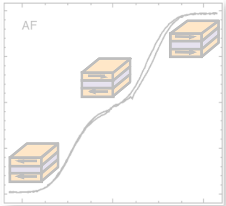
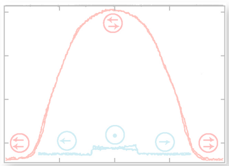
Overview

Introduction

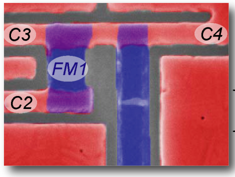


Interlayer exchange coupling

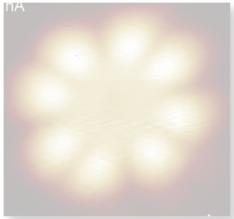


Giant and tunneling magnetoresistance

Current-induced magnetization dynamics



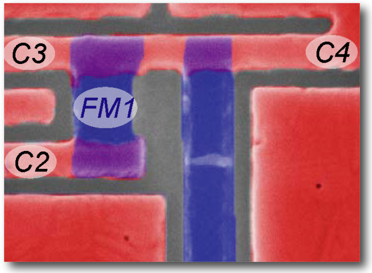
Pure spin current



Magnetic molecules

Conclusions

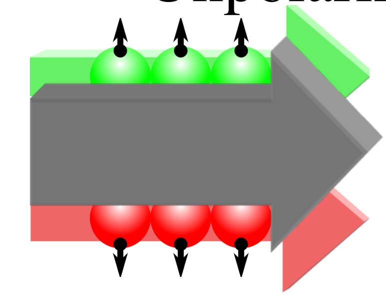
Outline: Pure spin current



- What is a pure spin current?
- Generation and detection of pure spin currents in lateral spin-valves (LSV)
- Example: In-situ FIB fabrication of LSV
- Pure spin current induced magnetization switching

Pure spin currents

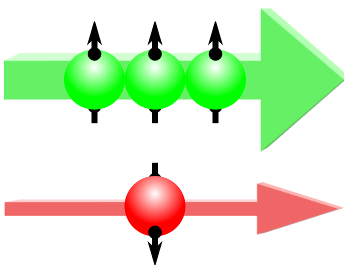
Unpolarized current:



$$\frac{dQ}{dt} \neq 0$$

$$\frac{d\vec{s}}{dt} = 0$$

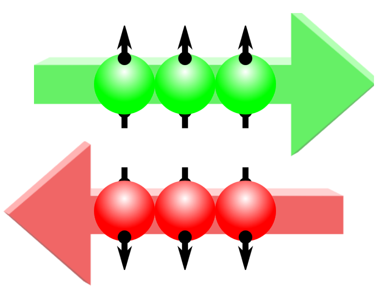
Spin-polarized current:



$$\frac{dQ}{dt} \neq 0$$

$$\frac{d\vec{s}}{dt} \neq 0$$

Pure spin current:



$$\frac{dQ}{dt} = 0$$

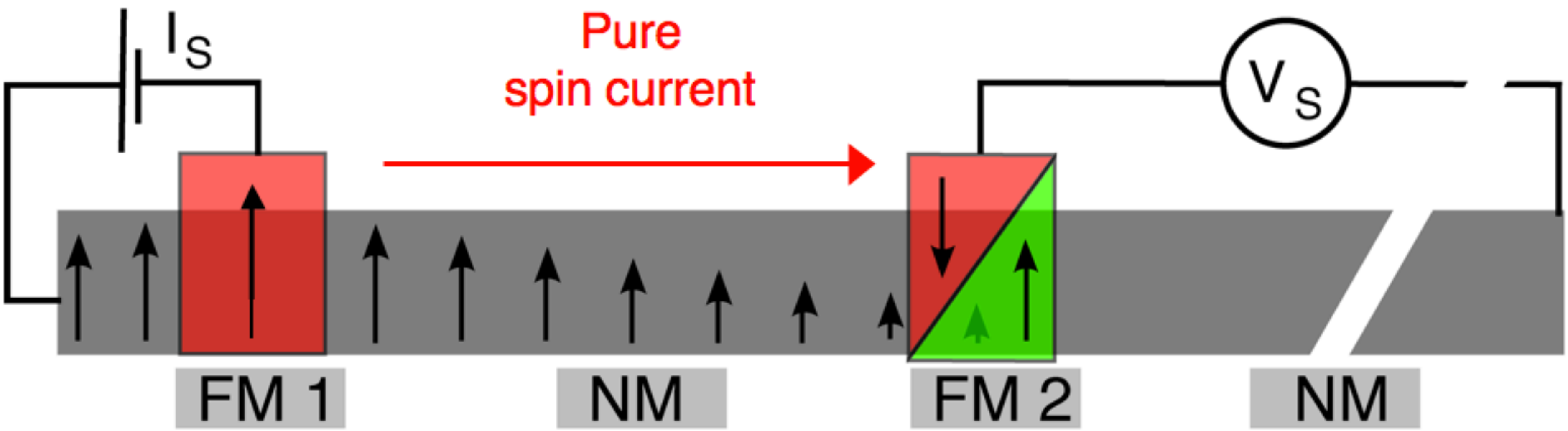
$$\frac{d\vec{s}}{dt} \neq 0$$

- transport spin momentum
- without (net) charge motion
- do not give rise to Oersted fields
- do not create resistive voltage drops
- do not produce Joule heating

$\Rightarrow$ Potential to significantly reduce power dissipation of (spin-)electronic devices

Generation and detection of pure spin currents

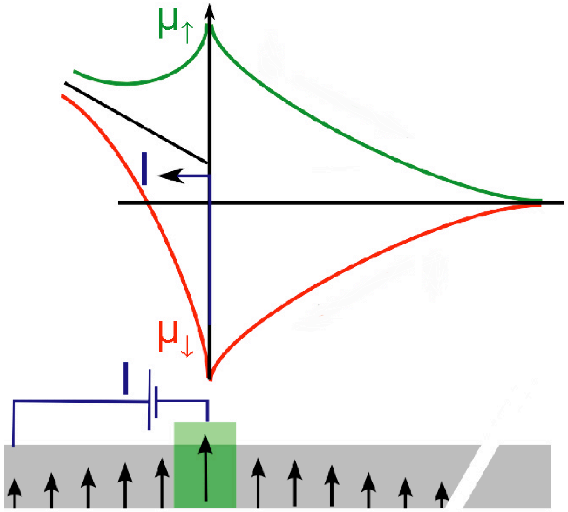
Non-local transport measurement in a "lateral spin valve"



M. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55,** 1790 (1985); F. J. Jedema *et al*., Nature **410**, 345 (2001)
Y. Ji *et al*., Appl. Phys. Lett. **85**, 6218 (2004); T. Yang *et al*., Nat. Phys. **4**, 851 (2008)

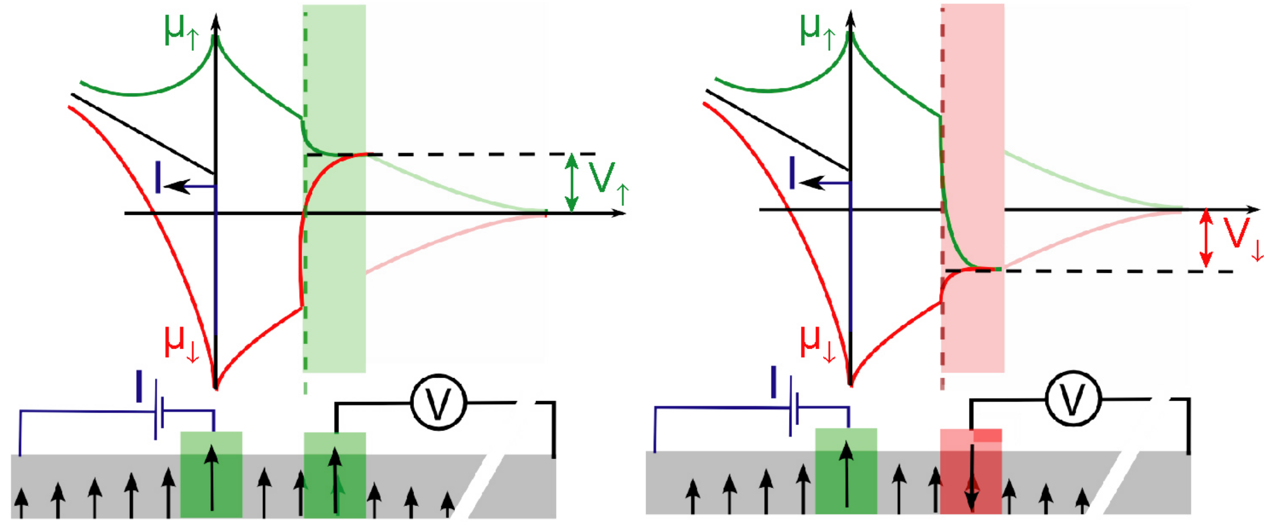
Pure spin currents in lateral spin-valves (LSV)

Generation:



Spin accumulation at FM/NM interface
⇒ splitting of chemical potential $\mu_{\uparrow,\downarrow}$
⇒ diffusion of spins due to $\nabla\mu_{\uparrow,\downarrow}$

Detection:



Detection of spin accumulation with a FM probe located within the spin diffusion length:

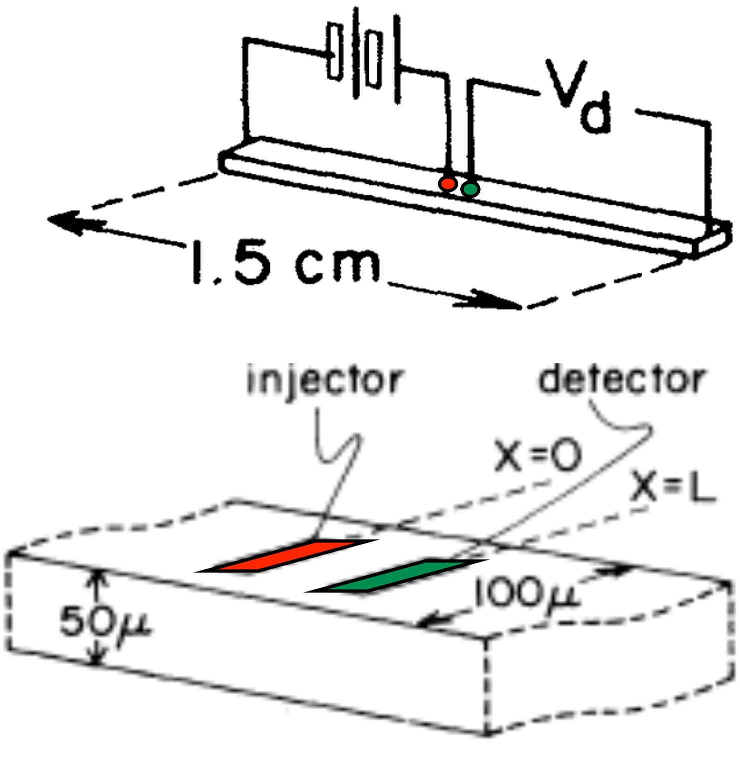
Parallel alignment:
⇒ Probe potential adjusts to $\mu_{\uparrow}$

Antiparallel alignment:
⇒ Probe potential adjusts to $\mu_{\downarrow}$

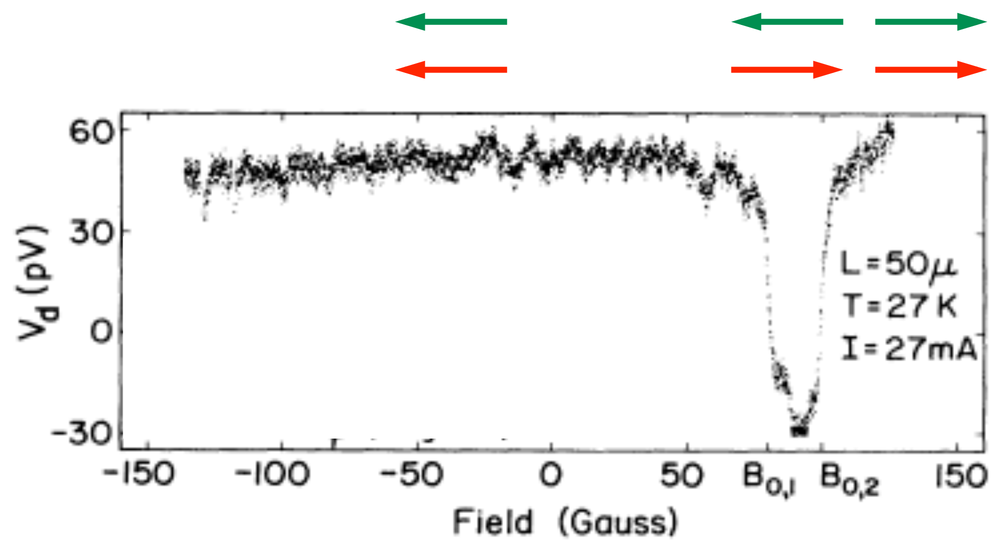
F. Casanova *et al.*; Phys. Rev. B **79,** 184415 (2009)

First observation of pure spin currents

M. Johnson and R. H. Silsbee, Phys. Rev. Lett. **55,** 1790 (1985)

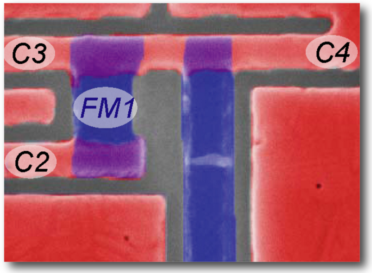


- Pure Al bulk material
- Permalloy injector and detector



F. J. Jedema *et al*., Nature **410**, 345 (2001);
Y. Ji *et al*., Appl. Phys. Lett. **85**, 6218 (2004); F. Casanova *et al*.; Phys. Rev. B **79,** 184415 (2009)

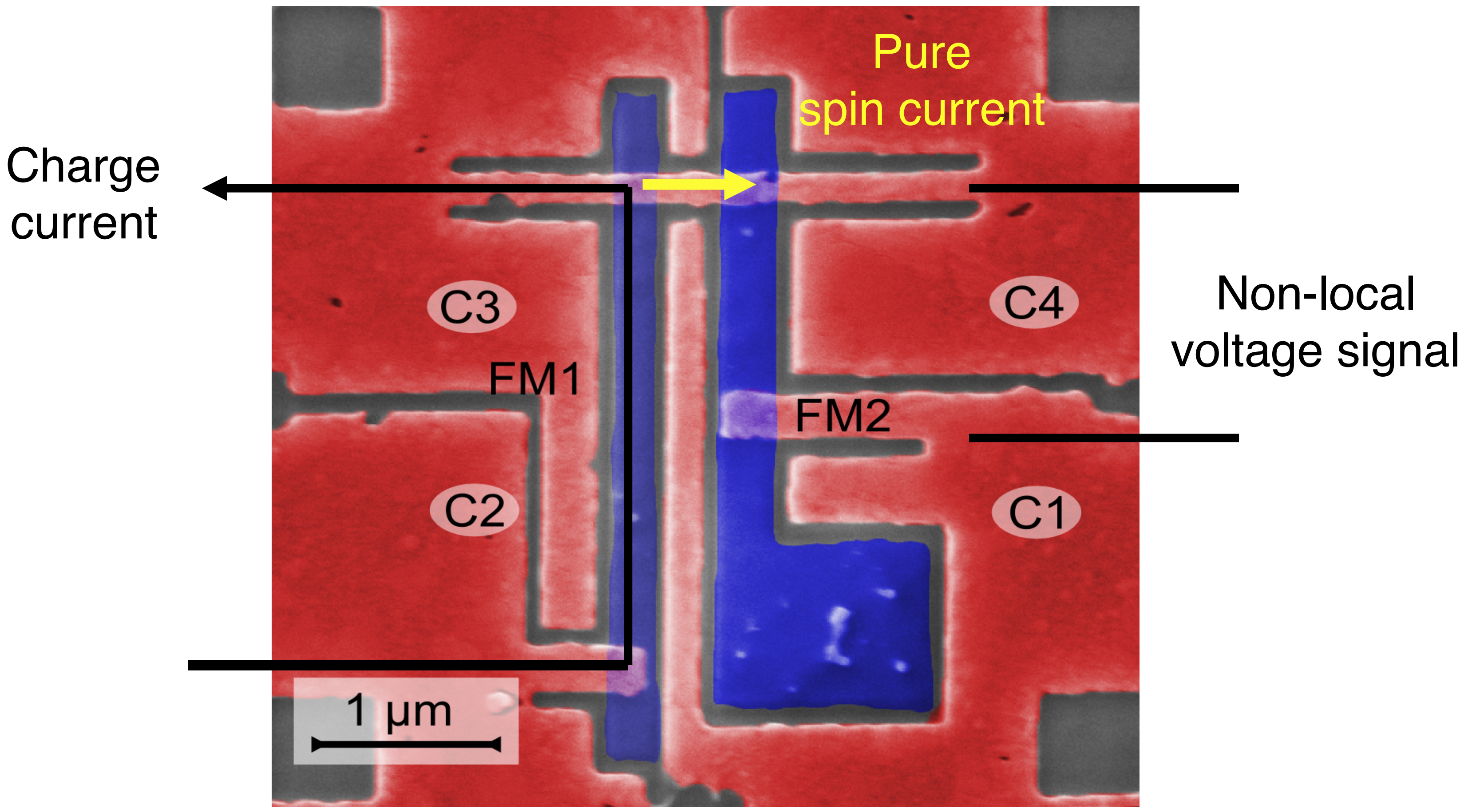
Outline: Pure spin current



- What is a pure spin current?
- Generation and detection of pure spin currents in lateral spin-valves (LSV)
- Example: In-situ FIB fabrication of LSV
- Pure spin current induced magnetization switching

In-situ focused ion-beam (FIB) fabrication of a LSV

In-situ SEM of lateral spin-valve with topmost FM layers

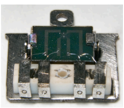


J. Mennig, D.E. Bürgler *et al*., J. Appl. Phys. **111**, 07C504 (2012)

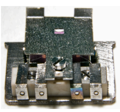
In-situ fabrication of lateral spin-valves

ex situ

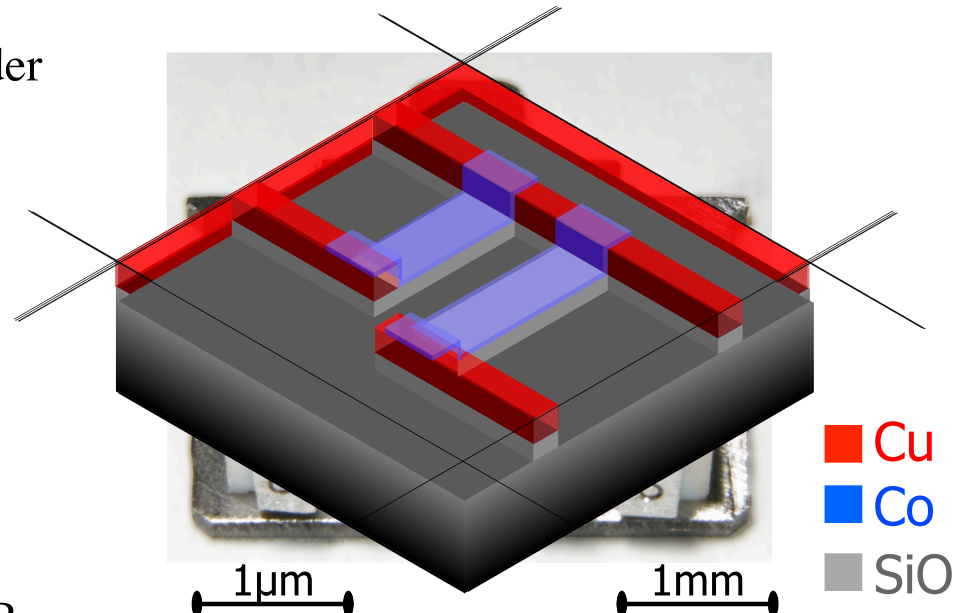
- 50 nm Cu contacts covered by 2 nm Au grown by MBE through shadow mask



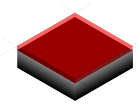
- Wire bonding to 4-probe sample holder



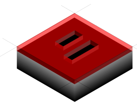
- Hole aperture to protect contact and contact pads



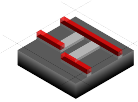
in situ



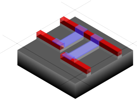
- Ar sputtering to remove Au cap layer



- Definition of magnet positions by FIB



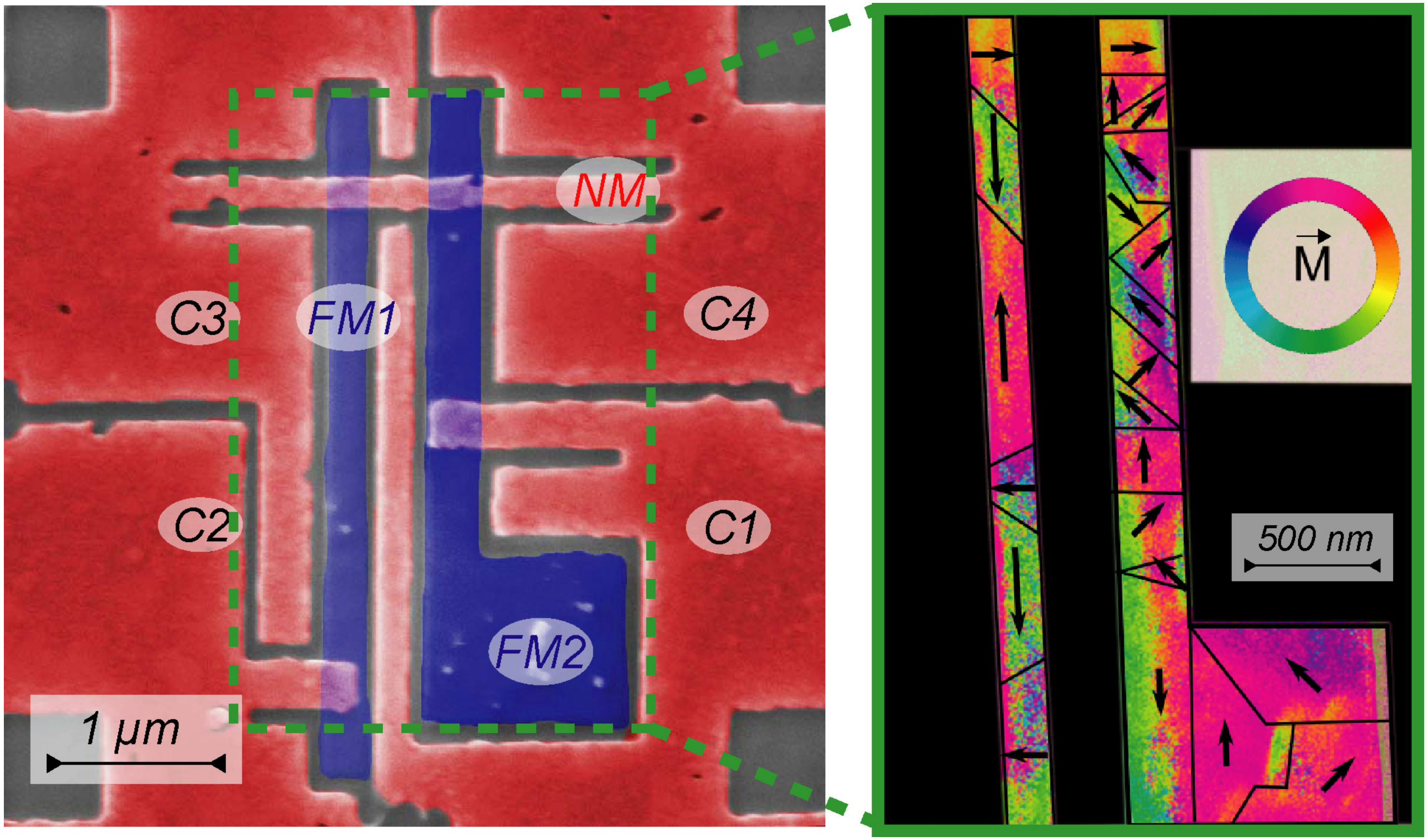
- FIB Structuring of the Cu (red) leads
  Deposition of Co (blue) layer by thermal evaporation



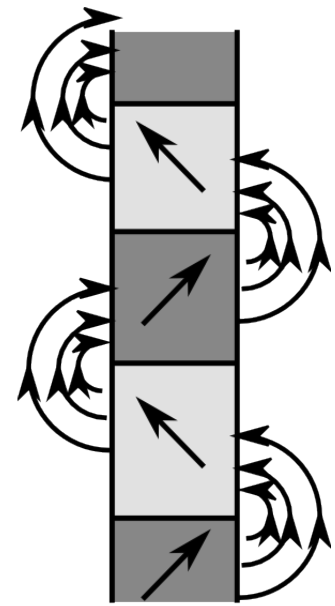
- Structuring of Co film to nanomagnets

SEM and SEMPA of an in-situ prepared LSV

Widths of FMs are 220 nm for FM1 and 280 nm for FM2



“Concertina” domain structure

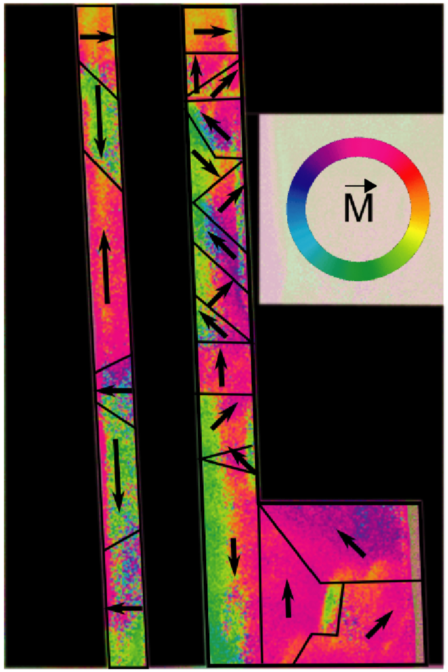


⇒ Both Co electrodes reveal a multi-domain state that clearly deviates from the single-domain behavior expected for the wire dimensions

J. Mennig, D.E. Bürgler *et al*., J. Appl. Phys. **111**, 07C504 (2012)

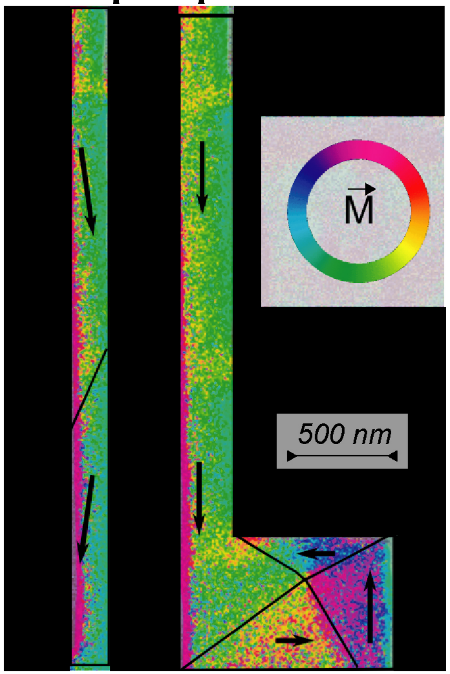
Reason for multi-domain formation

Narrow Co structures (220 and 280 nm) with different properties:



LSV with narrow FMs
Co on Cu after FIB
Growth at 170 K

Co on Cu after FIB
Growth at 270 K
⇒ Larger grains

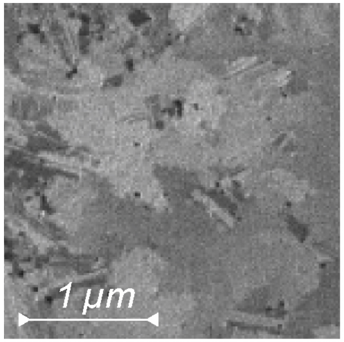


Co on Cu, no FIB
Growth at 170 K
⇒ Smoother Cu

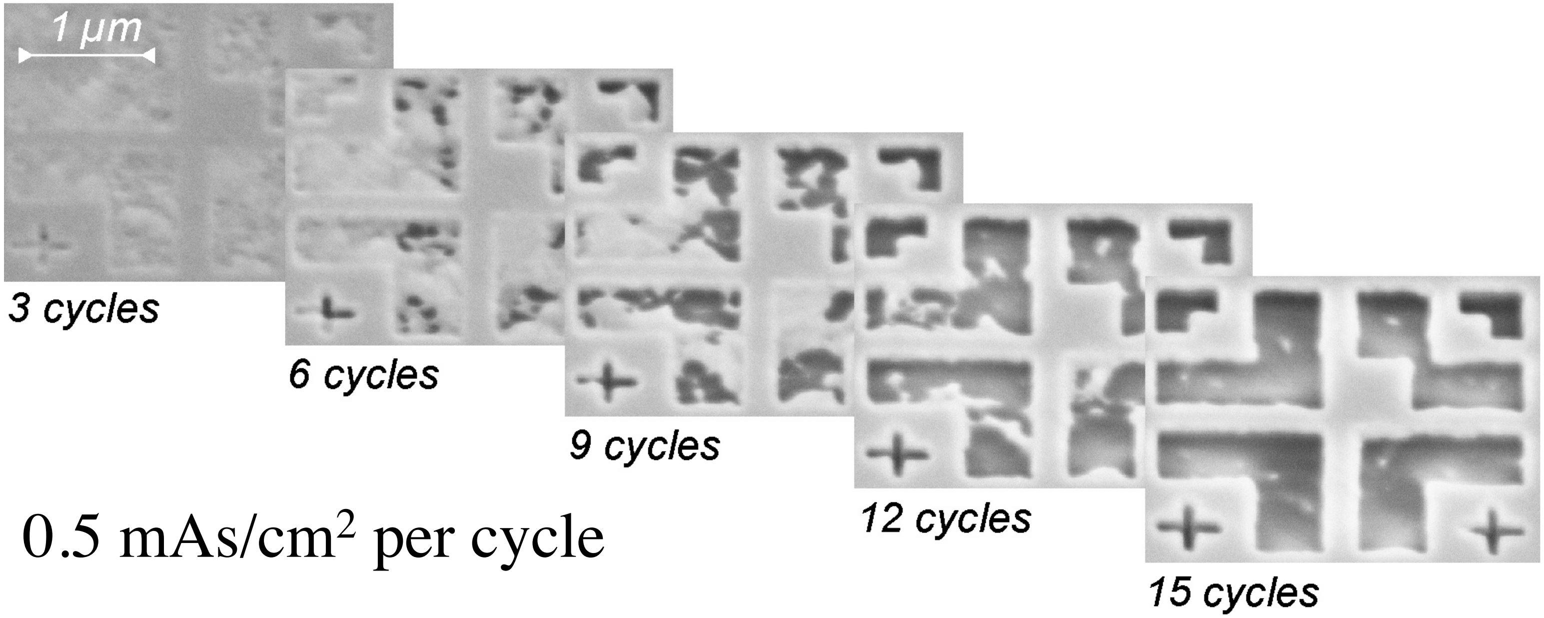
⇒ FIB-induced roughness of Cu substrate gives rise to formation of multi-domain state in the Co electrodes

J. Mennig, D.E. Bürgler *et al*., J. Appl. Phys. **111**, 07C504 (2012)

Origin of FIB-induced roughness



- Both Co and Cu films are polycrystalline due to the amorphous SiO_x substrate
- FIB sputter yield depends on orientation of crystallites via channeling and atomic layer densities



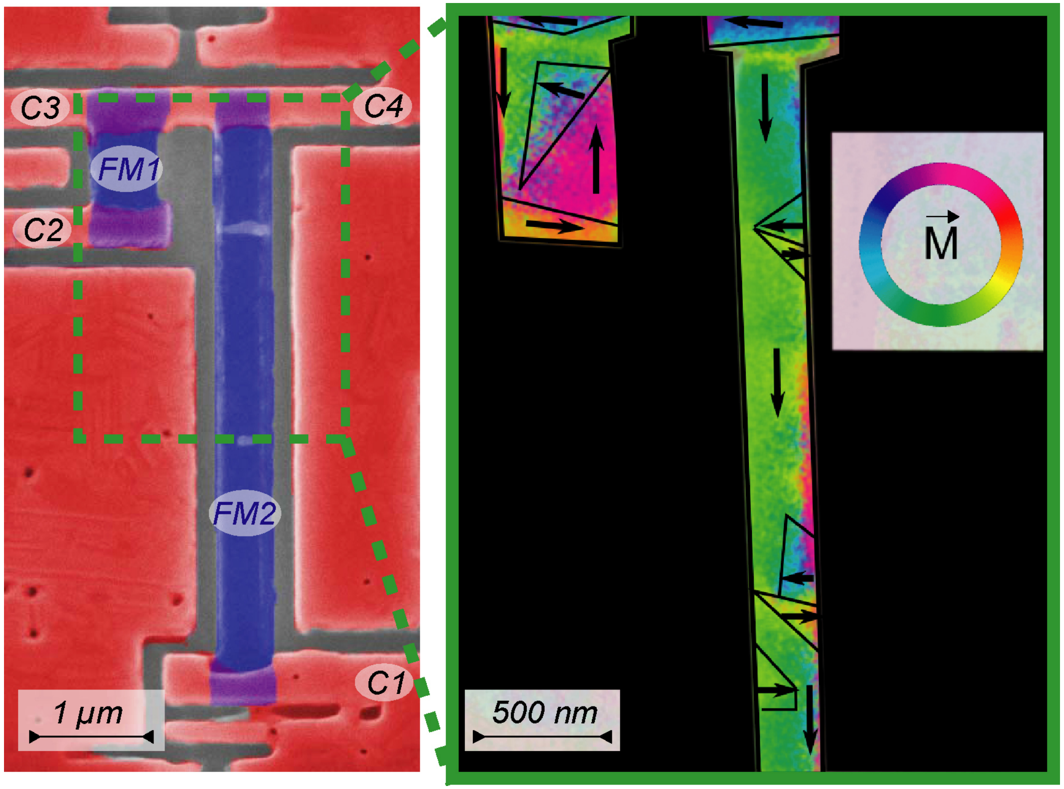
0.5 mAs/cm^2 per cycle

⇒ FIB-induced roughness with a typical lateral size of about 250 nm

J. Mennig, D.E. Bürgler *et al*., J. Appl. Phys. **111**, 07C504 (2012)

SEM and SEMPA of LSV with wide FMs

Width of FMs (480 nm for FM1 and 350 nm for FM2) is larger than the typical lateral size of the FIB-induced roughness

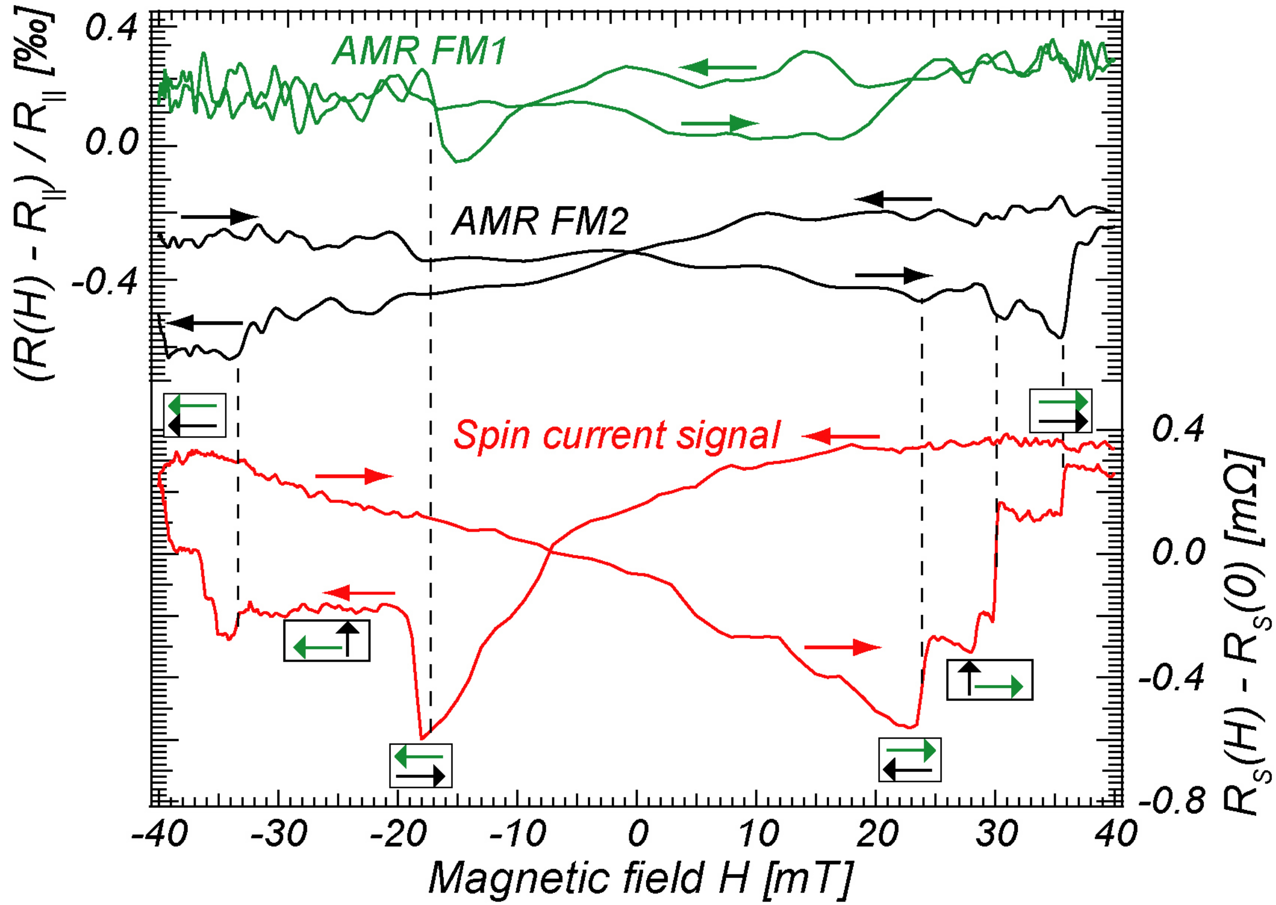


⇒ Landau-like magnetization pattern in the left Co element

⇒ Almost single-domain state in the right Co element

J. Mennig, D.E. Bürgler *et al*., J. Appl. Phys. **111**, 07C504 (2012)

AMR and spin signal of LSV with wide FMs



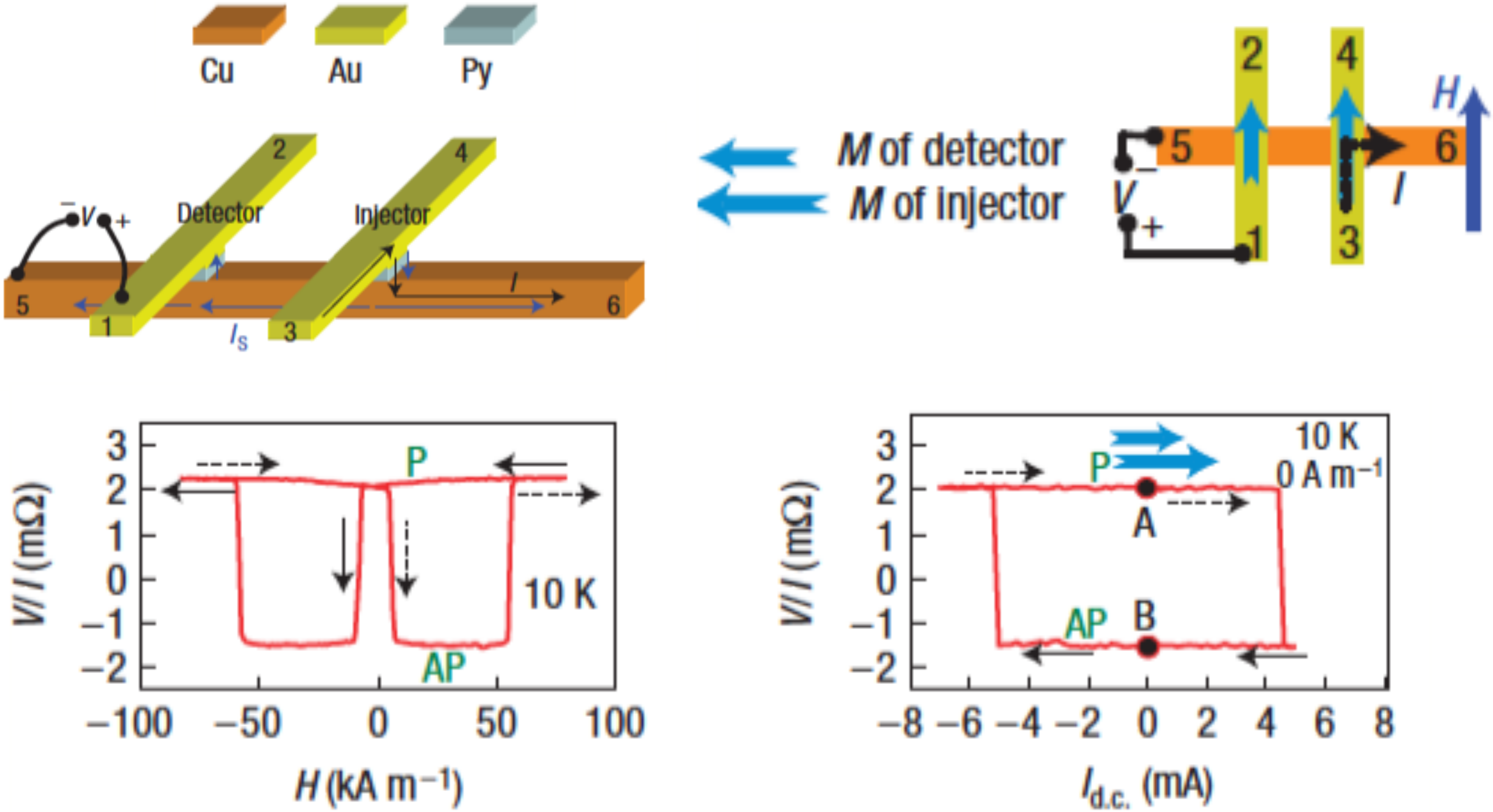
⇒ Switching fields of AMR and R_S are correlated (dashed lines)

⇒ R_S of up to 0.9 mΩ indicates clean interfaces

J. Mennig, D.E. Bürgler *et al*., J. Appl. Phys. **111**, 07C504 (2012)

Pure spin current induced magnetization switching

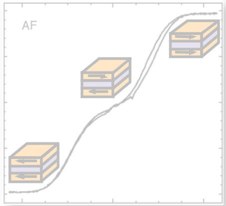
Injector and detector are Py nanomagnets (80×170 nm^2 and 75×170 nm^2)



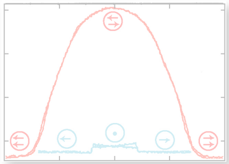
T. Yang *et al.*, Nature Physics **4**, 851 (2008)

Overview

Introduction

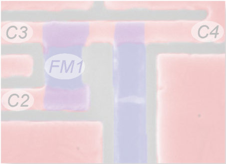


Interlayer exchange coupling

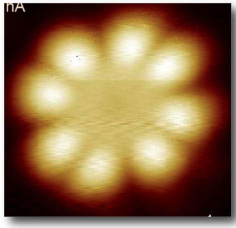


Giant and tunneling magnetoresistance

Current-induced magnetization dynamics



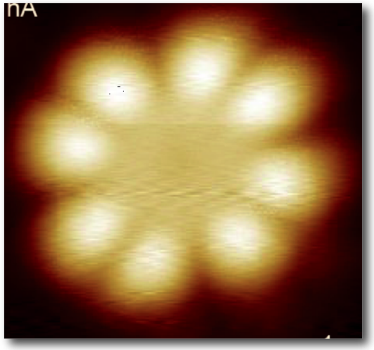
Pure spin current



Magnetic molecules

Conclusions

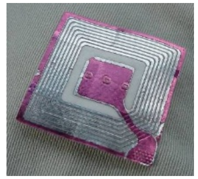
Outline: Magnetic molecules



- Why magnetic molecules?
- Challenges of the interface between molecule and substrate/electrode
- Example: Nd phthalocyanine double-decker ($NdPc_2$) molecules on Cu(100)

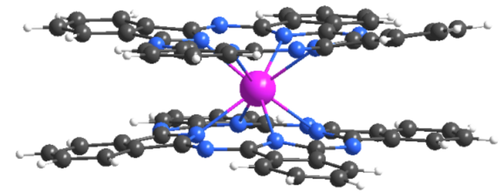
Length scales in magnetism

Wind turbine



Anti-theft device

Magnetic recording



Molecular magnetism

1 m	1 mm	1 ∝m	1 nm	1 Å

macroscopic ⟷ nanoscopic

Single molecule magnets (SMM)

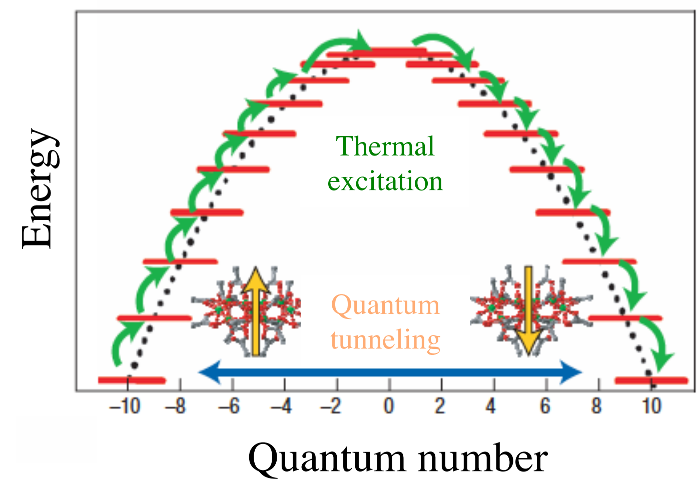
Molecules with

- Magnetic moment
- Zero-field splitting

⇒ Anisotropy

⇒ Enhanced relaxation time

⇒ Blocking temperature



L. Bogani und W. Wernsdorfer, Nat. Mat. **7**, 179 (2008)

Molecular spintronics

Combines molecular electronics and spintronics

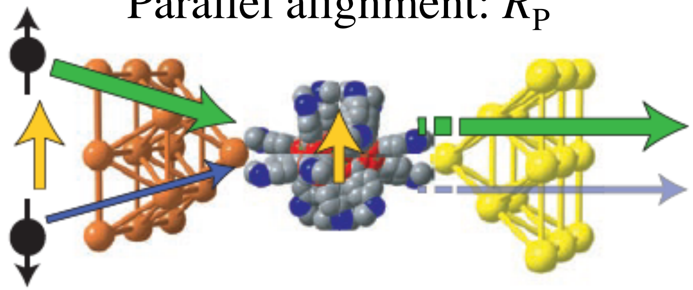
to exploit the rich diversity and functionality of molecules and

the spin degree of freedom for novel nanoelectronic device concepts

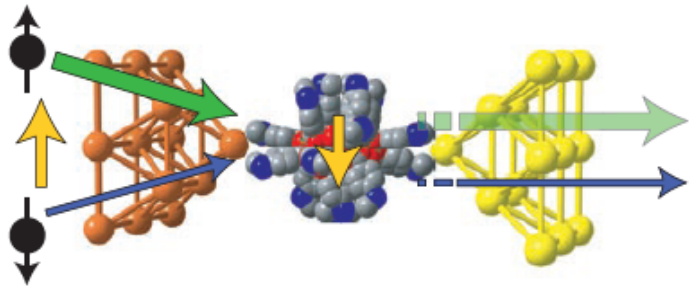
Example of spintronic functionality:

SMM in ferromagnet/non-magnet junction

Parallel alignment: R_P



Antiparallel alignment: R_{AP}



Charge transport: $R_P < R_{AP}$

$\Rightarrow$ Spintronic functionality

L. Bogani und W. Wernsdorfer, Nat. Mat. **7**, 179 (2008)

Realization of molecular spintronics

Molecules need to be supported

- How do molecules adsorb on surfaces?
- Do they decompose upon deposition?
- What is their adsorption geometry and site?

Adsorption properties on substrates

Molecules need to be electrically contacted

- Role of metal-molecule interaction?
- Impact of metal-molecule hybridization?
- Impact of metal surface on magnetic moment?
- Do the "magnetic" orbitals contribute to charge transport?

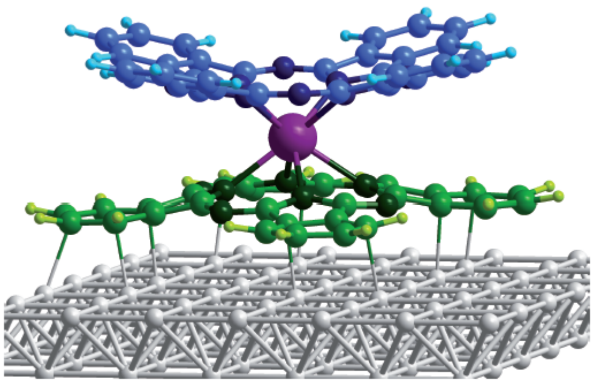
Electronic structure of absorbed/contacted molecules

Molecule-substrate interaction

Physisorption (weak bonding)

- van-der-Waals (dipole-dipole) forces

⇒ Little impact on electronic structure



Chemisorption (strong bonding)

- Ionic and covalent bonding
- Charge transfer and hybridization

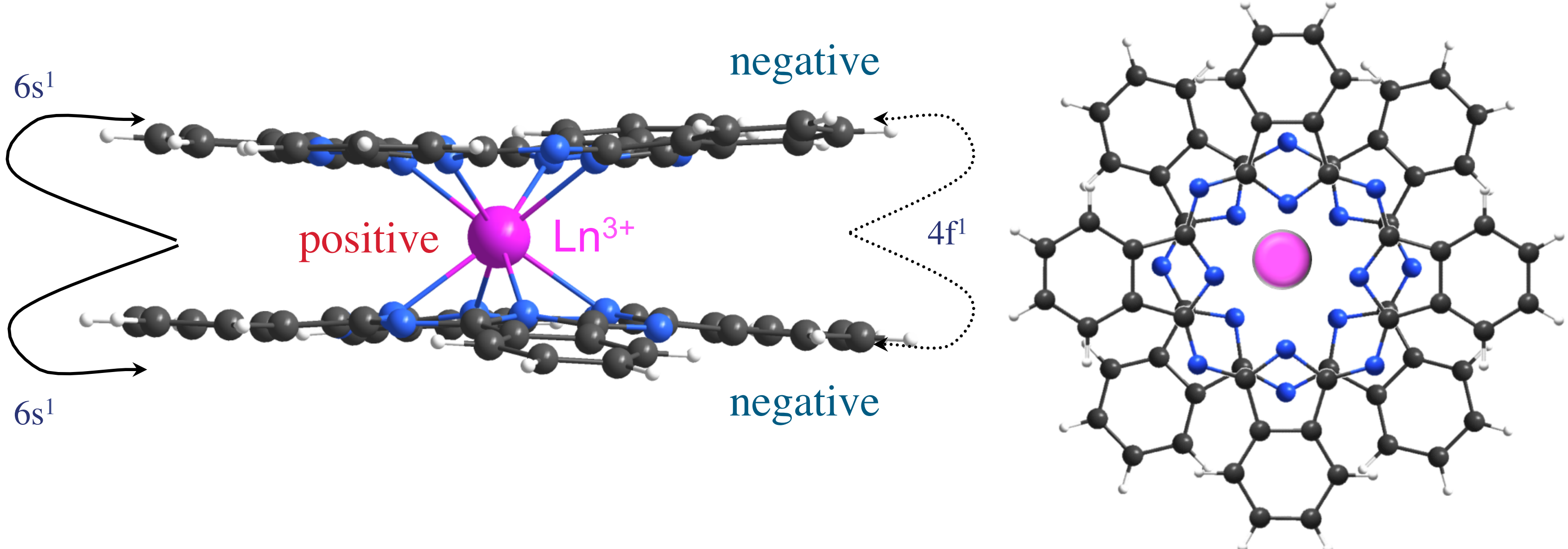
⇒ Strong impact on electronic structure

⇒ Formation of hybrid orbitals

⇒ May influence [1,2] or quench the molecular magnetic moment [3]

[1] A. Mugarza *et al.*, Phys. Rev. B **85**, 155437 (2012)
[2] C. Iacovita *et al.*, Phys. Rev. Lett. **101**, 116602 (2008)
[3] J. Brede *et al.*, Phys. Rev. Lett. **105**, 047204 (2010)

Lanthanide double-decker phthalocyanines ($LnPc_2$)



- Intramolecular interaction between the Pc ligands and the central Ln ion is mainly of electrostatic nature
  - Relative angle of 45° between the two Pc ligand

- Some $LnPc_2$, e.g. $TbPc_2$, $DyPc_2$, and $HoPc_2$ [1,2] are known to be SMMs with blocking temperatures of several tens of Kelvin
  - Accessing Tb 4f-states in $TbPc_2$ by STM is not possible [3]

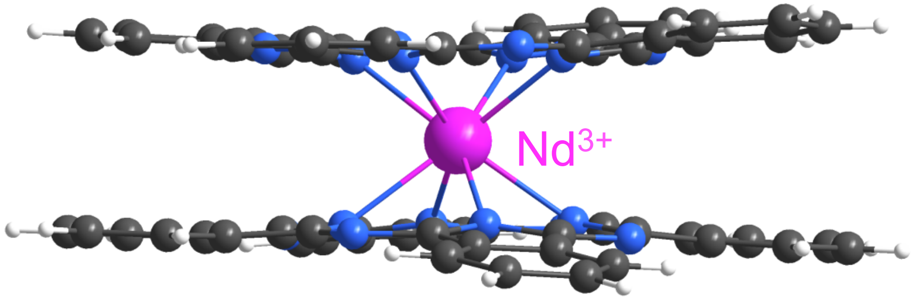
[1] Ishikawa *et al*., J. Phys. Chem. B **108**, 11265 (2004);
[2] F. Branzoli *et al*., J. Am. Chem. Soc. **131**:4387 (2009); [3] Schwöbel *et al*., Nat. Commun. **3**, 953 (2012)

JARA|FIT

JÜLICH FORSCHUNGSZENTRUM

"bis(phthalocyaninato)-neodymium(III)"

Neodymium double-decker phthalocyanine ($NdPc_2$)



- $NdPc_2$ is a promising SMM, but has not examined under this aspect

Lanthanoides:

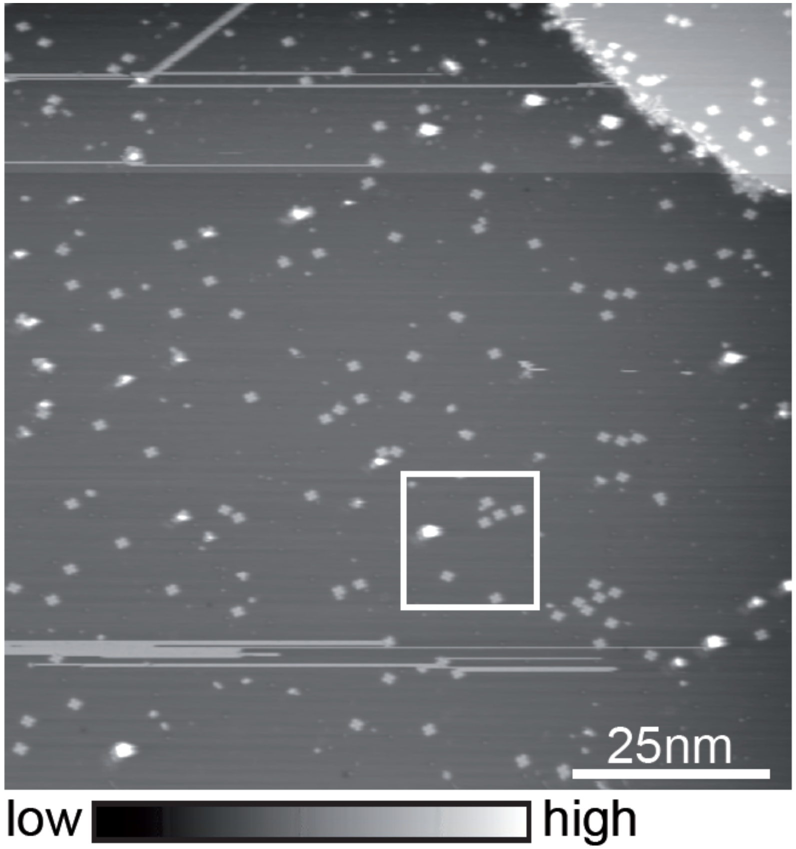
57 La	…	60 Nd $4f^4$ $6s^2$	…..	65 Tb $4f^9$ $6s^2$	66 Dy $4f^{10}$ $6s^2$	….

←

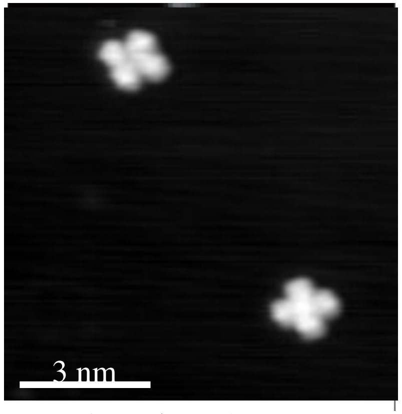
Increasing ionic radius
Increasing spatial extent of 4f orbitals
Nd 4f-states move closer to the Fermi level

⇒ Nd 4f-states can be accessed and imaged by STM

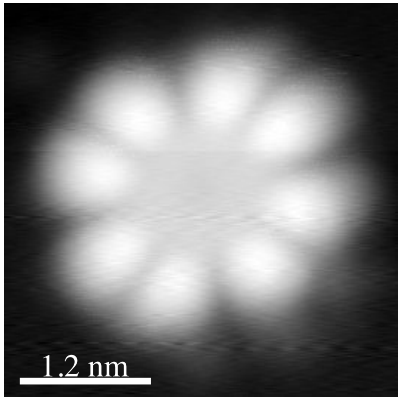
NdPc$_2$ on Cu(100)



- Molecules sublimated at 850 K
  metal substrate held at 300 K
- STM in UHV and at 4 K; etched W tips
- Bias voltage modulation (30 mV, 2.7 kHz) for d*I*/d*V*-spectra and d*I*/d*V*-maps



Single-decker



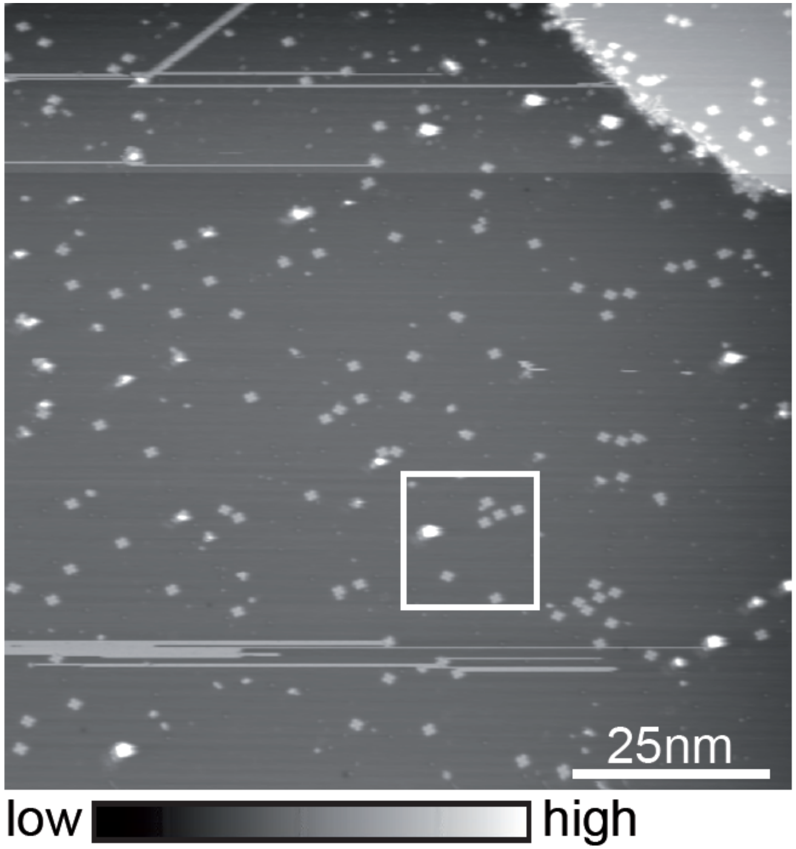
Double-decker

2 types of molecules, each in 2 orientations:

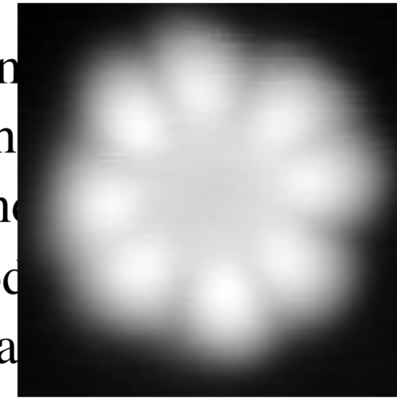
⇒ Double-decker (NdPc$_2$) and single-decker (NdPc, Pc)

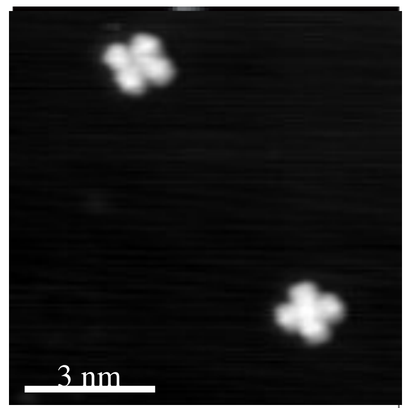
⇒ NdPc$_2$ molecules break up upon deposition

$NdPc_2$ on Cu(100)

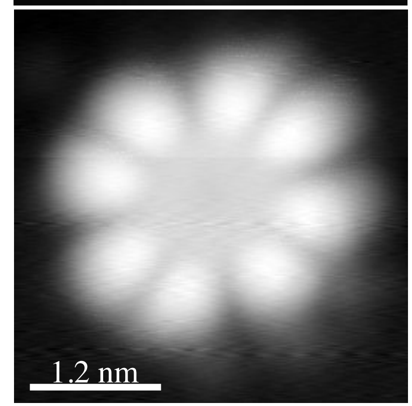


- Molecules sublin
  metal substrate h
- STM in UHV an tips
- Bias voltage mod 7 kHz)
  for dI/dV-spectra





Single-decker



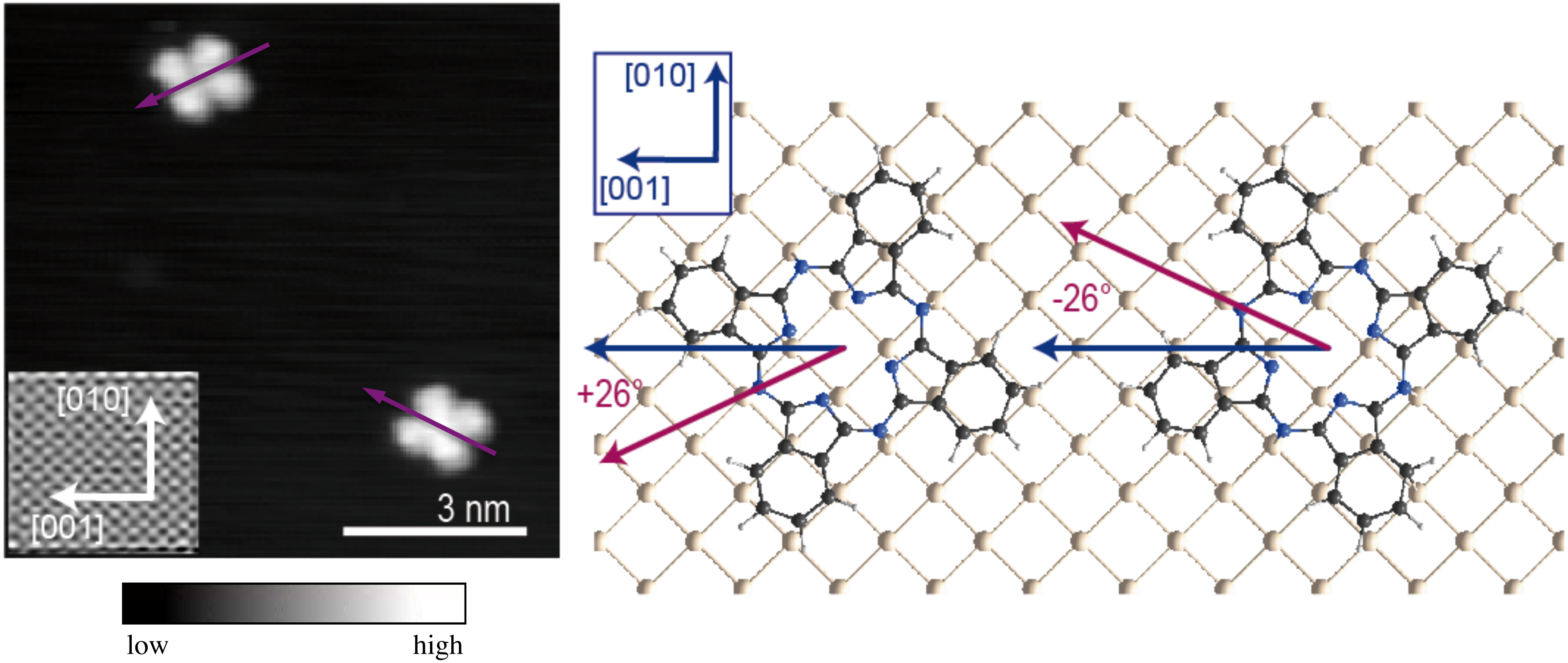
Double-decker

2 types of molecules, each in 2 orientations:

⇒ Double-decker ($NdPc_2$) and single-decker (NdPc, Pc)

⇒ $NdPc_2$ molecules break up upon deposition

Single-decker NdPc on Cu(100)

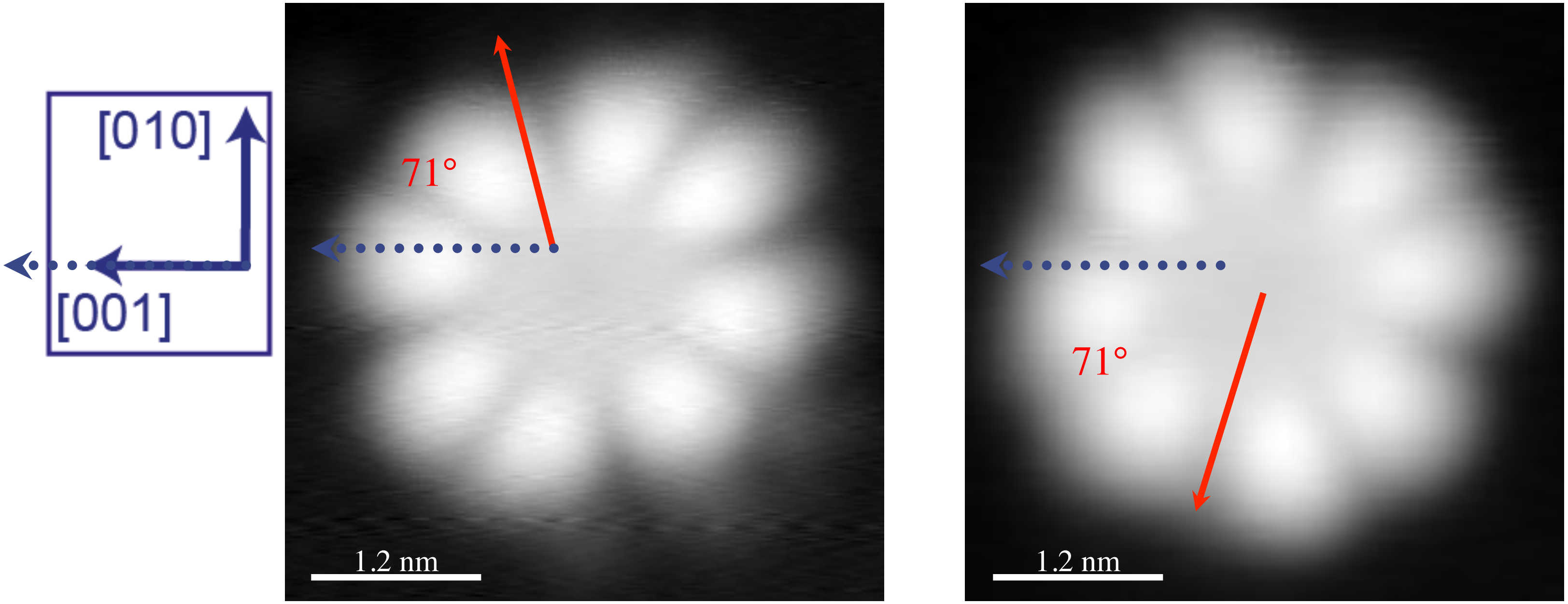


⇒ rotated with respect to [001] axis by ±(28±2)°

⇒ Agreement with theoretical prediction [1]: ±26° from [001] axis

[1] Lippel *et al*., Phys. Rev. Lett. **62**, 171 (1989)

Double-decker $NdPc_2$ on Cu(100)

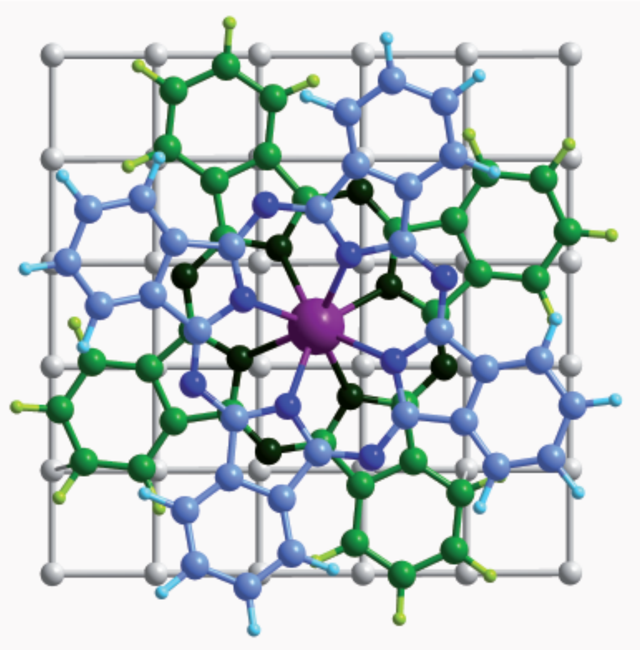


Upper ligand is imaged and its axes are rotated with respect to [001] axis by ±(71±2)°

Consider twist between ligand Pc: ±(26+45)°= ±71°

⇒ Absorption position is determined by the binding of lower Pc to the substrate

$NdPc_2$ on Cu(100): Calculations



- $NdPc_2$ on 5 layer of Cu
- GGA+U calculations (U=2.2 eV)
- Including van-der-Waals forces

Optimized and relaxed structure:

- $NdPc_2$ center above Cu hollow site
- Two symmetric and degenerate positions

We calculate:

- Contours of constant DOS
- Local DOS versus V
- Maps of DOS at given V_{bias}

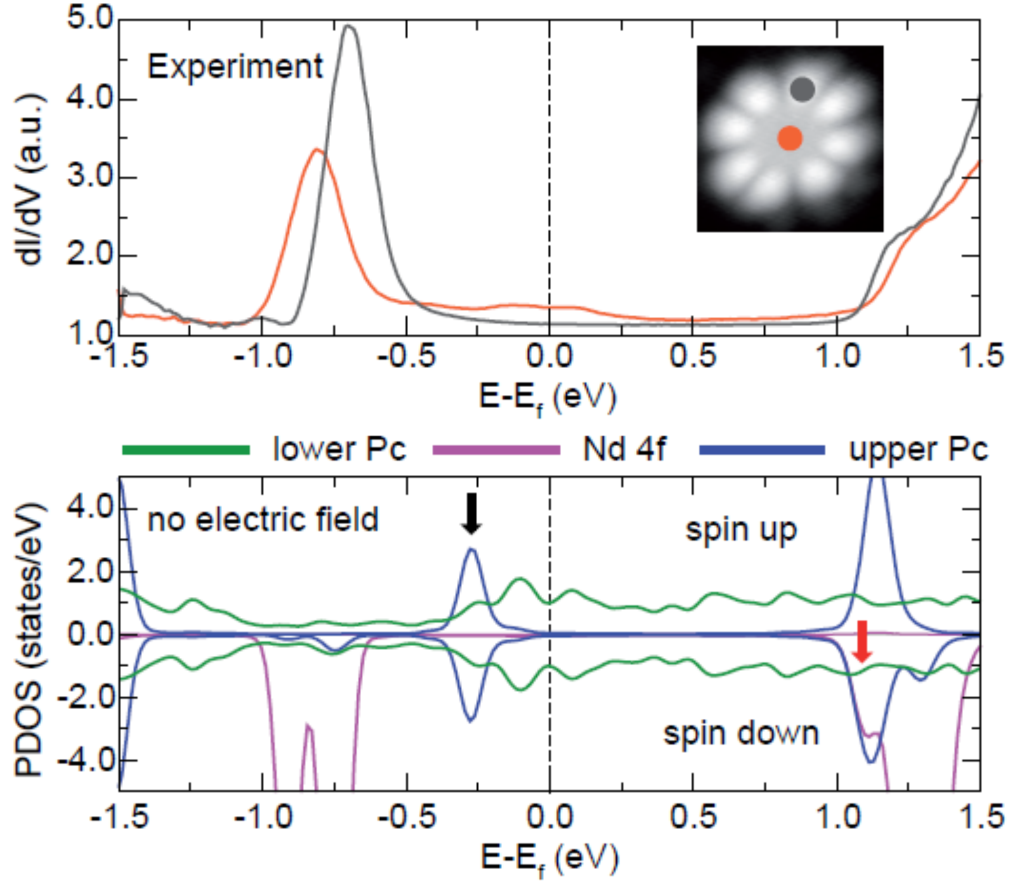
We measure:

-> STM topography

-> dI/dV-curves

-> dI/dV-maps at V_{bias}

$NdPc_2$ on Cu(100)

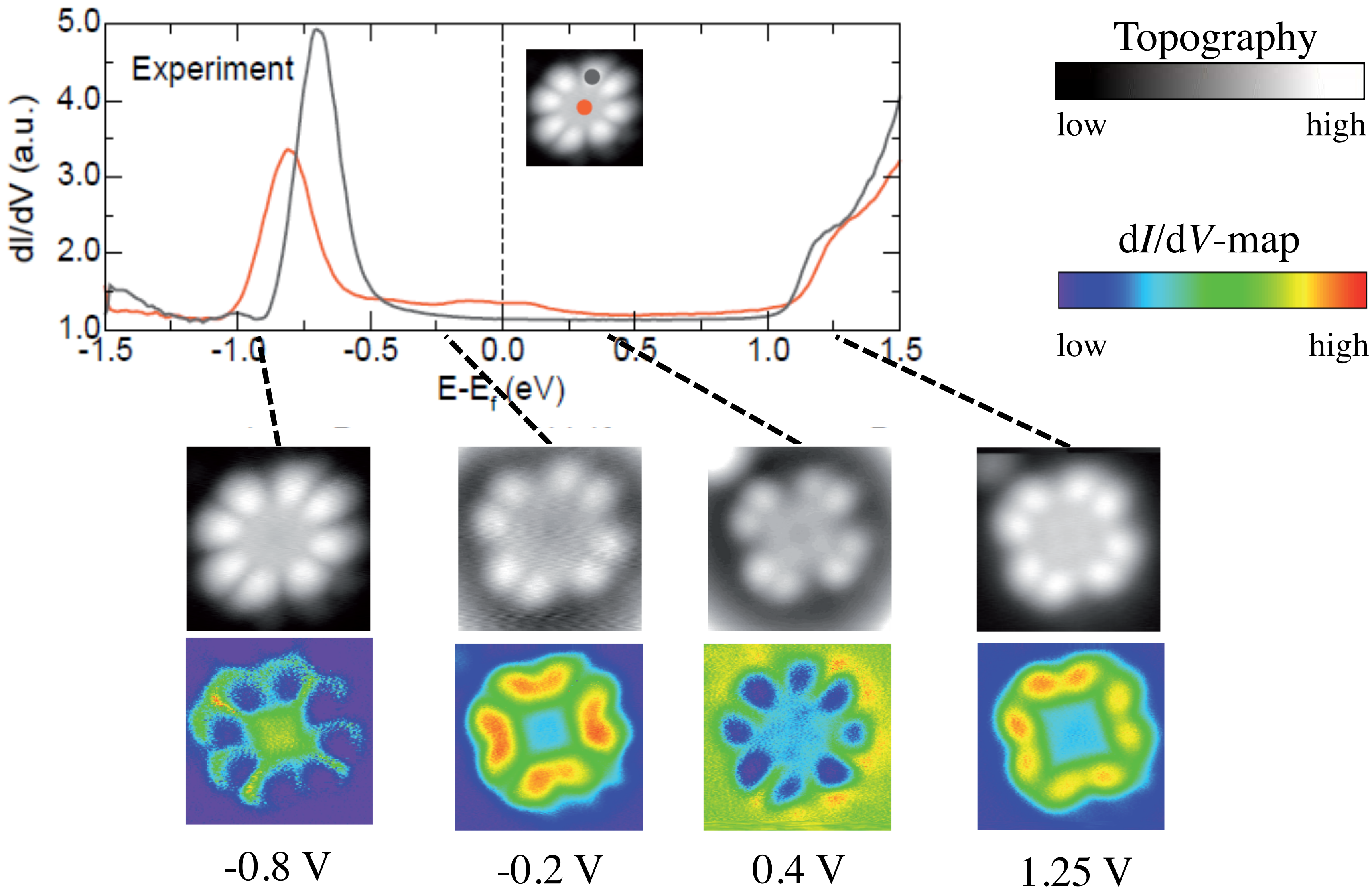


⇒ Direct detection of spin-polarized 4f-states

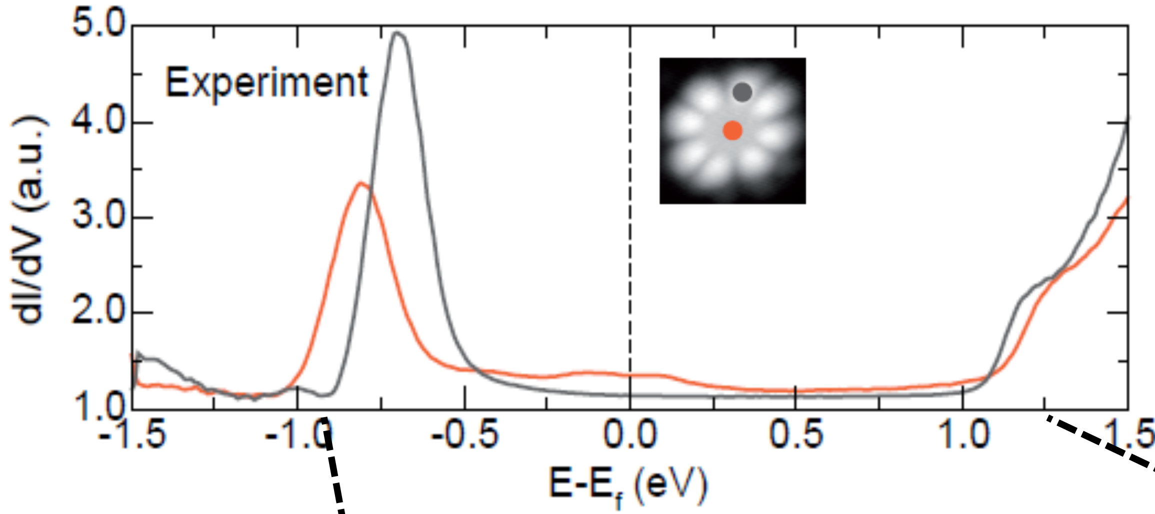
⇒ Lower Pc strongly hybridizes with substrate

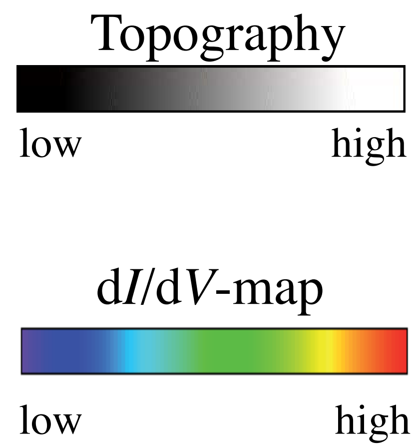
⇒ Upper Pc keeps molecular-type states

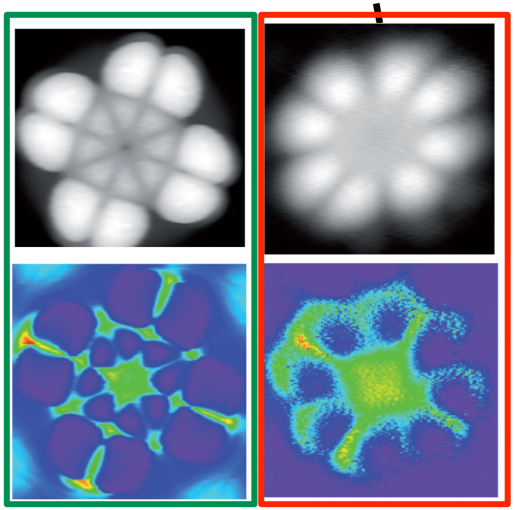
$NdPc_2$ on Cu(100)



$NdPc_2$ on Cu(100)

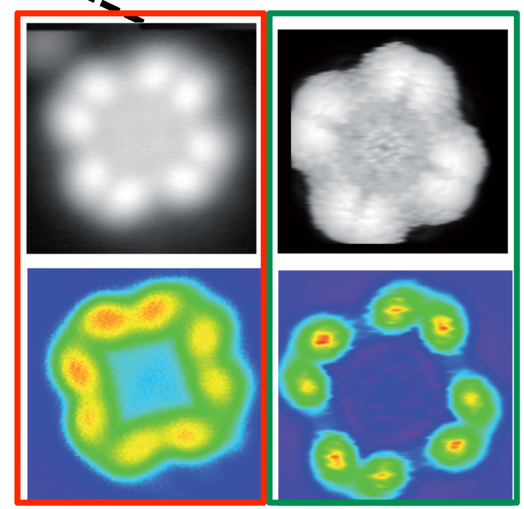






⇒ Direct detection of spin-polarized Nd 4f-states by STM

⇒ Prospects for electrical manipulation/detection of molecular spin

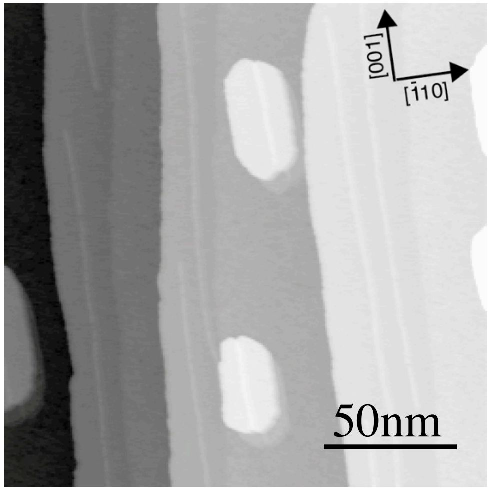


Theory / Experiment

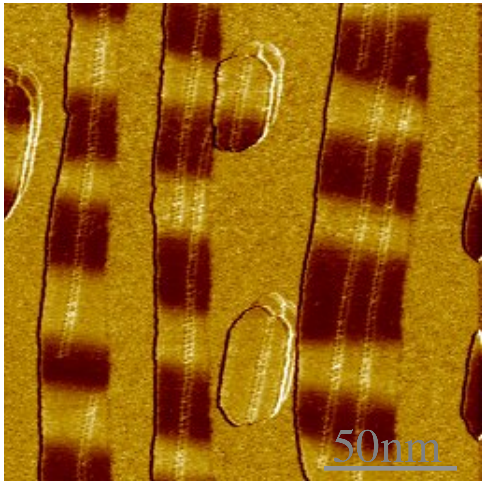
Experiment / Theory

Two atomic layers of Fe on W(110): Model system

Topography

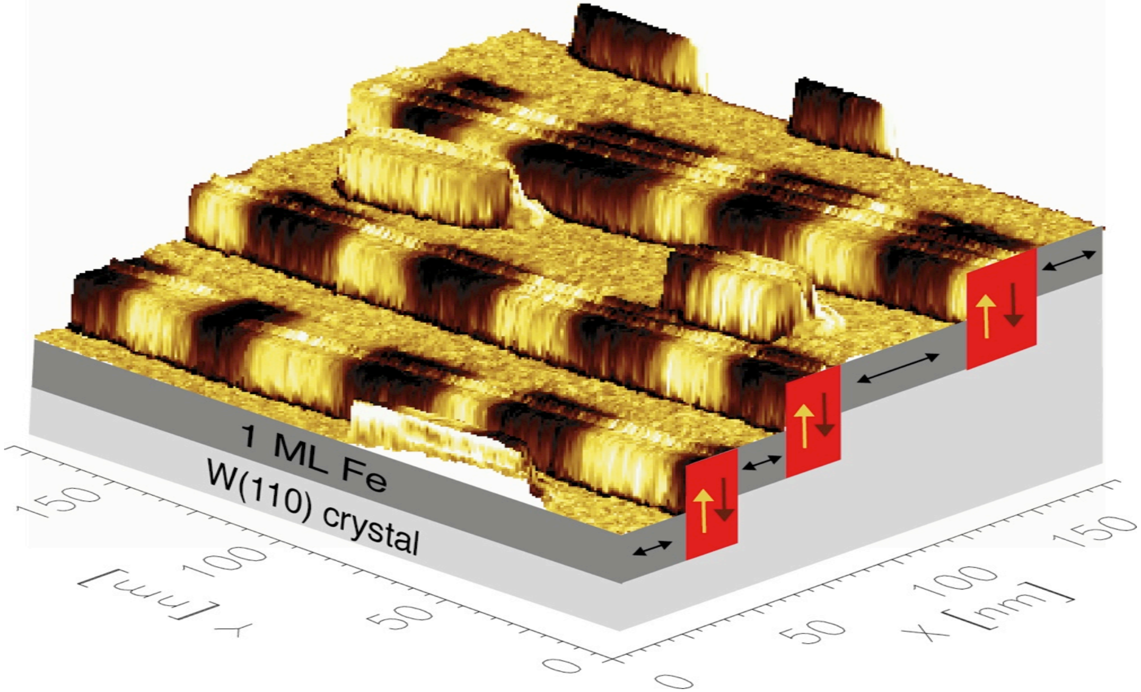


Magnetic contrast
(dI/dV)

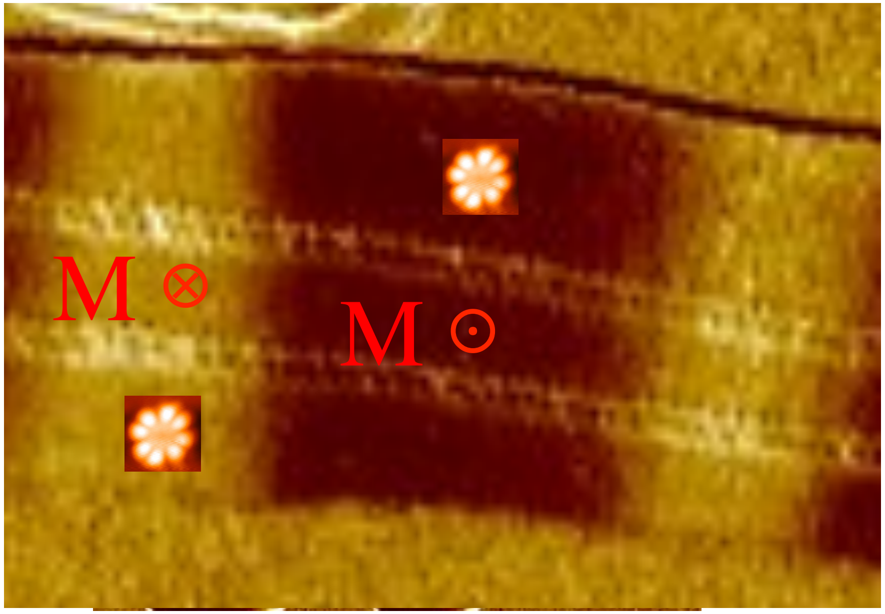


Model system for magnetic surfaces

- 1st AL Fe is in-plane magnetized
- 2nd AL Fe is out-of-plane magnetized



Future experimental route



Requirements:

- Magnetic tip
- "Clean" surface
- Certain density of intact molecules
- Magnetic coupling of molecule to surface

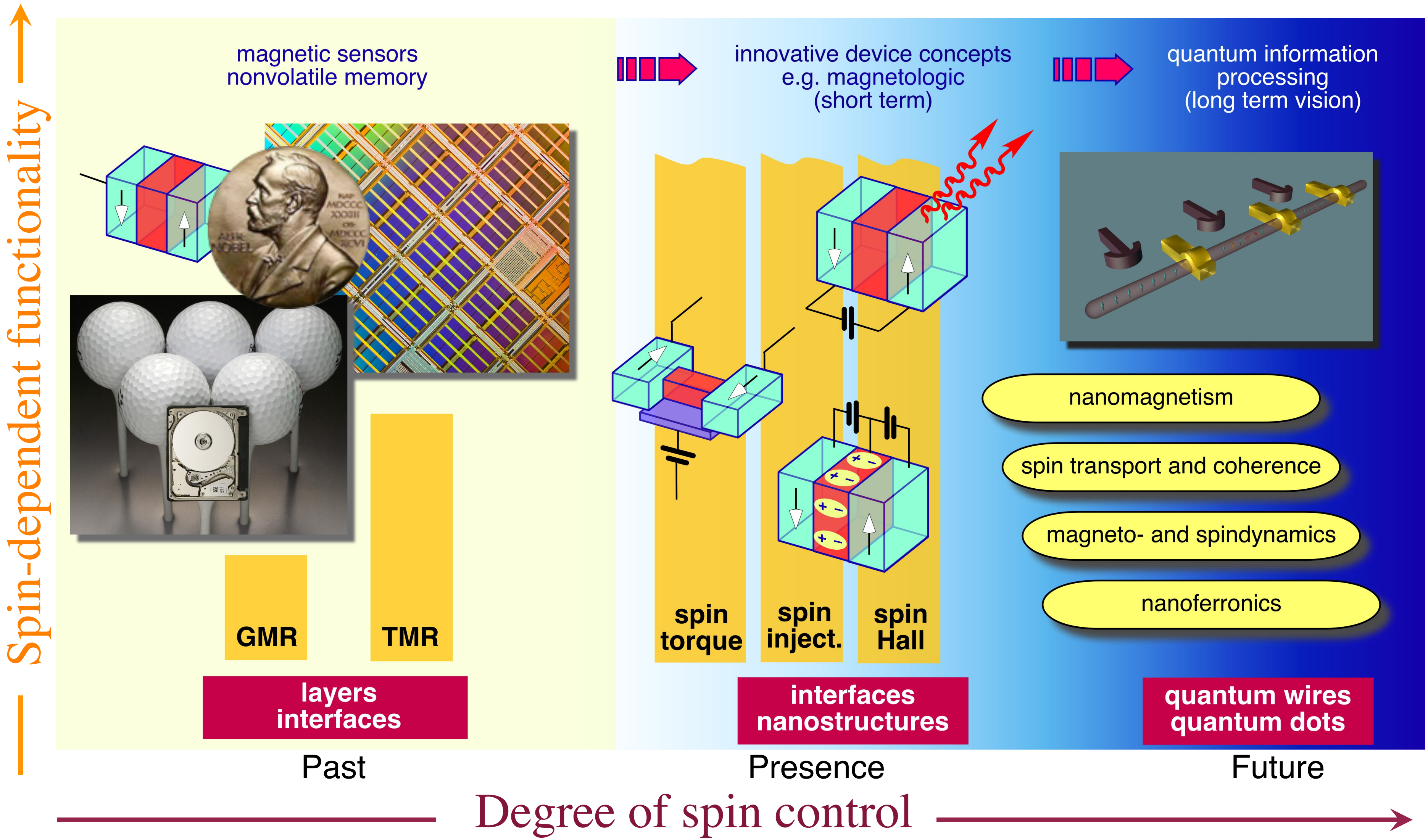
The “History” of Spintronics

1986 Discovery of magnetic interlayer exchange coupling (Grünberg)
1988 Discovery of GMR (Grünberg, Fert)
1995 Realization of TMR at room temperature (Miyazaki, Moodera)
1996 Prediction of spin-transfer effects (Slonczewski, Berger)
1998 First commercial harddisks with GMR sensors (IBM)
2000 Experimental observation of spin-transfer effects (Cornell)
2001 Commercial harddisks with AFC media (IBM)
2004 Giant TMR across epitaxial MgO barriers (Parkin, Yuasa)
2006 Commercialization of MRAM based on TMR (Freescale)
2007 Demo: MRAM based on giant TMR and spin-transfer (Hitachi)

… short transfer times from basic research to applications in mass markets

… there is more to come: *e.g.* quantum information technology

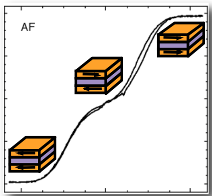
Future of Spintronics



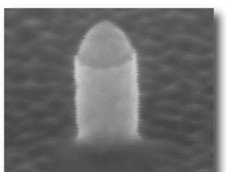
Take-home message

Spintronics relies on manipulating and detecting magnetization states of nm-sized FM objects

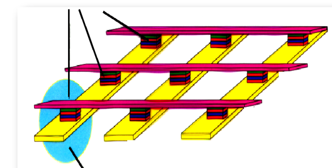
Spin-transfer processes enable such functionalities:

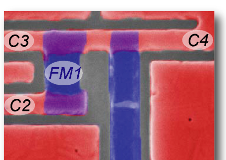


- Established: GMR and IEC in HDD

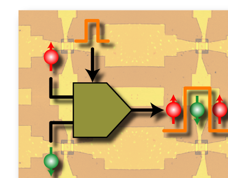


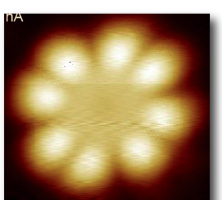
- Currently: Spin-transfer torque in MRAMs



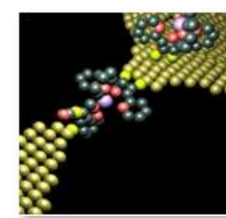


- Future: Pure spin currents in low-dissipation devices





- Future: Magnetic molecules in molecular transistors and in artificial neuronal magnetic networks



Thanks …

• Sarah Fahrendorf, Julius Mennig, Saban Tirpanci, Frank Matthes, Peter Grünberg, Claus M. Schneider (FZ Jülich)
• Ronald Lehndorff (now Sensitec Mainz Germany)
• Volker Sluka, Alina Deac (now Helmholtz-Zentrum Rossendorf)

• Zbigniew Celinski (Colorado Springs, USA)

• Sebastian Gliga, Attila Kákay (FZ Jülich)
• Riccardo Hertel (now CNRS Strasbourg, France)

• Claire Besson, Paul Kögerler (RWTH Aachen and FZ Jülich)

• Nicolae Atodiresei, Vasile Caciuc, Stefan Blügel (FZ Jülich)