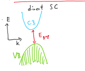
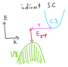
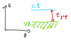
Lecture 12-13

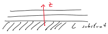
Wednesday, 20. July 2022 13:56

5. Semiconductor QT

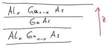

direct SC
E
k
CB
VB
E_{gap}

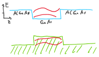

indirect SC
E
k
CB
q
VB
E_{gap}


E
z
CB
VB
E_{gap}



non-homogene band gap

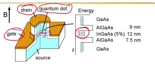

$Al_x Ga_{1-x} As$
$Ga As$
$Al_x Ga_{1-x} As$
z


E
z
AlGaAs
GaAs
AlGaAs

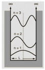
- quantum well (2D)
- quantum wire (1D)
- quantum dot (0D)

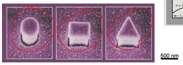
- Bandenergieänderung : Potentialänderung für e^- und h^+
  - ↝ e^- oder h kann in der Heterostruktur gefangen werden
  - ↝ Teilchen im Topfpotential
  - ↝ diskrete Energieniveaus
- Dotierung in der Nähe der Heterostruktur, um quantum well mit e oder h zu besetzen
  - ↝ lange mittlere Weglänge, da Defekt außerhalb
- viele interessante Phenomäne und Anwendungen

Vertical Quantum Dots


B
drain
quantum dot
gate
source
Energy
z
GaAs
AlGaAs 9 nm
InGaAs (5%) 12 nm
AlGaAs 7.5 nm
GaAs

Realization of a "particle-in-a-box":

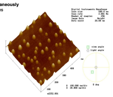




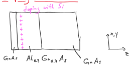
Self-Assembled Quantum Dots

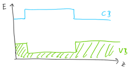
- Quantum Dots form **spontaneously** in suitable growth conditions

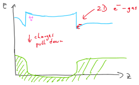
Quantum DOTS
Yep, They're That small


Digital Instruments NanoScope
view angle
light angle
0 deg

Doping with e^-

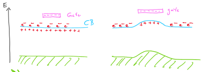

doping with Si
x,y
z
GaAs
$Al_{0.3} Ga_{0.7} As$
GaAs

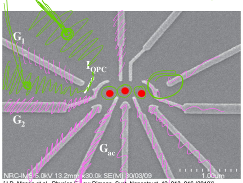



E
2D e^--gas
e^-
charges pull down
z

important
- doping make disorder which would disturb e^--transport (scattering) however, e^- are gathered in a region without defects
  ⇒ high e^--mobility

Gate effect

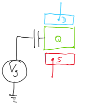

E
Gate
CB
gate

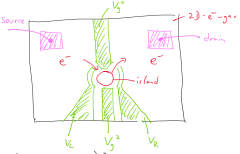

G_1
I_{QPC}
G_2
G_{ac}
NRC-IMS 5.0kV 13.2mm x30.0k SE(M) 30/03/09
1.00um

[J.D. Mason et al., Physica E Low Dimens. Syst. Nanostruct. 42, 813–816 (2010)]

gate

Transport through quantum dots

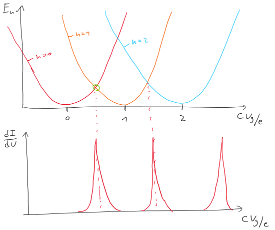


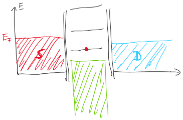

V_g^1
Source
2D-e^--gas
drain
e^-
e^-
island
V_L
V_g^2
V_R

$C = C_g + C_L + C_R$

$$E_n = \frac{e^2}{C}\left(n - \frac{CU_g}{e}\right)^2$$

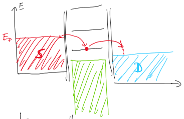
$E_c = \frac{e^2}{C}$: charging energy



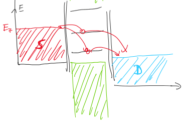


Coulomb blockade

conductance = 0



conductance ≠ 0

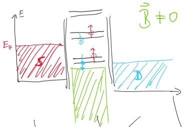


conductance ≠ 0

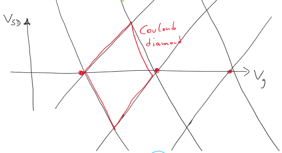
SET in magnetic fields

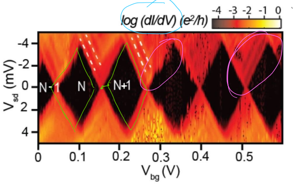
$E_{|\uparrow\rangle} - E_{|\downarrow\rangle} = g\mu_B B$

$\vec{B} \neq 0$

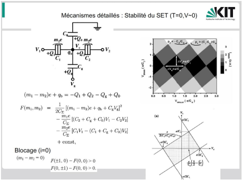


conductance ≠ 0





[Ganjipour et al., Phys. Rev. B 91, 161301 (2015)]



Mécanismes détaillés : Stabilité du SET (T=0,V~0)

C_0
m_1e
$+Q_0$
m_2e
V_1
V_c
V_2
$+Q_1$
q_b
$+Q_2$
C_1
C_2
C_g
$+Q_g$
V_g
$p_r = -C_0/C_g$
$p_l = (C_1-C_g)/C_g$
$\Delta V_b = e/C_\Sigma$
$\Delta V_g = e/C_g$
V_{bias} (e/C$_\Sigma$)
V_{GATE} (e/C$_G$)
(a)
V_1
V_2
$e/2C_1$
e/C_Σ
-e/2C$_2$
e/2C$_g$

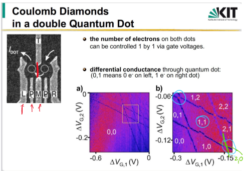
$$(m_1 - m_2)e + q_b = -Q_1 + Q_2 - Q_g + Q_0$$

$$\begin{aligned} F(m_1, m_2) \;=\; & \frac{1}{2C_\Sigma}\left[(m_1 - m_2)e + q_b + C_g V_g\right]^2 \\ & - \frac{m_1 e}{C_\Sigma}\left[(C_2 + C_g + C_0)V_1 - C_2 V_2\right] \\ & - \frac{m_2 e}{C_\Sigma}\left[C_1 V_1 - (C_1 + C_g + C_0)V_2\right] \\ & + \text{const}, \end{aligned}$$

Blocage (i=0)

$(m_1 - m_2 = 0)$

$$F(\pm1, 0) - F(0,0) > 0$$
$$F(0, \pm1) - F(0,0) > 0.$$

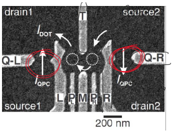


Coulomb Diamonds in a double Quantum Dot

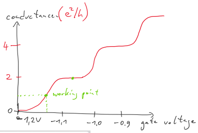
- **the number of electrons** on both dots can be controlled 1 by 1 via gate voltages.
- **differential conductance** through quantum dot: (0,1 means 0 e⁻ on left, 1 e⁻ on right dot)

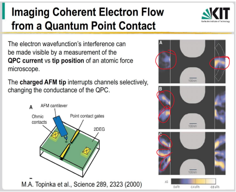
I_{DOT}
T
L
PL
M
PR
R
a)
0
-0.2
$\Delta V_{G,2}$ (V)
0,0
-0.6
0
$\Delta V_{G,1}$ (V)
b)
-0.06
-0.12
$\Delta V_{G,2}$ (V)
1,2
2,2
0,1
1,1
2,1
0,0
1,0
-0.3
-0.15
$\Delta V_{G,1}$ (V)
2,0

Readout of Quantum Dots by a Quantum Point Contact (QPC)


drain1
source2
T
I_{DOT}
Q-L
Q-R
I_{QPC}
I_{QPC}
source1
L
PL
M
PR
R
drain2
200 nm

- QPC is a narrow channel of size comparable to e^- wavelength λ_e
- control of channel with gate
- transport is quantized





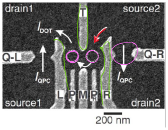
Imaging Coherent Electron Flow from a Quantum Point Contact

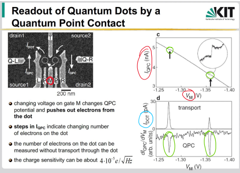
The electron wavefunction's interference can be made visible by a measurement of the **QPC current** vs **tip position** of an atomic force microscope.

The **charged AFM tip** interrupts channels selectively, changing the conductance of the QPC.

A
AFM cantilever
Ohmic contacts
Point contact gates
2DEG
A
B
C
100nm
100nm
100nm
ΔG
0 e²/h
-0.4 e²/h
-0.8 e²/h

M.A. Topinka et al., Science 289, 2323 (2000)


drain1
source2
T
I_{DOT}
Q-L
Q-R
I_{QPC}
I_{QPC}
source1
L
PL
M
PR
R
drain2
200 nm

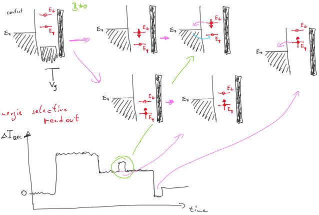


Readout of Quantum Dots by a Quantum Point Contact

drain1
source2
T
I_{DOT}
Q-L
Q-R
I_{QPC}
I_{QPC}
L
P
M
P
R
source1
drain2
200 nm
c
I_{QPC} (nA)
5
4
3
-1.25
-1.30
-1.35
-1.40
V_M (V)
d
30
I_{DOT} (pA)
0
transport
dI_{QPC}/dV_M (arb. units)
QPC
-1.25
-1.30
-1.35
-1.40
V_M (V)

- changing voltage on gate M changes QPC potential and **pushes out electrons from the dot**
- **steps in I_{QPC}** indicate changing number of electrons on the dot
- the number of electrons on the dot can be measured without transport through the dot
- the charge sensitivity can be about $4 \cdot 10^{-5} e/\sqrt{Hz}$

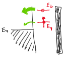
Spin to charge conversion



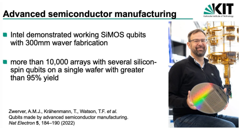
B≠0
contact
E_F
$E_\downarrow$
$E_\uparrow$
V_g
E_F
$E_\downarrow$
$E_\uparrow$
E_F
$E_\downarrow$
$E_\uparrow$
E_F
$E_\downarrow$
$E_\uparrow$
E_F
$E_\downarrow$
$E_\uparrow$
E_F
$E_\downarrow$
$E_\uparrow$
ΔI_{QPC}
0
time

Energie selective readout

Tunneling - Rate selective readout



E_F
$E_\downarrow$
$E_\uparrow$

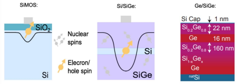


Advanced semiconductor manufacturing

- Intel demonstrated working SiMOS qubits with 300mm waver fabrication
- more than 10,000 arrays with several silicon-spin qubits on a single wafer with greater than 95% yield

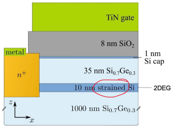
Zwerver, A.M.J., Krähenmann, T., Watson, T.F. *et al.* Qubits made by advanced semiconductor manufacturing. *Nat Electron* **5**, 184–190 (2022)

Examples:



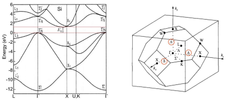
SiMOS:
SiO_2
Si
Nuclear spins
Elecron/ hole spin
Si/SiGe:
Si
SiGe
Ge/SiGe:
Si Cap
1 nm
$Si_{0.2}Ge_{0.8}$
22 nm
Ge
16 nm
$Si_{0.2}Ge_{0.8}$
160 nm
$Si_{1-x}Ge_x$
Ge
^{nat}Si

$Si/Si_{0.7}Ge_{0.3}$ heterostructure

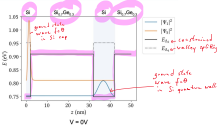


TiN gate
8 nm SiO_2
metal
1 nm Si cap
n^+
35 nm $Si_{0.7}Ge_{0.3}$
10 nm strained Si
2DEG
1000 nm $Si_{0.7}Ge_{0.3}$
z
x

Bandstructure of unstrained Si

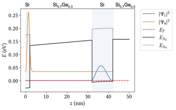


$Si/Si_{0.7}Ge_{0.3}$ conduction band edge profile

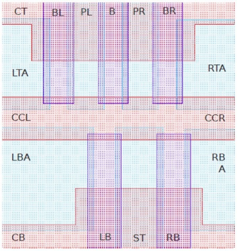


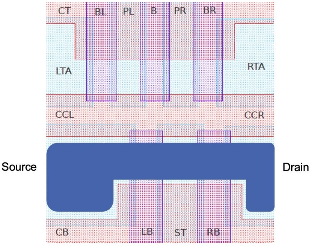
V = 0V

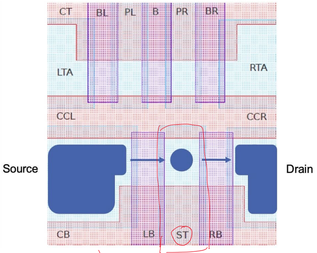
$Si/Si_{0.7}Ge_{0.3}$ conduction band edge profile



V > V_{acc}


CT
BL
PL
B
PR
BR
LTA
RTA
CCL
CCR
LBA
RB
A
CB
LB
ST
RB


CT
BL
PL
B
PR
BR
LTA
RTA
CCL
CCR
Source
Drain
CB
LB
ST
RB


CT
BL
PL
B
PR
BR
LTA
RTA
CCL
CCR
Source
Drain
CB
LB
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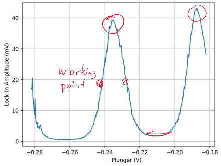
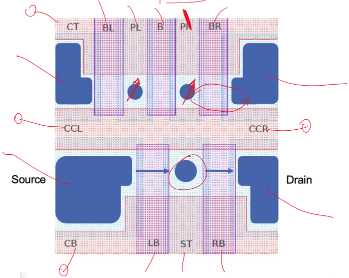
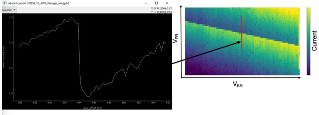
RB



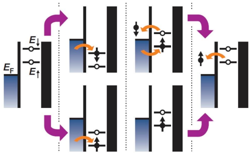

CT
BL
PL
B
PR
BR
CCL
CCR
Source
Drain
CB
LB
ST
RB


adwin1.current 105959_1D_AWG_Plunger_sweep.h5

Line Plot
X: 9.441206e-01 V
Y: 1.244476e-09 A
adwin1.current (nA)
1.3
1.2
1.1
1.0
936
938
940
942
944
946
948
950
952
954
956
awg_offset (mV)
V_{PR}
V_{BR}
Current

Spin to charge conversion

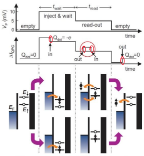
Elzerman readout


$E_\downarrow$
E_F
$E_\uparrow$

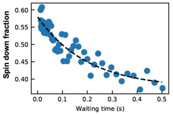
[Elzerman et al. 2004, Nature]

Spin to charge conversion

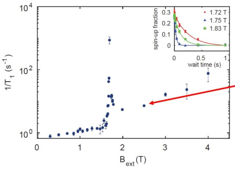
Elzerman readout

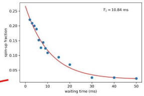

V_P (mV)
10
5
0
t_{wait}
t_{read}
inject & wait
read-out
empty
empty
time
ΔI_{QPC}
Q_{dot} = -e
Q_{dot}=0
Q_{dot}=0
in
out
in
out
time
$E_\downarrow$
E_F
$E_\uparrow$

[Elzerman et al. 2004, Nature]



[N. Dumoulin Stuyck PhD thesis 2021]



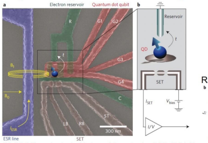


Matches quite good with expectations

State-of-the-art:

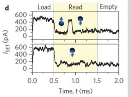
Long coherence times by using spin-free Silicon

- **Problem:** strong dephasing from nuclear spin bath: T_2<1 µs in GaAs/AlGaAs and Si/SiGe quantum dots
- Create Si/SiGe dots using isotopically pure ^{28}Si: T_2 = 120 µs, $\mathbf{T_2^* = 28}$ **ms** (with refocussing)

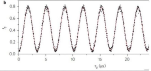

a
Electron reservoir
Quantum dot qubit
b
R
G1
G2
G3
G4
C
LB
RB
ST
B_1
B_0
I_{ESR}
300 nm
ESR line
SET
Reservoir
QD
t
SET
I_{SET}
V_{bias}
I/V

M. Veldhorst et al., Nature Nanotech. 216 (2014)

SET readout



Rabi oscillation (gate fidelity 99.59%)



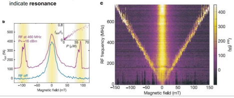
Resonant Spin Control

F.H.L. Koppens et al., Nature 442, 766 (2006)

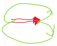
- **Spectroscopy**

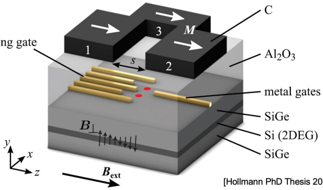
apply an rf **oscillating magnetic field**, vary **polarizing static field** strength

Peaks in the current through the dot indicate **resonance**



Electric dipole spin resonance qubit




driving gate
C
1
2
3
M
s
Al_2O_3
metal gates
SiGe
Si (2DEG)
SiGe
$B_\perp$
B_{ext}
y
x
z

[Hollmann PhD Thesis 2019]

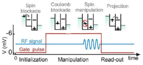
Resonant Spin Control

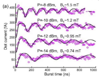
F.H.L. Koppens et al., Nature 442, 766 (2006)

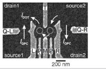
- **Rabi oscillation**

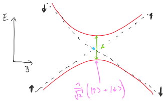
a **spin-up** electron can't leave the dot due to **spin-blockade**

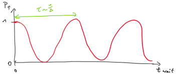
flipping the spin via resonant drive starts current through dot


Spin blockade
Coulomb blockade
Spin manipulation
Projection
-6
0
V (mV)
RF signal
Gate pulse
0
Initialization
Manipulation
Read-out
time

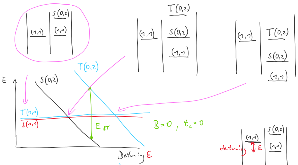


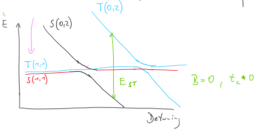

drain1
source2
T
I_{DOT}
Q-L
Q-R
I_{QPC}
I_{QPC}
L
P_L
M
P_R
R
source1
drain2
200 nm

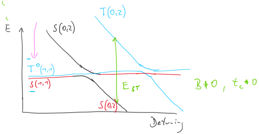

E
3
$\frac{1}{\sqrt{2}}(|\uparrow\rangle+|\downarrow\rangle)$



singlet - triplet - readout


(1,1)
S(0,2)
(1,1)
T(0,2)
(1,1)
S(0,2)
(1,1)
(1,1)
T(0,2)
S(0,2)
(1,1)
E
S(0,2)
T(0,2)
T(1,1)
S(1,1)
E_{ST}
$B=0,\ t_c=0$
Detuning ε
(1,1)
S(0,2)
(1,1)
detuning ε


E
S(0,2)
T(0,2)
T(1,1)
S(1,1)
E_{ST}
$B=0,\ t_c\neq 0$
Detuning


E
S(0,2)
T(0,2)
T^0(1,1)
S(1,1)
E_{ST}
S(0,2)
$B\neq 0,\ t_c\neq 0$
Detuning