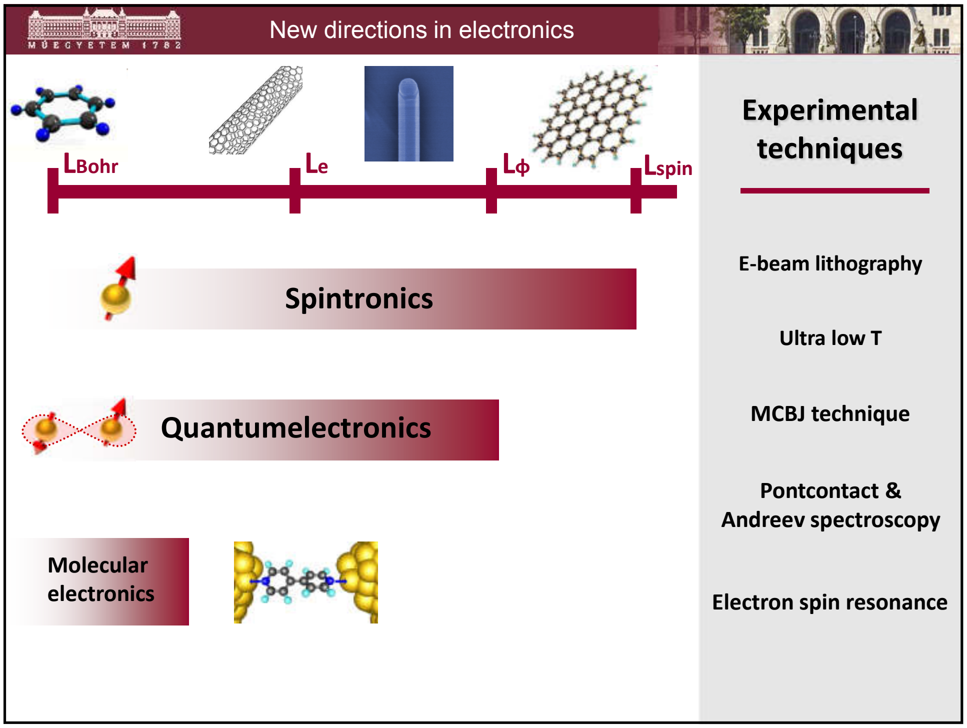


New directions in electronics

Spintronics

Quantumelectronics

Molecular electronics

Experimental techniques

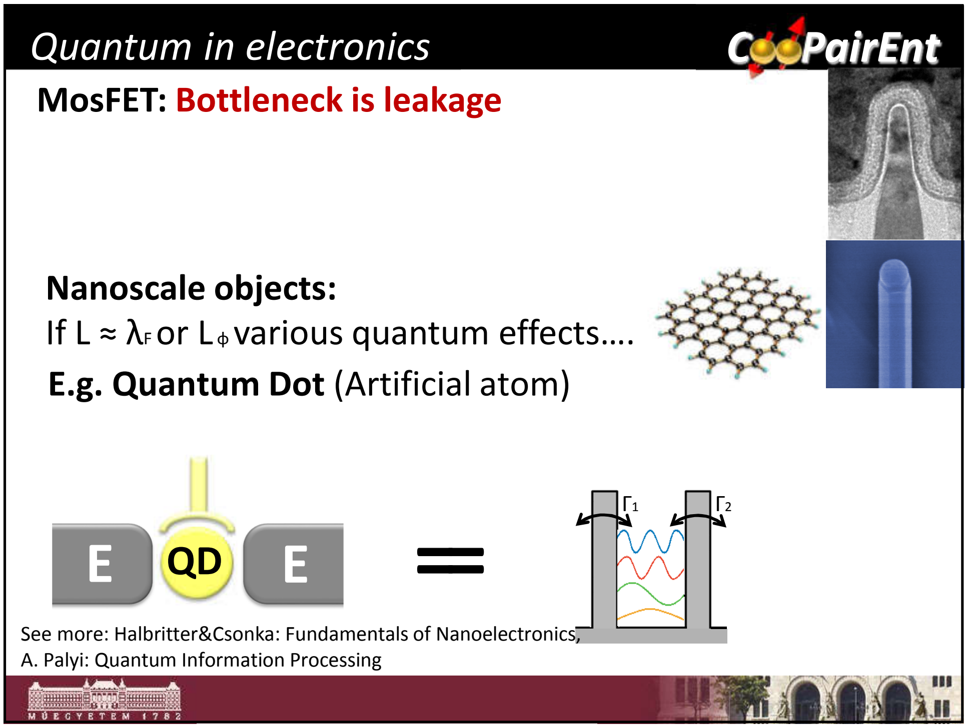
E-beam lithography

Ultra low T

MCBJ technique

Pontcontact & Andreev spectroscopy

Electron spin resonance



Quantum in electronics

MosFET: Bottleneck is leakage

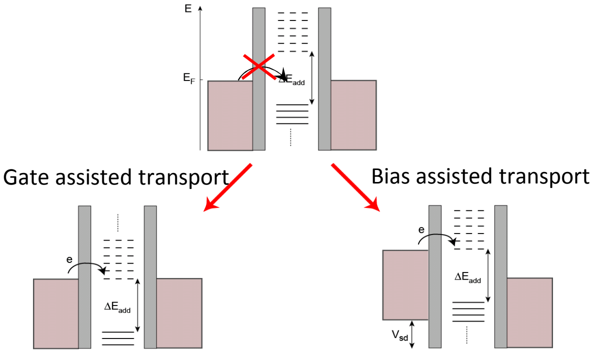
Nanoscale objects:

If L ≈ λ_F or L_ϕ various quantum effects….

E.g. Quantum Dot (Artificial atom)

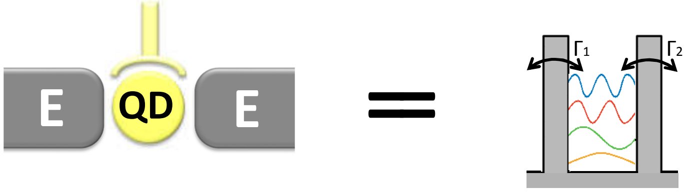
See more: Halbritter&Csonka: Fundamentals of Nanoelectronics,
A. Palyi: Quantum Information Processing

Quantum Dots



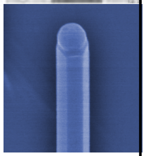
- discrete energy spectrum, ε_i
- Coulomb interaction, U_C
  → *Coulomb blockade*

- Gate electrode to shift energy levels, V_g
- Γ: coupling to electrodes



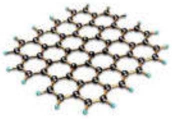
Quantumelectronics

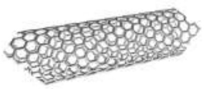
MosFET: Bottleneck is leakage



Nanoscale objects:

If L ≈ λ_F or L_ϕ various quantum effects….

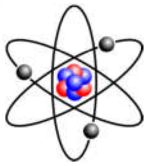


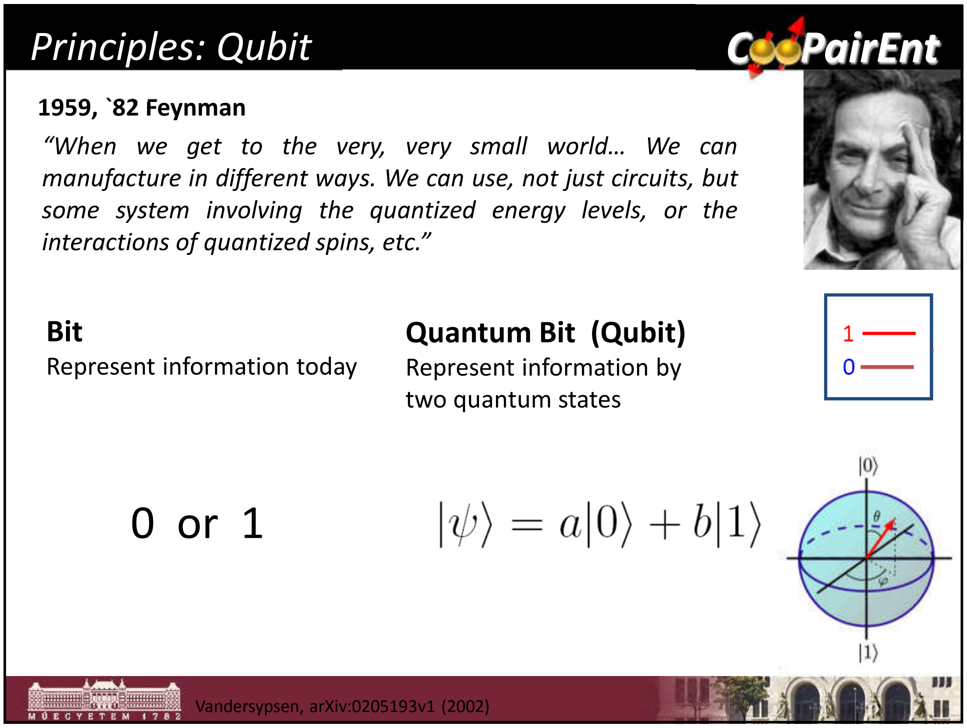


Quantum electronics:

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."

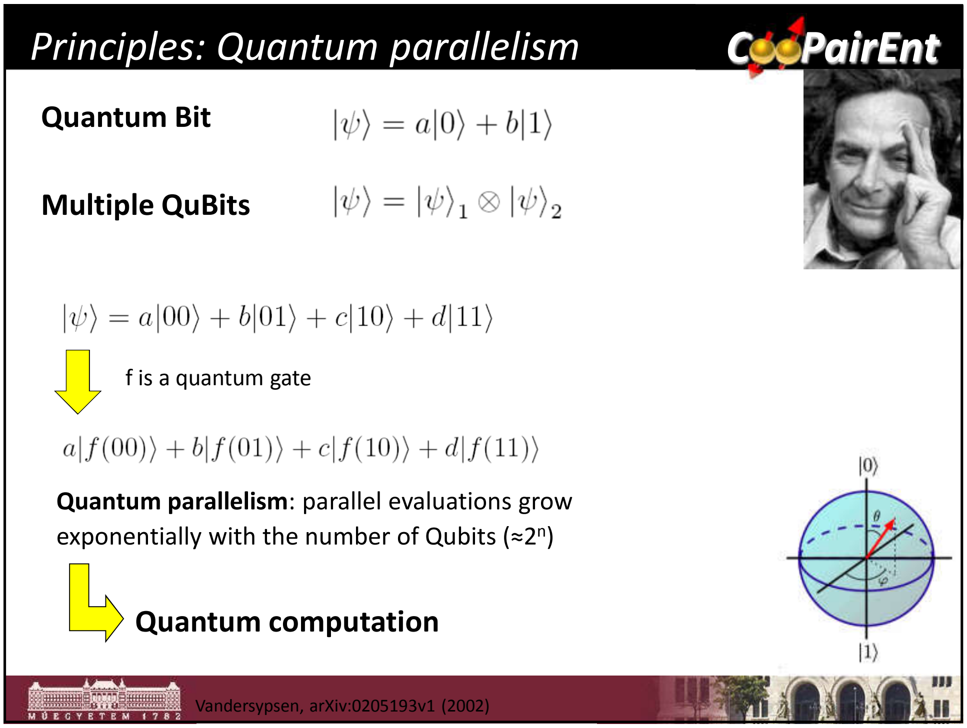
Bit
Represent information today

0 or 1

Quantum Bit (Qubit)
Represent information by two quantum states

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

Vandersypsen, arXiv:0205193v1 (2002)



Principles: Quantum parallelism

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

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

$$|\psi\rangle = a|00\rangle + b|01\rangle + c|10\rangle + d|11\rangle$$

f is a quantum gate

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

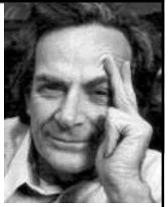
Quantum parallelism: parallel evaluations grow exponentially with the number of Qubits (≈2^n)

Quantum computation

Vandersypsen, arXiv:0205193v1 (2002)

Principles: Nonlocality, entanglement

CooPairEnt



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)

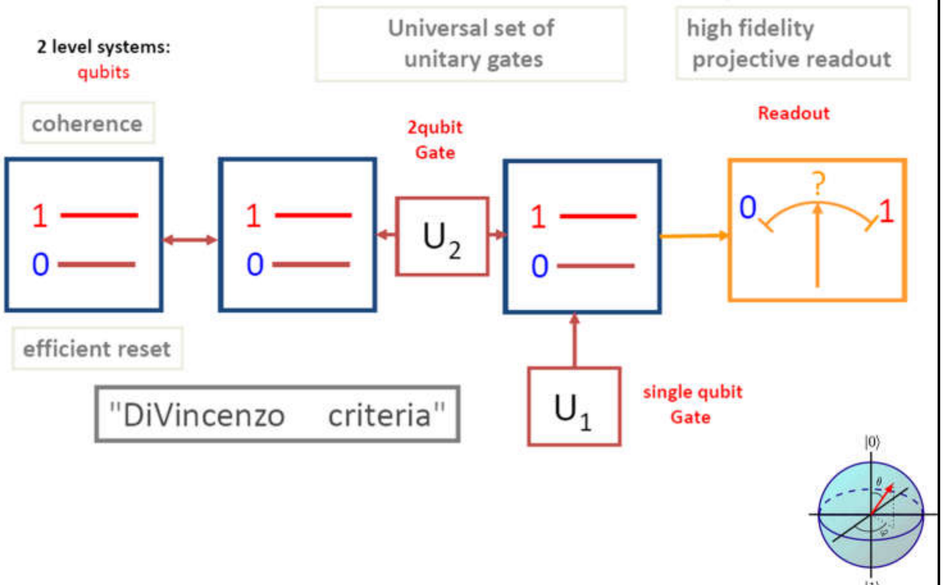
Nonlocality: manipulation of QBit1 has consequence on QBit2

Quantum computation & communication

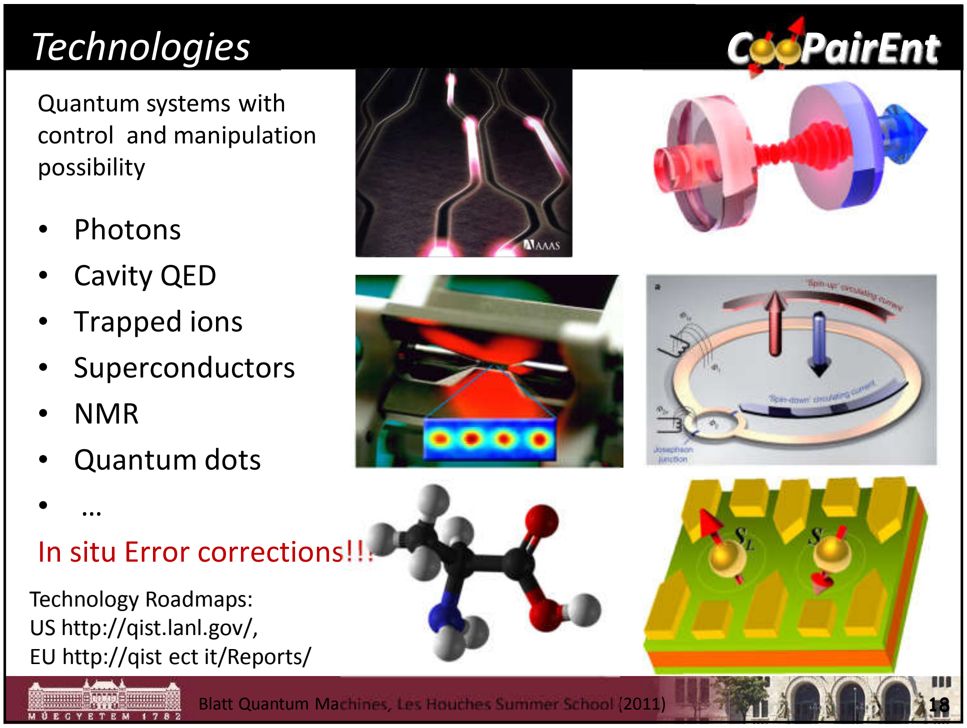
MŰEGYETEM 1782 Vandersypsen, arXiv:0205193v1 (2002)

Parts and Requirements of QC

CooPairEnt



MŰEGYETEM 1782 Esteve, Quantum Machines, Les Houches Summer School (2011)



Technologies

CooPairEnt

Quantum systems with control and manipulation possibility

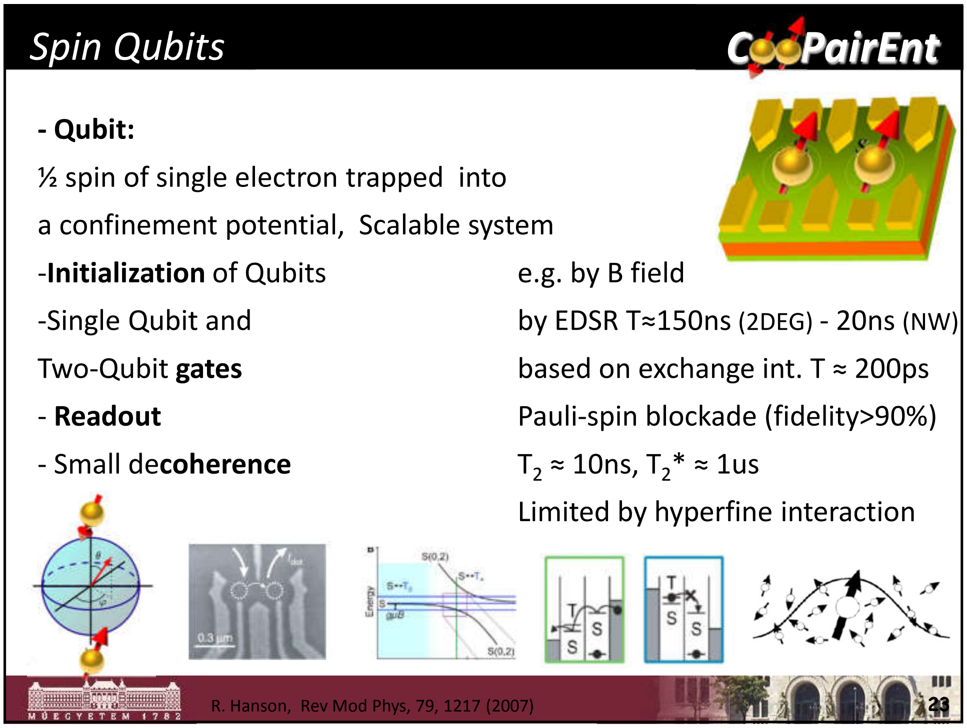
- Photons
- Cavity QED
- Trapped ions
- Superconductors
- NMR
- Quantum dots
- …

In situ Error corrections!!!

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

MŰEGYETEM 1782

Blatt Quantum Machines, Les Houches Summer School (2011)



Spin Qubits

CooPairEnt

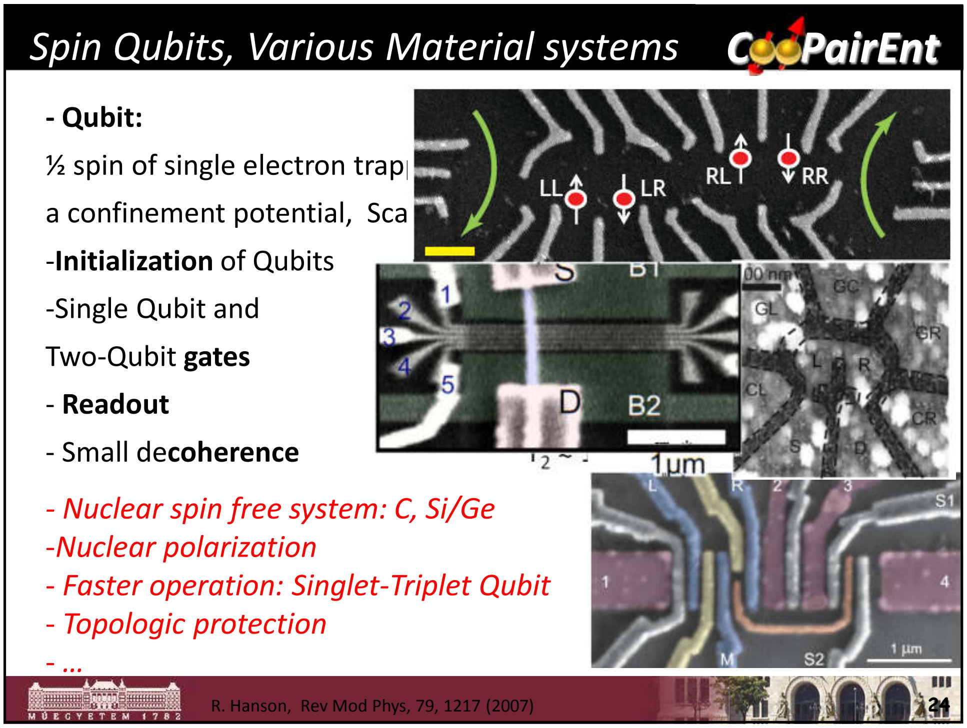
- Qubit:

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

MŰEGYETEM 1782

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



Spin Qubits, Various Material systems

- **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

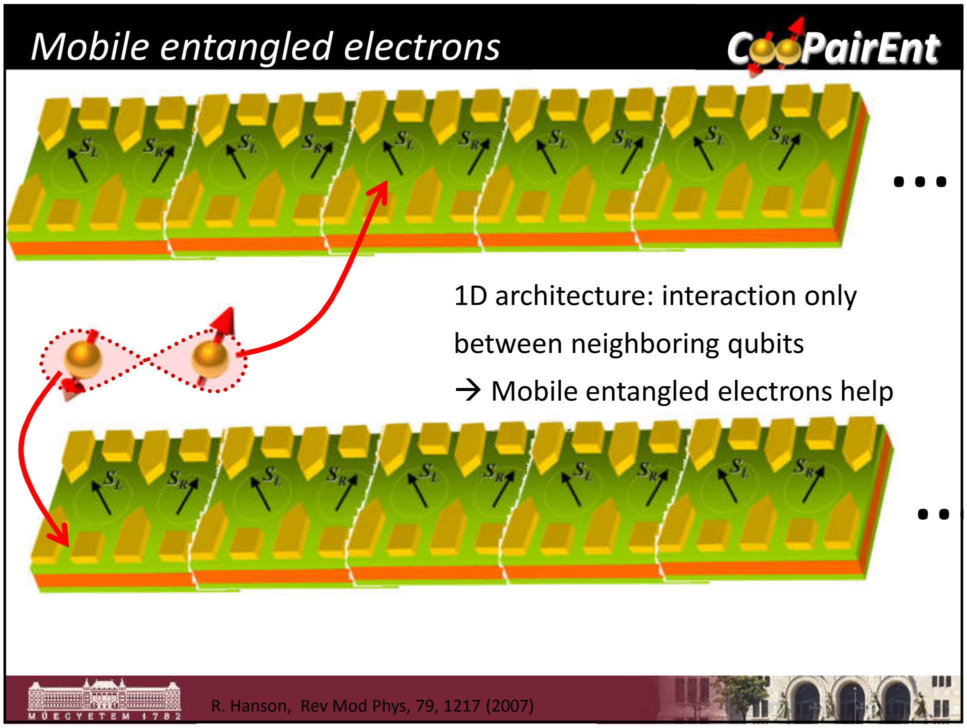
-Nuclear polarization

- Faster operation: Singlet-Triplet Qubit

- Topologic protection

- …

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

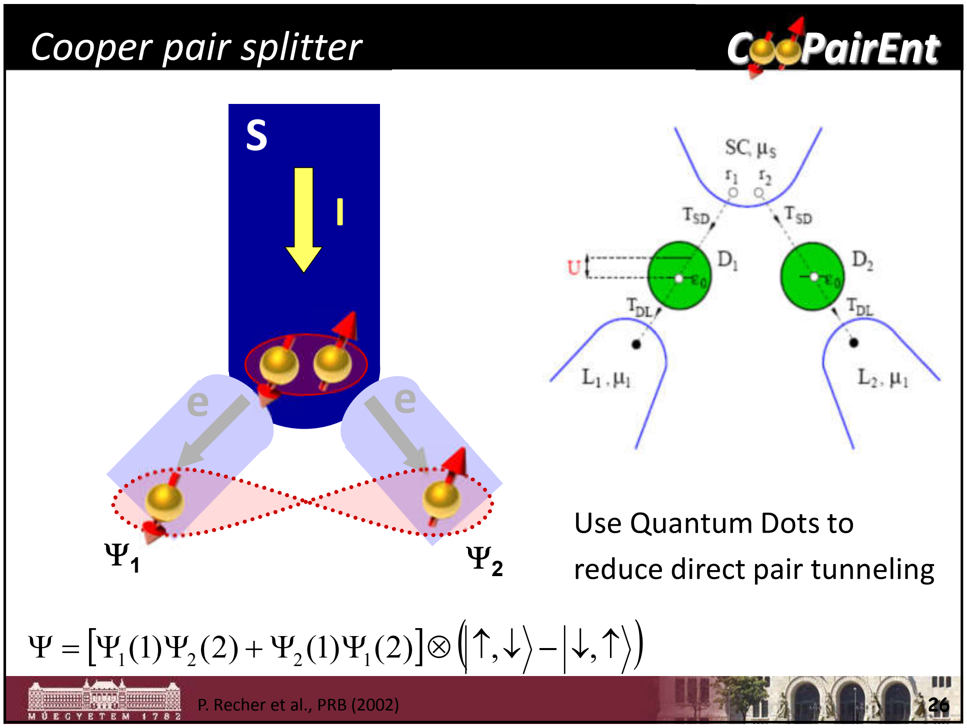


Mobile entangled electrons

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

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

P. Recher et al., PRB (2002)

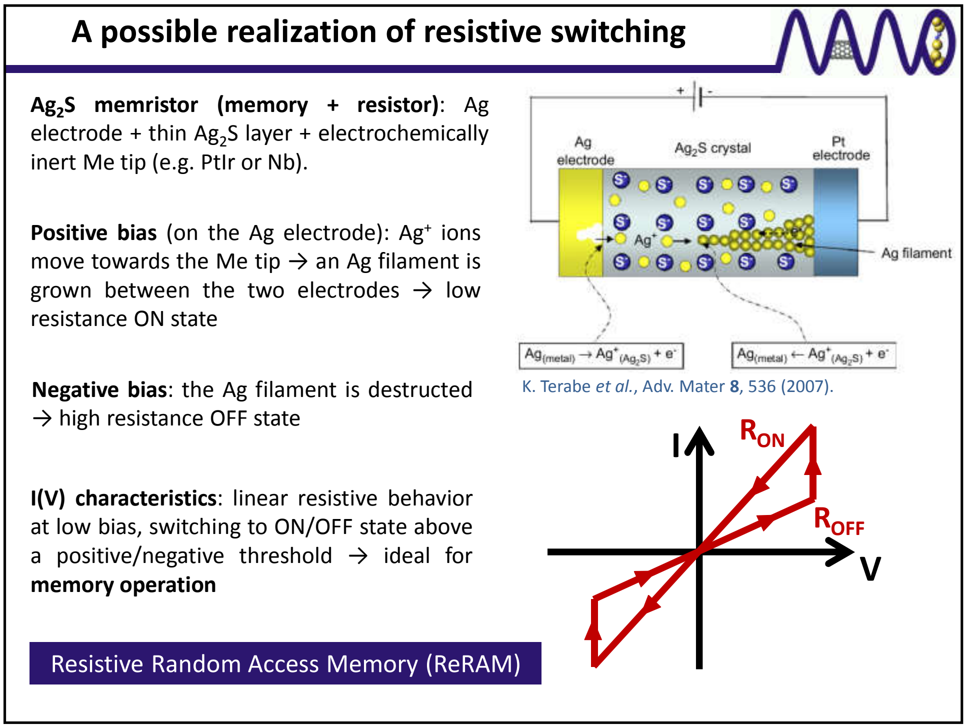
Atomic scale switches - Memristors

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).

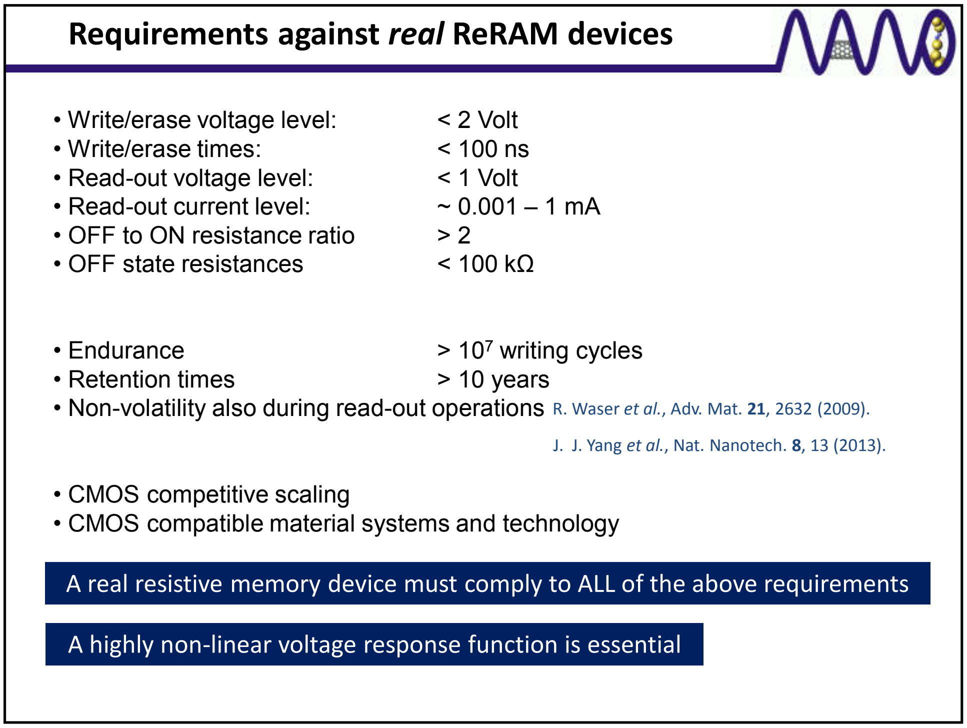
Positive bias (on the Ag electrode): Ag^+ ions move towards the Me tip → an Ag filament is grown between the two electrodes → low resistance ON state

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**

Resistive Random Access Memory (ReRAM)

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



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

Nb$_2$O$_5$ memristors

PtIr tip

Nb$_2$O$_5$

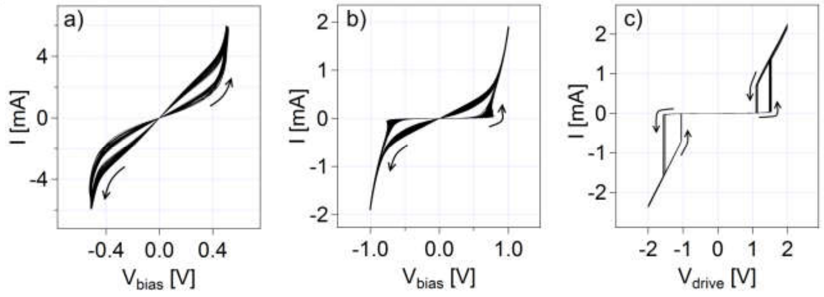
Nb film

Industry-friendly material, already used in SMD capacitors

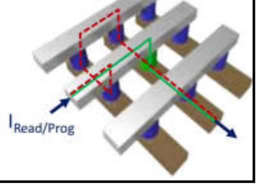
Oxygen ions move due to the electric field.

Regions with oxygen deficit are conducting.

Both bipolar and unipolar resistive switching is observed.

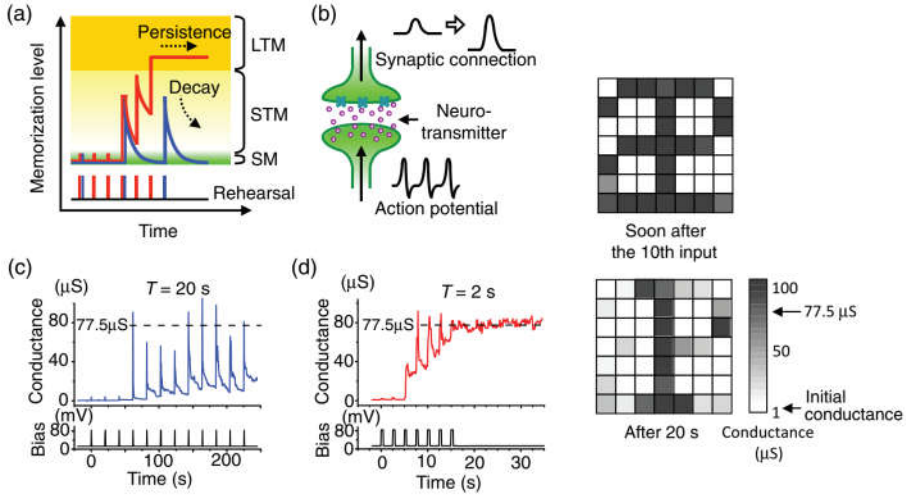


- Highly nonlinear intrinsic I(V) characteristics: the Nb$_2$O$_5$ memristor can be its own selector.
- Bipolar characteristics involving metallic states: fast switching
- Unipolar characteristics: high resistance at low bias in both states, avoiding sneak-path currents during read-out



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).

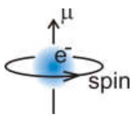
Short intro to Spintronics

Outline:
- Motivation of a spin based electronics
- GMR
- Spin injection and detection
- Spin transfer torque
- Spin Hall effect

See more:
Halbritter & Csonka: Fundamentals of Nanoelectronics

Motivation

Spin: intrinsic degree of freedom



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

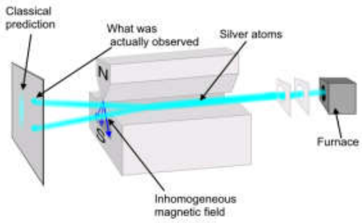
Early studies: Dirac equation → series expansion in the nonrelativistic limit

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

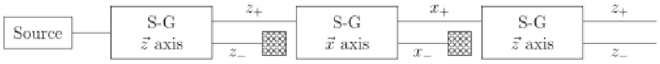
Spin-magnetic field interaction

Spin-orbit interaction

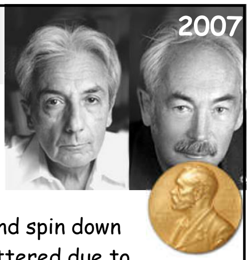
Stern-Gerlach experiment



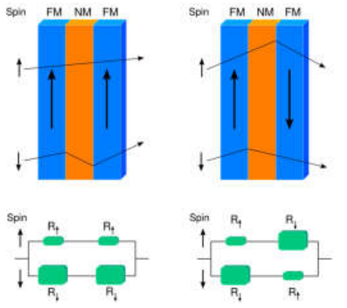
The true quantummechanical nature of the electronspin is demonstrated.



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

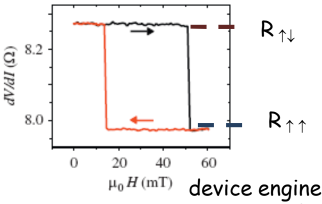
role of the nonmagnetic spacer: no direct exchange between FM layers

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



Direct electrical measurement of the magnetic state!

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

A. Fert, P. Grünberg

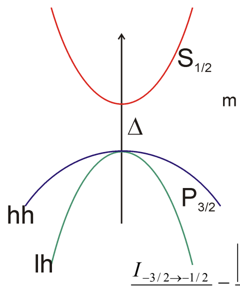
J. F. Gregg, et al, J. Phys. D 35, 121 (2002)

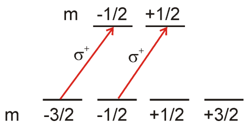
Spin injection and detection

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

Optical pumping/orientation (semiconductors)

incident circularly polarized light





due to selection rules the intensity ratio is:

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

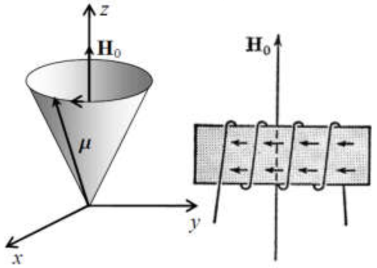
max. value

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

See more: T. Feher: Group theory,
S. Bordacs Optical spectroscopy

Electron spin resonance:

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



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

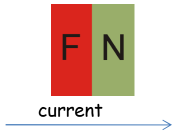
usually H is swept as the microwave lines are tuned to a specific frequency

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

See more: T. Feher: Magnetic resonances

Spin injection and detection

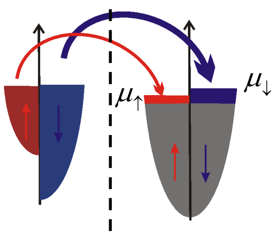
FM-NM interface

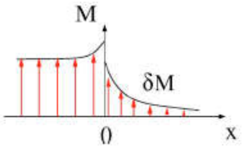


Proper handling is the Valet-Fert model, i. e. Boltzmann equation for two subbands

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

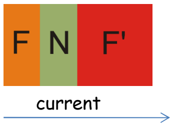
$\ell_s = \sqrt{D\tau_s}$ with $\tau_m \ll \tau_s$

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

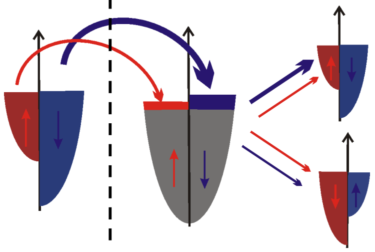
J. Bass and W. P. Pratt Jr, J. Phys.: Condens. Matter 19, 183201 (2007)

Spin injection and detection

Principle of GMR

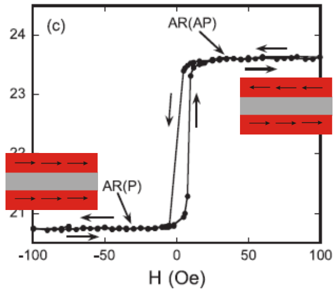


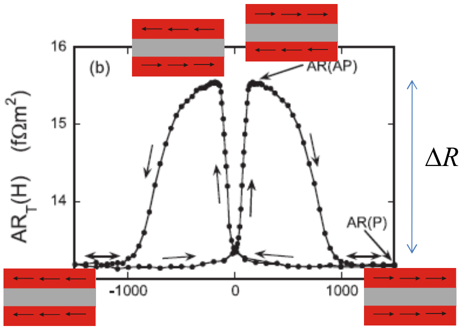
the F layers have different coercive fields (e.g. different layer thickness)



parallel: large current

antiparallel: suppressed current

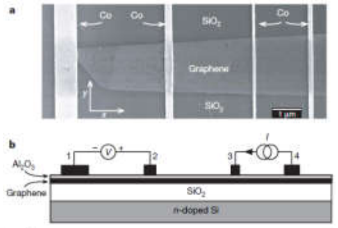


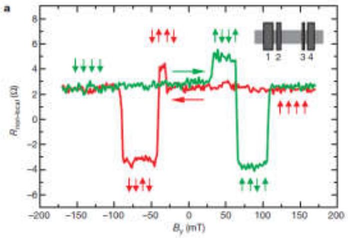


J. Bass and W. P. Pratt Jr, J. Phys.: Condens. Matter 19, 183201 (2007)

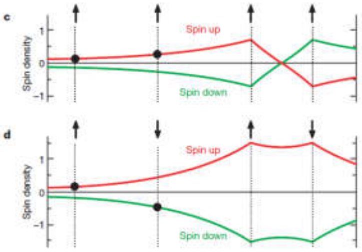
Spin injection and detection

Nonlocal measurements for graphene



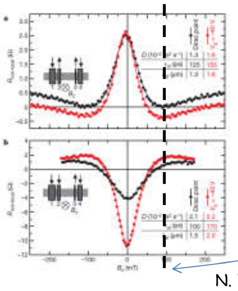


Recent measurements spin diffusion length ~ 10μm



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

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



in principle: oscillatory behavior

limitations: spin dephasing, diffusive transport

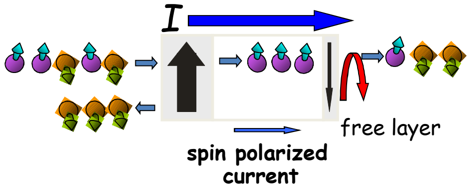
rotation of 180°

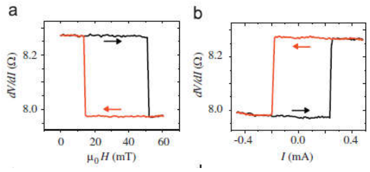
N. Tombros et al, Nature, 448, 571 (2007)

Spin Transfer Torque

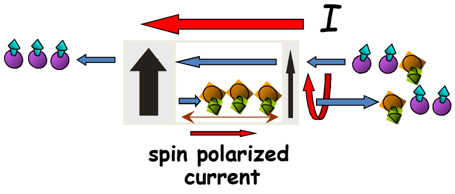
previously: versatile devices, but external magnetic field is necessary to alter spin states. All electric control would be better.

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

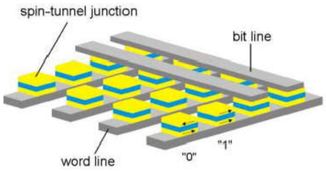




Potential application: memory cell



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

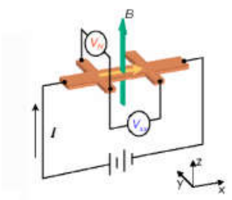


Current density: 10^9 A/cm^2
Only feasible in nano!

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

Spin Hall effect

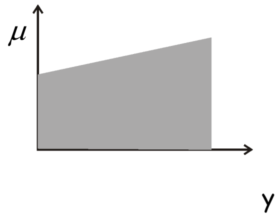
Ordinary Hall effect:



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

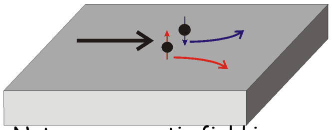
$$R_H = \frac{E_y}{j_x B_z} \quad \text{with} \quad R_H = -\frac{1}{ne}$$

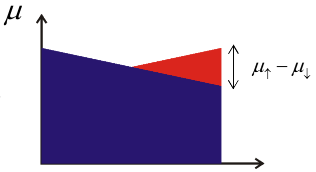
The result is a net electric field in the y direction



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

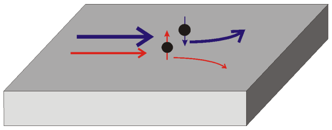
$$l_m < L_y << l_S$$

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

Spin Hall effect

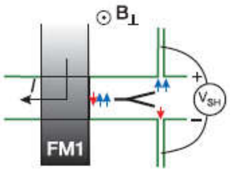
How to measure it?

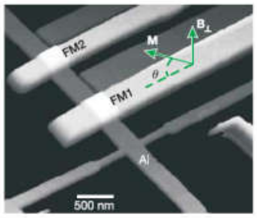
Idea: if the incident current is already spin polarized, then a measureable voltage develops



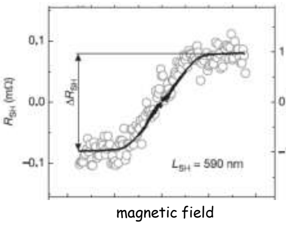
Out-of-plane magnetic field is necessary to have such magnetization to generate a signal

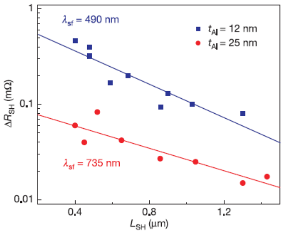
In actual nonlocal experiments, there is no net current through the device, however, the spin imbalance develops

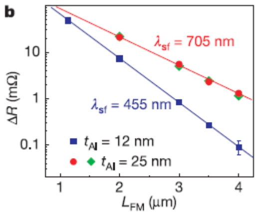




the device is characterized using FM2 in a standard nonlocal measurement







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

Literature

Prepared by A. Geresdi

Basics:
I. Zutic, J. Fabian and S. Das Darma, Rev. Mod. Phys, 76, 323 (2004)
J. F. Gregg, I. Petej, E. Jouguelet and C. Dennis, J. Phys. D 35, 121 (2002)
M. N. Baibich, J. M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, Phys. Rev. Letters, 61, 2472 (1988)
Cserti József,Természet Világa 2005/9. 386
Wikipedia
ESR:
Fehér Titusz, ESR mérésleírás (2010)
Dario Quintavalle, PhD thesis (2008)
GMR in CPP geometry, spin diffusion length:
J. Bass and W. P. Pratt Jr, J. Phys.: Condens. Matter 19, 183201 (2007)
H. Kurt, R. Loloee, K. Eid, W. P. Pratt, Jr., and J. Bassa, Appl. Phys. Letters, 81, 4787 (2002)
A. Jensen, J. R. Hauptmann, J. Nygård, and P. E. Lindelof, Phys. Rev. B, 72, 035419 2005
Spin relaxation models:
J. Fabian and S. Das Darma, J. Vac. Sci. Technol. B, 17, 1708 (1999)
J. Fabian and S. Das Darma, J. Appl. Phys, 85, 5075 (1999)
J. Fabian and S. Das Darma, Phys. Rev. Letters, 83, 1211 (1999)
M. Gradhand, M. Czerner, D. V. Fedorov, P. Zahn, B. Yu. Yavorsky, L. Szunyogh, and I. Mertig, Phys. Rev. B, 80, 224413 (2009)
Nonlocal measurements:
F. J. Jedema, A. T. Filip and B. J. van Wees, Nature, 410, 345 (2001)
N. Tombros, Cs. Jozsa, M. Popinciuc, H. T. Jonkman and B. J. van Wees, Nature, 448, 571 (2007)
Semiconductor spintronics:
H. J. Zhu, M. Ramsteiner, H. Kostial, M. Wassermeier, H.-P. Schönherr, and K. H. Ploog, Phys. Rev. Letters, 87, 016601 (2001)
Y. Ohno, D. K. Young, B. Beschoten, F. Matsukura, H. Ohno and D. D. Awschalom, Nature, 402, 790 (1999)
X. J.Wang, I. A. Buyanova, F. Zhao, D. Lagarde, A. Balocchi, X. Marie, C.W. Tu, J. C. Harmand and W. M. Chen, Nature Materials, 8, 178 (2009)

Literature

Spin transfer torque:
D. C. Ralph and M. D. Stiles, J. of Magn. Mag. Mater. 320, 1190 (2007)
M. Covington, M. AlHajDarwish, Y. Ding, N. J. Gokemeijer, and M. A. Seigler, Phys. Rev. B, 69, 184406 (2004)
Y. Huai, AAPS Bulletin, 18, 33 (2008)
S. Kaka, M. R. Pufall, W. H. Rippard, T. J. Silva, S. E. Russek and J. A. Katine, Nature, 437, 389 (2005)
Spin Hall effect:
J. E. Hirsch, Phys. Rev. Letters, 83, 1834 (1999)
S. O. Valenzuela and M. Tinkham, Nature, 442, 176 (2006)
H. Kontani, T. Tanaka, D. S. Hirashima, K. Yamada and J. Inoue, Phys. Rev. Letters, 102, 016601 (2009)
AFM based TMR:
A. Scholl, M. Liberati, E. Arenholz, H. Ohldag, and J. Stohr, Phys. Rev. Letters, 92, 274201 (2004)
B. G. Park, J.Wunderlich, X. Martí, V. Holý, Y. Kurosaki, M. Yamada, H. Yamamoto, A. Nishide, J. Hayakawa, H. Takahashi, A. B. Shick and T. Jungwirth, Nature Materials, 10, 347 (2011)
R. Duine, Nature Materials News and Views, 10, 344 (2011)