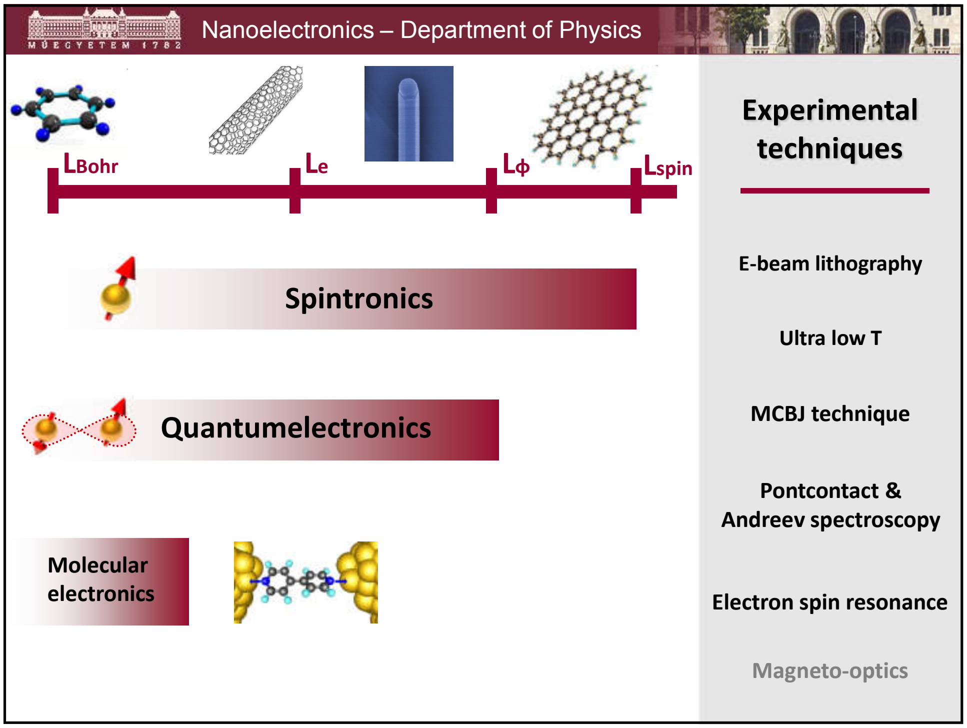


Nanoelectronics – Department of Physics

L

L_{Bohr} L_e L_ϕ L_{spin}

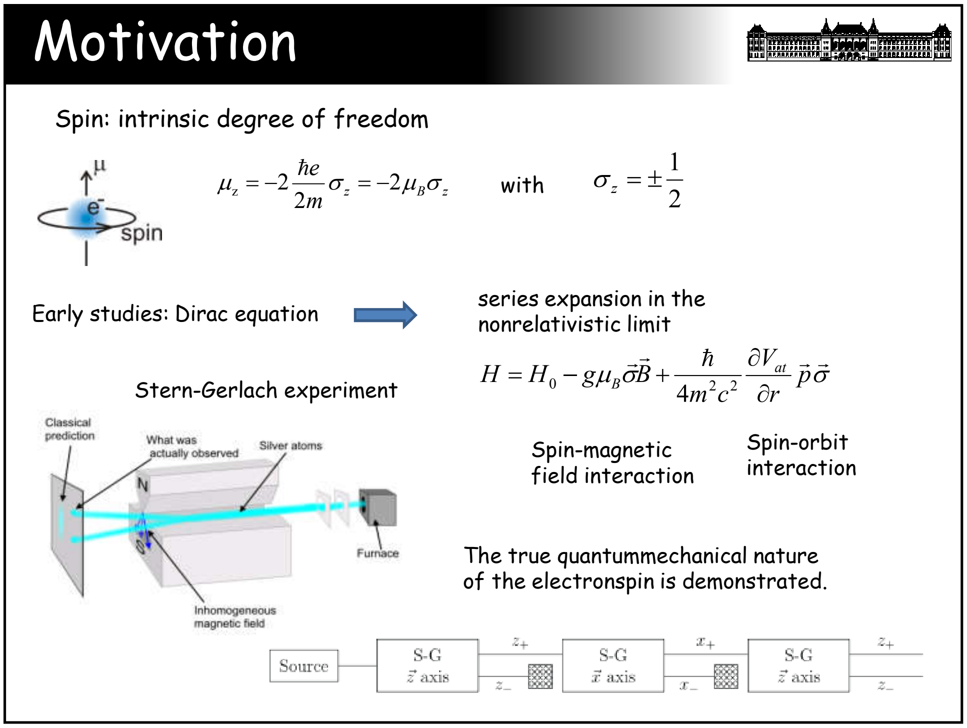
Spintronics

Quantumelectronics

Molecular electronics

Experimental techniques

- E-beam lithography
- Ultra low T
- MCBJ technique
- Pontcontact & Andreev spectroscopy
- Electron spin resonance
- Magneto-optics



Motivation

Spin: intrinsic degree of freedom

$$\mu_z = -2\frac{\hbar e}{2m}\sigma_z = -2\mu_B\sigma_z \quad \text{with} \quad \sigma_z = \pm\frac{1}{2}$$

Early studies: Dirac equation → series expansion in the nonrelativistic limit

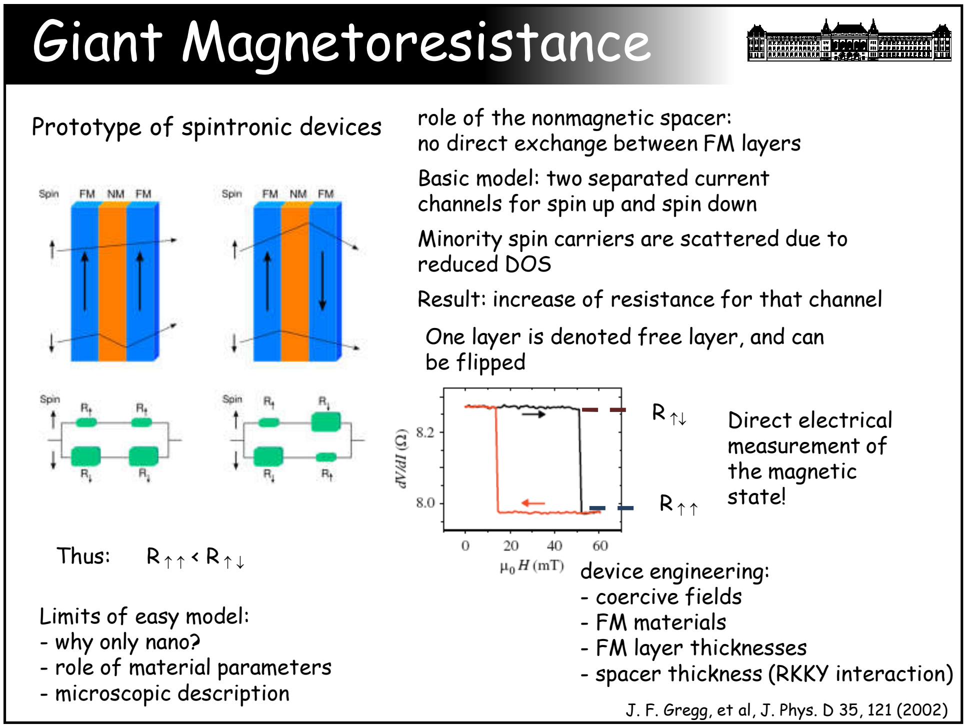
$$H = H_0 - g\mu_B\vec{\sigma}\vec{B} + \frac{\hbar}{4m^2c^2}\frac{\partial V_{at}}{\partial r}\vec{p}\vec{\sigma}$$

Spin-magnetic field interaction

Spin-orbit interaction

Stern-Gerlach experiment

The true quantummechanical nature of the electronspin is demonstrated.



Giant Magnetoresistance

Prototype of spintronic devices

Thus: $R_{\uparrow\uparrow} < R_{\uparrow\downarrow}$

Limits of easy model:
- why only nano?
- role of material parameters
- microscopic description

role of the nonmagnetic spacer: no direct exchange between FM layers

Basic model: two separated current channels for spin up and spin down

Minority spin carriers are scattered due to reduced DOS

Result: increase of resistance for that channel

One layer is denoted free layer, and can be flipped

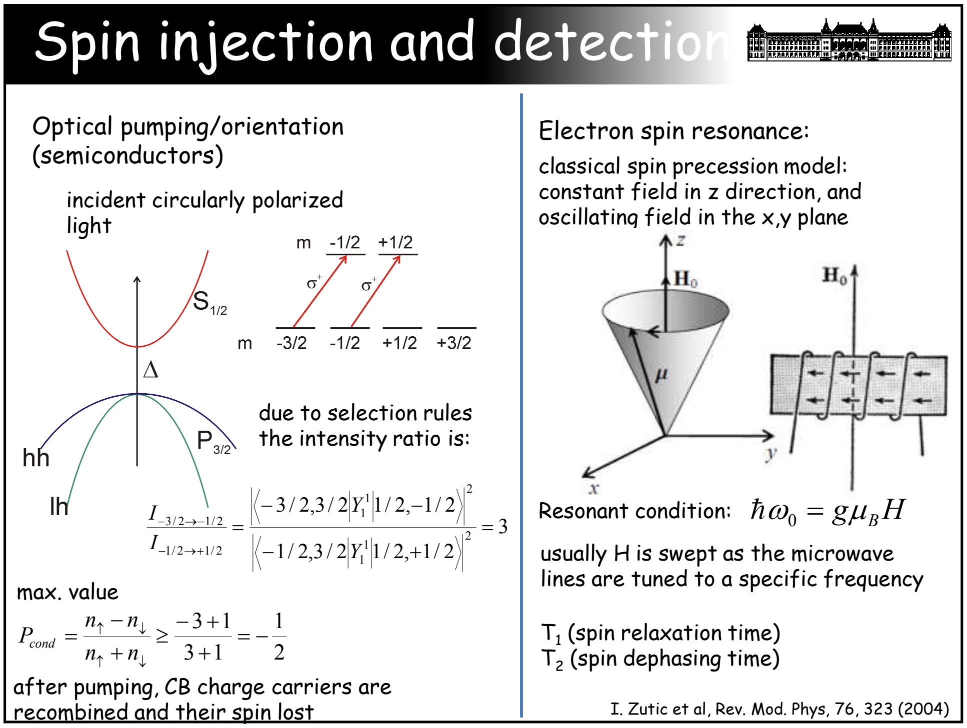
$R_{\uparrow\downarrow}$

$R_{\uparrow\uparrow}$

Direct electrical measurement of the magnetic state!

device engineering:
- coercive fields
- FM materials
- FM layer thicknesses
- spacer thickness (RKKY interaction)

J. F. Gregg, et al, J. Phys. D 35, 121 (2002)



Spin injection and detection

Optical pumping/orientation (semiconductors)

incident circularly polarized light

due to selection rules the intensity ratio is:

$$\frac{I_{-3/2\to-1/2}}{I_{-1/2\to+1/2}} = \frac{\left|\langle -3/2,3/2|Y_1^1|1/2,-1/2\rangle\right|^2}{\left|\langle -1/2,3/2|Y_1^1|1/2,+1/2\rangle\right|^2} = 3$$

max. value

$$P_{cond} = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} \geq \frac{-3+1}{3+1} = -\frac{1}{2}$$

after pumping, CB charge carriers are recombined and their spin lost

Electron spin resonance:

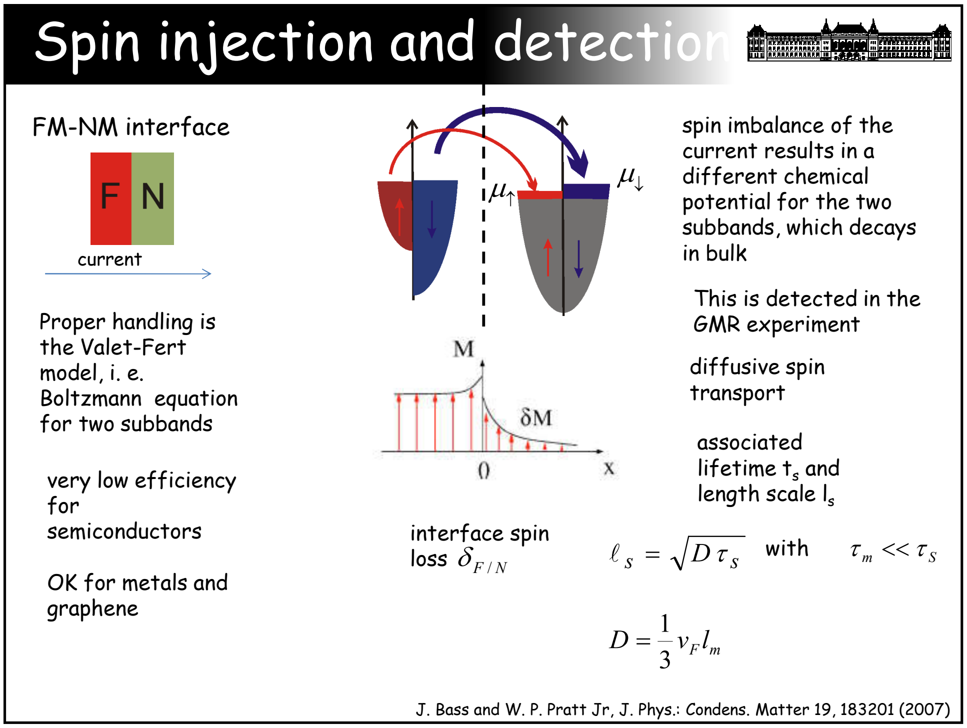
classical spin precession model: constant field in z direction, and oscillating field in the x,y plane

Resonant condition: $\hbar\omega_0 = g\mu_B H$

usually H is swept as the microwave lines are tuned to a specific frequency

T_1 (spin relaxation time)
T_2 (spin dephasing time)

I. Zutic et al, Rev. Mod. Phys, 76, 323 (2004)



Spin injection and detection

FM-NM interface

Proper handling is the Valet-Fert model, i. e. Boltzmann equation for two subbands

very low efficiency for semiconductors

OK for metals and graphene

interface spin loss $\delta_{F/N}$

spin imbalance of the current results in a different chemical potential for the two subbands, which decays in bulk

This is detected in the GMR experiment

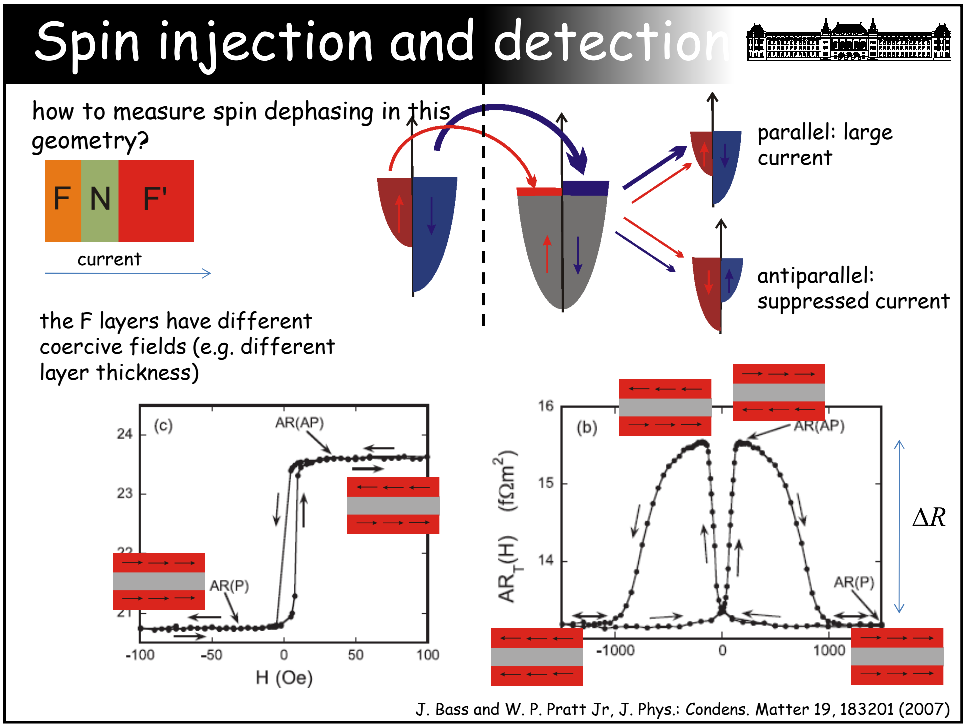
diffusive spin transport

associated lifetime t_s and length scale l_s

$\ell_s = \sqrt{D\tau_s}$ with $\tau_m \ll \tau_s$

$$D = \frac{1}{3} v_F l_m$$

J. Bass and W. P. Pratt Jr, J. Phys.: Condens. Matter 19, 183201 (2007)



Spin injection and detection

how to measure spin dephasing in this geometry?

parallel: large current

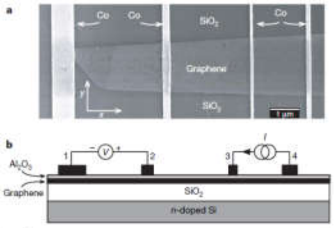
antiparallel: suppressed current

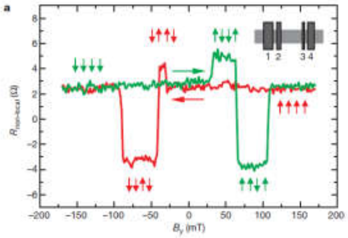
the F layers have different coercive fields (e.g. different layer thickness)

J. Bass and W. P. Pratt Jr, J. Phys.: Condens. Matter 19, 183201 (2007)

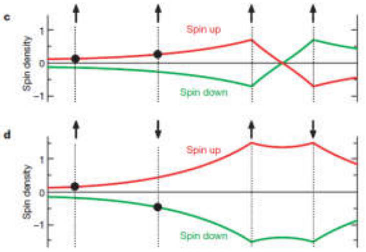
Spin injection and detection

Nonlocal measurements for graphene



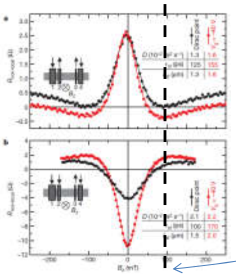


spin diffusion length is estimated to be 2μm



4 terminal device voltage terminals measure the chemical potential of the corresponding subband

in a small perpendicular B, precession was also studied (Hanle effect)



in principle: oscillatory behavior

limitations: spin dephasing, diffusive transport

rotation of 180°

N. Tombros et al, Nature, 448, 571 (2007)

Spin relaxation models

Elliott-Yafett model

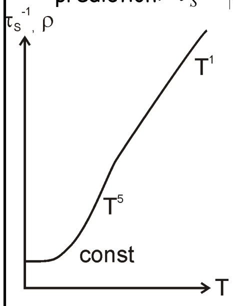
based on the spin-orbit interaction change in the momentum, i.e. scattering changes the spin state, too

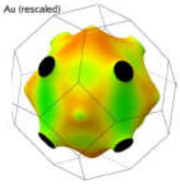
$$V_{SO} = \frac{\hbar}{4m^2c^2}\frac{\partial V_{at}}{\partial r}\vec{p}\vec{\sigma}$$

prediction: $\tau_S = |b|^2 \tau_m$ with $|b|^2 \sim 10^{-5}...10^{-3}$

material dependent constant

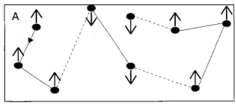
actually, worse than that. It even has a distribution on the Fermi surface

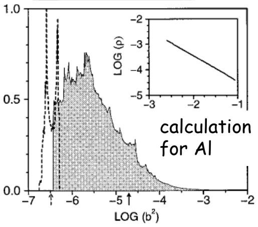




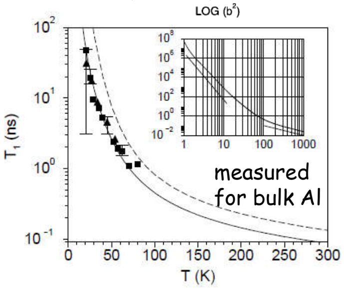
calculation for Au

The spin-flip time scales with the transport lifetime temp. dependence: Bloch-Grüneisen law





calculation for Al

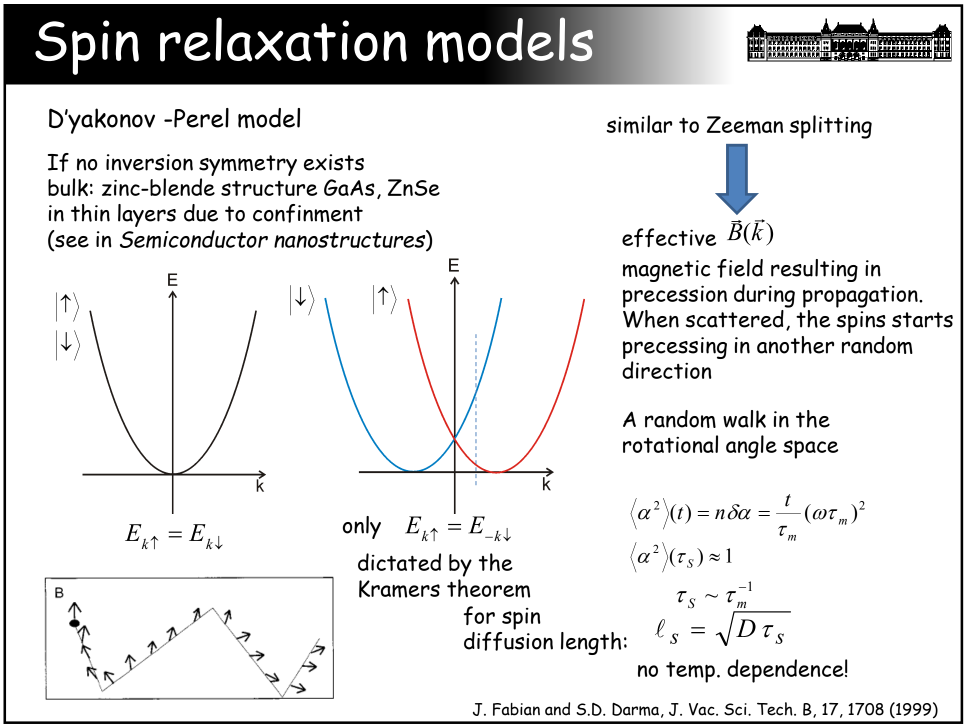


measured for bulk Al

for the spin diffusion length:

$$\ell_S = \sqrt{D\tau_S} \text{ with } D = \frac{1}{3}v_F l_m \rightarrow l_S(T) \sim \tau_m(T)$$

J. Fabian and S.D. Darma, J. Vac. Sci. Tech. B, 17, 1708 (1999) J. Fabian and S.D. Darma, J. Appl. Phys, 85, 5075 (1999)
J. Fabian and S.D. Darma, Phys. Rev. Letters, 83, 1211 (1999) M. Gradhand, et al, Phys. Rev. B, 80, 224413 (2009)



Spin relaxation models

D'yakonov -Perel model

If no inversion symmetry exists
bulk: zinc-blende structure GaAs, ZnSe
in thin layers due to confinment
(see in *Semiconductor nanostructures*)

$E_{k\uparrow} = E_{k\downarrow}$

only $E_{k\uparrow} = E_{-k\downarrow}$

dictated by the Kramers theorem

similar to Zeeman splitting

effective $\vec{B}(\vec{k})$ magnetic field resulting in precession during propagation. When scattered, the spins starts precessing in another random direction

A random walk in the rotational angle space

$$\langle\alpha^2\rangle(t) = n\delta\alpha = \frac{t}{\tau_m}(\omega\tau_m)^2$$

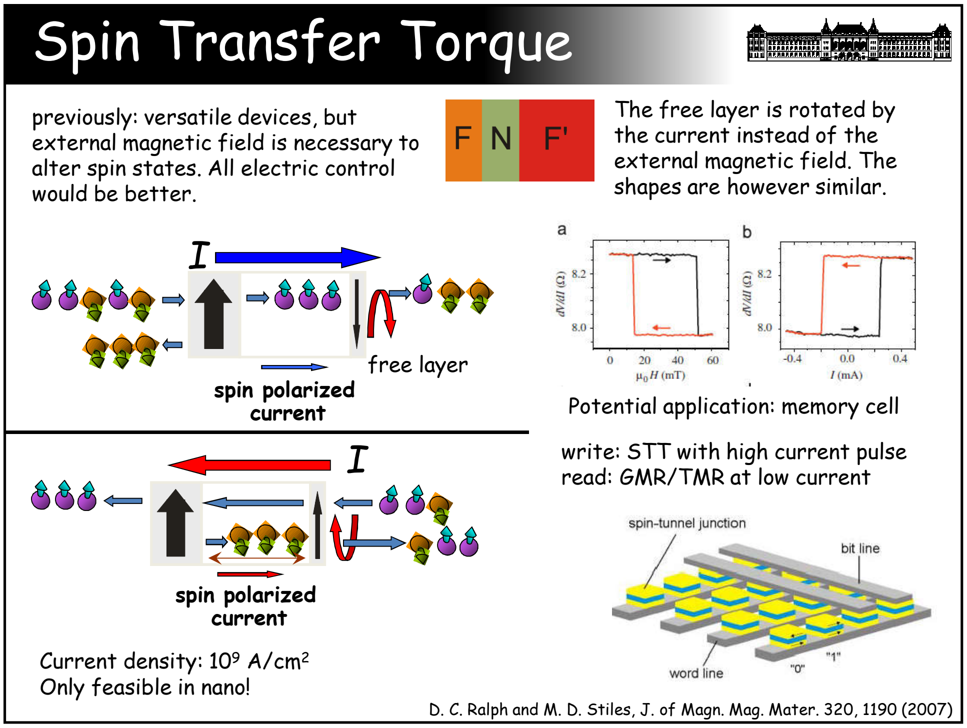
$$\langle\alpha^2\rangle(\tau_S) \approx 1$$

$$\tau_S \sim \tau_m^{-1}$$

for spin diffusion length: $\ell_S = \sqrt{D\tau_S}$

no temp. dependence!

J. Fabian and S.D. Darma, J. Vac. Sci. Tech. B, 17, 1708 (1999)



Spin Transfer Torque

previously: versatile devices, but external magnetic field is necessary to alter spin states. All electric control would be better.

The free layer is rotated by the current instead of the external magnetic field. The shapes are however similar.

spin polarized current

Potential application: memory cell

write: STT with high current pulse
read: GMR/TMR at low current

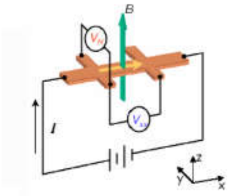
spin polarized current

Current density: 10^9 A/cm^2
Only feasible in nano!

D. C. Ralph and M. D. Stiles, J. of Magn. Mag. Mater. 320, 1190 (2007)

Spin Hall effect

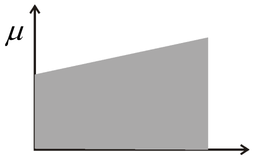
Ordinary Hall effect:



classical model: due to Lorentz force, electrons carrying the current get deflected

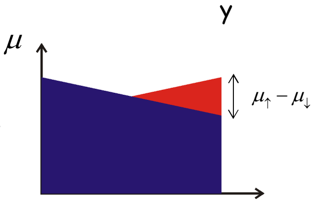
$$R_H = \frac{E_y}{j_x B_z} \text{ with } R_H = -\frac{1}{ne}$$

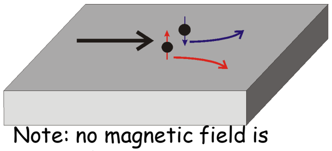
The result is a net electric field in the y direction



If spin-orbit coupling present, momentum scattering becomes anizotropic for each subband

$$V_{SO} = \frac{\hbar}{4m^2c^2}\frac{\partial V_{at}}{\partial r}\vec{p}\vec{\sigma}$$





No net voltage, only magnetization is visible at the edges

$$m \approx g\mu_B \frac{\partial \rho}{\partial \varepsilon}(\mu_\uparrow - \mu_\downarrow)$$

Note: no magnetic field is present!

For realistic parameters (Al, 10^6 A/cm^2), a small effect is predicted

$$\mu_\uparrow - \mu_\downarrow \approx 10neV$$

The generated spin polarization is out-of-plane: $\vec{m} \sim \vec{k}_i \times \vec{k}_f$

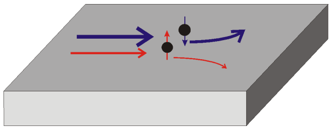
the device size is limited $l_m < L_y << l_S$

J. E. Hirsch, Phys. Rev. Letters, 83, 1834 (1999)

Spin Hall effect

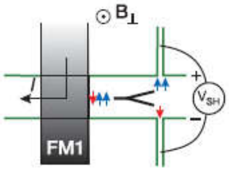
How to measure it?

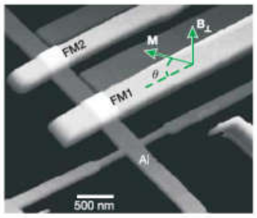
Idea: if the incident current is already spin polarized, then a measureable voltage develops



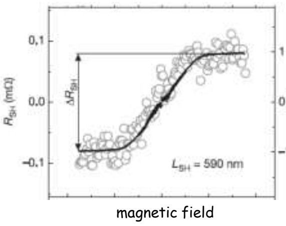
Out-of-plane magnetic field is necessary to have such magnetization to generate a signal

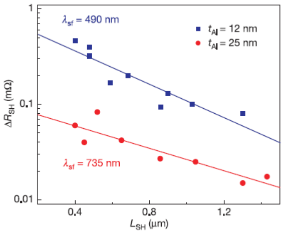
In actual nonlocal experiments, there is no net current through the device, however, the spin imbalance develops

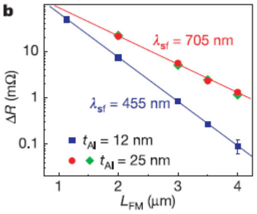




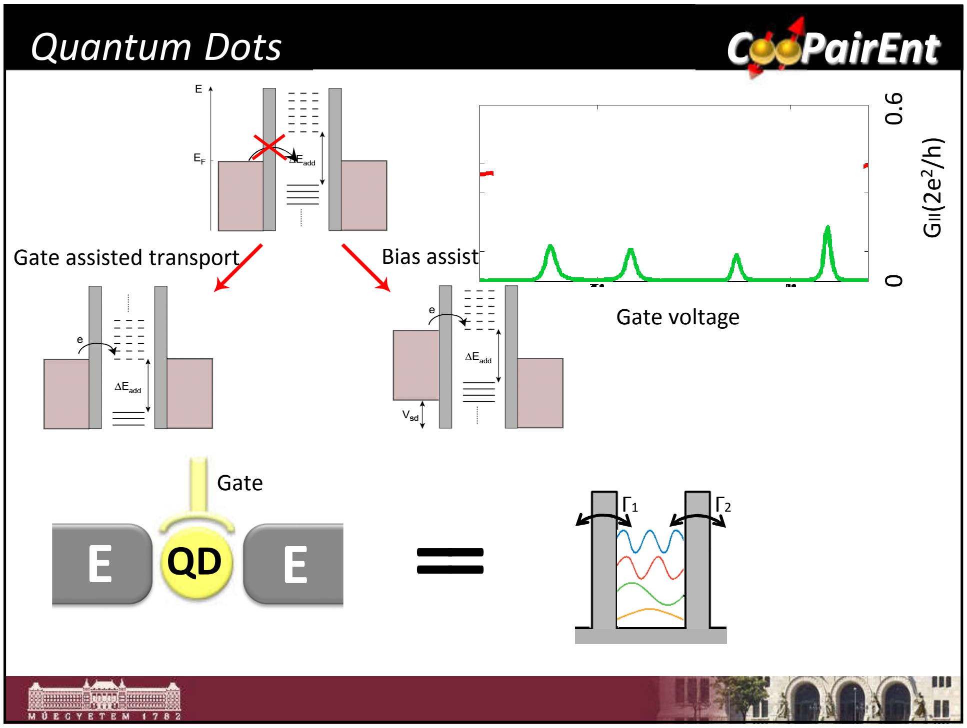
the device is characterized using FM2 in a standard nonlocal measurement



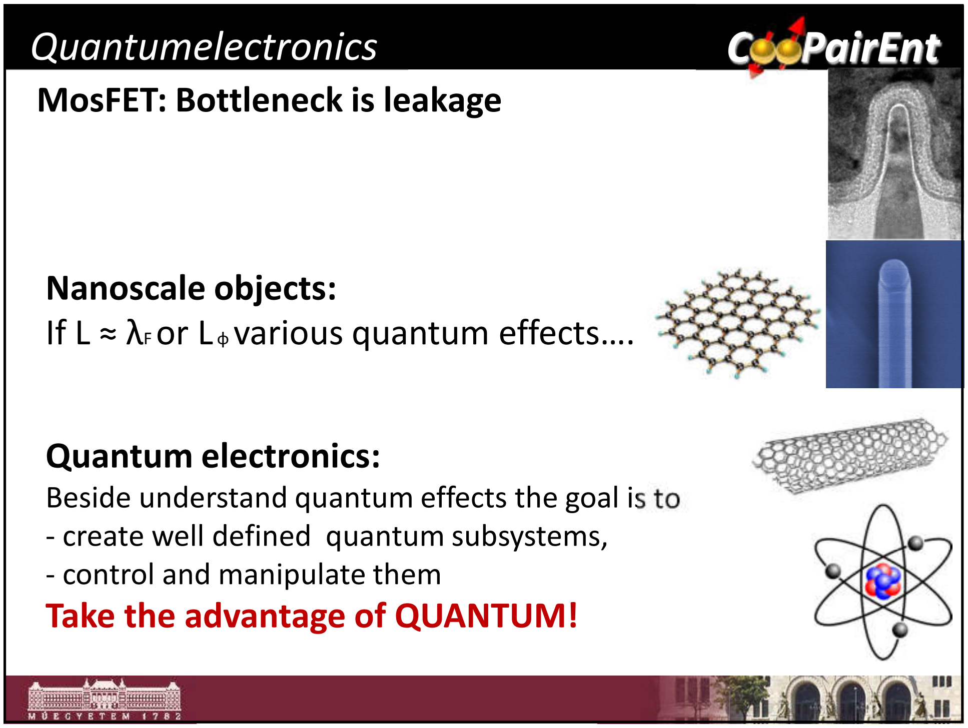




S. O. Valenzuela and M. Tinkham, Nature, 442, 176 (2006)



Quantum Dots



Quantumelectronics

MosFET: Bottleneck is leakage

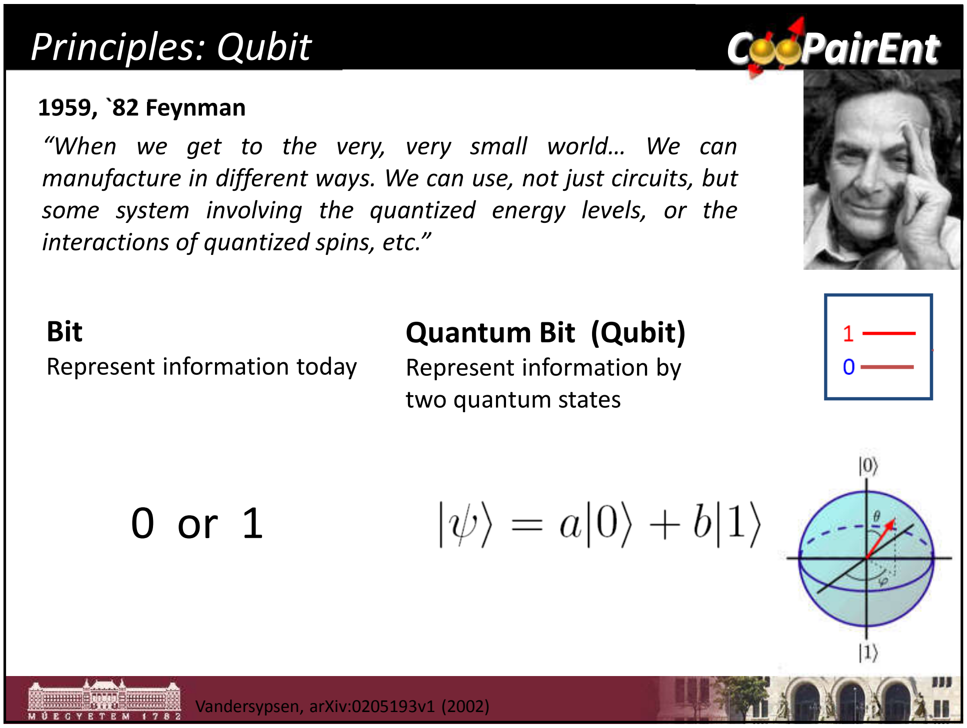
Nanoscale objects:

If $L \approx \lambda_F$ or L_ϕ various quantum effects….

Quantum electronics:

Beside understand quantum effects the goal is to
- create well defined quantum subsystems,
- control and manipulate them

Take the advantage of QUANTUM!



Principles: Qubit

1959, `82 Feynman

"When we get to the very, very small world… We can manufacture in different ways. We can use, not just circuits, but some system involving the quantized energy levels, or the interactions of quantized spins, etc."

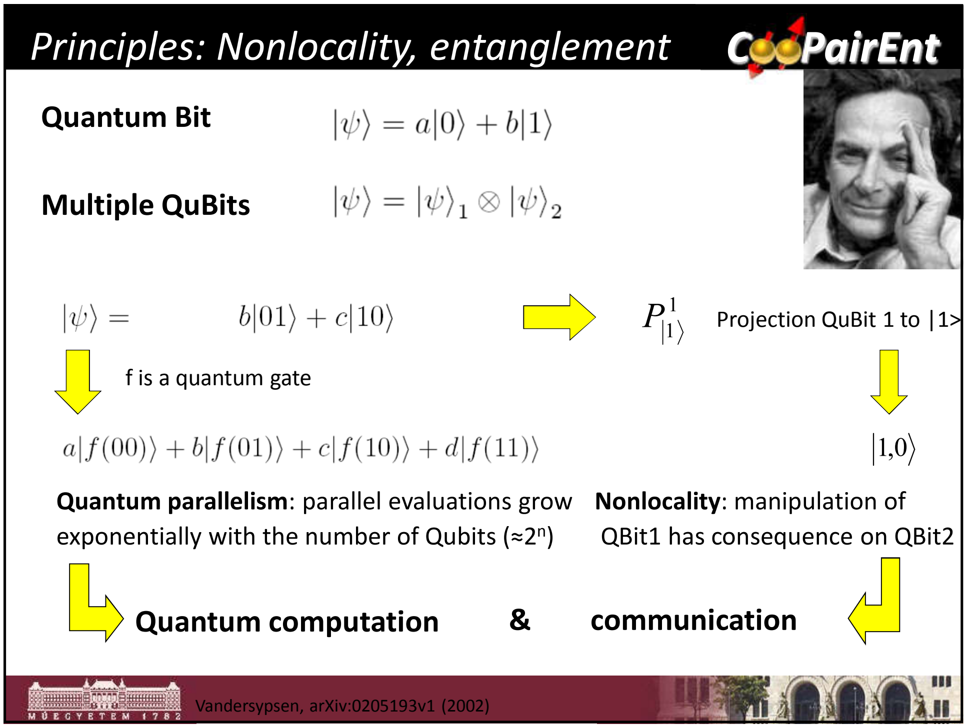
Bit
Represent information today

Quantum Bit (Qubit)
Represent information by two quantum states

0 or 1

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

Vandersypsen, arXiv:0205193v1 (2002)



Principles: Nonlocality, entanglement

Quantum Bit $|\psi\rangle = a|0\rangle + b|1\rangle$

Multiple QuBits $|\psi\rangle = |\psi\rangle_1 \otimes |\psi\rangle_2$

$|\psi\rangle = \quad b|01\rangle + c|10\rangle$ ⇒ $P^1_{|1\rangle}$ Projection QuBit 1 to |1>

f is a quantum gate

$a|f(00)\rangle + b|f(01)\rangle + c|f(10)\rangle + d|f(11)\rangle$

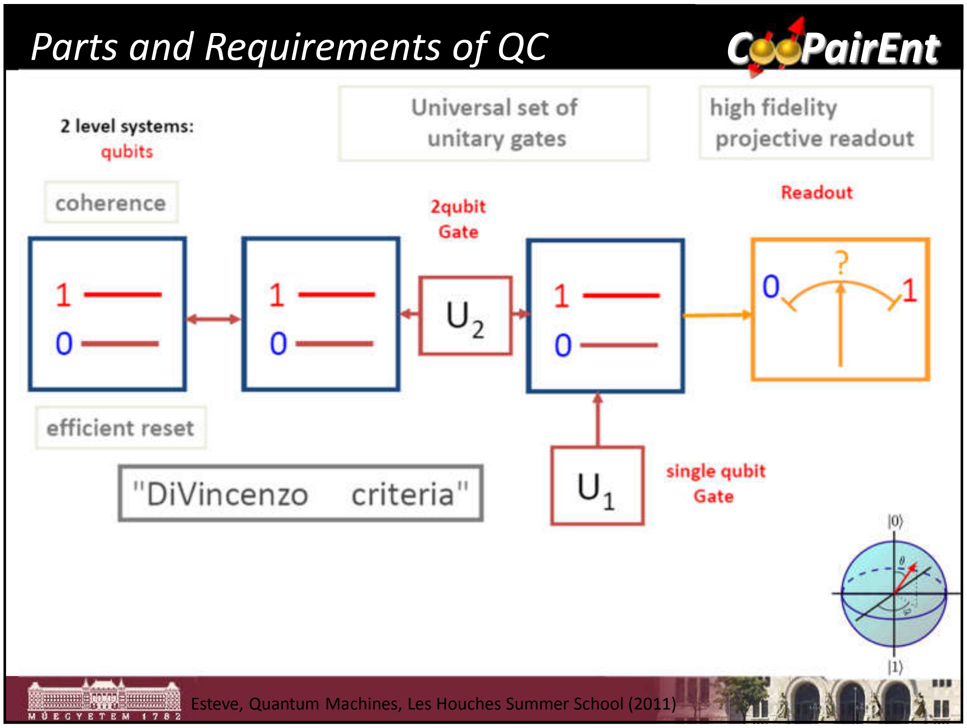
$|1,0\rangle$

Quantum parallelism: parallel evaluations grow exponentially with the number of Qubits (≈2^n)

Nonlocality: manipulation of QBit1 has consequence on QBit2

Quantum computation **&** **communication**

Vandersypsen, arXiv:0205193v1 (2002)



Parts and Requirements of QC

2 level systems:
qubits

Universal set of unitary gates

high fidelity projective readout

coherence

2qubit Gate

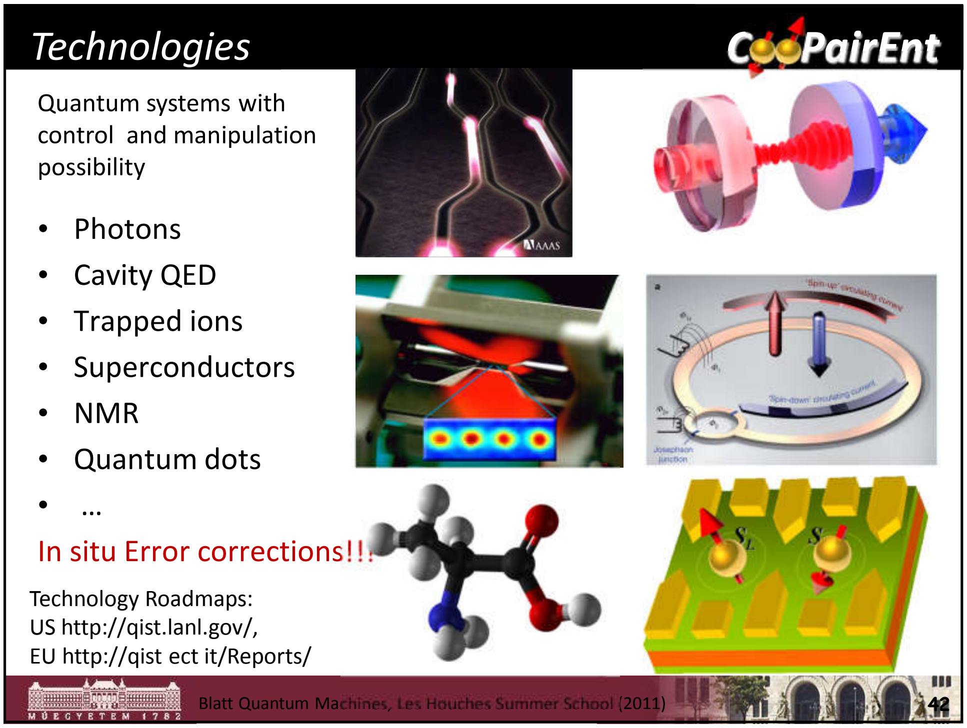
Readout

efficient reset

"DiVincenzo criteria"

single qubit Gate

Esteve, Quantum Machines, Les Houches Summer School (2011)



Technologies

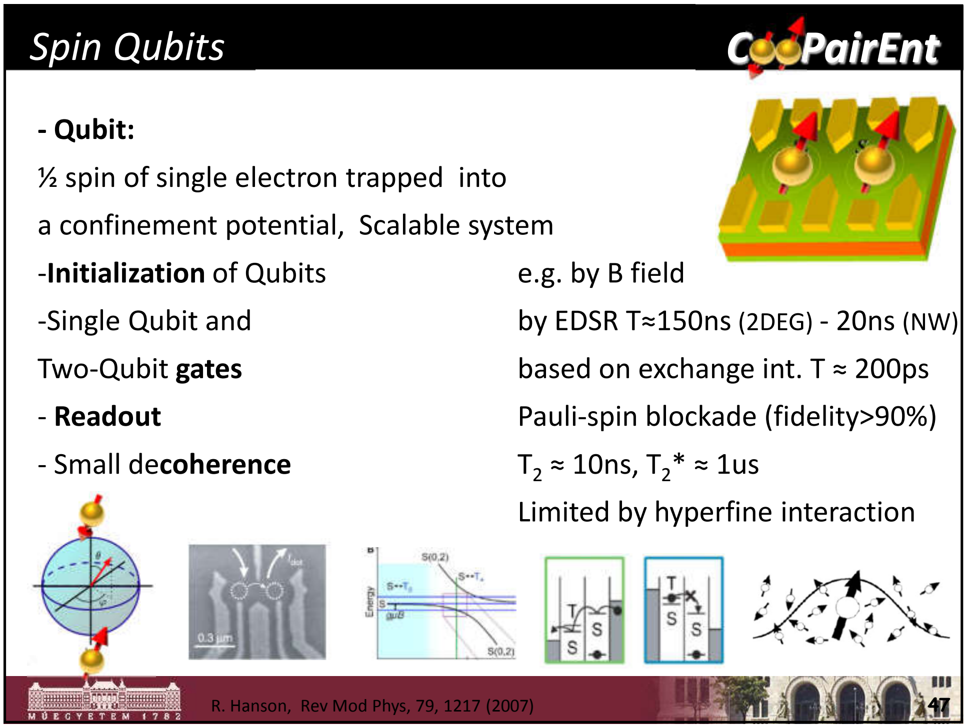
Quantum systems with control and manipulation possibility

- Photons
- Cavity QED
- Trapped ions
- Superconductors
- NMR
- Quantum dots
- …

In situ Error corrections!!!

Technology Roadmaps:
US http://qist.lanl.gov/,
EU http://qist ect it/Reports/

Blatt Quantum Machines, Les Houches Summer School (2011)



Spin Qubits

CoolPairEnt

- **Qubit:**

½ spin of single electron trapped into
a confinement potential, Scalable system

-**Initialization** of Qubits e.g. by B field

-Single Qubit and by EDSR T≈150ns (2DEG) - 20ns (NW)

Two-Qubit **gates** based on exchange int. T ≈ 200ps

- **Readout** Pauli-spin blockade (fidelity>90%)

- Small de**coherence** $T_2 \approx$ 10ns, $T_2^* \approx$ 1us

Limited by hyperfine interaction

R. Hanson, Rev Mod Phys, 79, 1217 (2007)

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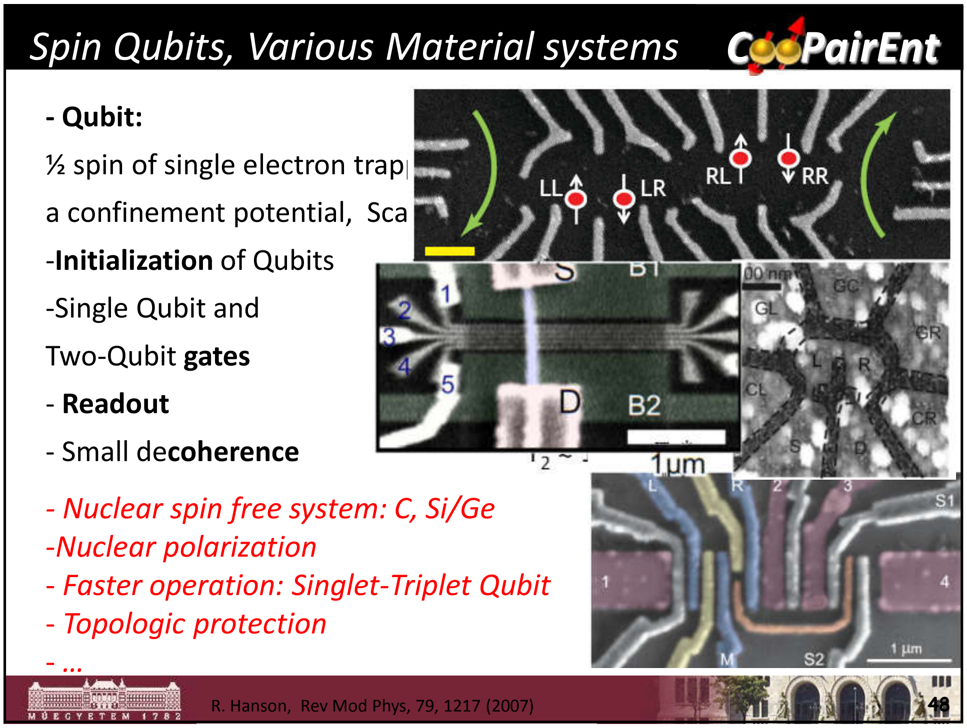

Spin Qubits, Various Material systems

CoolPairEnt

- **Qubit:**

½ spin of single electron trap
a confinement potential, Sca

-**Initialization** of Qubits

-Single Qubit and

Two-Qubit **gates**

- **Readout**

- Small de**coherence**

- Nuclear spin free system: C, Si/Ge
-Nuclear polarization
- Faster operation: Singlet-Triplet Qubit
- Topologic protection
- …

R. Hanson, Rev Mod Phys, 79, 1217 (2007)

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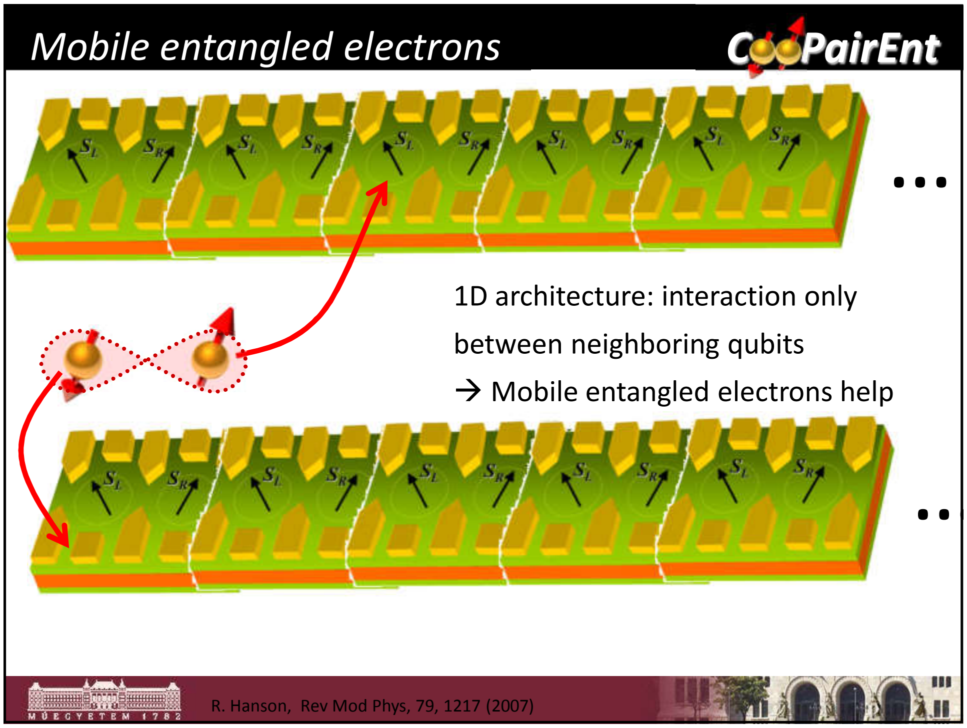
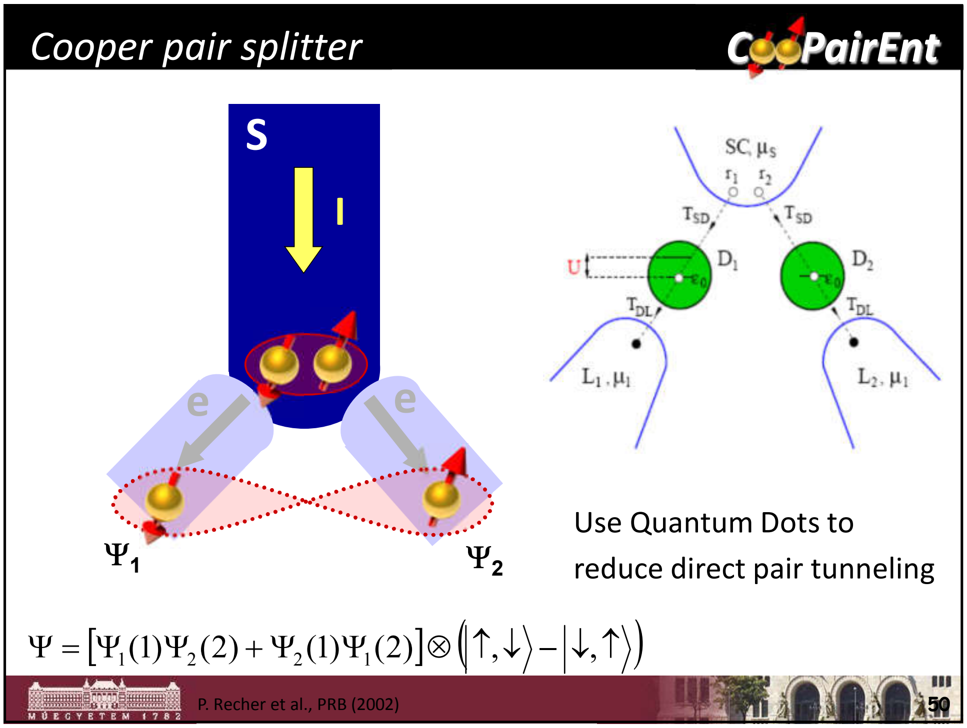


Mobile entangled electrons

1D architecture: interaction only between neighboring qubits

→ Mobile entangled electrons help

R. Hanson, Rev Mod Phys, 79, 1217 (2007)



Cooper pair splitter

Use Quantum Dots to reduce direct pair tunneling

$$\Psi = [\Psi_1(1)\Psi_2(2) + \Psi_2(1)\Psi_1(2)] \otimes \left(|\uparrow,\downarrow\rangle - |\downarrow,\uparrow\rangle\right)$$

P. Recher et al., PRB (2002)

Atomic scale switches - Memristors

Introduction
- What is a *memristor*? How does it work?
- Applications
- Technology requirements against *real* memory devices

The Ag_2S system
- Experimental technique

Other systems
- Valence change mechanism and versatile switching characteristics in Nb_2O_5

New directions
- Artifical neural networks

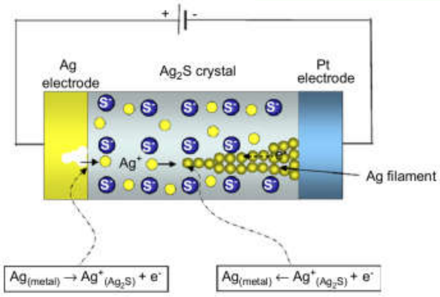
A possible realization of resistive switching

Ag_2S memristor (memory + resistor): Ag electrode + thin Ag_2S layer + electrochemically inert Me tip (e.g. PtIr or Nb).

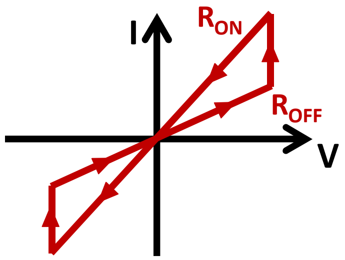
Positive bias (on the Ag electrode): Ag^+ ions move towards the Me tip → an Ag filament is grown between the two electrodes → low resistance ON state

Negative bias: the Ag filament is destructed → high resistance OFF state

I(V) characteristics: linear resistive behavior at low bias, switching to ON/OFF state above a positive/negative threshold → ideal for **memory operation**



K. Terabe *et al.*, Adv. Mater **8**, 536 (2007).



Resistive Random Access Memory (ReRAM)

Requirements against *real* ReRAM devices

• Write/erase voltage level:	< 2 Volt
• Write/erase times:	< 100 ns
• Read-out voltage level:	< 1 Volt
• Read-out current level:	~ 0.001 – 1 mA
• OFF to ON resistance ratio	> 2
• OFF state resistances	< 100 kΩ

• Endurance	> 10^7 writing cycles
• Retention times	> 10 years

- Non-volatility also during read-out operations

R. Waser *et al.*, Adv. Mat. **21**, 2632 (2009).

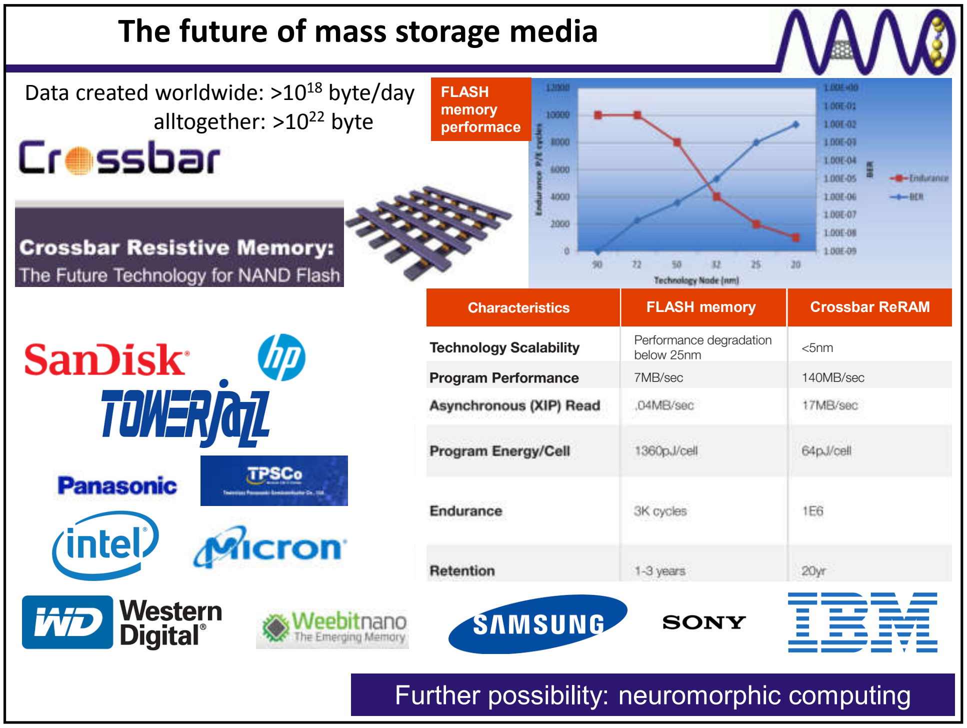
J. J. Yang *et al.*, Nat. Nanotech. **8**, 13 (2013).

- CMOS competitive scaling
- CMOS compatible material systems and technology

A real resistive memory device must comply to ALL of the above requirements

A highly non-linear voltage response function is essential

The future of mass storage media



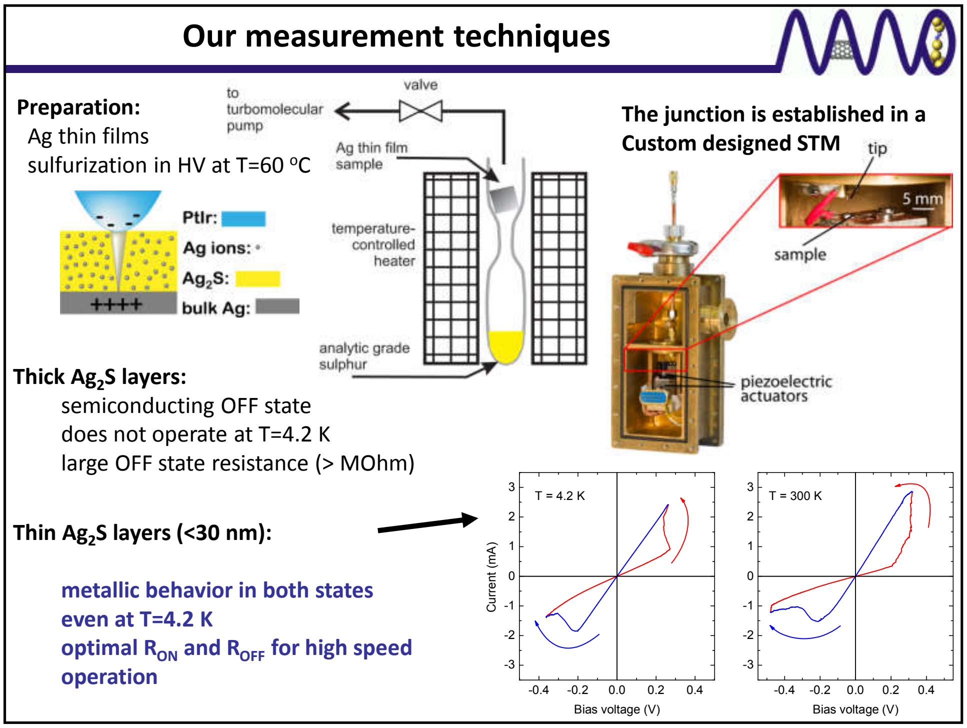
Data created worldwide: >10^{18} byte/day
alltogether: >10^{22} byte

Crossbar Resistive Memory:
The Future Technology for NAND Flash

FLASH memory performace

Characteristics	FLASH memory	Crossbar ReRAM
Technology Scalability	Performance degradation below 25nm	<5nm
Program Performance	7MB/sec	140MB/sec
Asynchronous (XIP) Read	.04MB/sec	17MB/sec
Program Energy/Cell	1360pJ/cell	64pJ/cell
Endurance	3K cycles	1E6
Retention	1-3 years	20yr

Further possibility: neuromorphic computing



Our measurement techniques

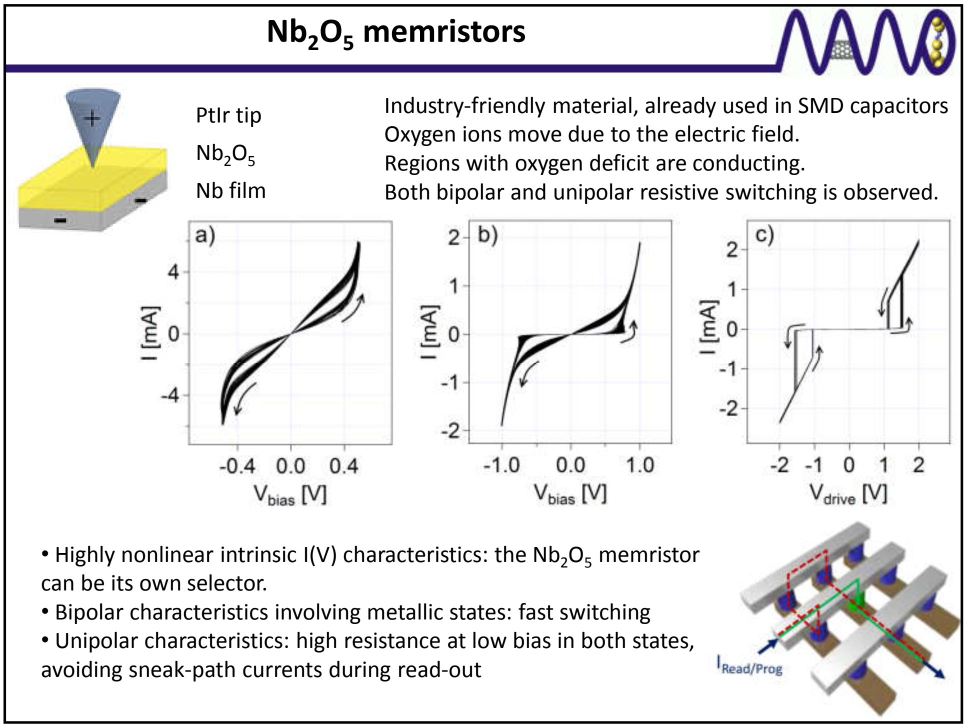
Preparation:
Ag thin films
sulfurization in HV at T=60 °C

The junction is established in a Custom designed STM

Thick Ag_2S layers:
semiconducting OFF state
does not operate at T=4.2 K
large OFF state resistance (> MOhm)

Thin Ag_2S layers (<30 nm):

metallic behavior in both states even at T=4.2 K
optimal R_{ON} and R_{OFF} for high speed operation

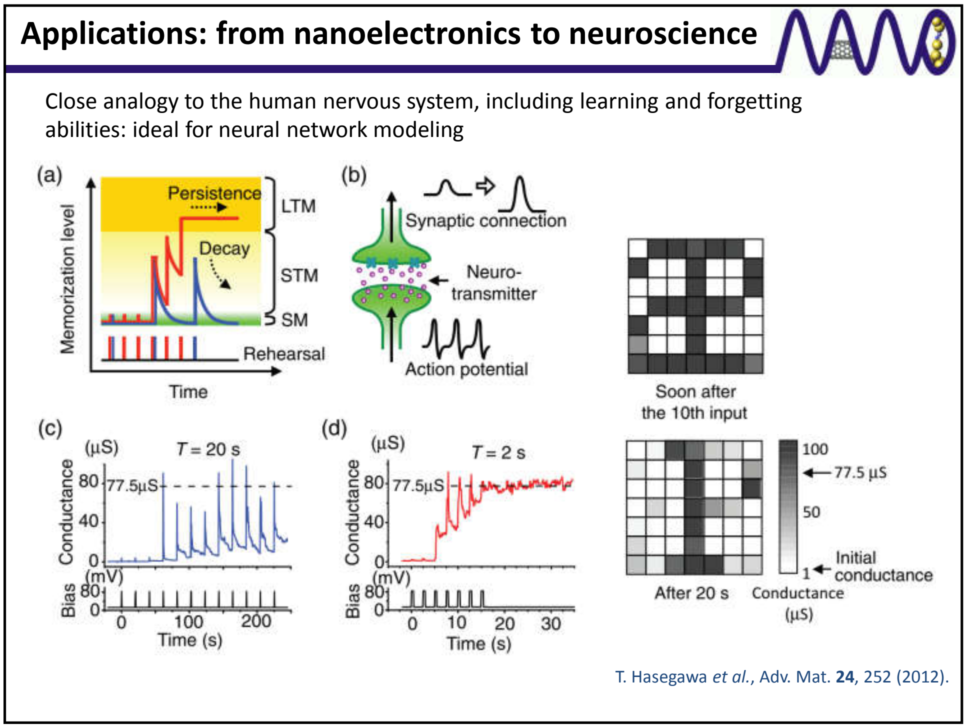


Nb_2O_5 memristors

PtIr tip
Nb_2O_5
Nb film

Industry-friendly material, already used in SMD capacitors
Oxygen ions move due to the electric field.
Regions with oxygen deficit are conducting.
Both bipolar and unipolar resistive switching is observed.

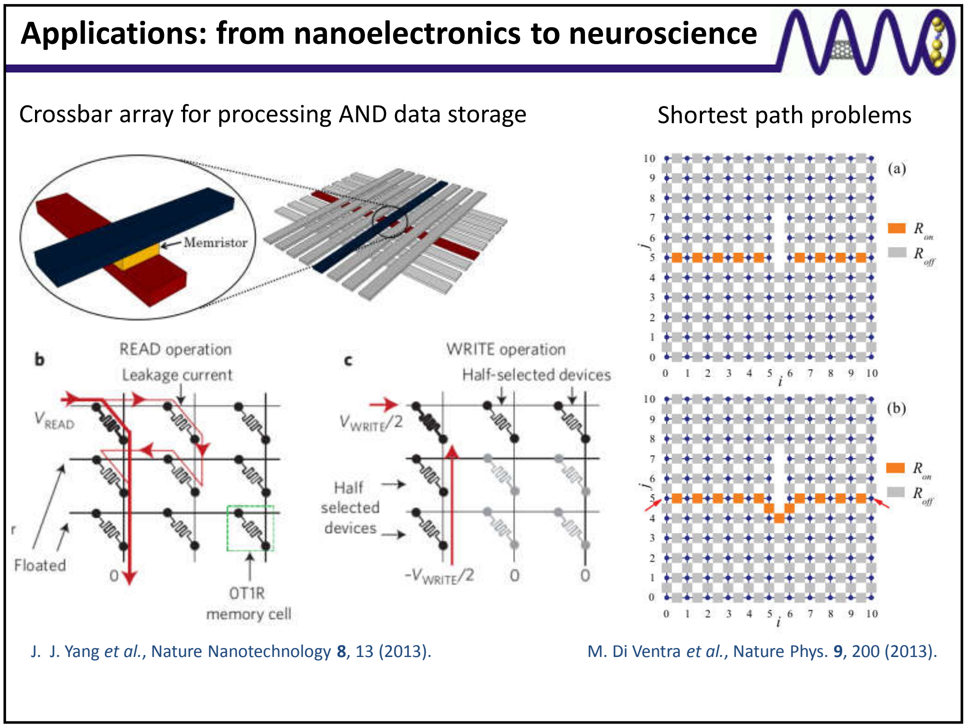
- Highly nonlinear intrinsic I(V) characteristics: the Nb_2O_5 memristor can be its own selector.
- Bipolar characteristics involving metallic states: fast switching
- Unipolar characteristics: high resistance at low bias in both states, avoiding sneak-path currents during read-out



Applications: from nanoelectronics to neuroscience

Close analogy to the human nervous system, including learning and forgetting abilities: ideal for neural network modeling

T. Hasegawa *et al.*, Adv. Mat. **24**, 252 (2012).



Applications: from nanoelectronics to neuroscience

Crossbar array for processing AND data storage

Shortest path problems

J. J. Yang *et al.*, Nature Nanotechnology **8**, 13 (2013).

M. Di Ventra *et al.*, Nature Phys. **9**, 200 (2013).