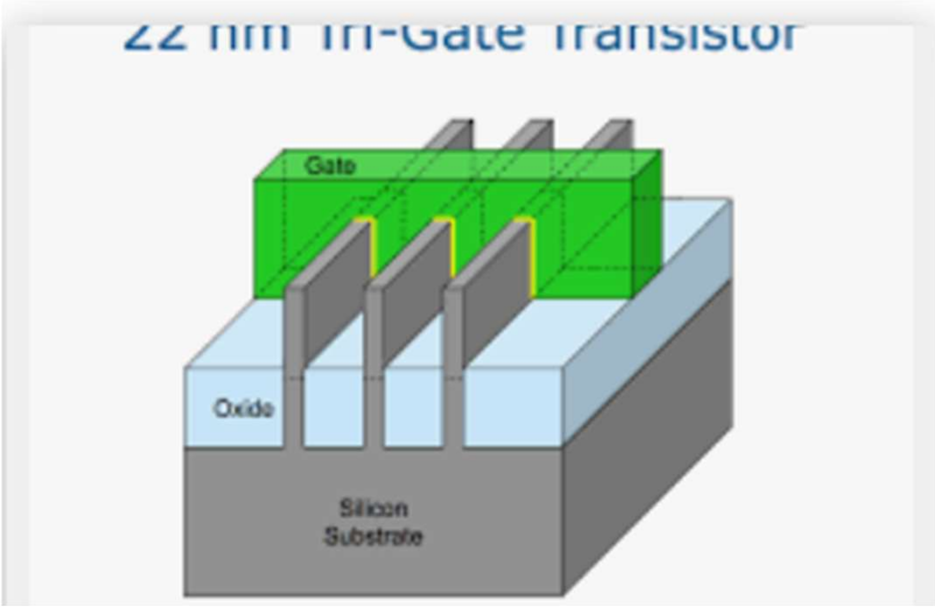
www-f1.ijs.si/~mravlje/nano



22 nm 1st Generation
Tri-gate Transistor

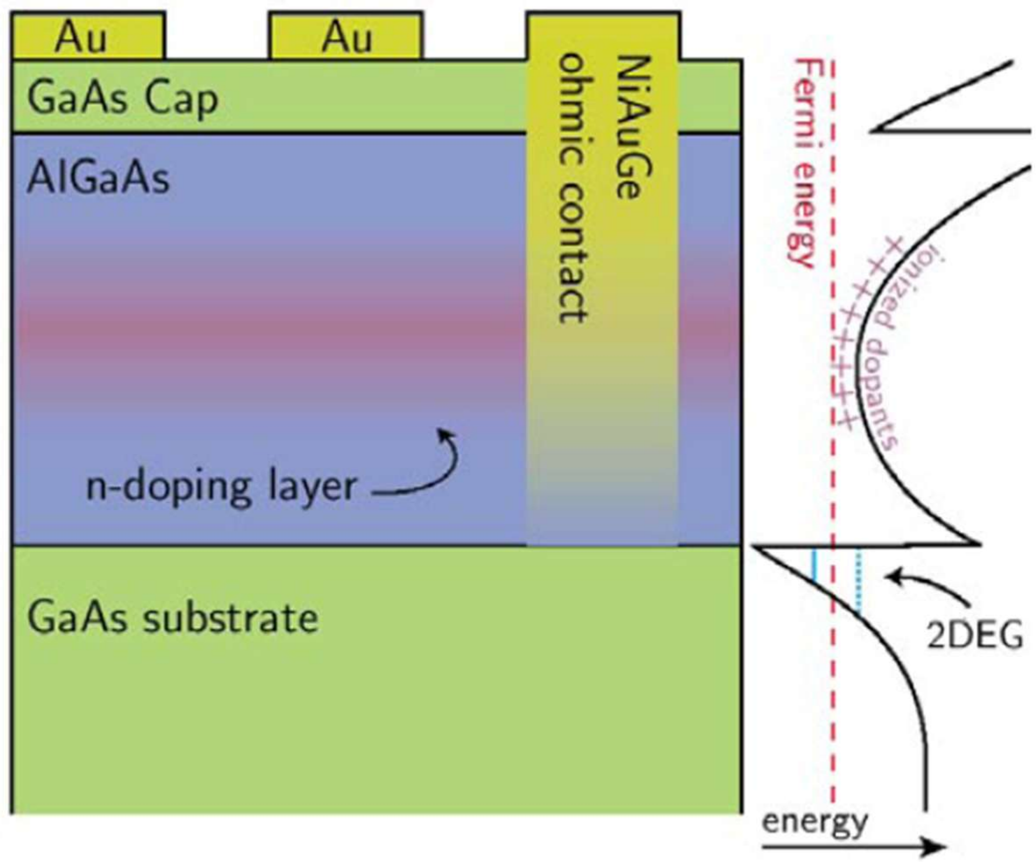


[nanoscale views: What do IBM's 7 nm transistors mean?]()

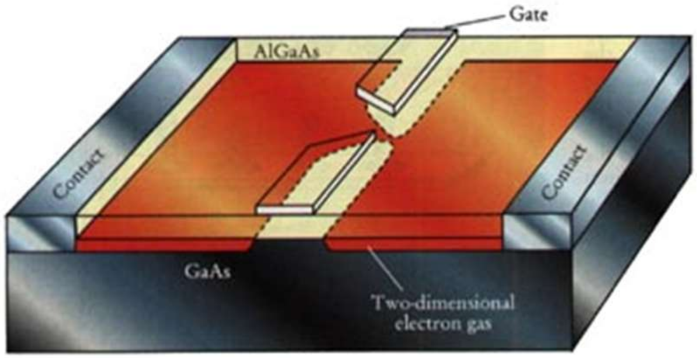


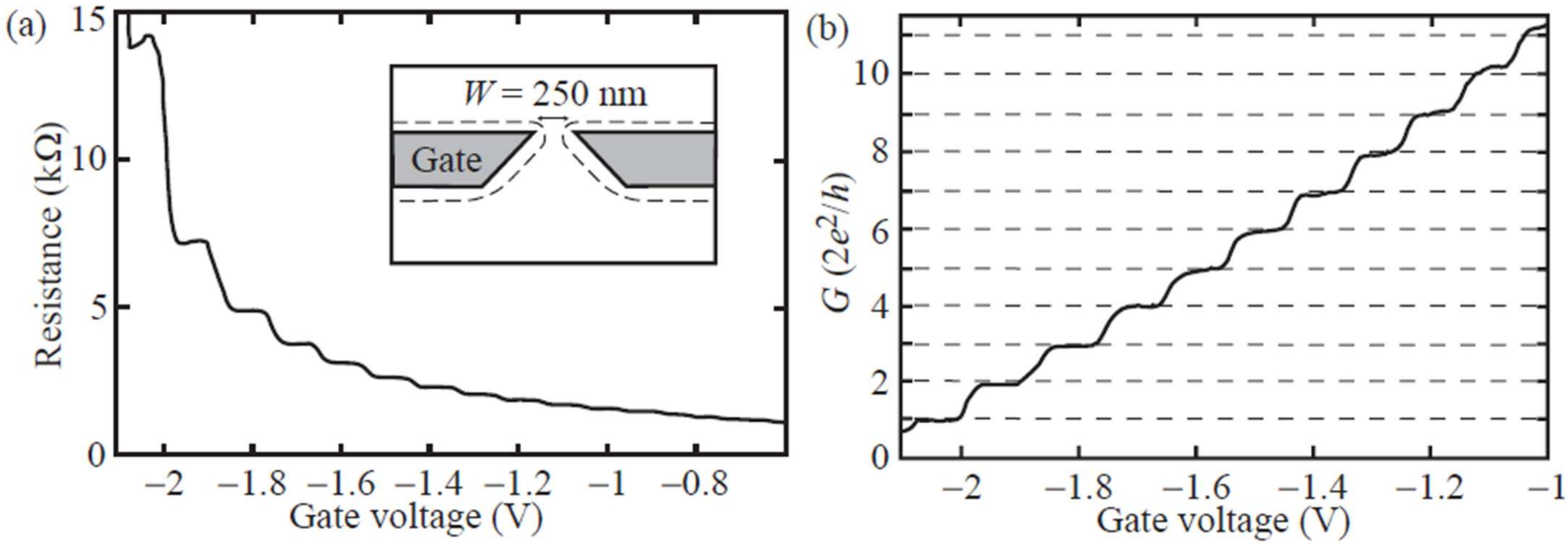
Photolitography : 193 nm –
10nm,14nm tehnologija
13.5 nm – extreme ultraviolet 2nm

2DEG



doktorat Sara Cronewett (www-f1.ijs.si/~mrav

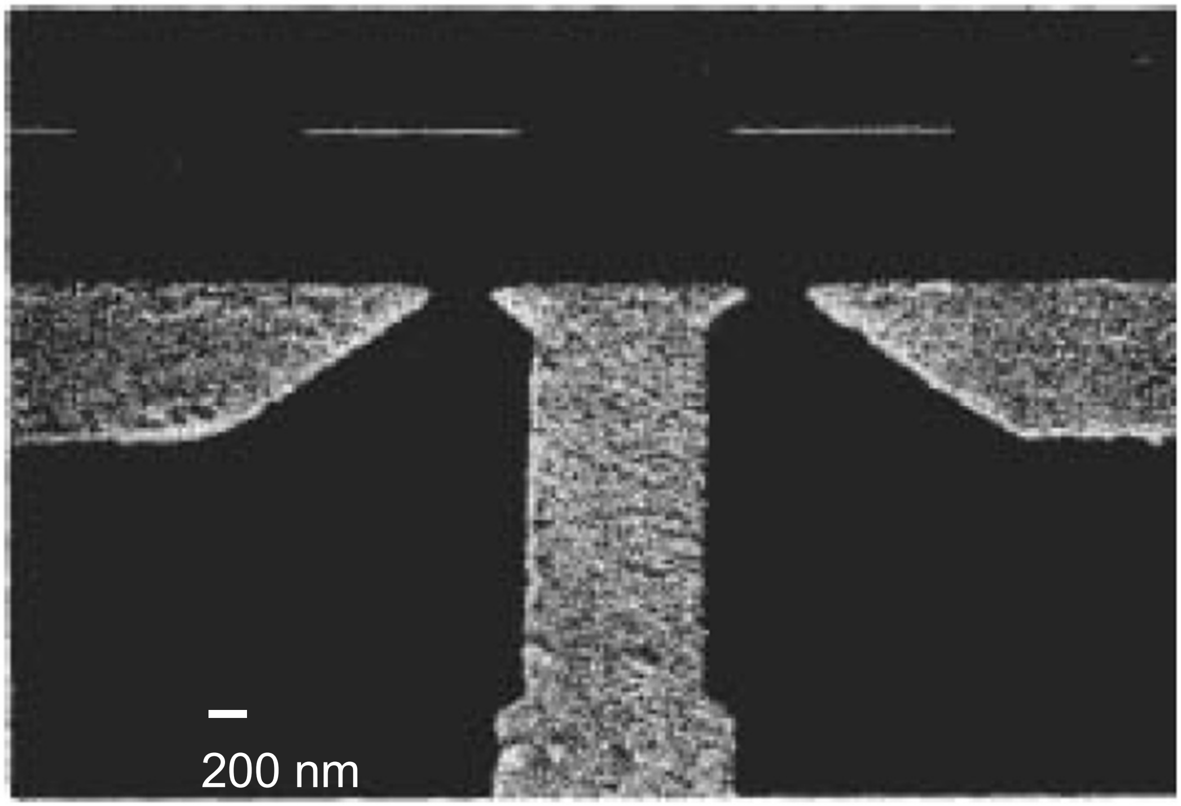

Gate
AlGaAs
Contact
Contact
GaAs
Two-dimensional
electron gas



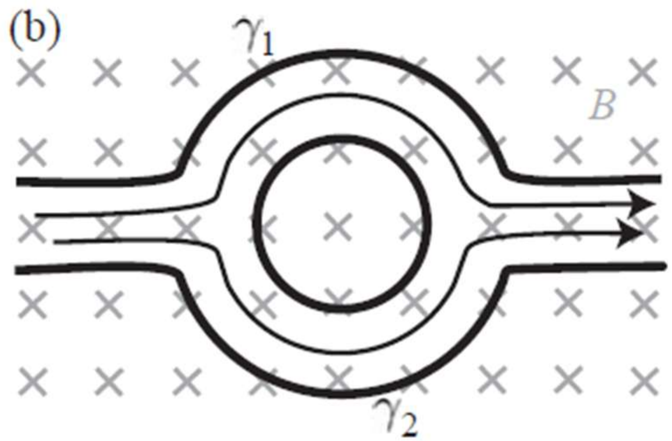
van Wees et al, 1988

QPC (kvantni točkovni stik)

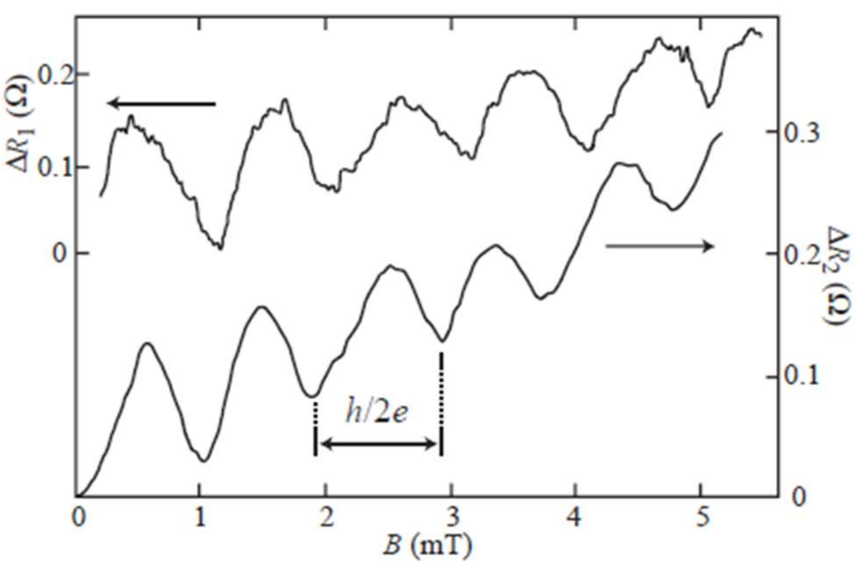
- par kvantnih točkovnih stikov

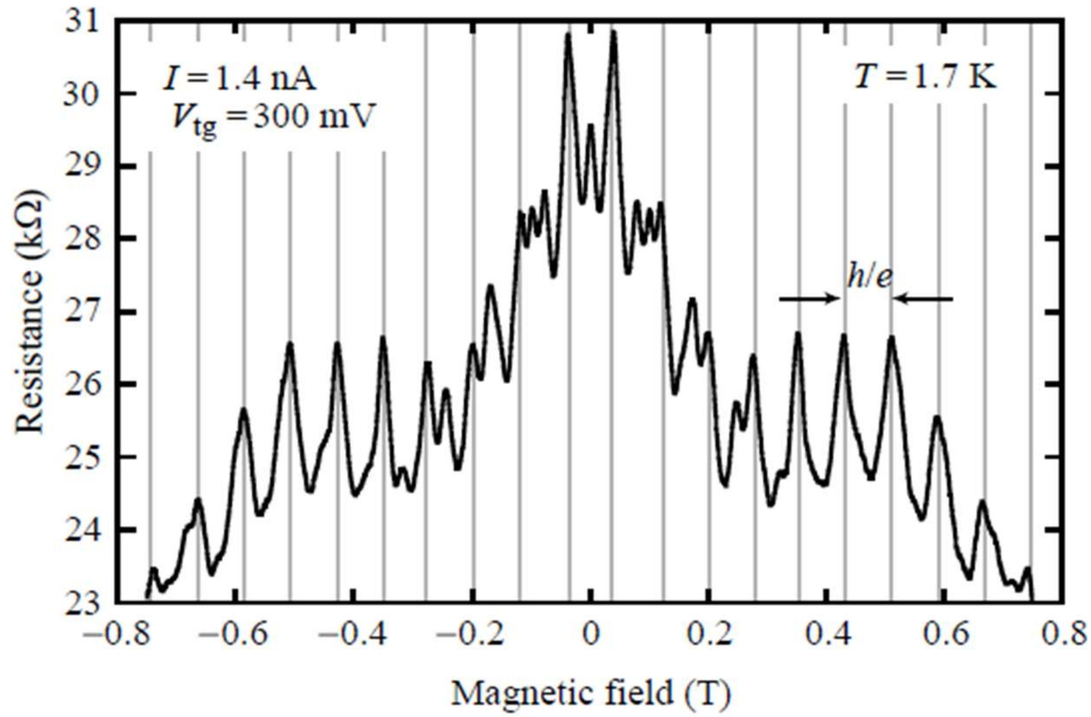


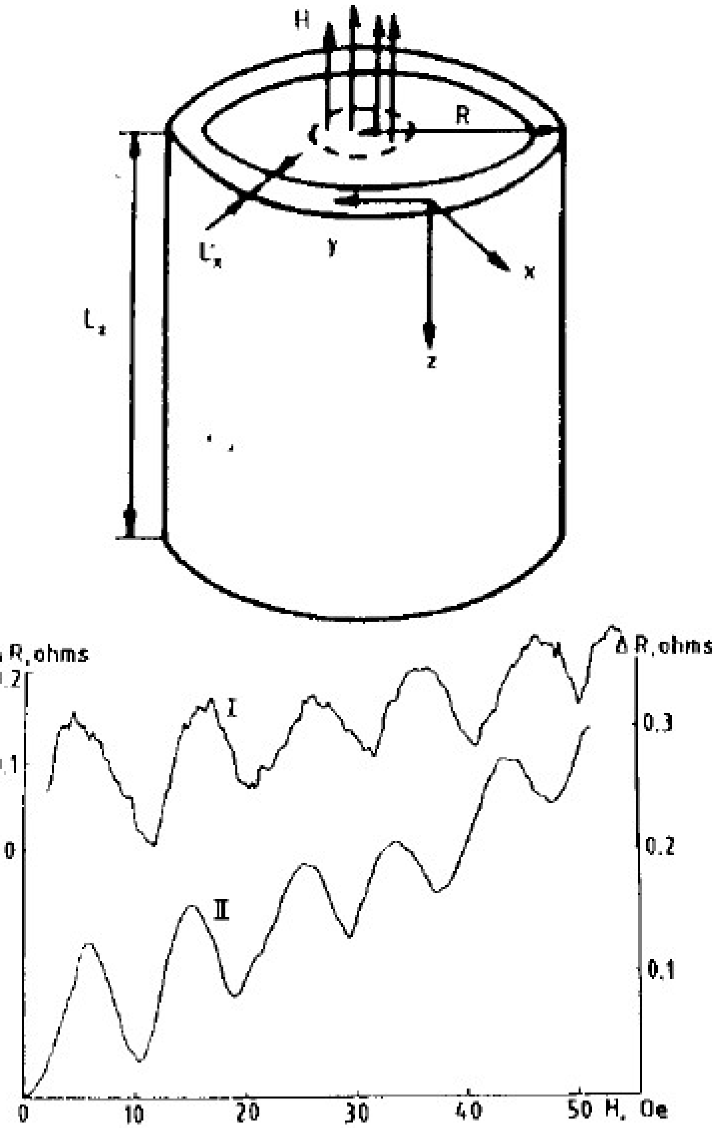
Aharonov-Bohm



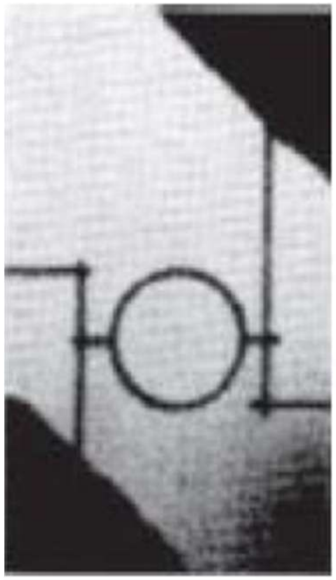
meritve 1980-1985
Gold ring Webb'85, 1microm

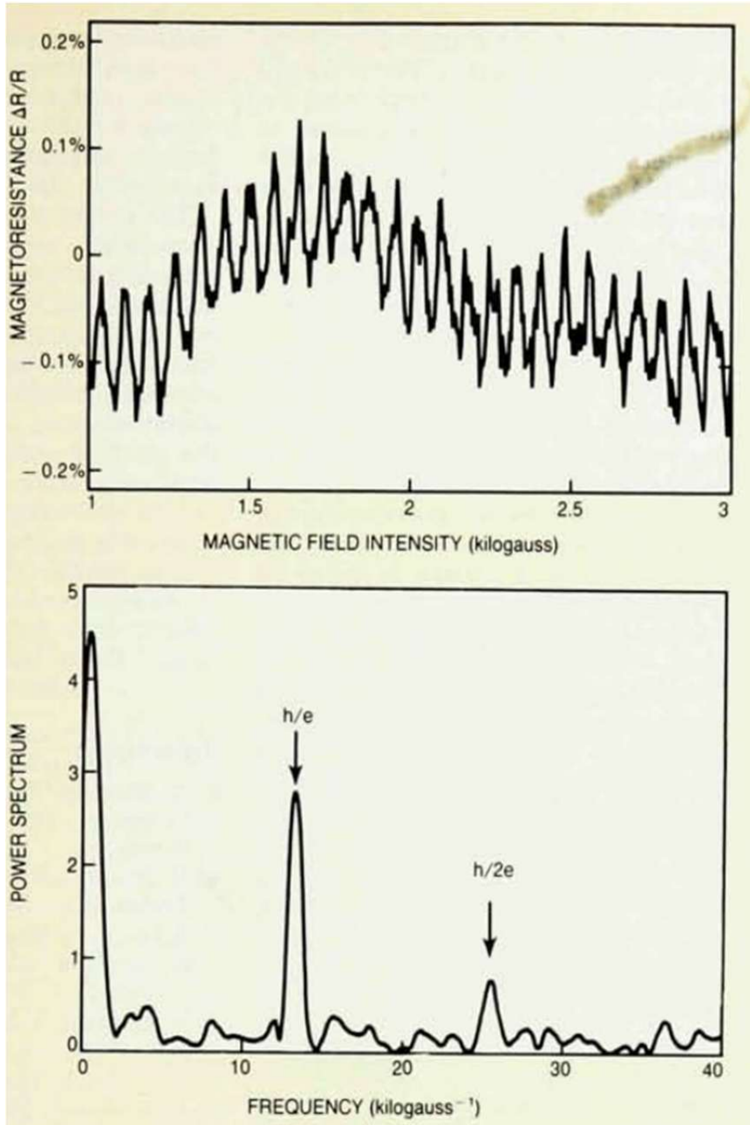






Sharvin Sharvin 1981

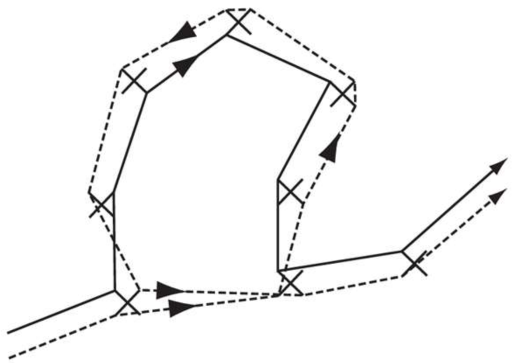




Gold ring
0.1kG=0.01T

Šibka lokalizacija (za $G>G_0$)

Interferenčni popravki k prevodnosti $-G_0$, ki izginejo v B



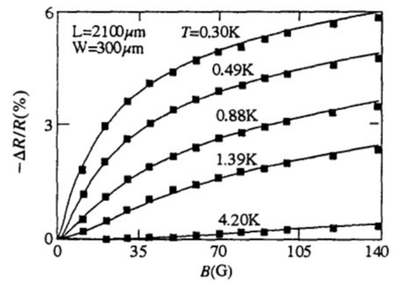
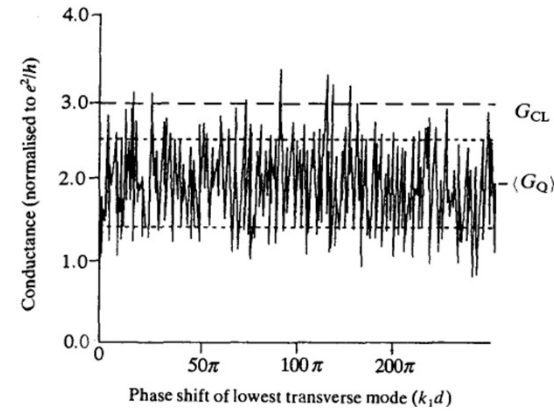
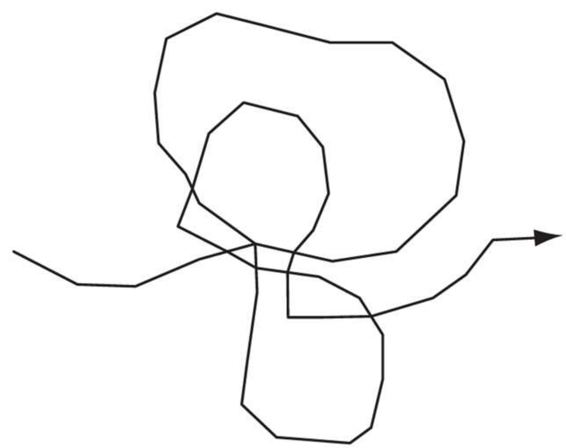


Fig. 5.3.2. Measured fractional change in the longitudinal resistance of a GaAs sample having $n_s = 1.6 \times 10^{11}/\text{cm}^2$, $\mu = 27\,000\ \text{cm}^2/\text{V s}$. The solid curves are theoretical fits with one adjustable parameter, namely, the phase-relaxation length. Adapted with permission from Fig. 1 of K.K. Choi, D. C. Tsui and K. Alavi (1987), *Phys. Rev. B*, **36**, 7751.

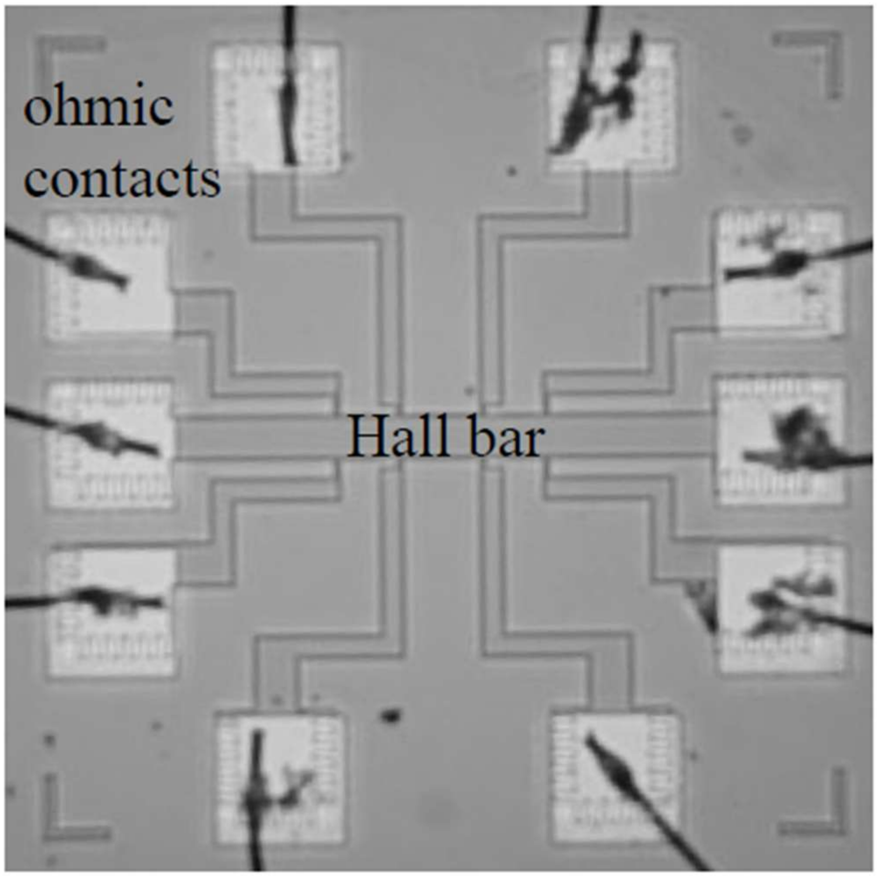


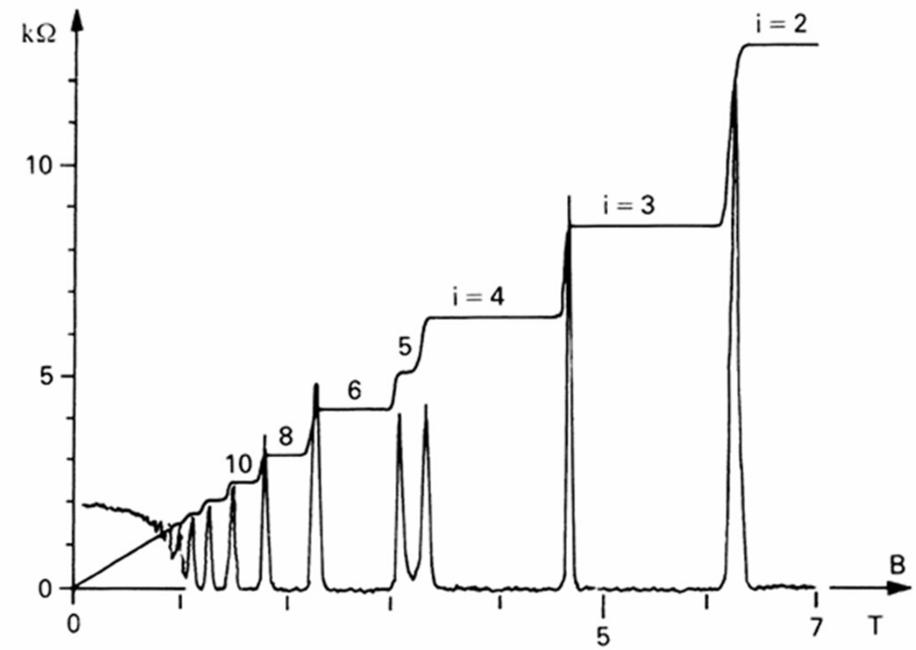
Močna lokalizacija ($G<G_0$)

Andersonova lokalizacija; eksponentno padanje prevodnosti z dolžino vodnika

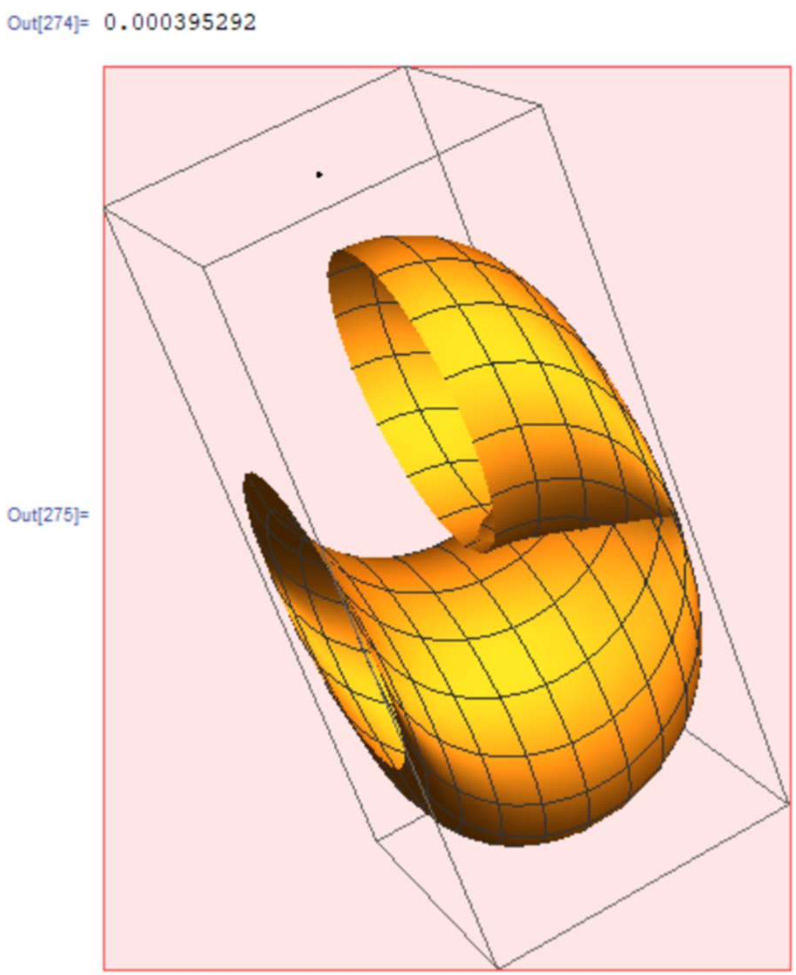


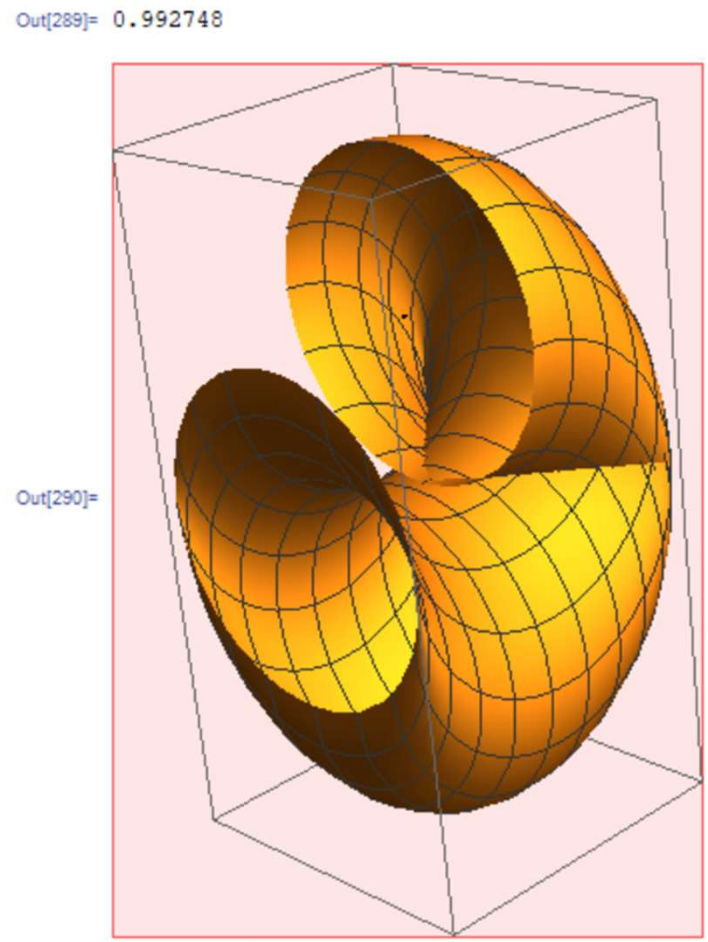
Integer Quantum Hall effect



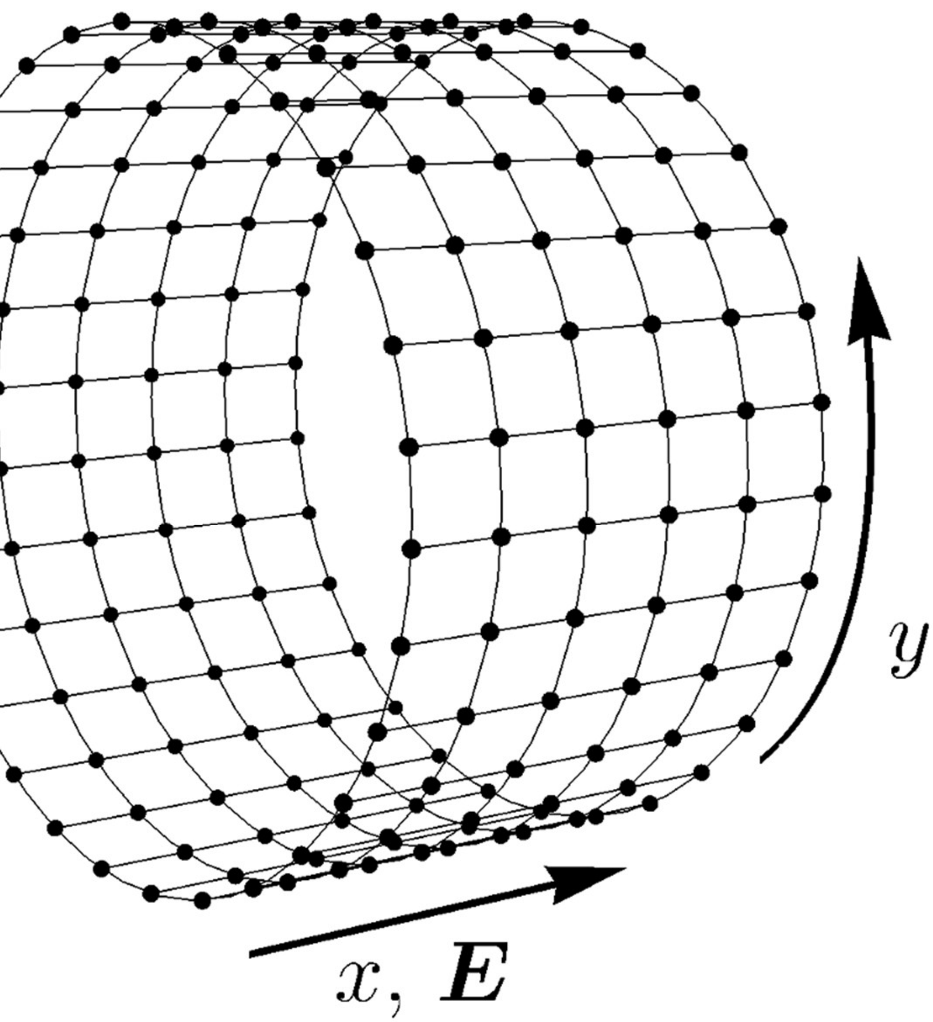


Chernovem izolator (QWZ model)



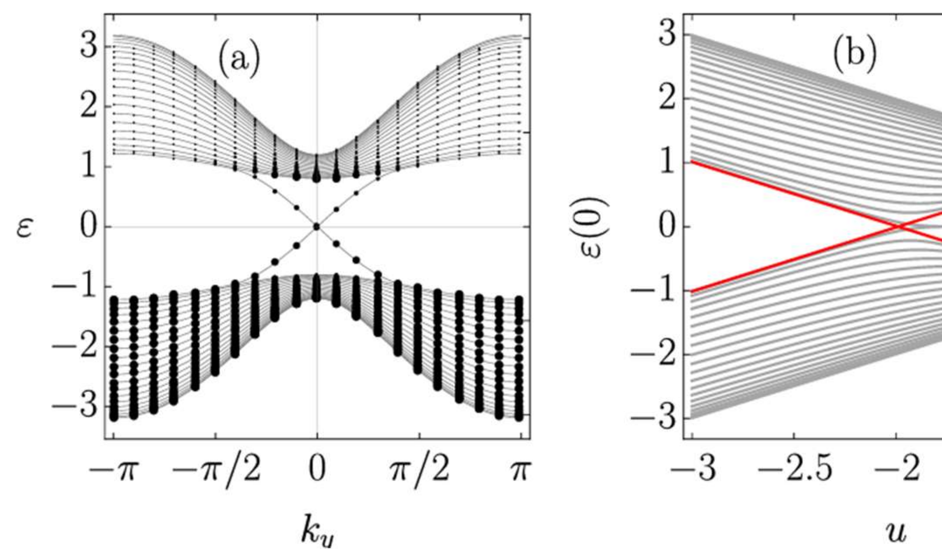


Robna stanja v Chernovem izolatorju (QWZ model)

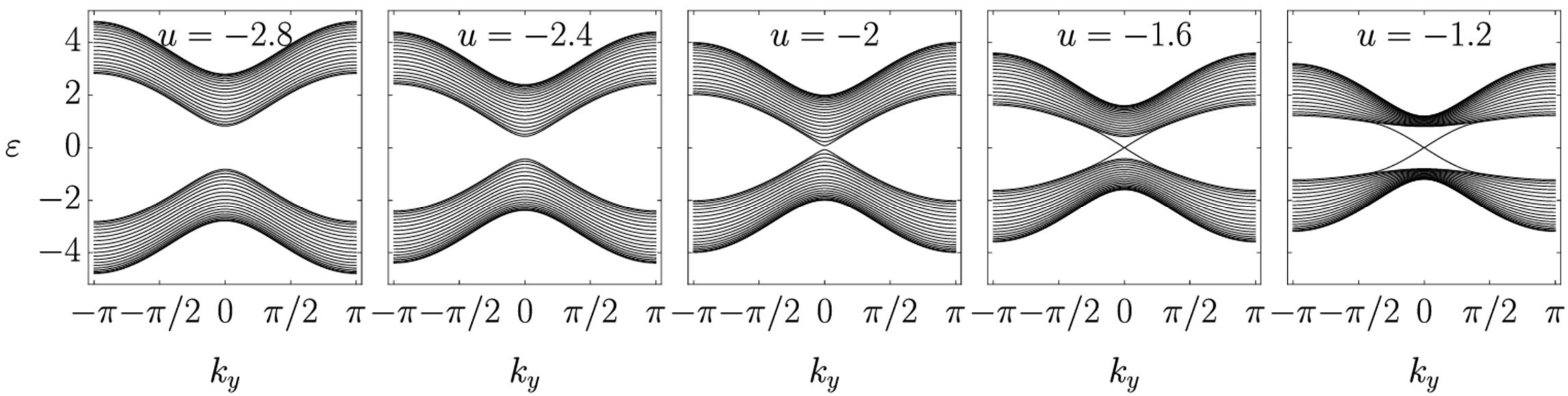


$$\hat{H}(k_y) = \sum_{x=1}^{N_x-1} |x+1\rangle\langle x| \otimes \hat{t}_x + \text{h.c.}+$$

$$\sum_{x=1}^{N_x} |x\rangle\langle x| \otimes \left((\cos k_y + u)\,\hat{\sigma}_z + \sin k_y \hat{\sigma}_y \right).$$



Robna stanja v Chernovem izolatorju (QWZ model)



Ulčakar, Mravlje, Rejec, PRB’19

SSH

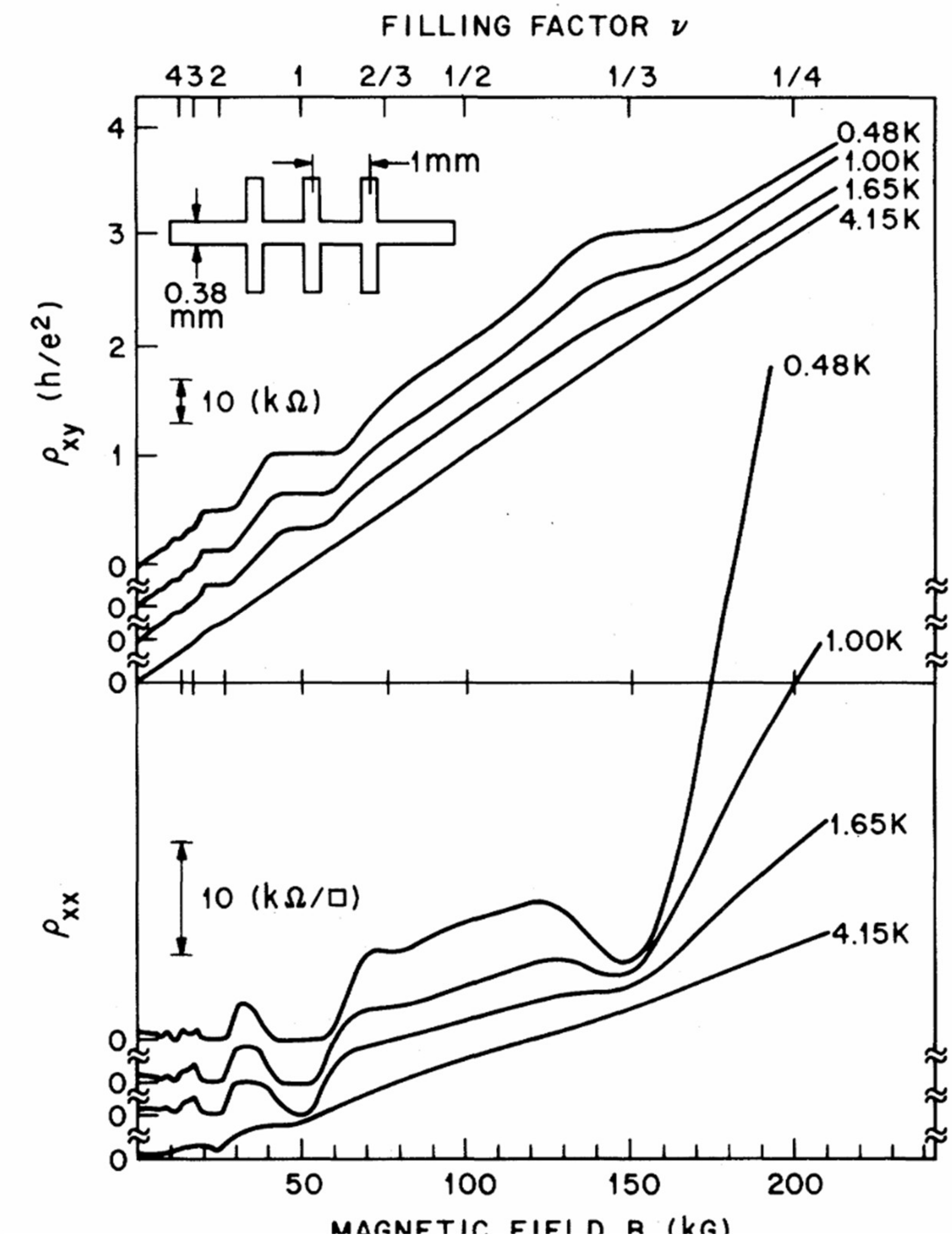
Chern

Z2

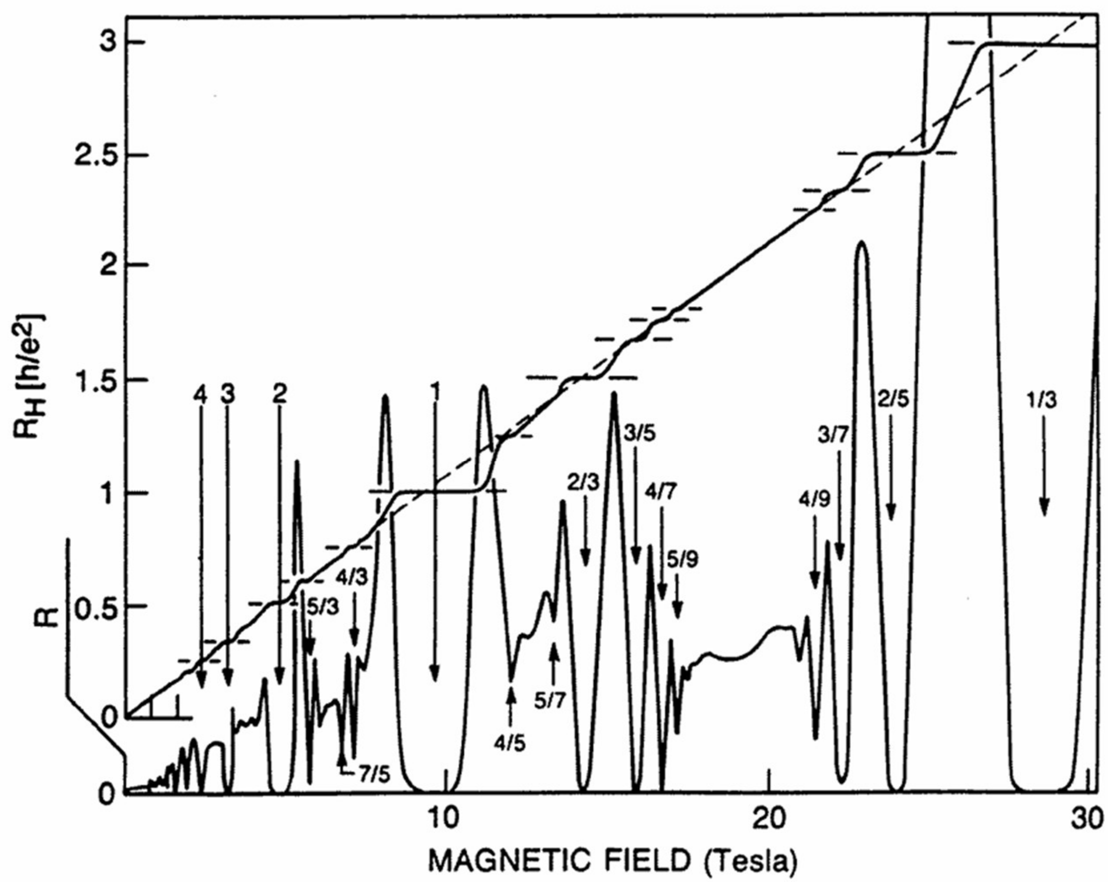
Symmetry class	$d=0$	$d=1$	$d=2$	$d=3$	$d=4$	$d=5$	$d=6$	$d=7$	$d=8$
A	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
AIII	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0
AI	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
BDI	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$
D	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$
DIII	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0
AII	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$
CII	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0
C	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
CI	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0

Symmetry Class	Time reversal symmetry	Particle hole symmetry	Chiral symmetry
A	No	No	No
AIII	No	No	Yes
AI	Yes, $T^2=1$	No	No
BDI	Yes, $T^2=1$	Yes, $C^2=1$	Yes
D	No	Yes, $C^2=1$	No
DIII	Yes, $T^2=-1$	Yes, $C^2=1$	Yes
AII	Yes, $T^2=-1$	No	No
CII	Yes, $T^2=-1$	Yes, $C^2=-1$	Yes
C	No	Yes, $C^2=-1$	No
CI	Yes, $T^2=1$	Yes, $C^2=-1$	Yes

Fractional Quantum Hall Effect



Tsui, Stormer, Gossard PRL'82

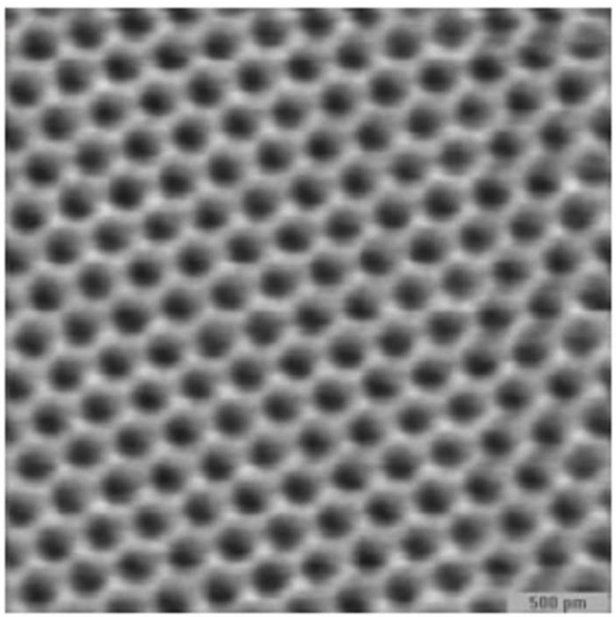


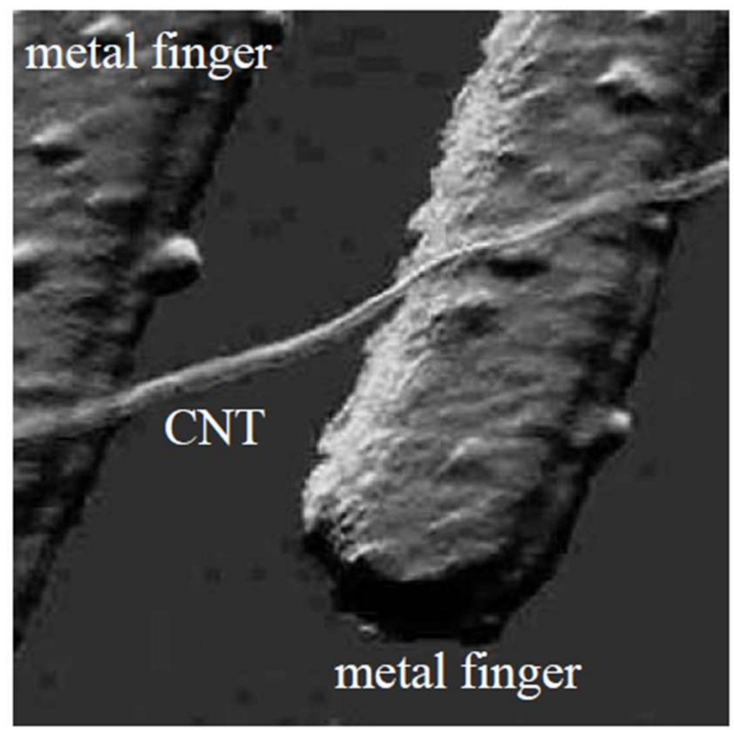
R_H [h/e^2]
R
MAGNETIC FIELD (Tesla)
0
0.5
1
1.5
2
2.5
3
0
10
20
30
4
3
2
1
5/3
4/3
7/5
4/5
5/7
2/3
3/5
4/7
5/9
4/9
3/7
2/5
1/3

Stormer '92

Grafen

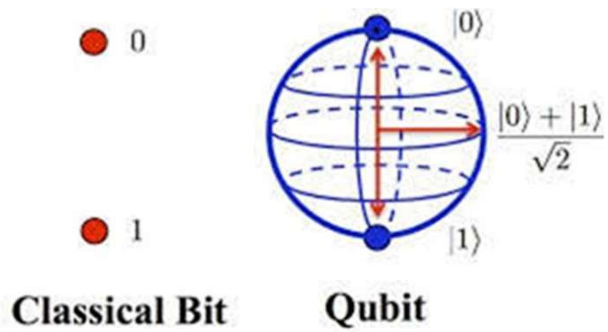
- grafen 2d snov (odkrito 2004)



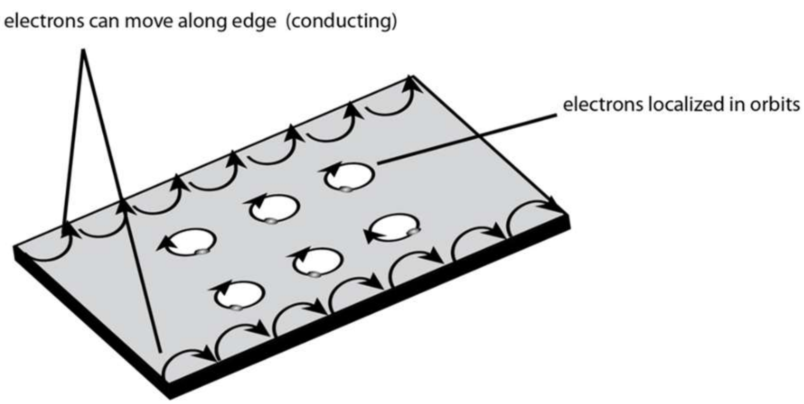


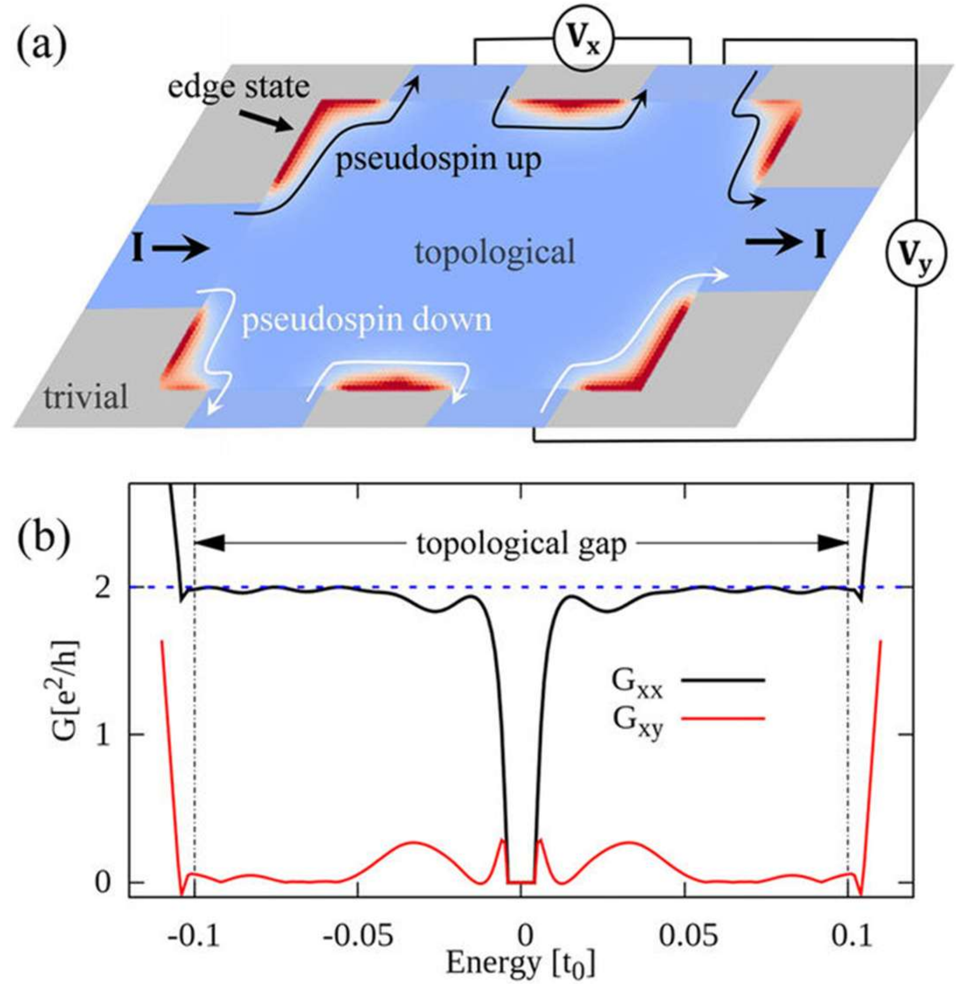
- nanocevke

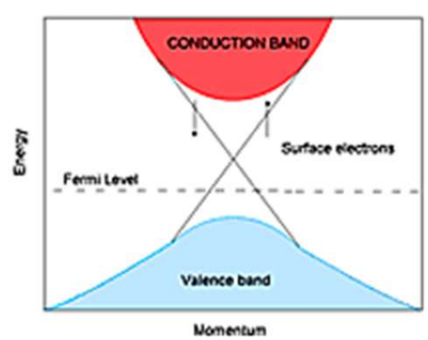
Kvantno računanje

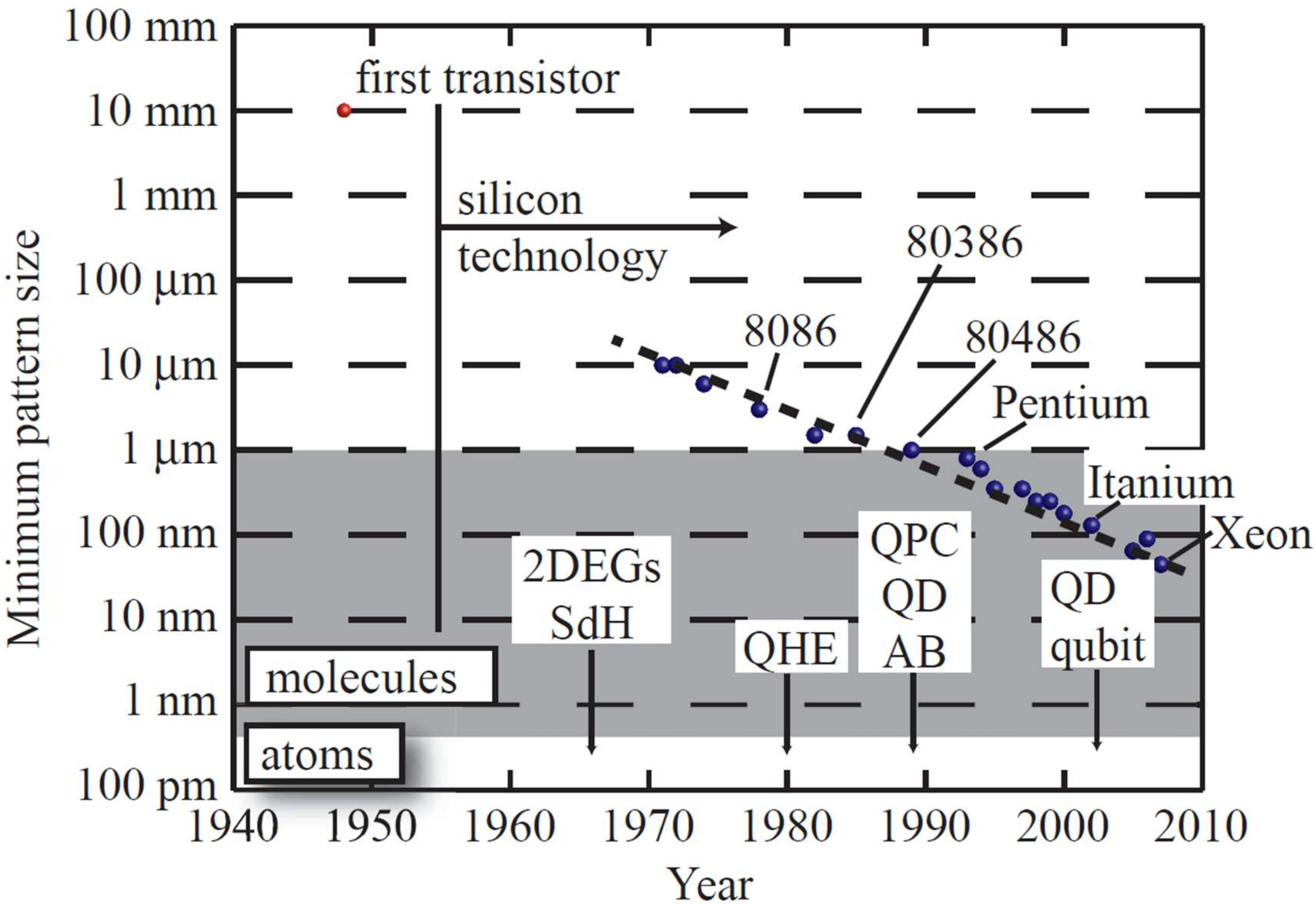


Robna stanja top. izolatorjev (2005)







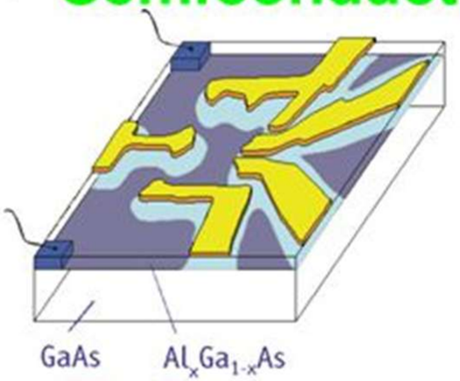


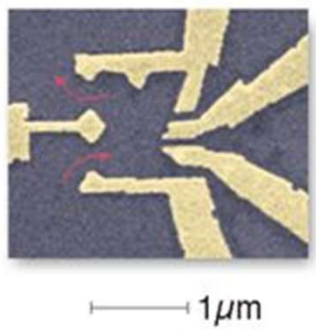
100 mm
10 mm
1 mm
100 µm
10 µm
1 µm
100 nm
10 nm
1 nm
100 pm
Minimum pattern size
1940
1950
1960
1970
1980
1990
2000
2010
Year
first transistor
silicon technology
8086
80386
80486
Pentium
Itanium
Xeon
molecules
atoms
2DEGs SdH
QHE
QPC QD AB
QD qubit

Quantum dots

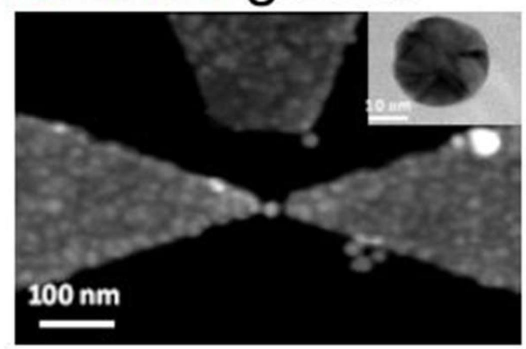
- "**0D**" systems:
  - Artificial atoms
  - Single electron transistors

- **Realizations**:
  - **Semiconductor** heterostructures

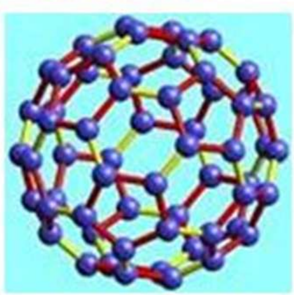


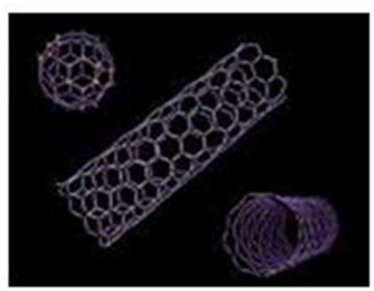


  - **Metallic** grains

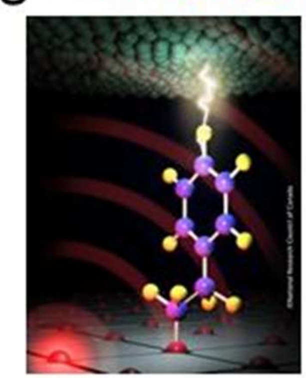


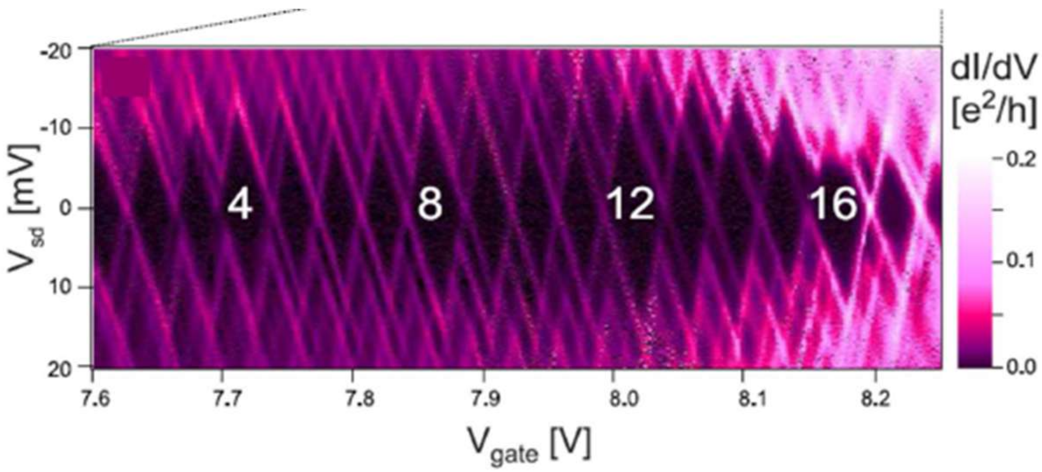
  - **Carbon** buckyballs & nanotubes





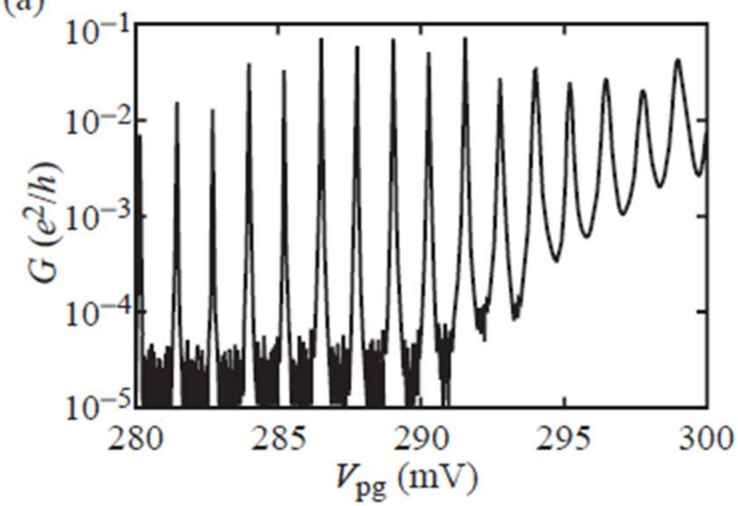
  - Single **molecules**



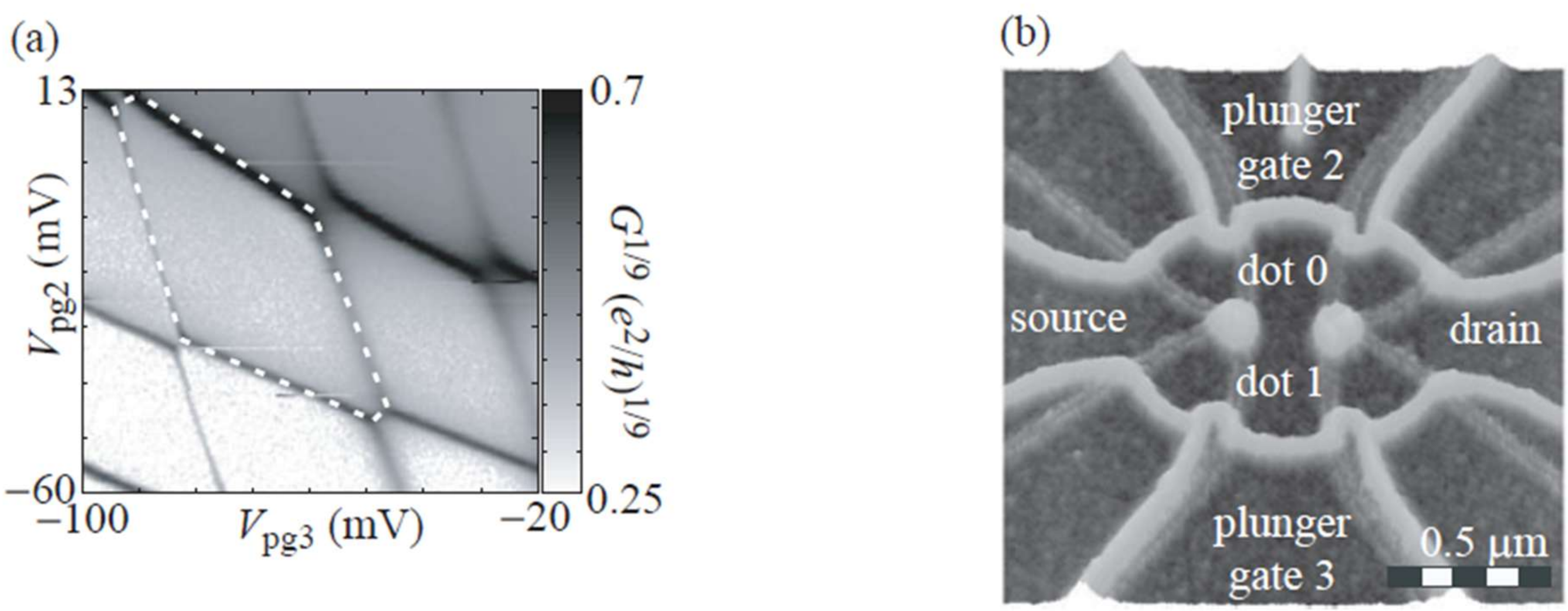


dI/dV
[e2/h]
0.2
0.1
0.0
4
8
12
16
-20
-10
0
10
20
Vsd [mV]
7.6
7.7
7.8
7.9
8.0
8.1
8.2
Vgate [V]

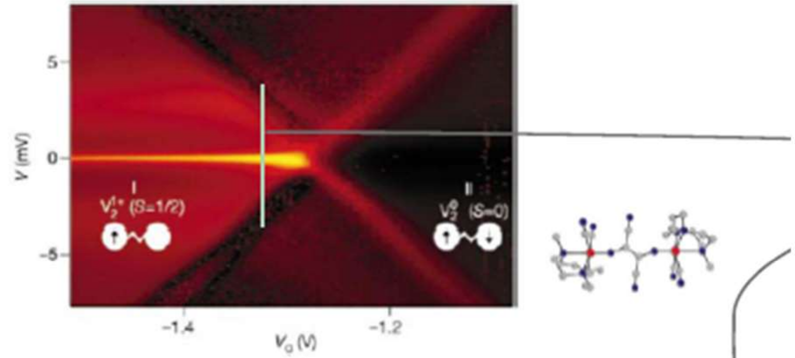
(a)



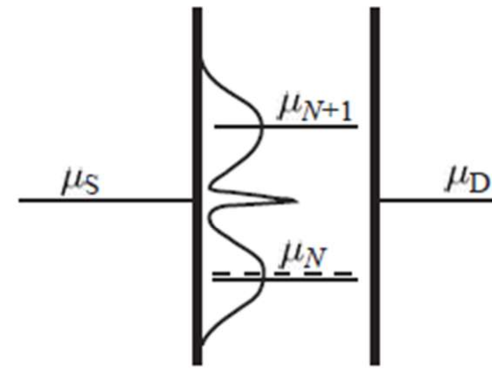
10−1
10−2
10−3
10−4
10−5
G (e2/h)
280
285
290
295
300
Vpg (mV)

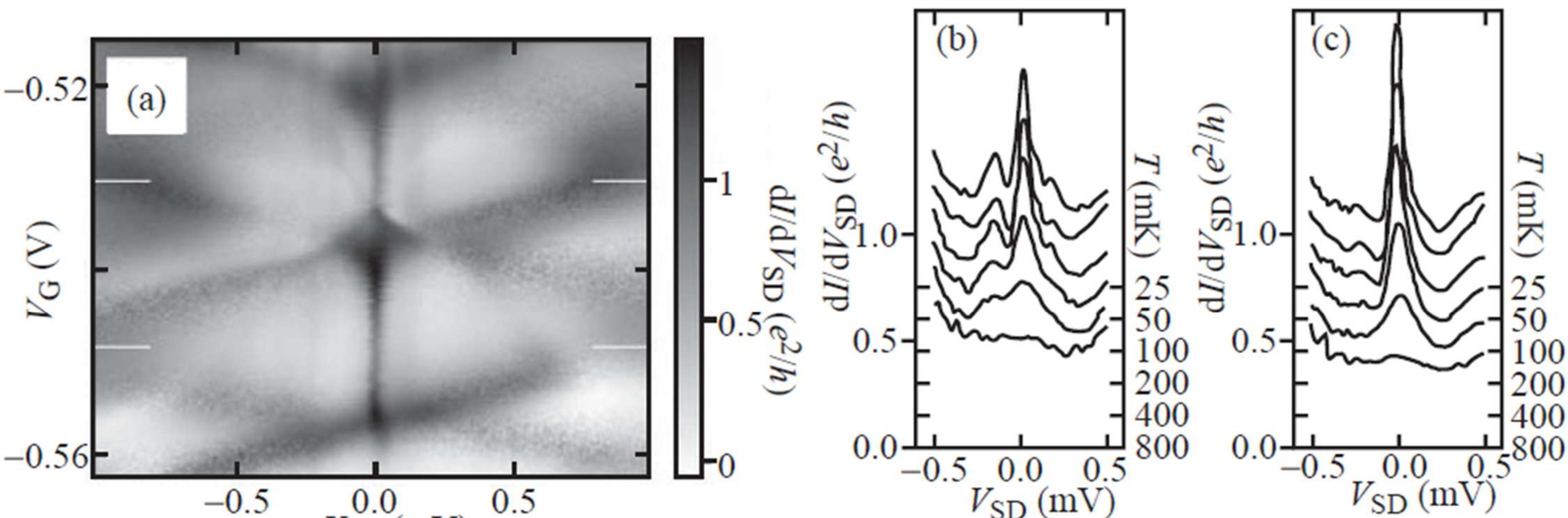


(a)
13
−60
−100
−20
V_{pg2} (mV)
V_{pg3} (mV)
0.7
0.25
$G^{1/9}$ $(e^2/h)^{1/9}$
(b)
plunger gate 2
dot 0
source
drain
dot 1
plunger gate 3
0.5 µm



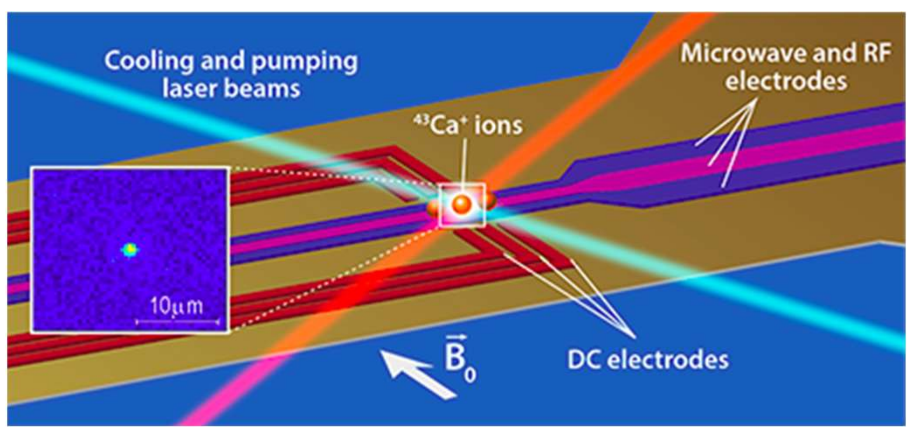
(Liang *et al.*, Nature 2002)



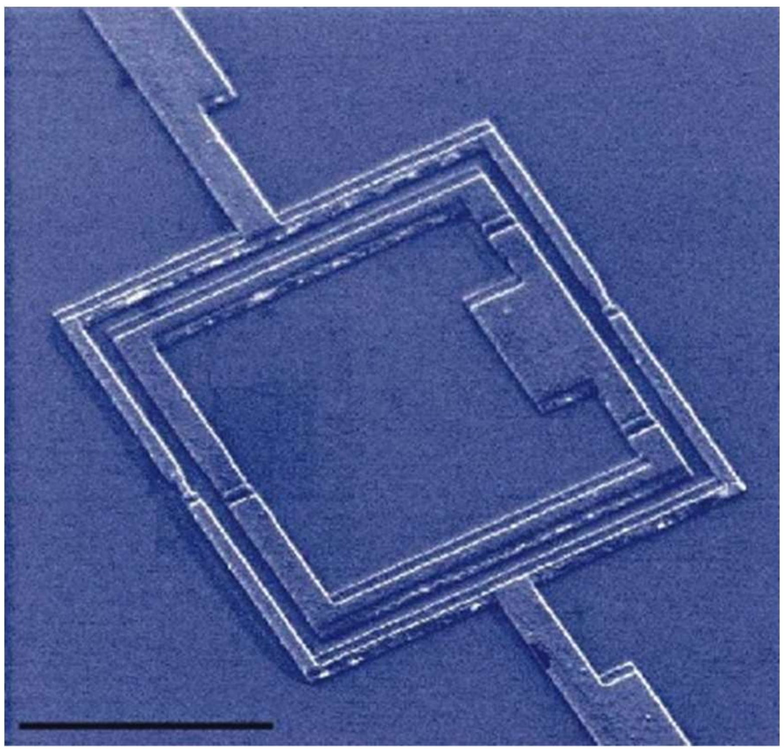


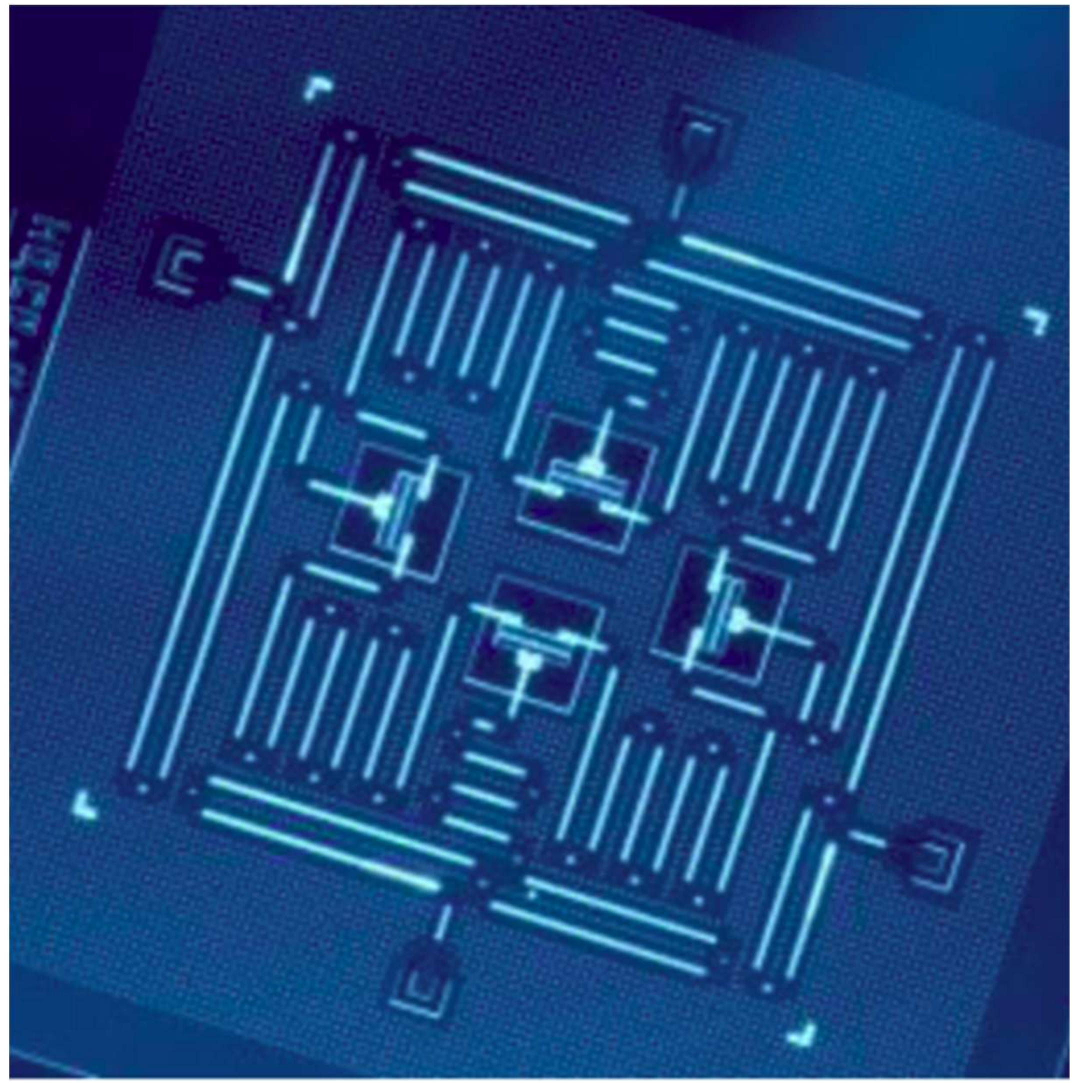
Trapped Ion


(a)
Laser
Laser


Cooling and pumping
laser beams
Microwave and RF
electrodes
43Ca+ ions
10μm
B0
DC electrodes

Josephsonovi kubiti

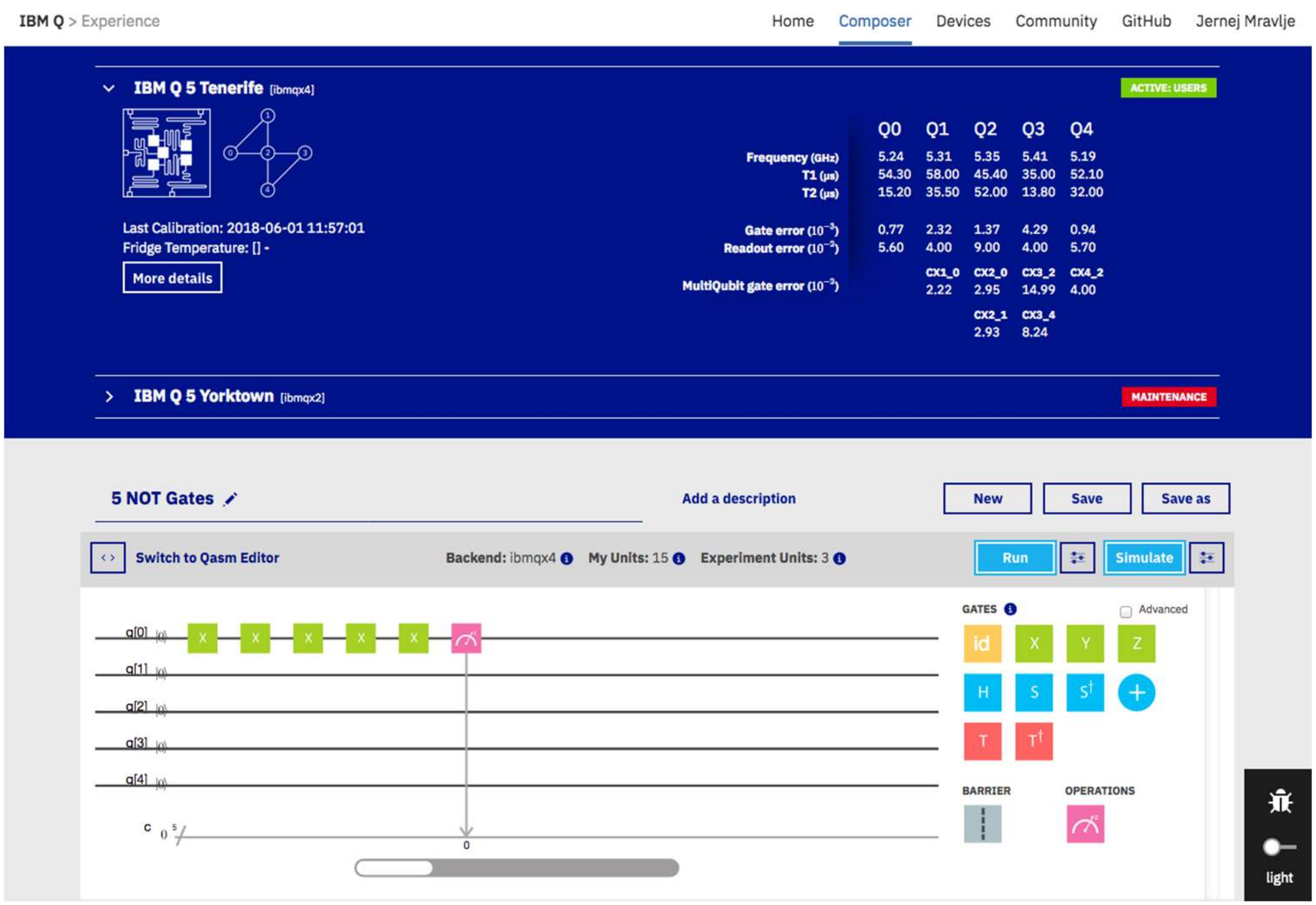


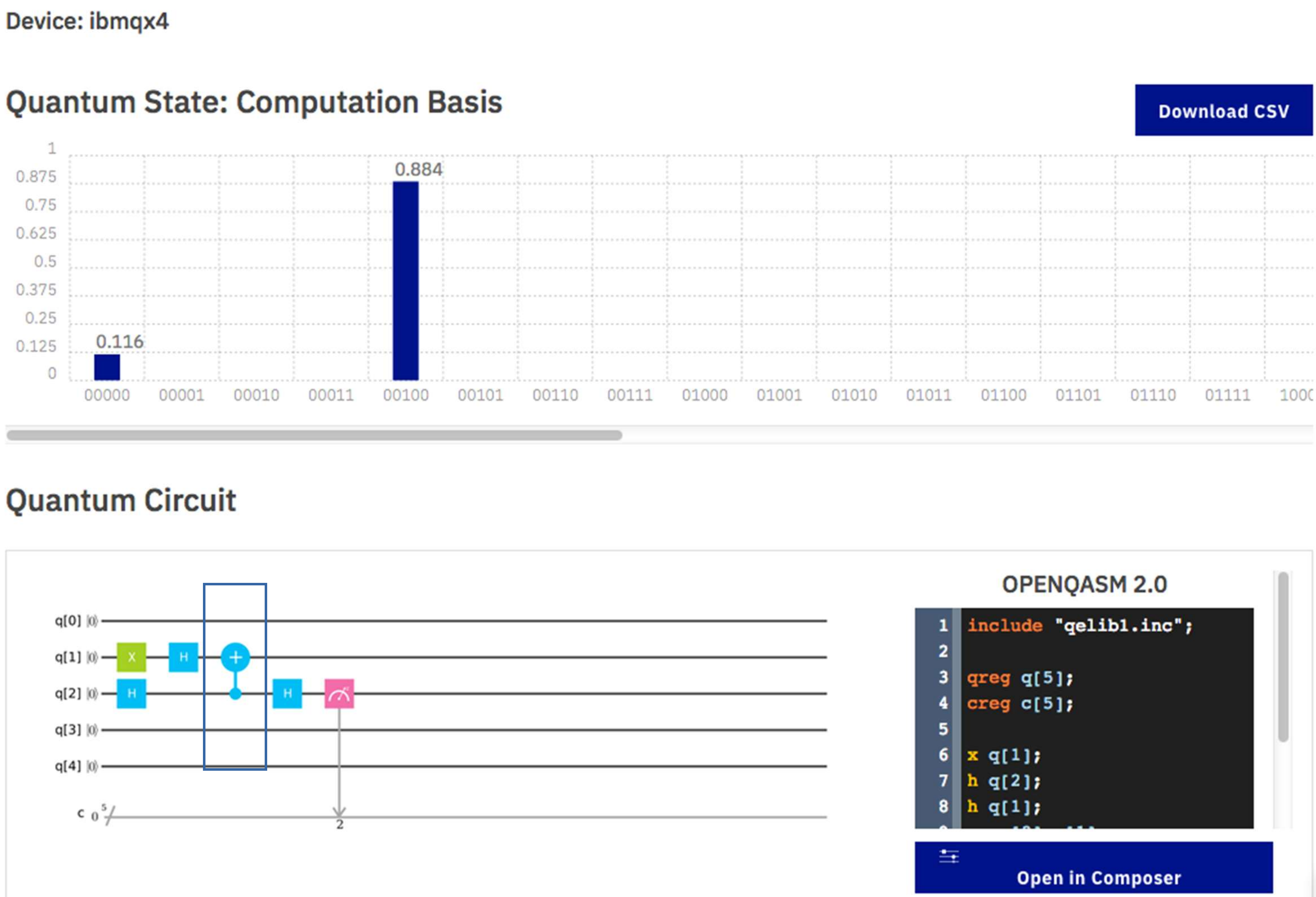


Ali so kvantni računalniki računalniki prihodnosti?

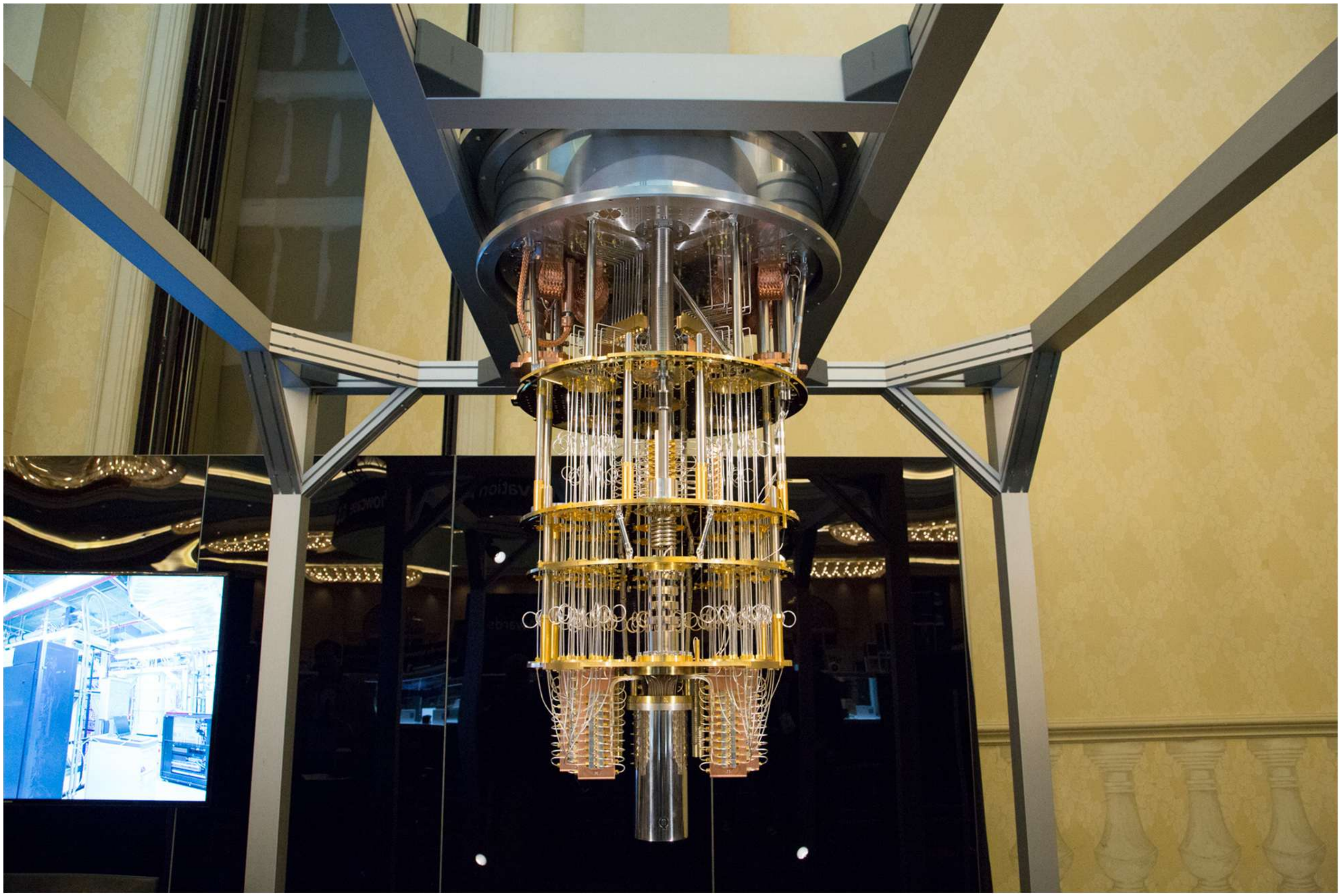
- Josephsonovi kvantni račun. so sedanjost!
- Aktivno tekmovanje med velikani:
  - IBM Quantum Experience (online platforma, odprta! 5 kubit 2016, 20 kubit 2017), 50 kubitov (konec 2017)
  - Google Bristlecone: 72 Josephsonovih kubitov (Marec 18)
  - Microsoft : topological quantum computing, Majoranini kubiti

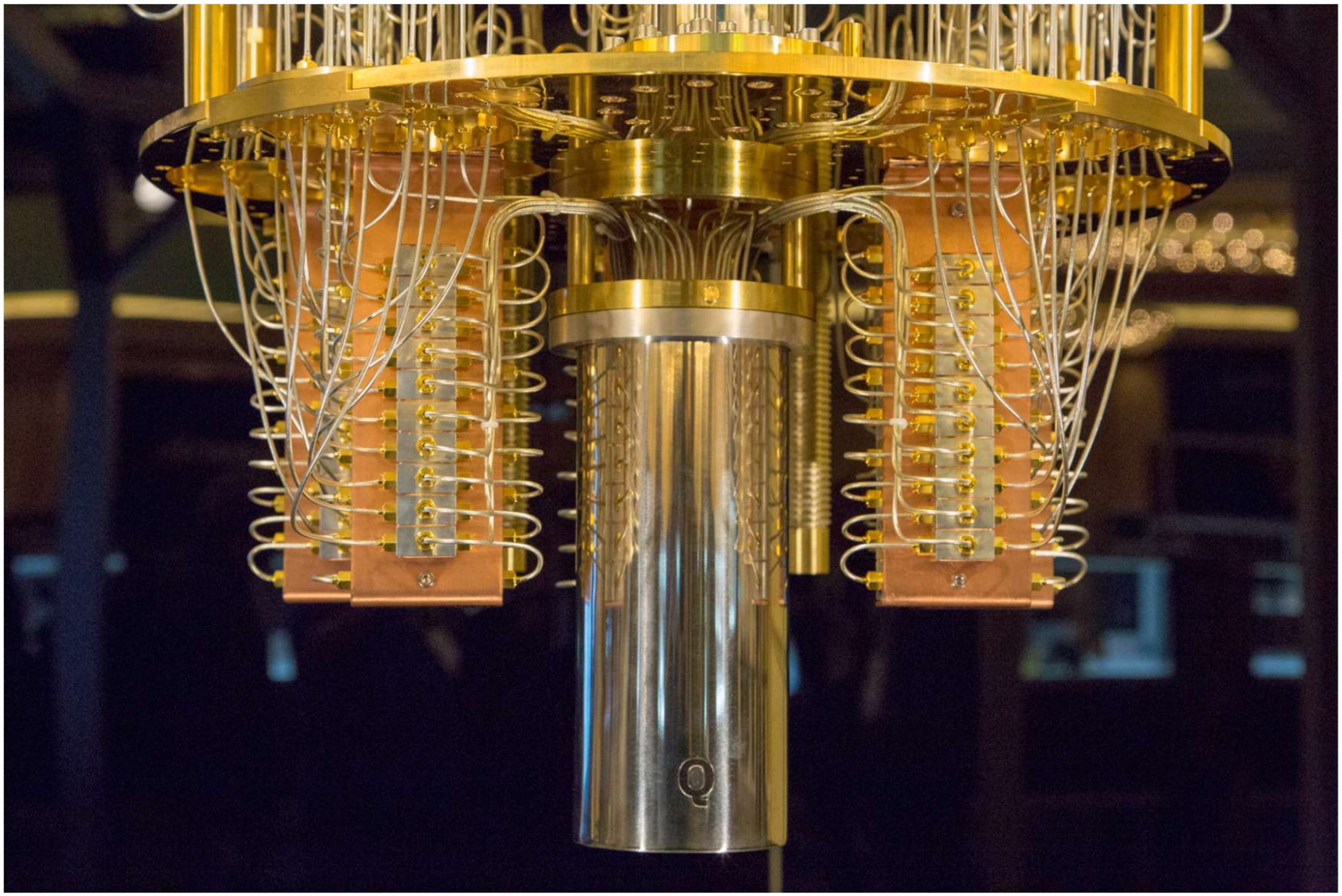
IBM Quantum Experience



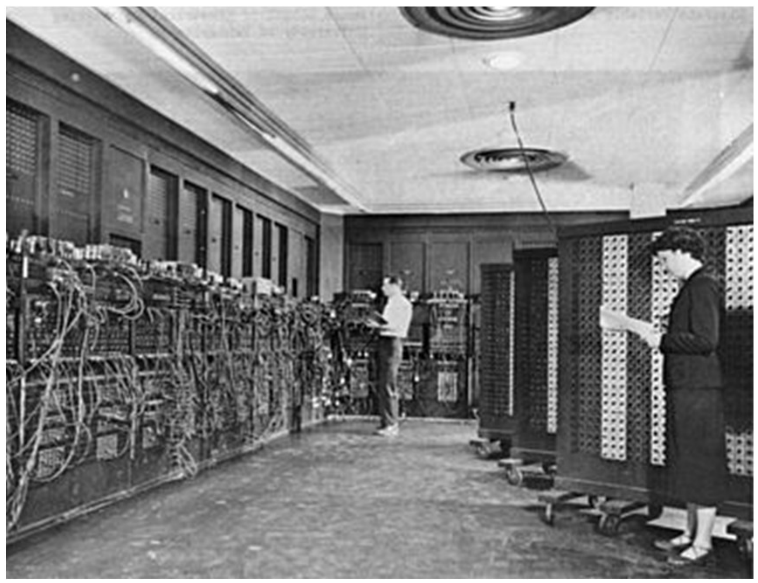

Device: ibmqx4
Quantum State: Computation Basis
Download CSV
1
0.875
0.75
0.625
0.5
0.375
0.25
0.125
0
0.884
0.116
00000
00001
00010
00011
00100
00101
00110
00111
01000
01001
01010
01011
01100
01101
01110
01111
Quantum Circuit
q[0] |0⟩
q[1] |0⟩
q[2] |0⟩
q[3] |0⟩
q[4] |0⟩
c 0 5
X
H
H
H
2
OPENQASM 2.0
1 include "qelib1.inc";
2
3 qreg q[5];
4 creg c[5];
5
6 x q[1];
7 h q[2];
8 h q[1];
Open in Composer

IBM Nov 2017 50kubitov

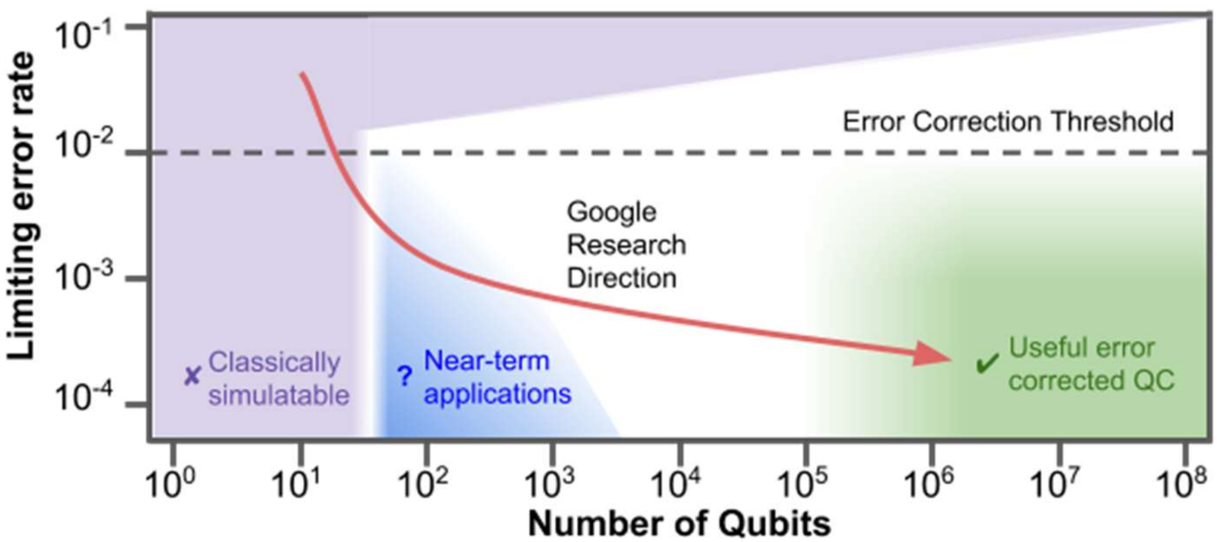




ENIAC 1945



Google Bristlecone 72 Josephsonovih kubitov



Microsoft : topološki kubiti (“1 naš kubit toliko kot 1000 njihovih”)

Microsoft Quantum labs and locations

Redmond

The Quantum Architectures and Computation (QuArC) group works to make quantum computers accessible to developers by creating a software stack.

Santa Barbara

Station Q at the University of California, Santa Barbara is working to understand how topological phases of matter can be used in quantum architecture.

Delft

The team in Delft is finding ways to suppress quantum decoherence through topological protection through a quantum-gate operation.

Copenhagen

The Center for Quantum Devices looks for ways to control and study the properties of Majorana fermions.

Sydney

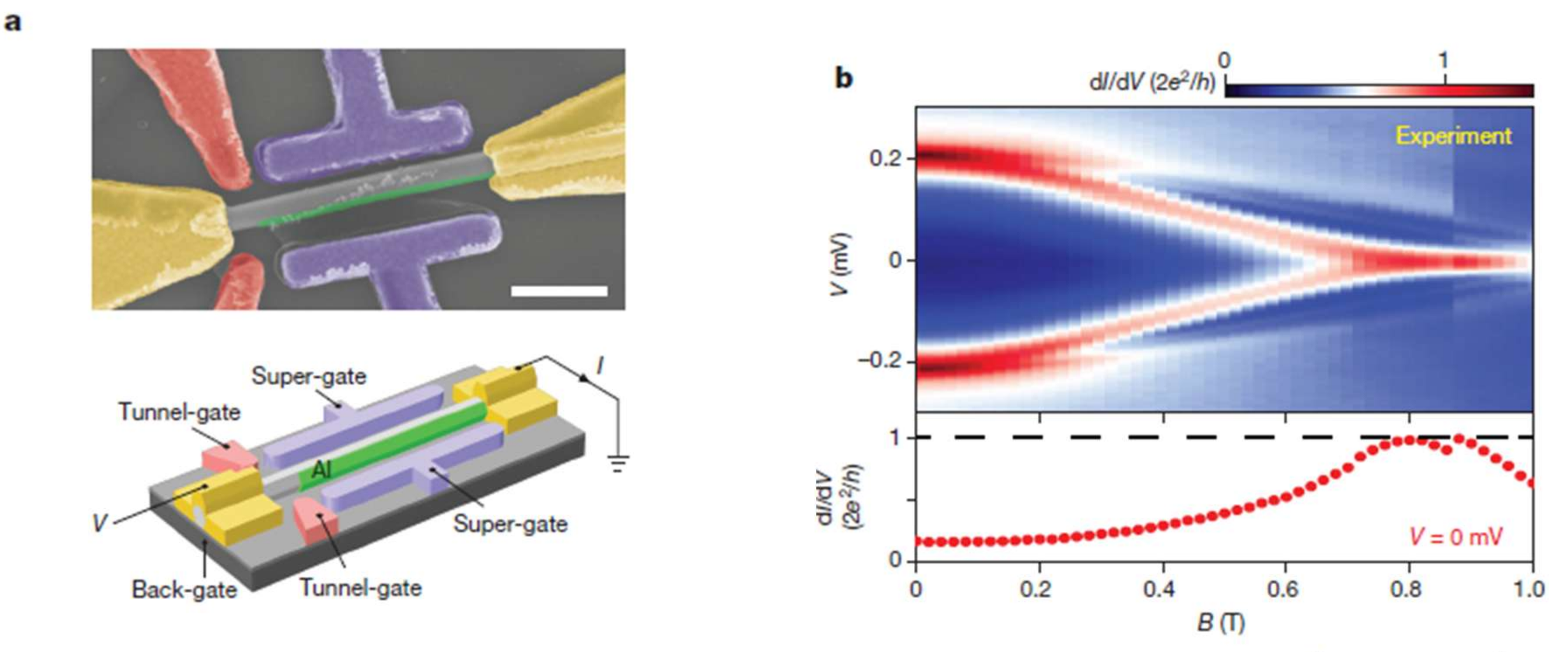
The team in Sydney is exploring the engineering challenges for reading out and controlling qubits in scaled-up architectures.

Lafayette

Station Q at Purdue University focuses on the quantum-mechanical properties of electrons in ultra-high purity III-V semiconductor devices.

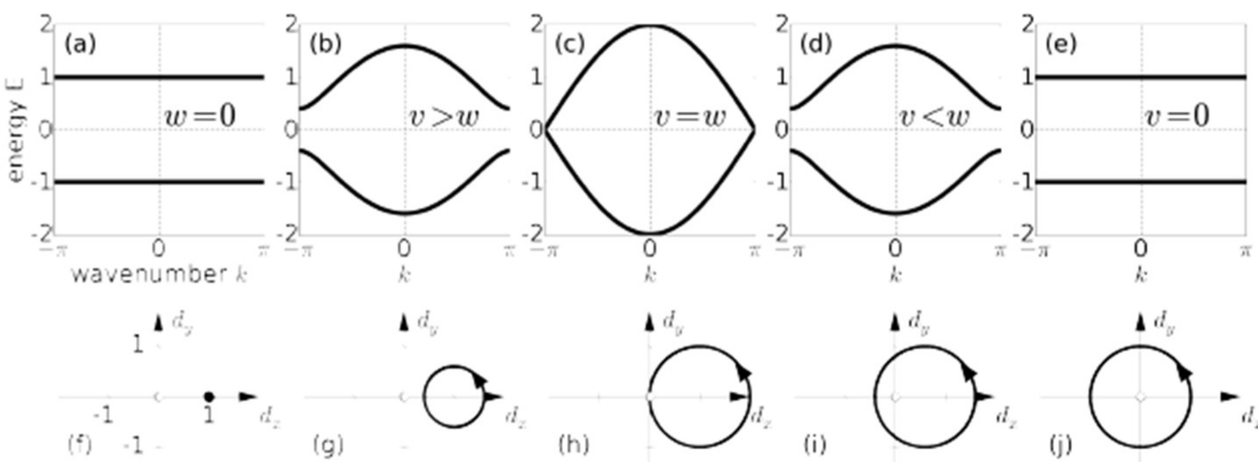
Quantized Majorana conductance

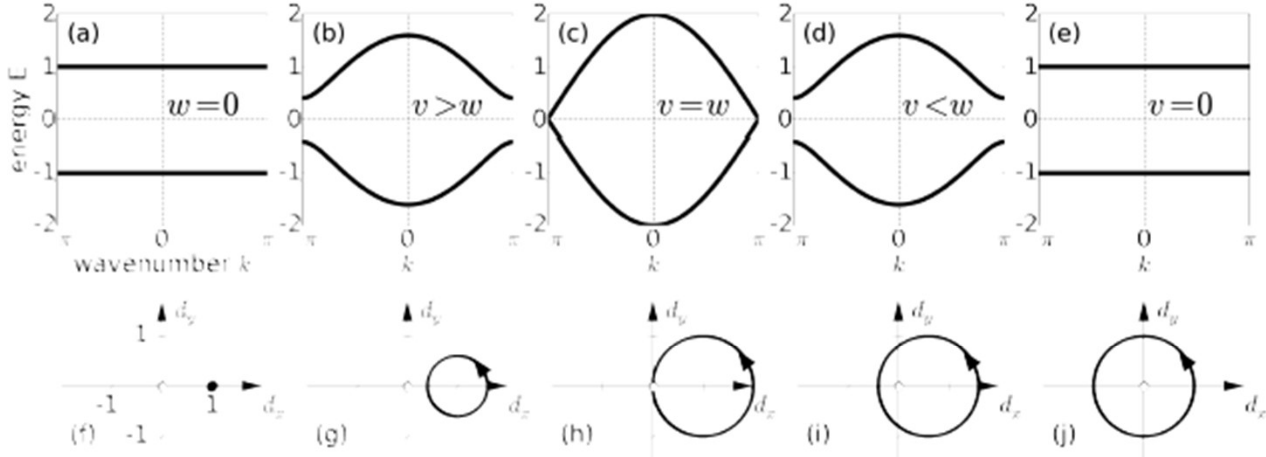
InSb nanozicka

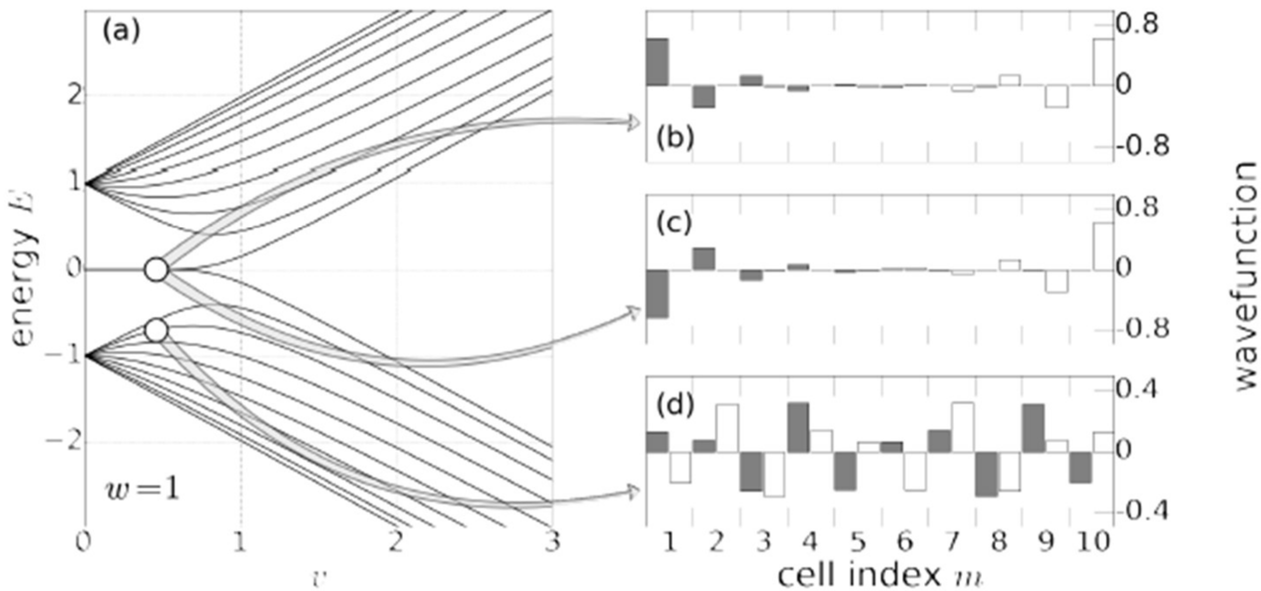


2. Mourik, V. *et al.* Signatures of Majorana fermions in hybrid superconductor-semiconductor nanowire devices. *Science* **336**, 1003–1007 (2012).

$$\hat{H} = v \sum_{m=1}^{N} \left(|m,B\rangle \langle m,A| + h.c. \right) + w \sum_{m=1}^{N-1} \left(|m+1,A\rangle \langle m,B| + h.c. \right)$$







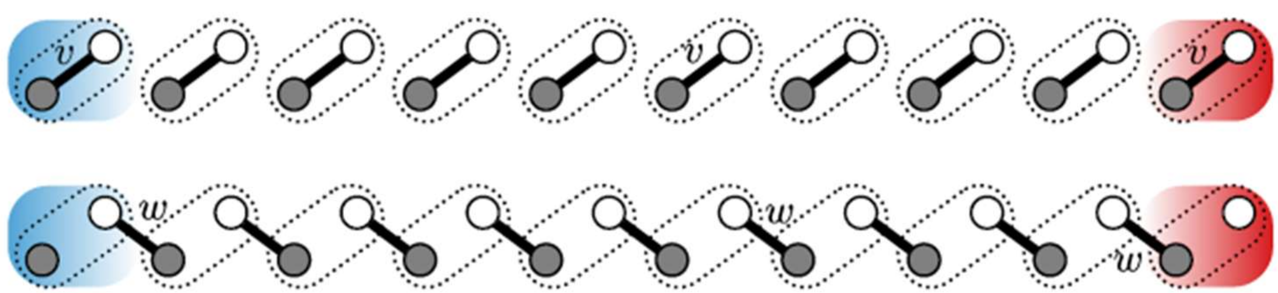
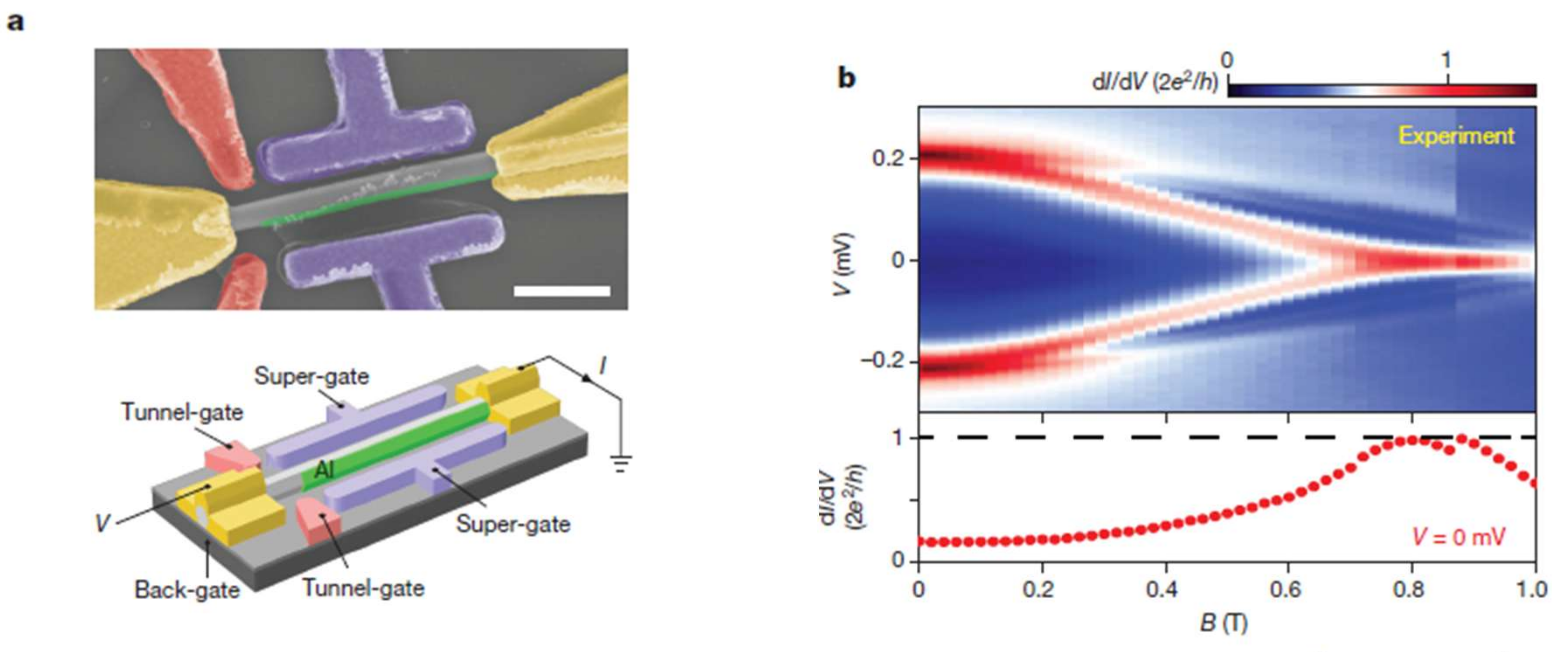


Fig. 1.3 Fully dimerized limits of the SSH model, where the chain has fallen apart to disconnected

Quantized Majorana conductance

InSb nanozicka



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2. Mourik, V. *et al.* Signatures of Majorana fermions in hybrid superconductor-semiconductor nanowire devices. *Science* **336**, 1003–1007 (2012).

Eksitacije z energijo 0: degenerirano osnovno stanje

- 2^N, kjer je $N=N_{majorana}/2$. Vsak par Majoraninih fermionov kubit.