Magnetoresistance and domain wall displacement in submicrometer Permalloy ring structures

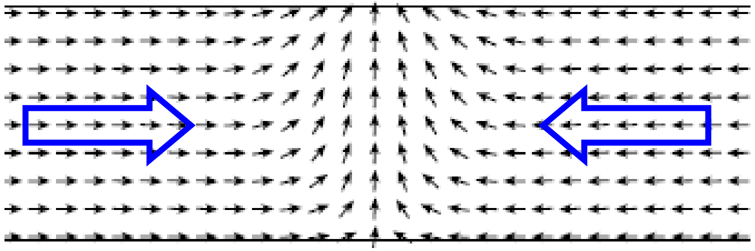
P. Vavassori

CIC nanoGUNE Consolider, San Sebastian, Spain

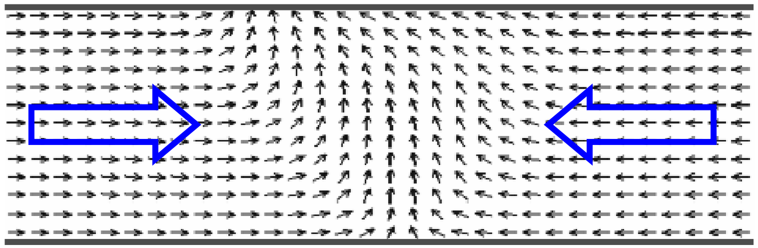
- Domain walls structure in nanostructures.
- Manipulation of magnetic domain walls in nanostructures (nanowires and nanorings) by the use of magnetic fields and electric current.
- Potential applications.
- Magnetotransport and head-to-head domain walls structure in Py square rings.
- Potential applications of devices based on this kind of structures to the detection of biomolecular recognition.

Domain walls structure in thin and nannrow strips

Large stray field → thin and narrow rings

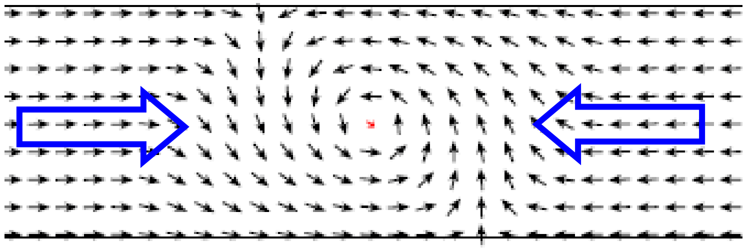


Transverse wall



Asymmetric Transverse Wall

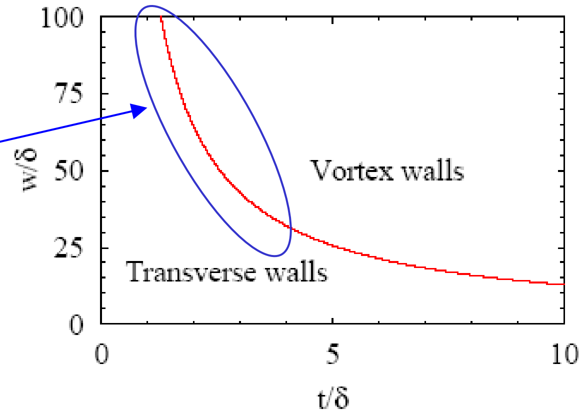
Large exchange energy → thick and wide rings



Vortex wall

Soft magnetic material

Wall phase diagram



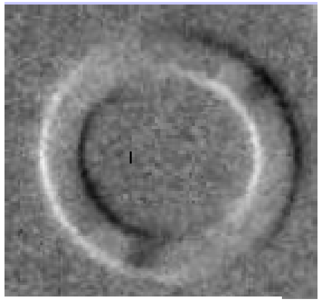
$\delta = (A/\mu_0 M_s^2)^{1/2}$ **Exchange lengh (~5 nm in Py)**

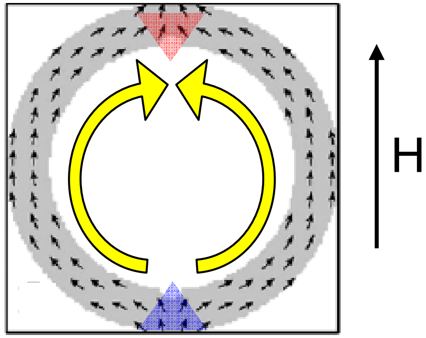
w is strip width

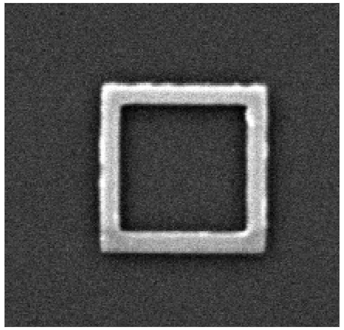
t is strip thickness

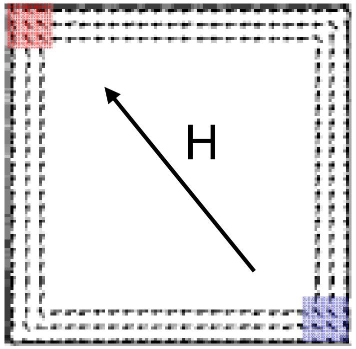
R.D. McMichael et al., IEEE Trans. Mag. **33**, 4167 (1997)
Y. Nakatani, J. Mang. Magn. Mater. **290**, 750 (2005)

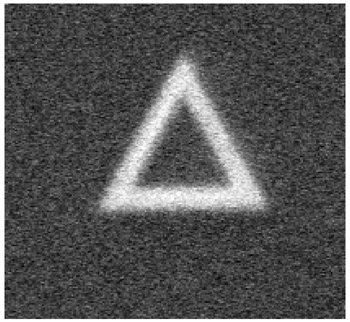
Domain wall in ring structures

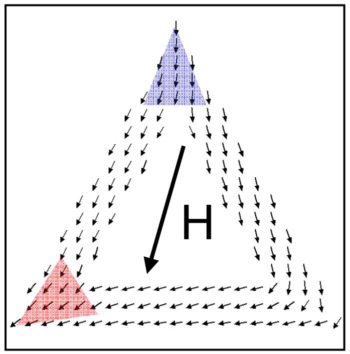










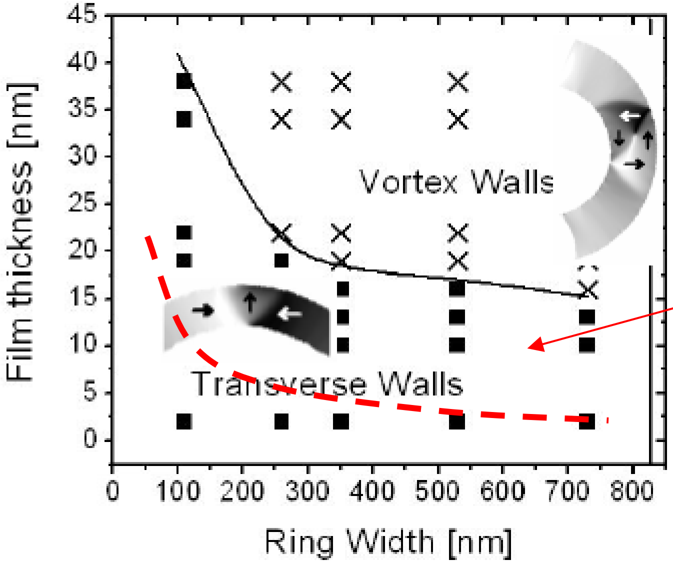


Head-to-head DW

Tail-to-tail DW

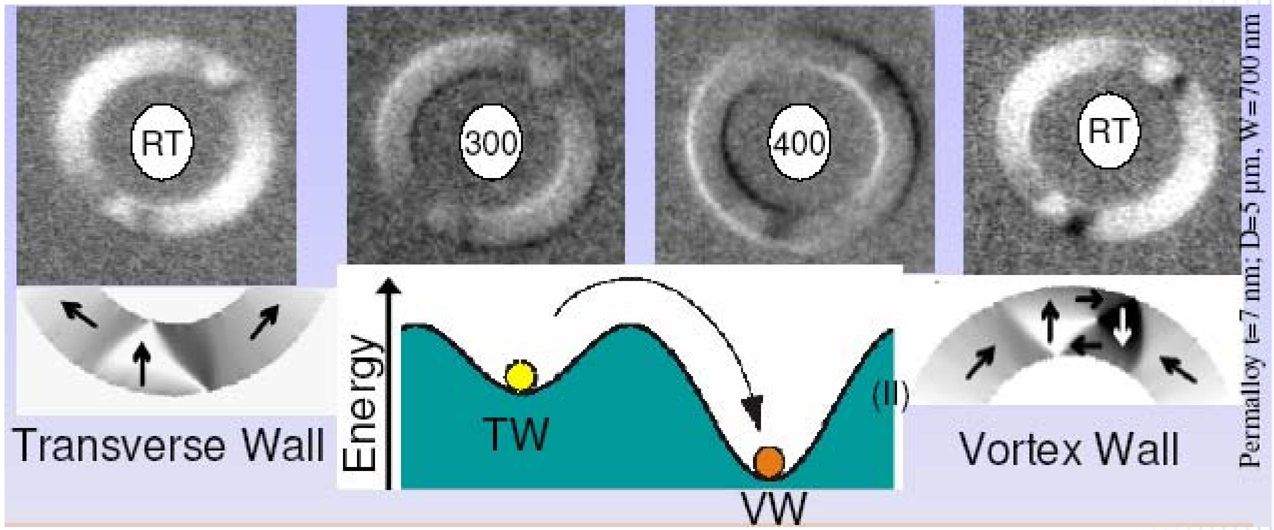
Eperimental phase diagram

Experimental phase diagram for Co and Py rings



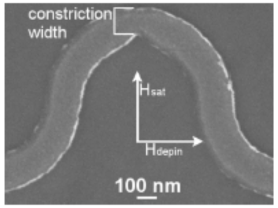
Theory.
TDWs constitute a local energy minimum, a barrier has to be overcome to attain a vortex wall. Thermally assisted transformation from TDW to VDW

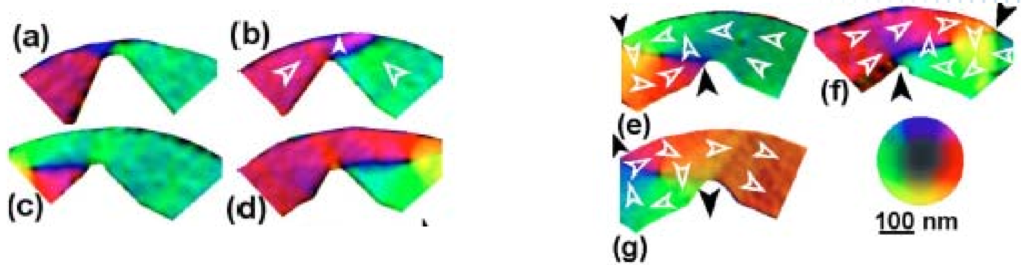
M. Laufenberg et al., Appl. Phys. Lett. **88**, 52507 (2006)



Domain wall pinning and manipulation

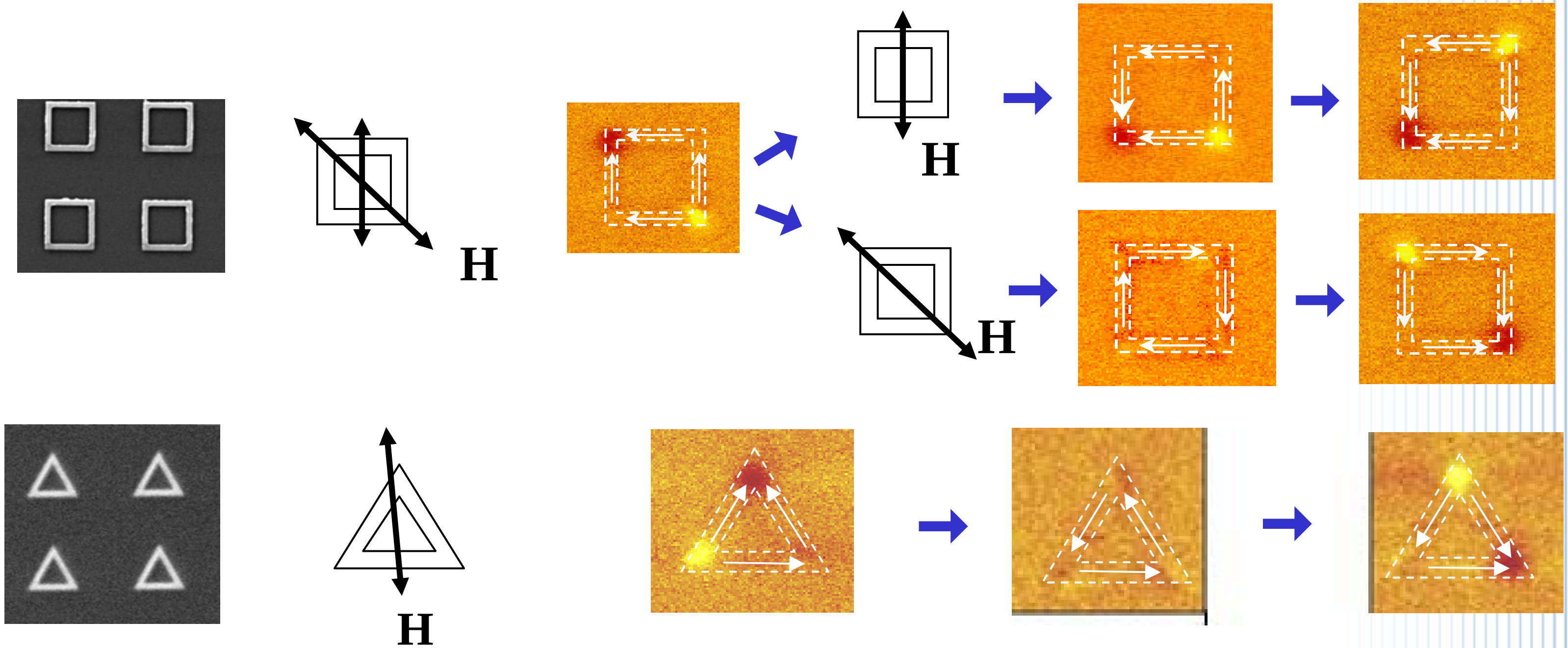
Corners or notches can be used to nucleate and pin these DW at a desired place; they can be easily moved with a field H.





M. Kläui et al., Appl. Phys. Lett. 87, 102509 (2005)

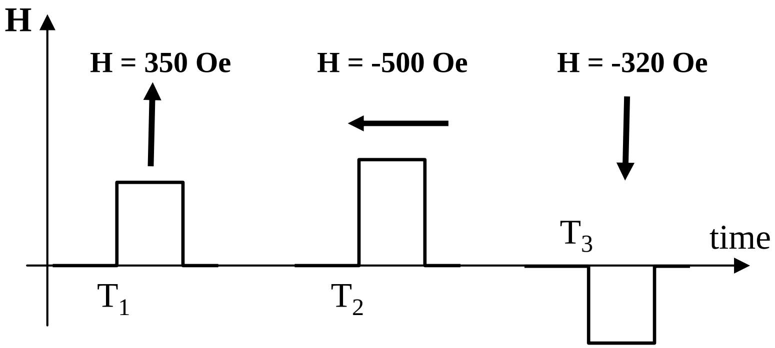
Electron olography

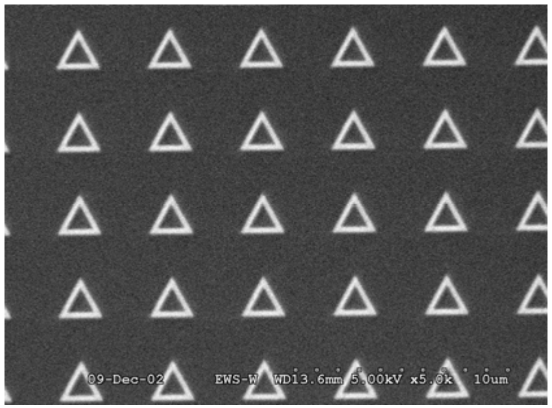


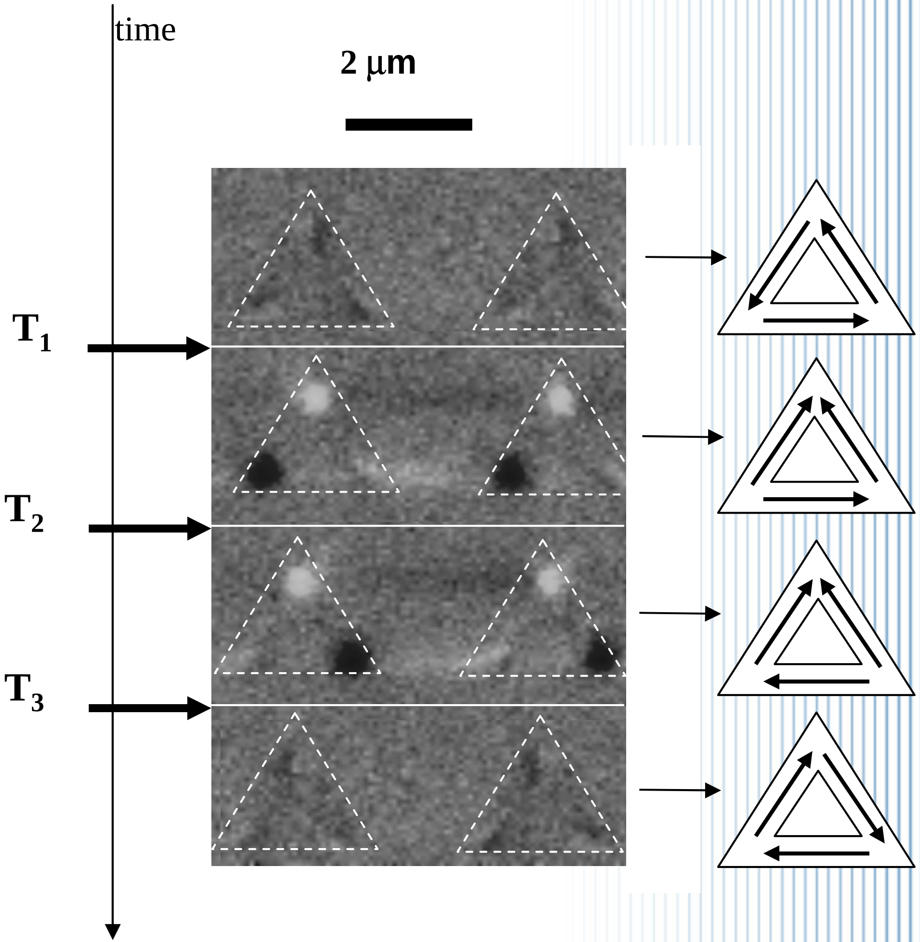
Magnetic force microscopy

P. Vavassori et al., Phys. Rev. **B 67**, 134429 (2003)
P. Vavassori et al., J. Appl. Phys. **101**, 023902 (2007)

Vortex rotation control with magnetic pulses



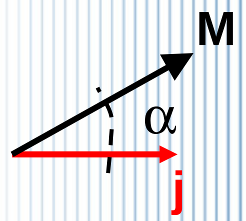


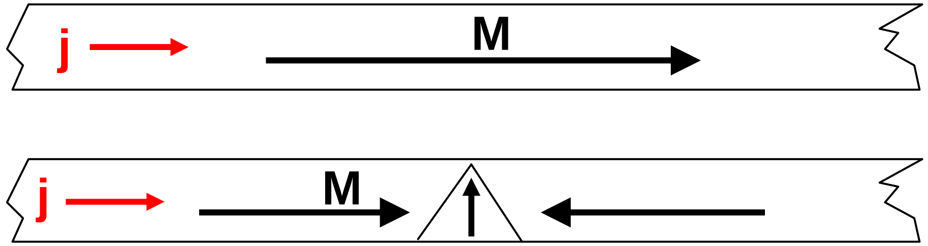


P. Vavassori et al., J. Appl. Phys. **101**, 023902 (2007)

Domain wall position probed using MR

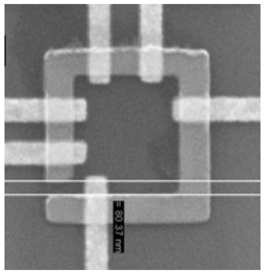
Anisotropic magnetoresistance effect (AMR) ($\rho=\rho_{\perp}+(\rho_{\parallel}-\rho_{\perp})\cos^2\alpha$)

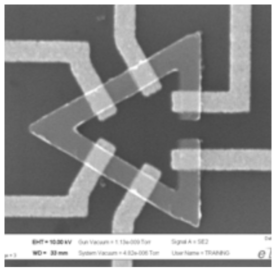


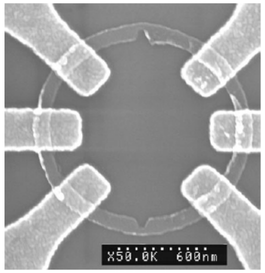


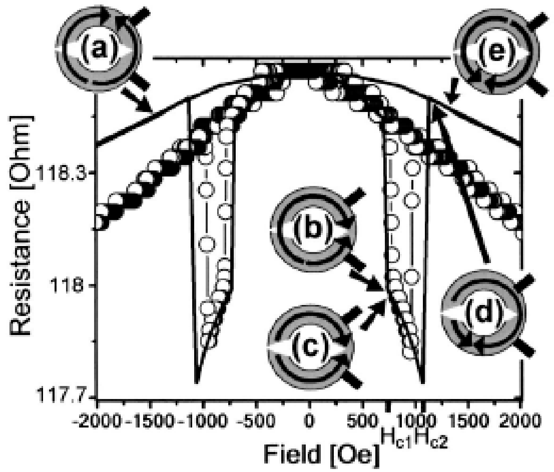
R high

R low



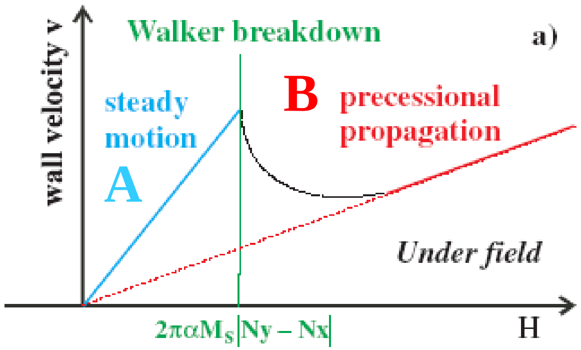






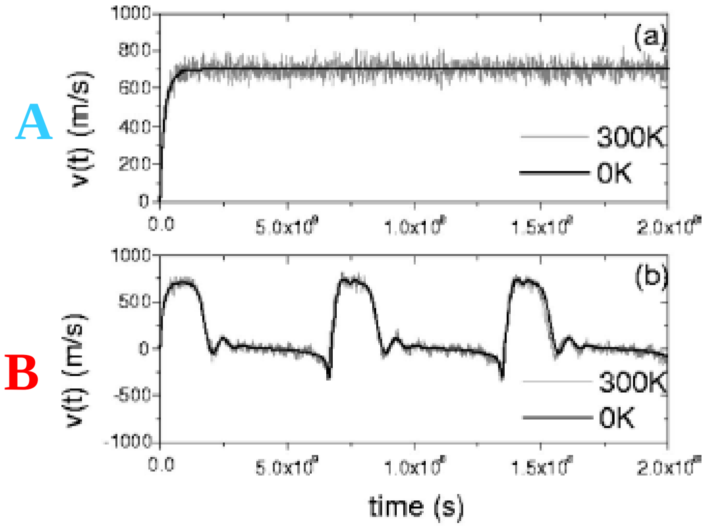
Domain wall dynamics

Theory

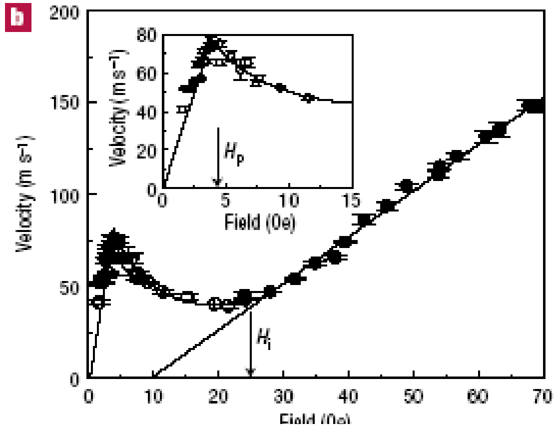


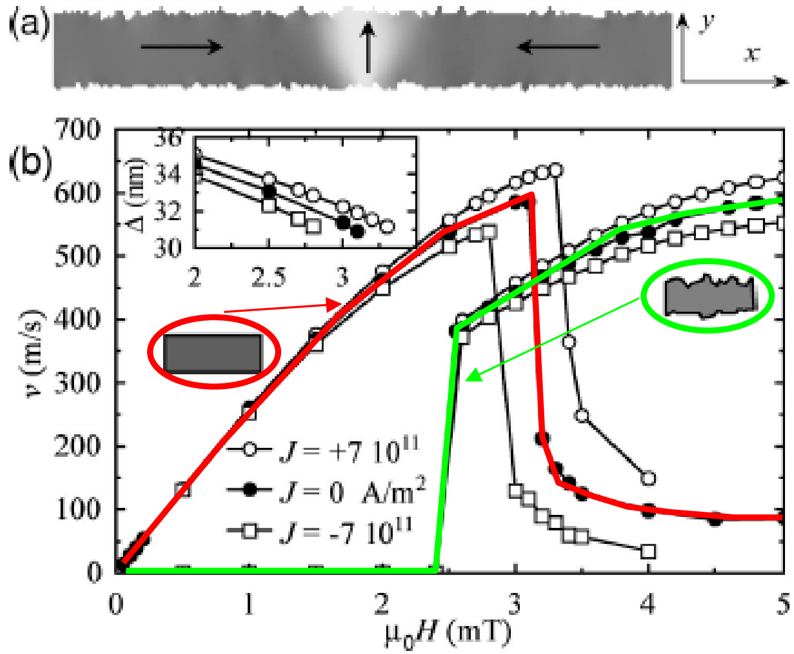
N. L. Schryer and L. R. Walker, J. Appl. Phys. 45, 5406 (1974)
J. C. Slonczewski, J. Appl. Phys. 45, 2705 (1974).

Micromagnetic simulations

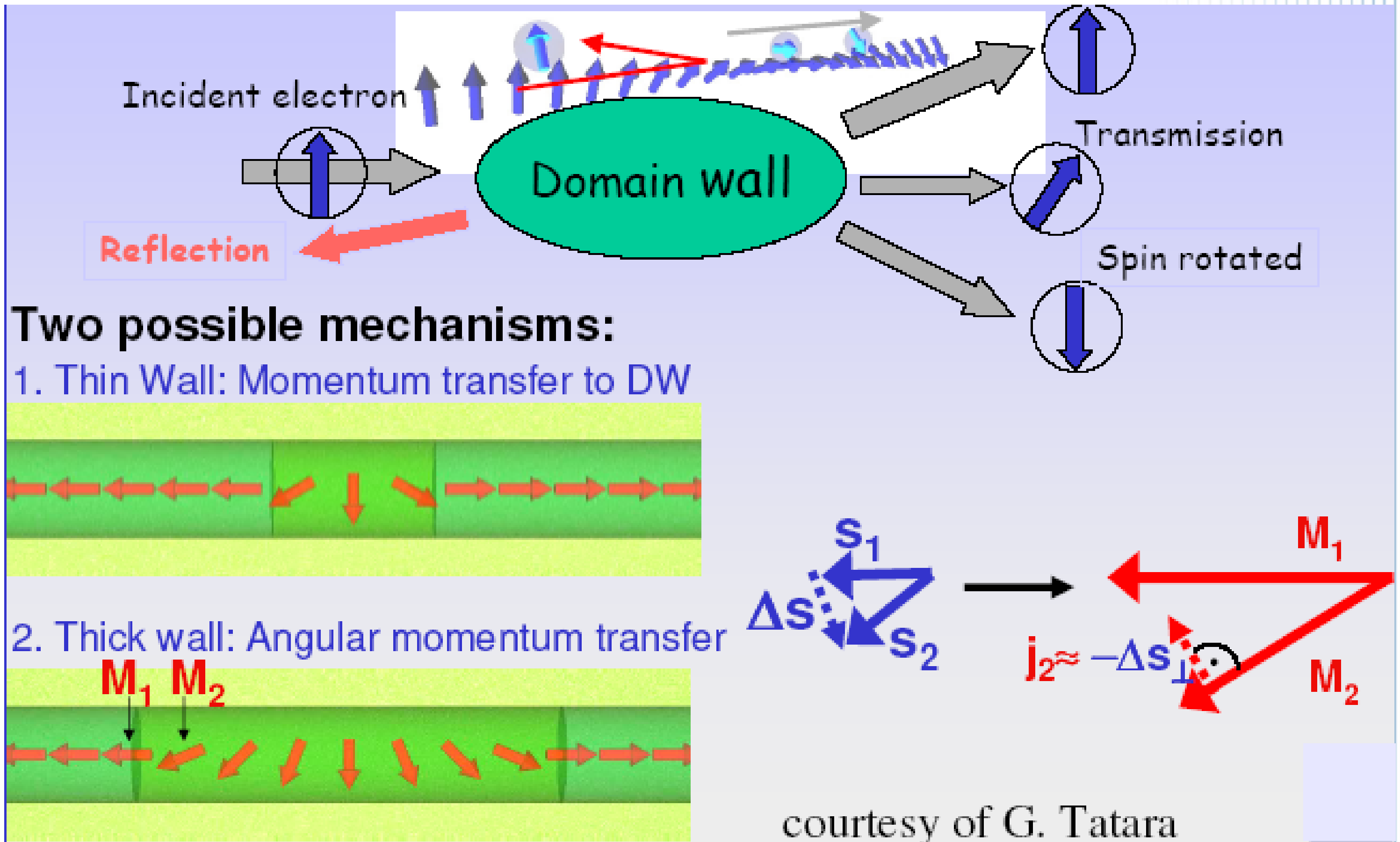


Experiement

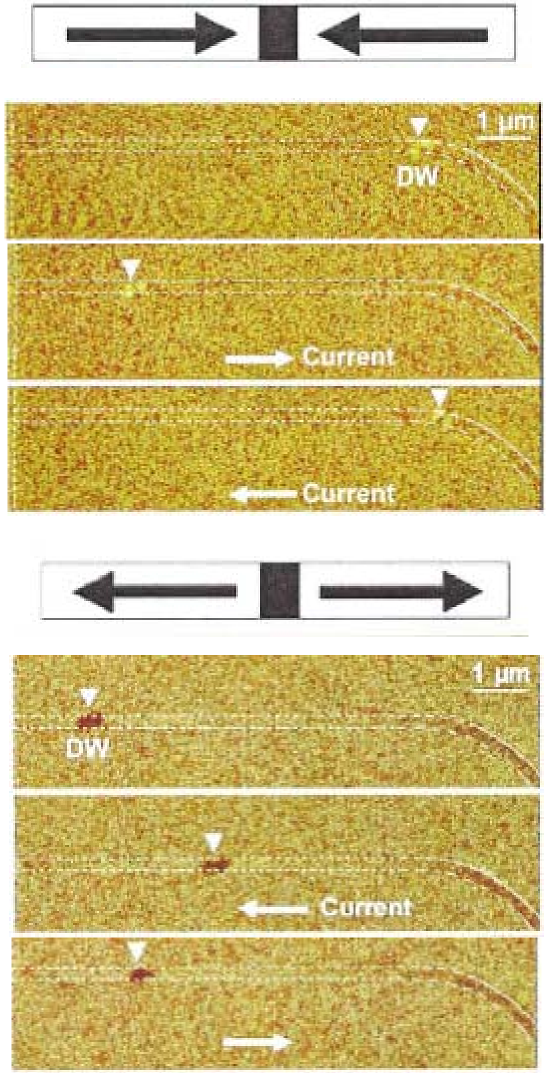


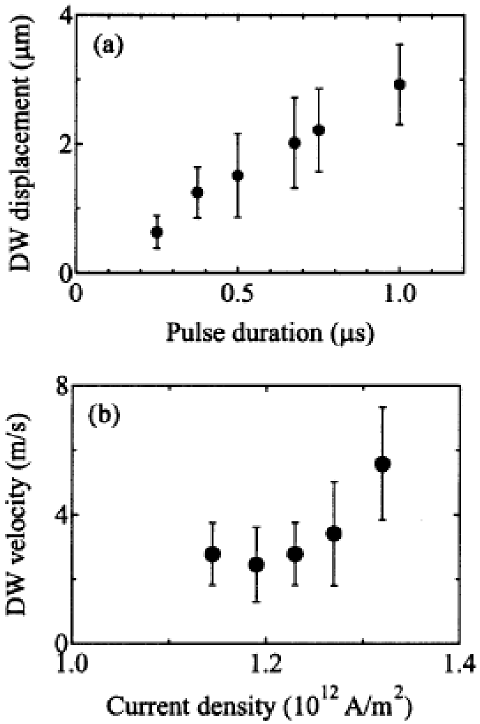


Spin torque transfer



Current induced domain wall displacement

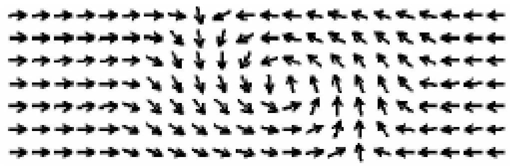


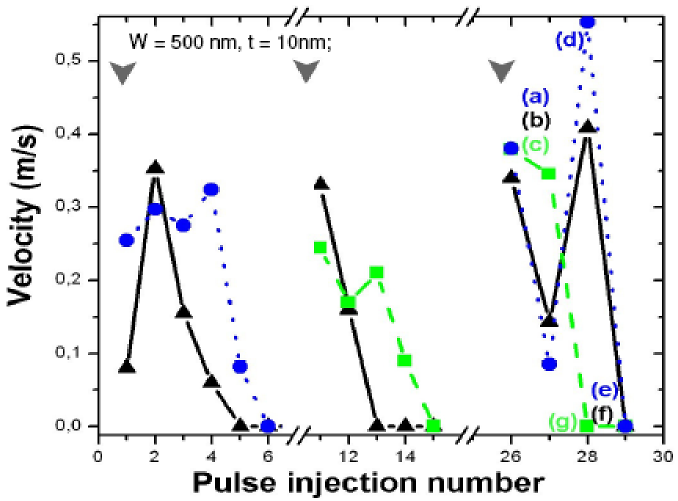


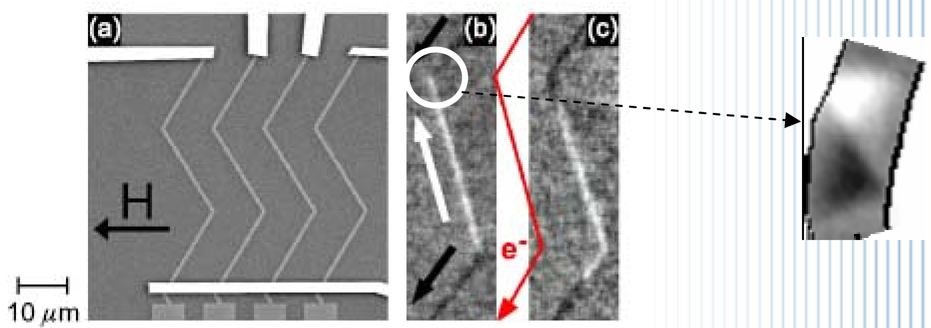
A. Yamaguchi et al., Phys. Rev. Lett. 92, 077204 (2004)

Using other materials (highly spin- polarized halfmetallic ferromagnets or materials with large anisotropies, etc.) lower critical current densities and higher velocities are obtained.

Current induced domain wall structure change





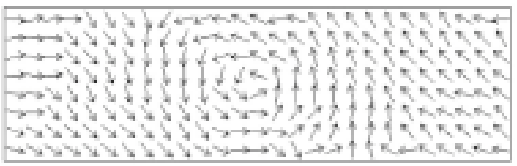


Wall velocity is constant at first but starts to vary.

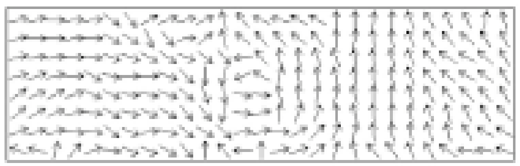
After a few injections the wall might stop.

The electrical current induces both motion and distortion of the wall

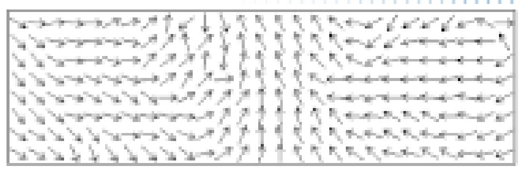
Pulse 1



Pulse 2



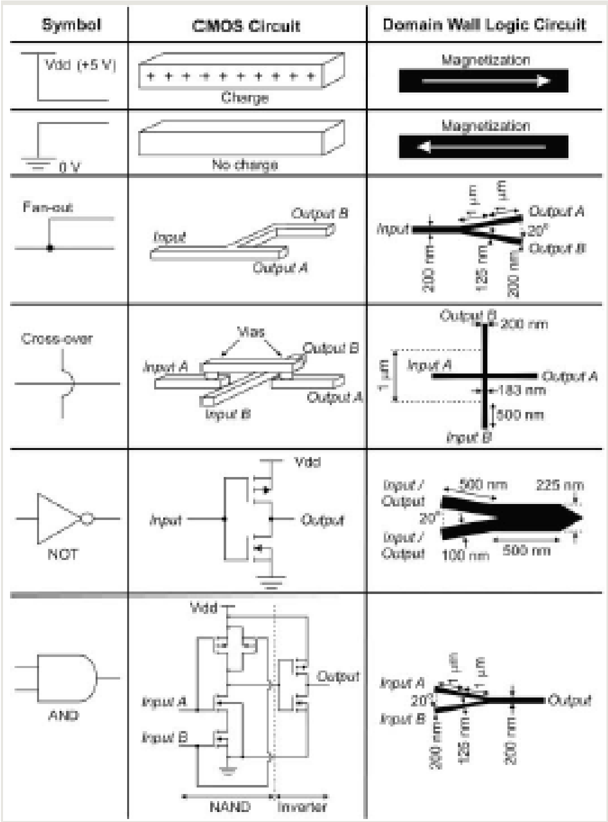
Pulse 3



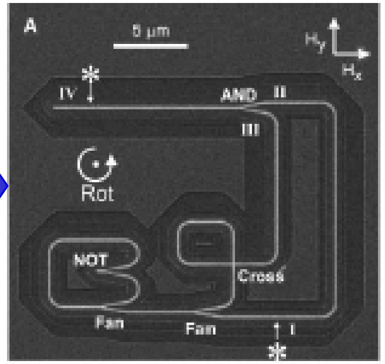
M. Kläui et al., Phys. Rev. Lett. 95, 026601 (2005)

Applications

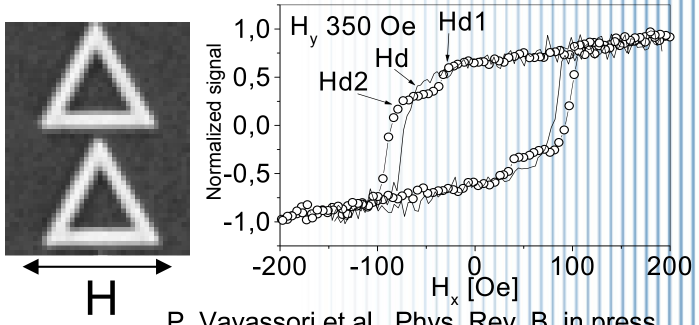
Magnetic Domain-Wall Logic devices



D. A. Allwood et al., Science 309, 1688 (2005)

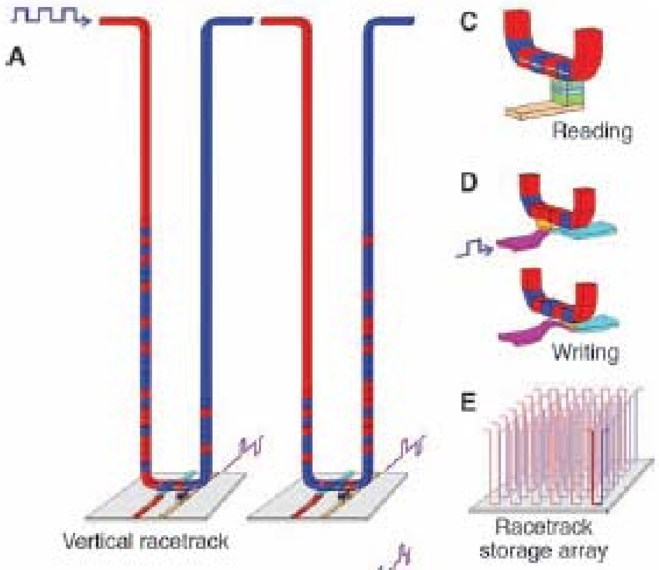


Domain-Wall displacement controlled by localized fields: logic gates.



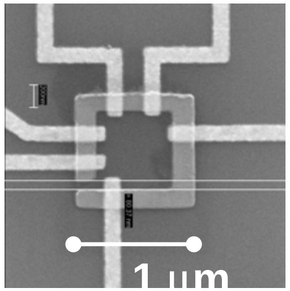
P. Vavassori et al., Phys. Rev. B, in press

Magnetic Domain-Wall Racetrack Memory



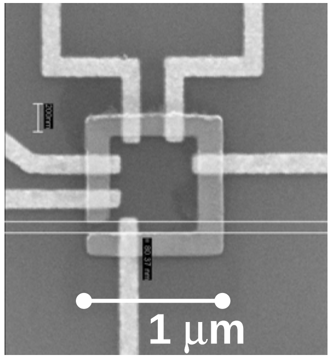
S. S. Parkin et al., Science 320 , 90 (2008)

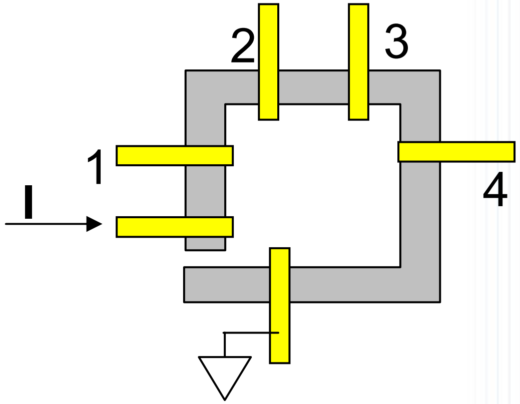
MRAM



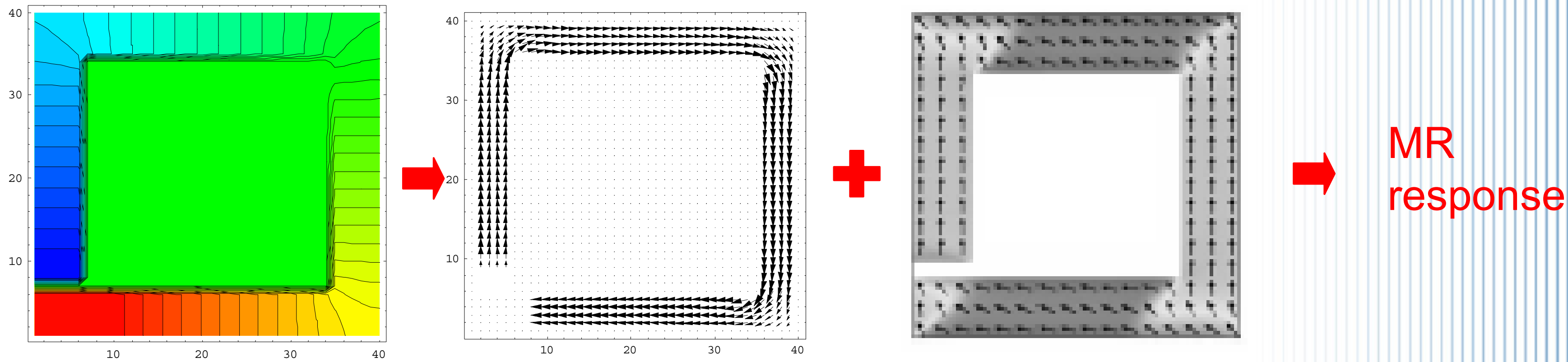
Magnetoresistance of square ring structures

Py thickness 30 nm,
width 150 nm
Au thickness 10 nm
width 100 nm
Contacts below structure



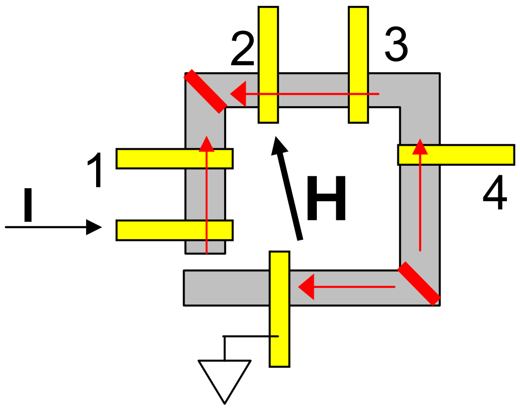


MR simulations assuming that the conventional AMR effect ($\rho=\rho_\perp+(\rho_\parallel-\rho_\perp)\cos^2\alpha$) due to the presence of head-to-head type domain walls is the main source of magnetoresistance.

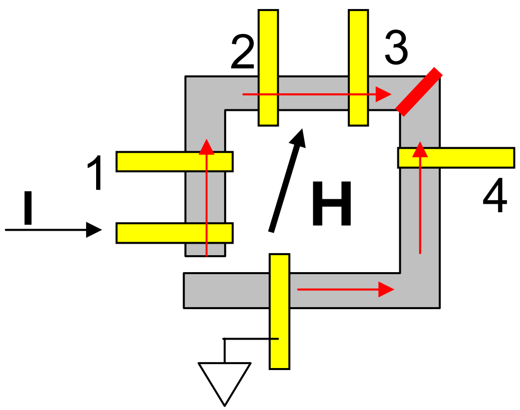


Equipotential Current Micromagnetics

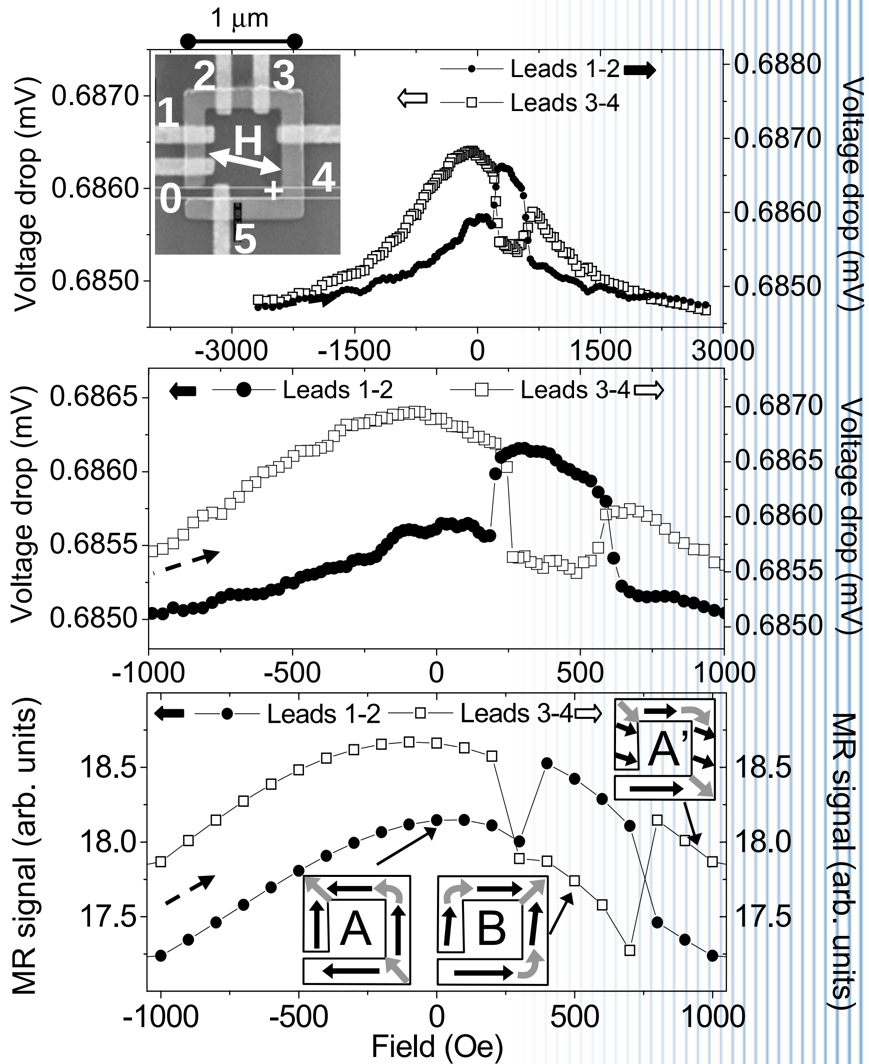
Comparison between measurements and simulations



Onion “A":
R12 low
R34 high

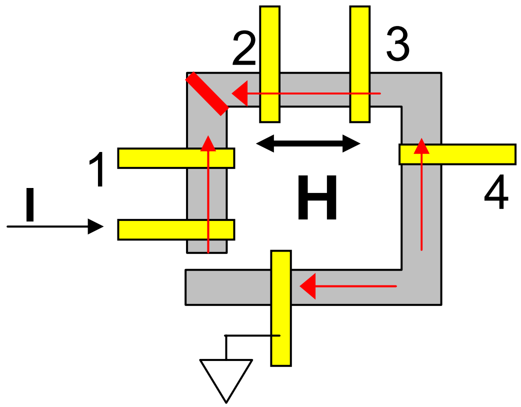


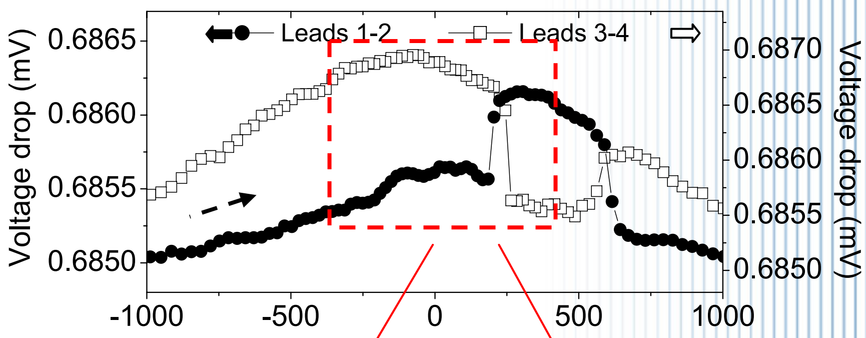
Onion “B":
R12 high
R34 low

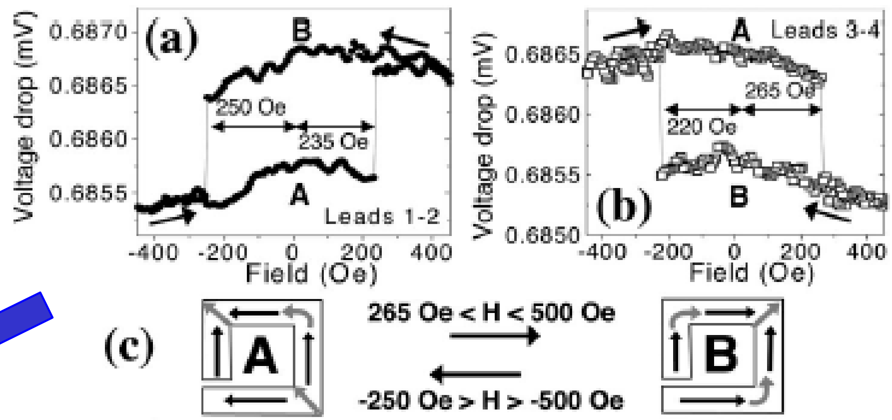


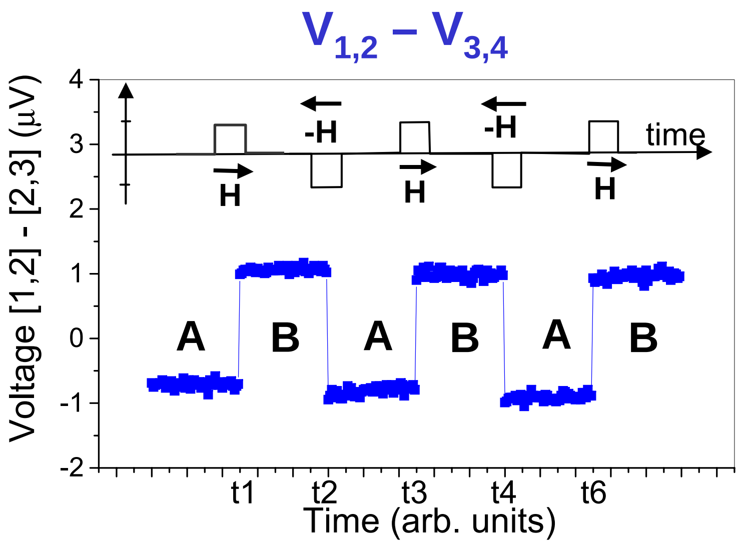
P. Vavassori et al. Appl. Phys. Lett. **91**, 091114 (2007)

Sweeping the DW back and forth with a field

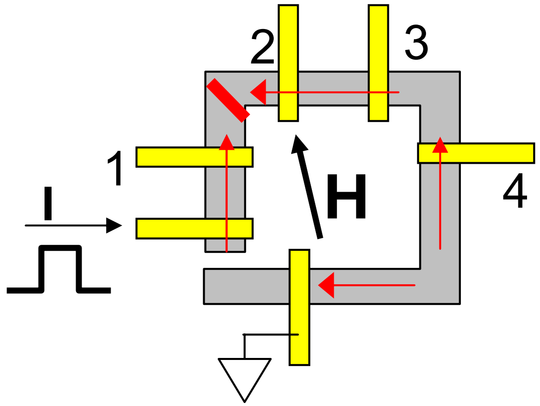




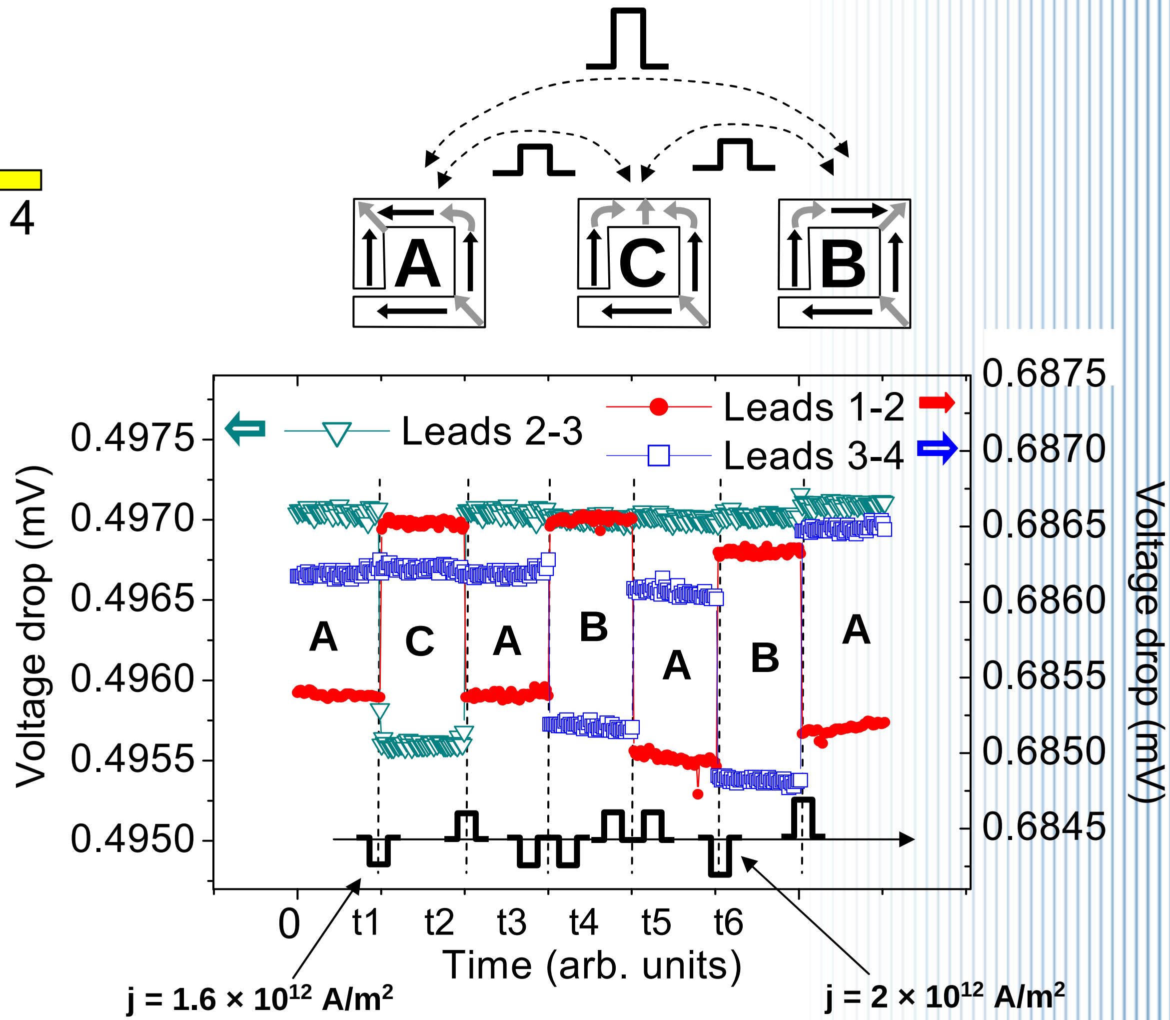




Current induced domain wall motion



j=1.6 - 2 × 10^{12} A/m²
Δt = 10 μs



The device can be fully operated with current

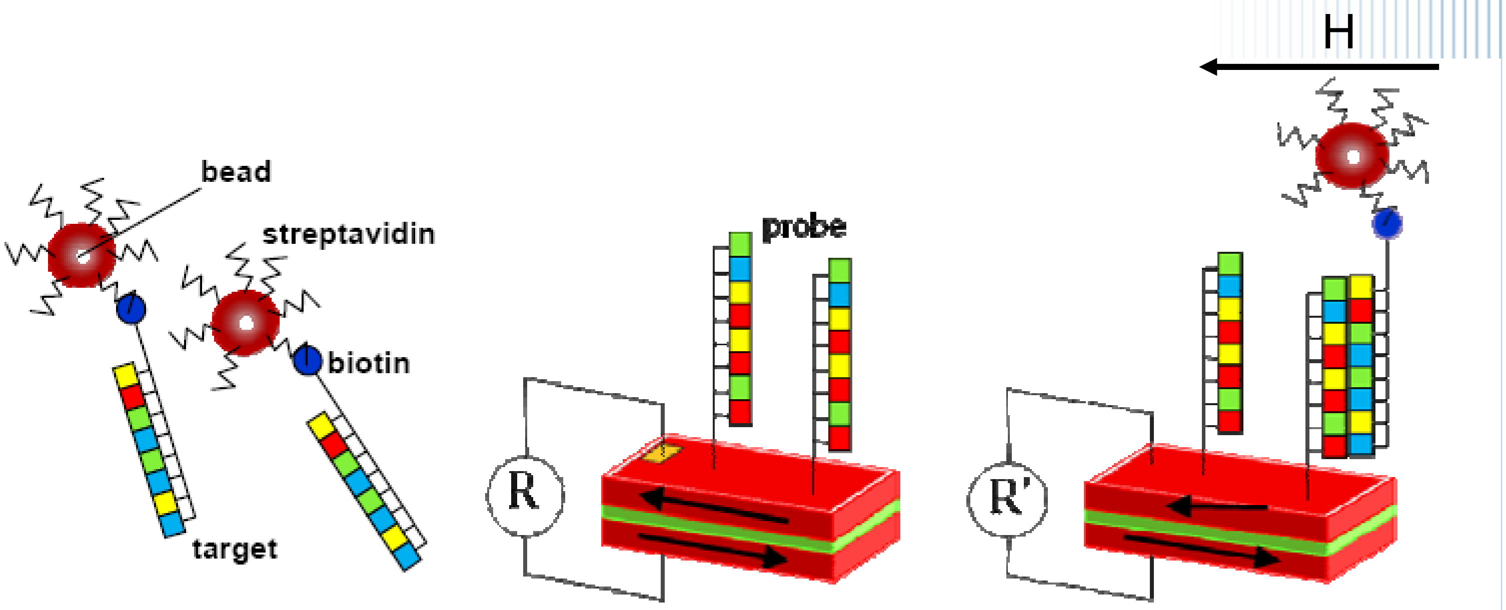
P. Vavassori et al. Appl. Phys. Lett. **91**, 093114 (2007)

Bimolecular recognition

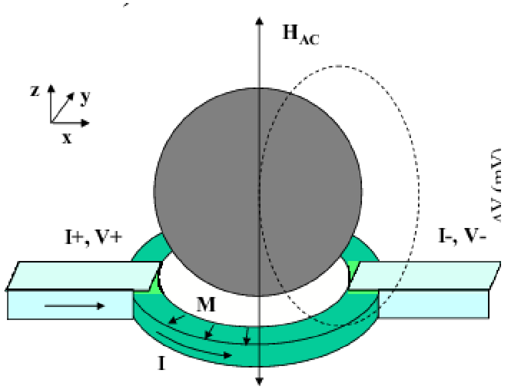
Biomolecular recognition is the interaction between biomolecules showing affinity towards each other or presenting some sort of complementarities between them.

Examples of these interactions are DNA-DNA hybridization, antibody-antigen recognition and general ligand-receptor binding.

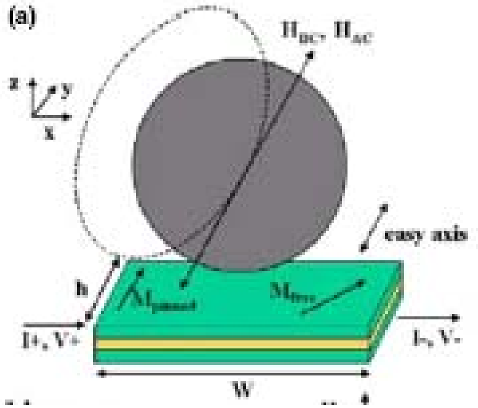
Detection of biomolecular recognition has a potential high impact on diagnosis in medicine, pharmaceutical research and environmental analysis.



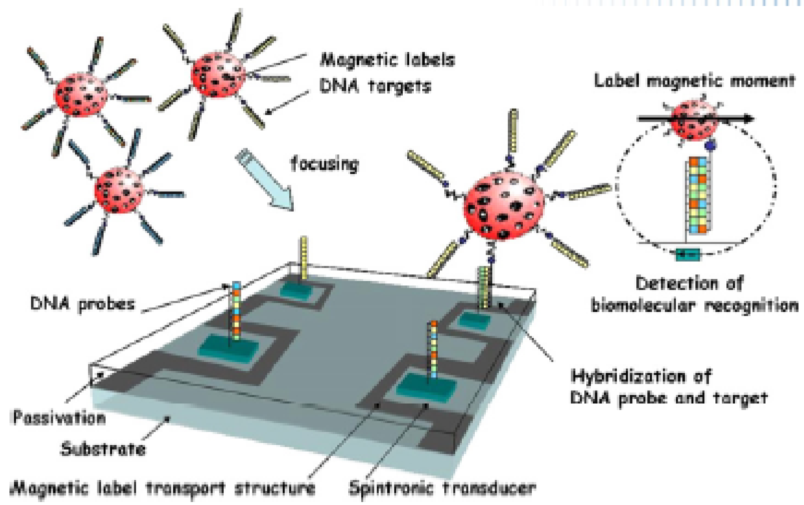
Spintronic nanosensor for detection of bimolecular recognition

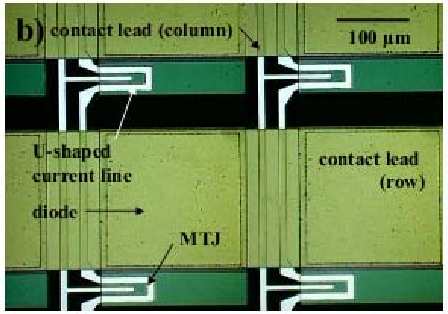


AMR



GMR - MTJ





Focusing lines

P. P. Freitas et al., J. Phys.: Condens. Matter **19** (2007) 165221

Detection of bimolecular recognition

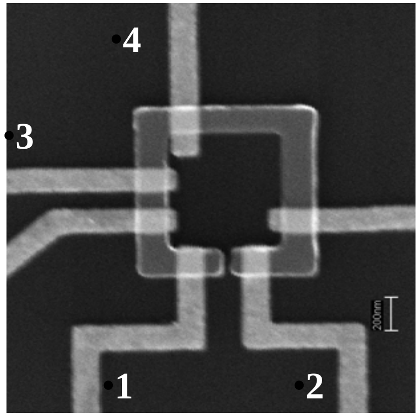
The label may be a radioisotope, enzyme, or a fluorescent molecule, as in the case of light induced fluorescence (LIF) detection techniques. Also label free techniques have been proposed (cantilever, optical resonators, electrochemical devices, ...).

Why magnetic beads:

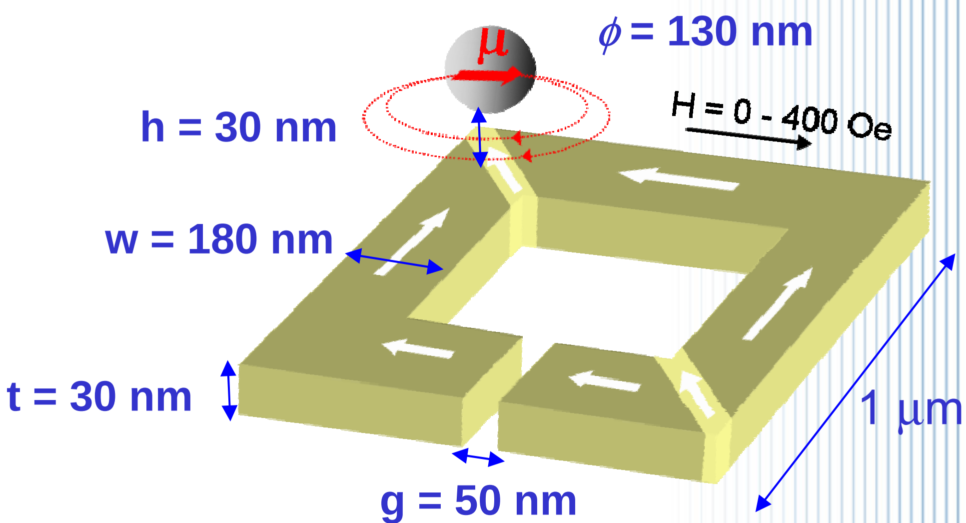
- a clear advantage of spintronic sensors with respect to LIF systems is represented by the electrical reading, not requiring bulky and expensive optical systems (lab-on-chip).
- the magnetic properties of the beads are stable over time, because magnetism is not affected by reagent chemistry or subject to photo-bleaching (a problem with fluorescent labelling);
- magnetism may be used to remotely manipulate the magnetic particles;
- a number of very sensitive magnetic field detection devices have been developed during recent years, such as GMR, MTJ, and Hall sensors.

- **Intense research is presently directed toward the development of high sensitivity magnetoresistive sensors for the detection of single magnetic beads of nanometric size in order to achieve the limit of one protein - one bead and to reduce the perturbation on the chemical affinity between target and probe molecules.**

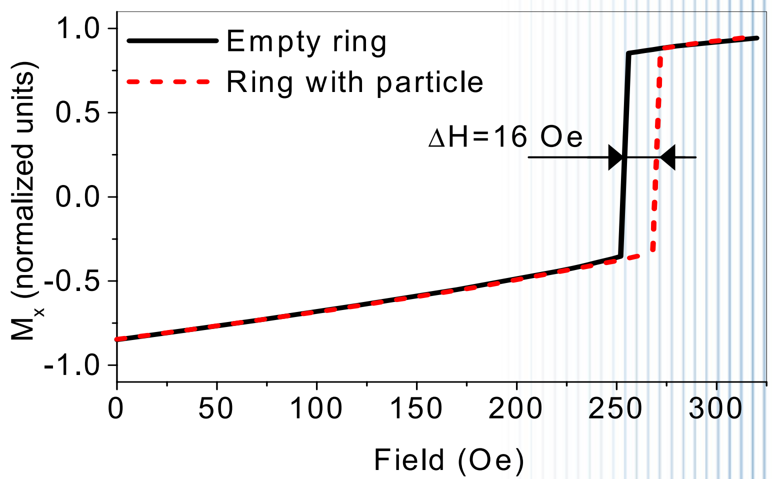
DW displacement for single nanometric magnetic bead detection



The structure has been capped with 30 nm thick SiO_2 layer



3D Micromagnetic simulations



Parameter used for the bead:

commercial MICROMOD nanomag®-D

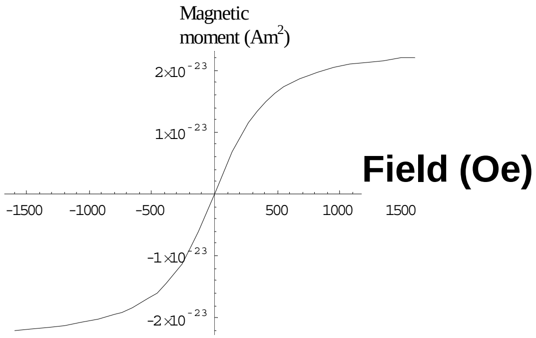
with diameter 130 nm and magnetic moment

$\mu \approx 150 \times 10^{-15}$ emu at 250 Oe (130 emu/cm^3)

P. Vavassori and R. Bertacco, patentt application TO2008A000314.
P. Vavassori et al. Appl. Phys. Lett., submitted.

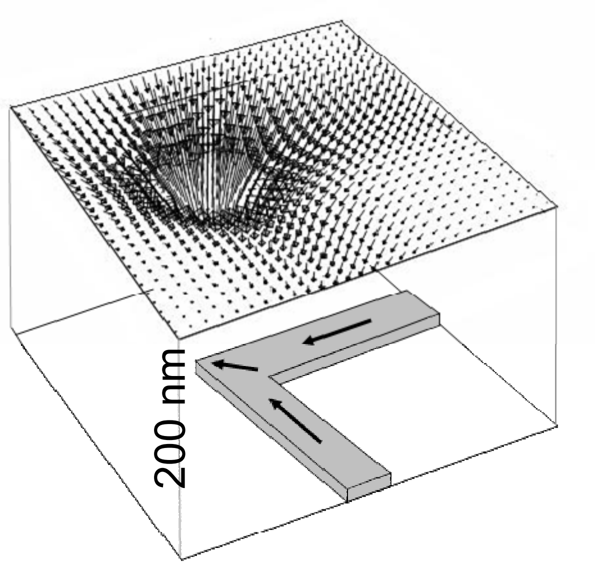
Trapping field

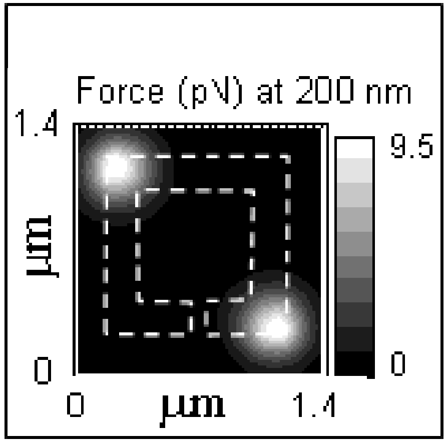
First advantage:
no external action is required to place the bead over the corner, the active area of the sensor, a problem common to all the magnetoresistive sensors developed so far.



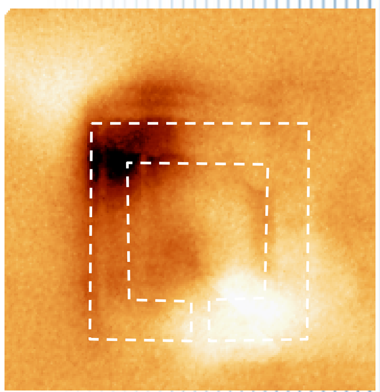
F = $-\mu_0(\mu\nabla)$ **H** where $\mu = \mu(H)$**h** with $\mu(H)$ the known magnetization curve of the bead (provided by the manufacturer) and **h** is a unit vector parallel to the field **H**.

The magnetic field **H** created in the surrounding space by the nano-structure in the magnetic configuration with a DW in the corner of the ring has been calculated with OOMMF.





Intensity plot of the force

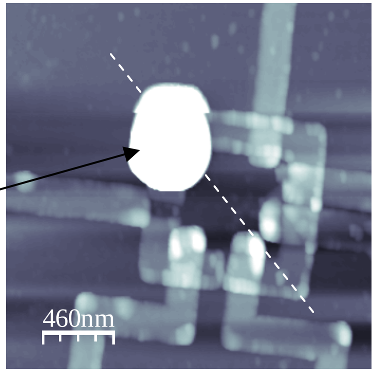


MFM image of the sensor

Preliminar experimental results

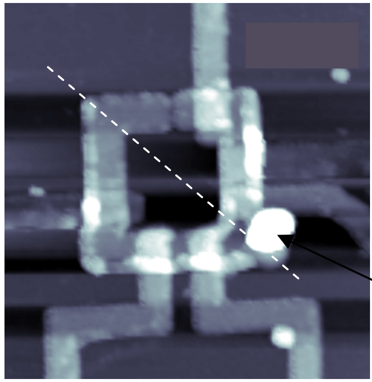
Test of self-focusing dispensing a solution containing the beads over the sensor

Beads 50 nm



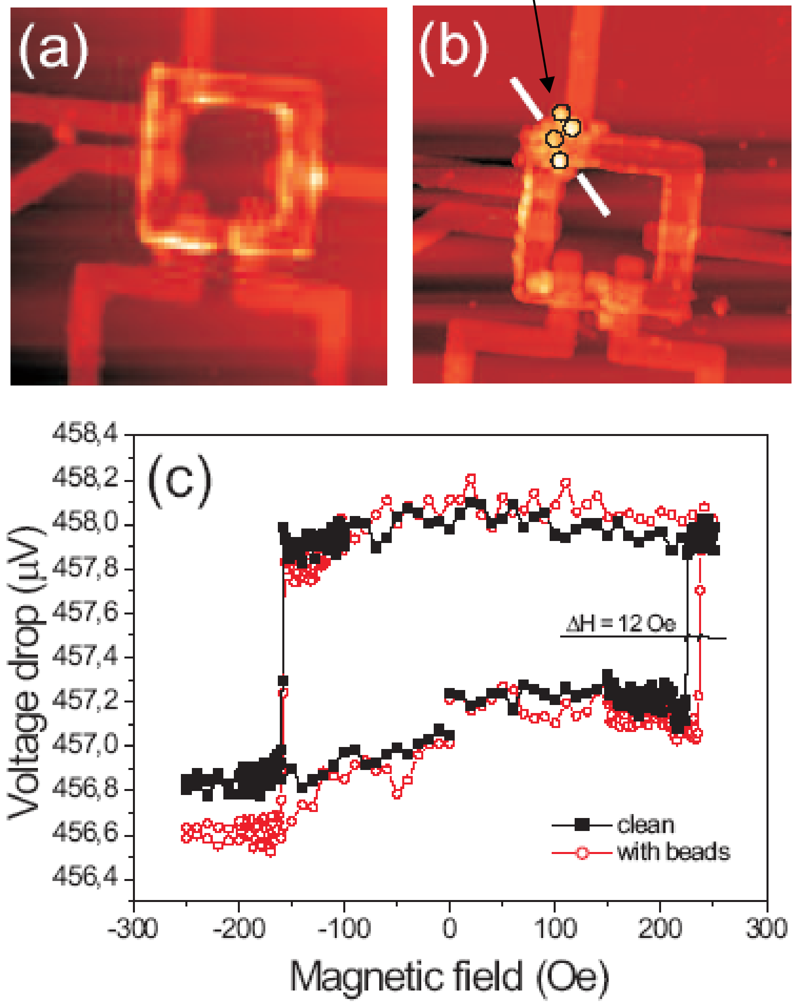
cluster

Beads 130 nm



single bead

Fragmentation in 80 nm diameter beads



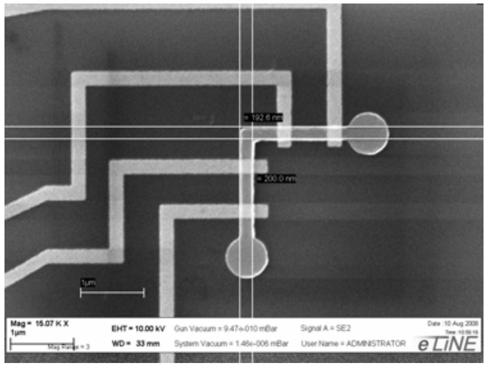
The width of the ring should be comparable with the bead diameter

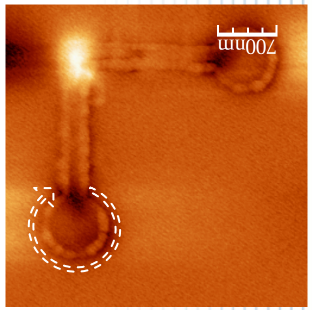
Preliminar conclusions and perspectives

The results demonstrate the viability of the sensing concept proposed.

Micromagnetic simulations show that the reduction of the width of the ring to the nano-bead diameter doubles the value of ΔH and will reduce the possibility of multiple beads clustering. This in conjunction with the use of nano-beads of a higher magnetic moment (values up to 5 times that of the beads used here are reported in the literature for non-commercial nano-beads) can increase the achievable value of ΔH by about ten times with respect to the value obtained in this preliminary experiment.

New device





Conclusions

• I presented a short review of the domain walls structure in nanostructures showing how they can be manipulated by the use of magnetic fields and electric current.

• Their potential applications to domain wall logic and memory devices have been briefly discussed.

• Magnetotransport and head-to-head domain walls structure in Py square rings: it is shown that a domain wall can be reversibly and controllably displaced by current pulses of different polarity

• Potential applications of devices based on this kind of structures to the detection of biomolecular recognition.

Collaborations

- *M. Grimsditch,*

Materials Science Division, Argonne National Laboratory, Argonne, IL.

- *V. Metlushko,*

Dept. of Electrical and Computer Engineering, University of Illinois at Chicago, IL.

- *B. Ilic,*

Cornell Nanofabrication Facility,Cornell University, Ithaca, NY.

- *R. Bertacco*

LNESS Center, Como, Italy.

Thank you!

CIC nanoGUNE
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