Leibniz-Institut
für Festkörper- und
Werkstoffforschung
Dresden

Shapeable magnetoelectronics

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INSTITUTE FOR
MAGNA
INTEGRATIVE NANOSCIENCES

Outline

A. Stretchable magnetoelectronics

I. GMR on flexible and stretchable polymer substrates

II. Stretching of GMR multilayers

B. Rolled-up GMR sensor

I. Rolled-up technology

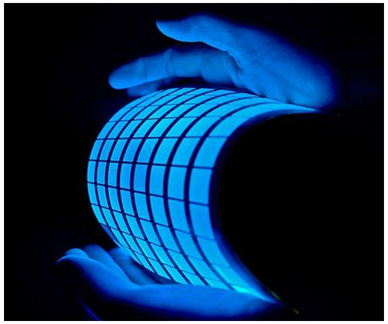
II. Micro-fluidics applications

Summary & Outlook

Stretchable magnetoelectronics

Electronics become flexible

LEDs

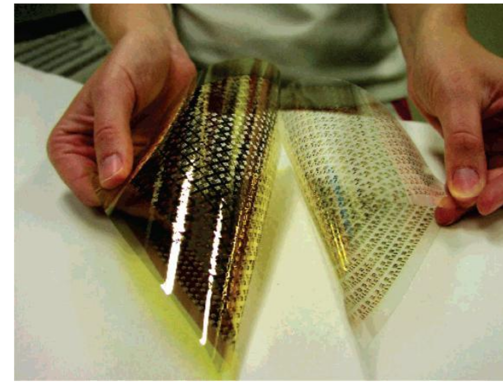


New York Times (2009)

Displays

Sony (2007)

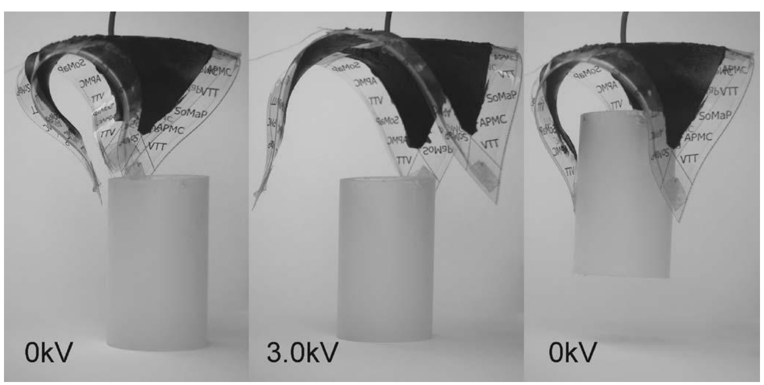
RFID-Tags



Kelley et al., Chem. Mater. (2004)

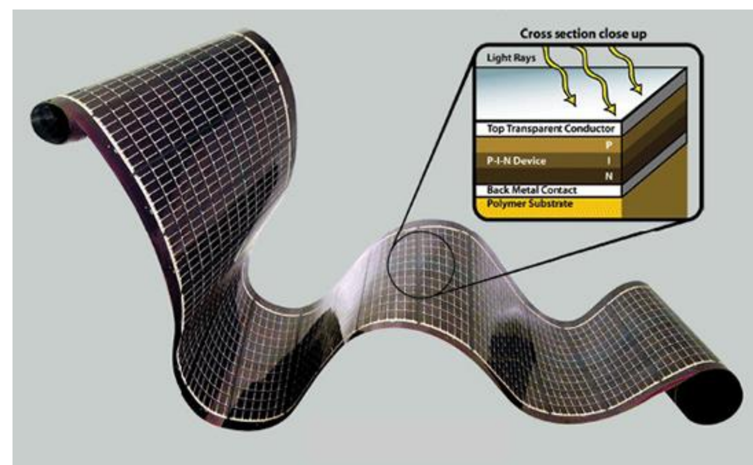
Flexible (and stretchable) magnetic sensor!

Actuators



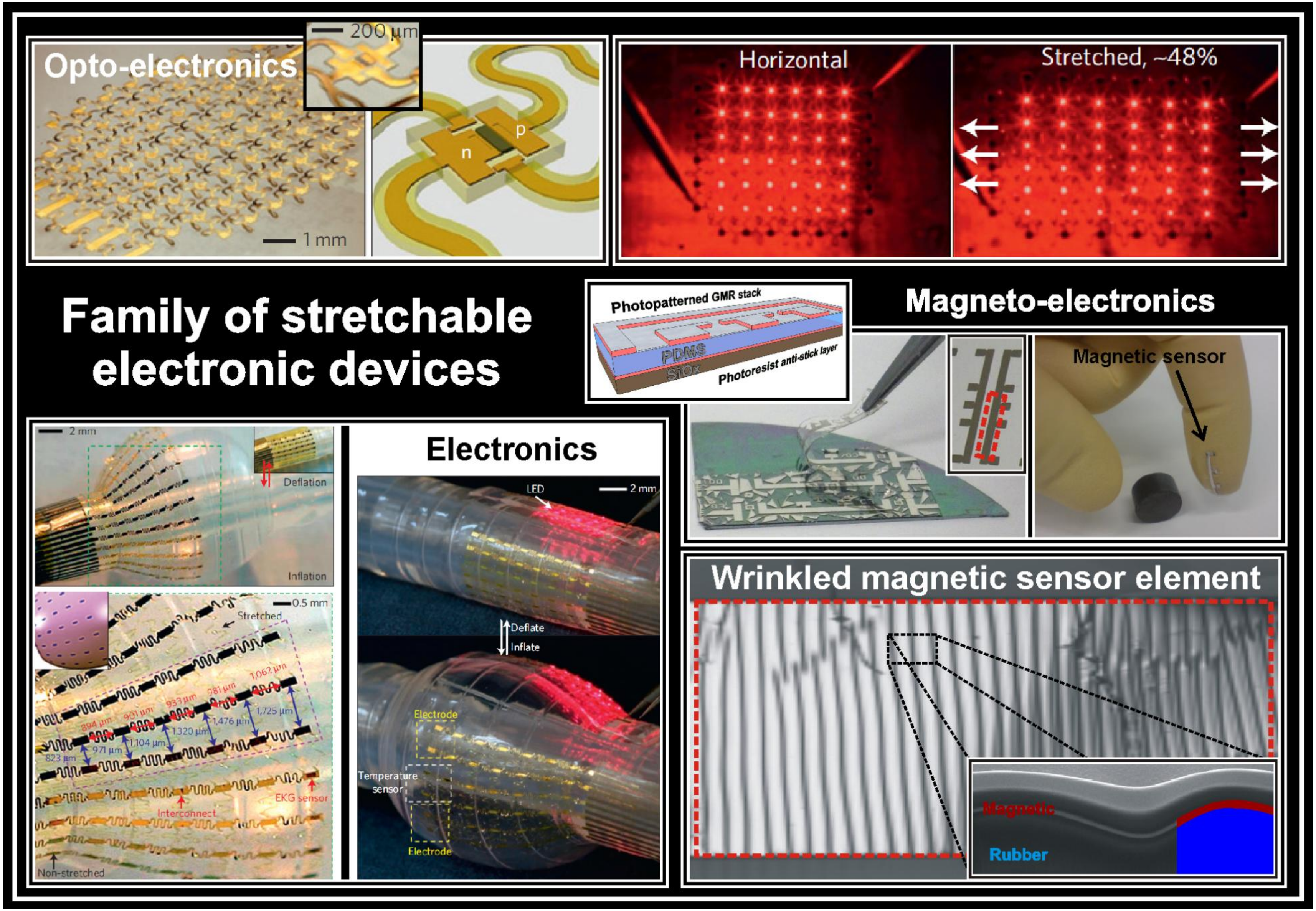
Kofod et al., Appl. Phys. Lett. (2007)

Solar Cells



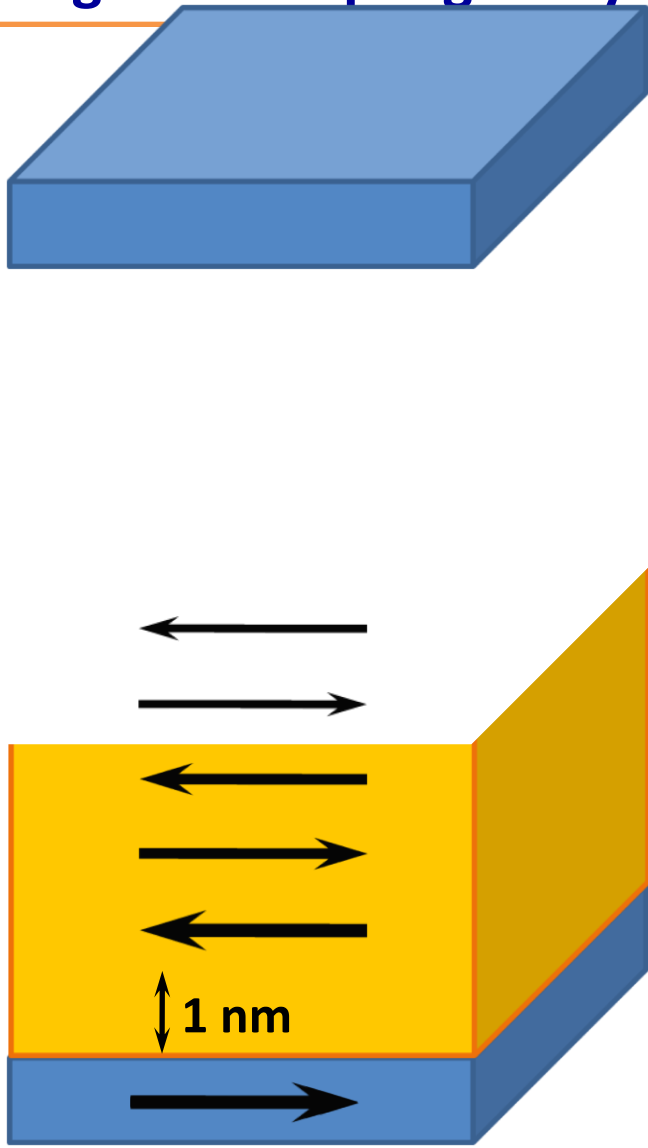
PowerFilm Solar (2010)

Electronics become flexible

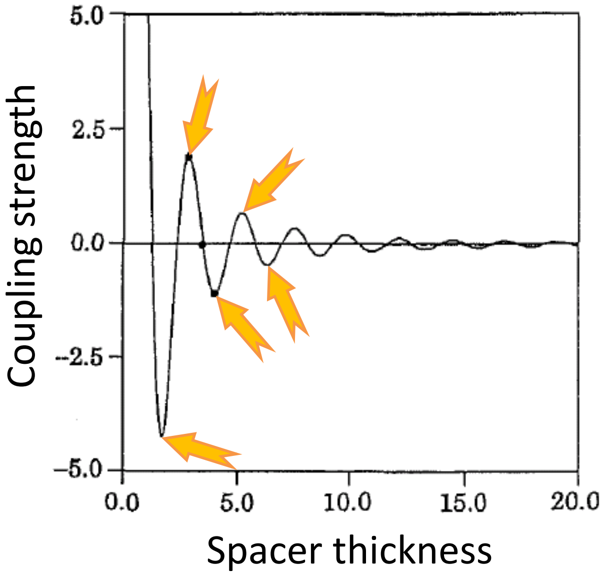


Kim et al., *Nature Mater.* **9**, 929 (2010); Kim et al., *Nature Mater.* **10**, 316 (2011); Melzer et al., *Nano Lett.*, accepted.

Magnetic coupling in layered structures



Interlayer Exchange Coupling[1]



Varies in an oszillatory manner with separation of magnetic layers

1st antiferromagnetic maximum

[1] Grünberg et al., *Phys. Rev. Lett.* **57**, 2442 (1986)

GMR in exchange coupled multilayers

GMR multilayer element

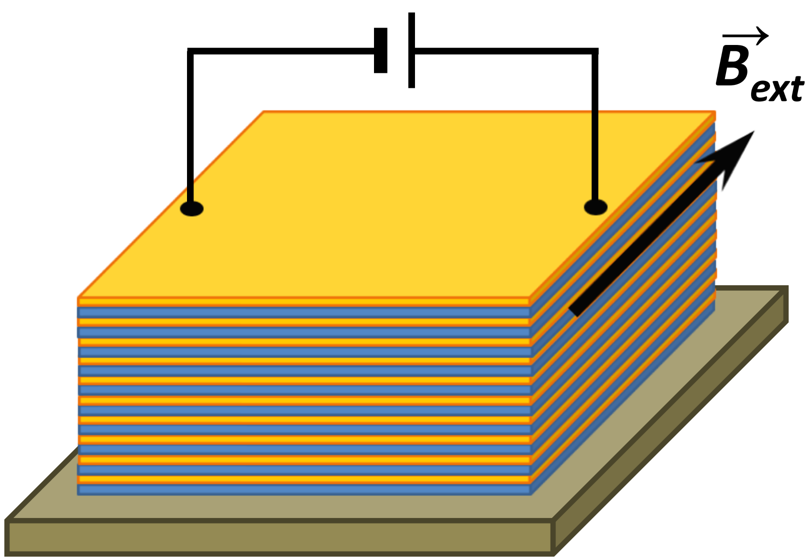
20 to 50 doublelayers of ferro- and nonmagnetic conductors

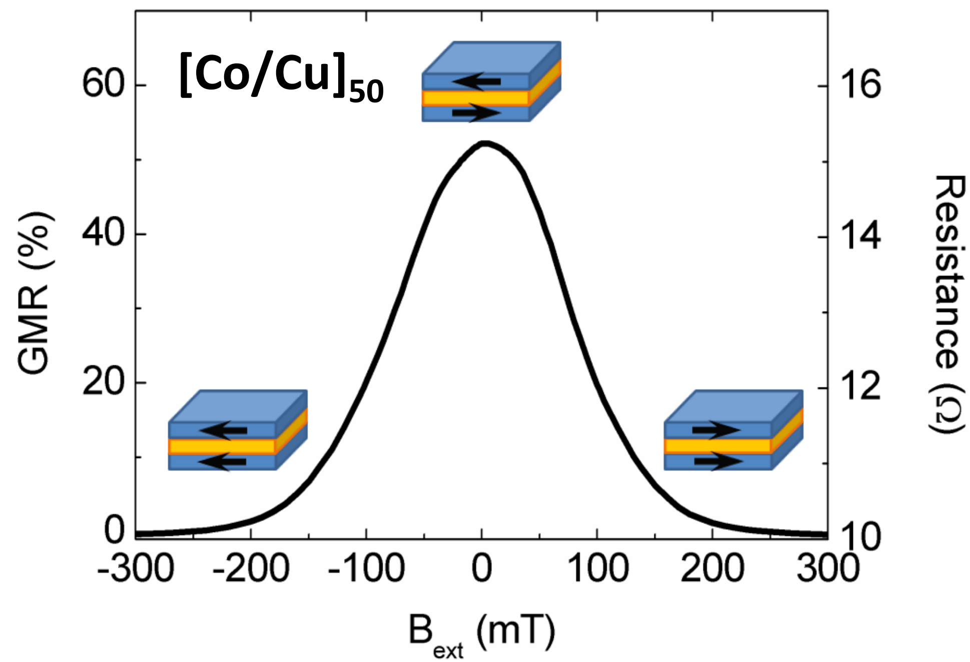
Current-in-plane (CIP)

Sensitive to in-plane fields

Giant **M**agneto-**R**esistance

$$GMR(B) = [R(B) - R_{sat}] / R_{sat}$$





Does GMR work on polymer materials?

Previous works

S.S.P. Parkin, et al. 1992: GMR Multilayers on Kapton[3]

Polymer substrates for light-weight HDD read heads

GMR ratio of up to 38% for Co/Cu multilayers at room temperature

S.S.P. Parkin 1996: EBS on polymer substrates[4]

Exchange biased sandwich (EBS) structures for lower saturation fields

Various polymer substrates tested: Kapton, PE, Mylar, Ultem

Magnetoresistance ratios of ≈ 3%

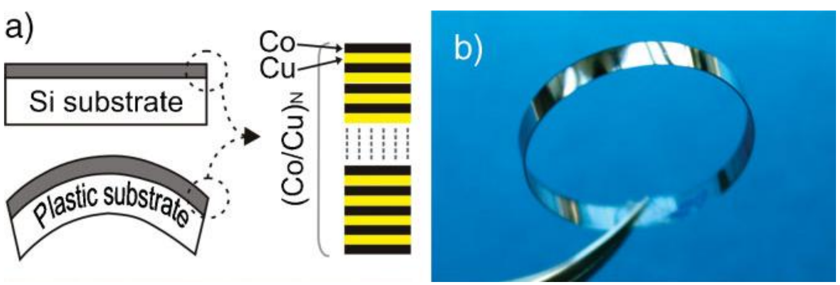
> silicon or glass substrates. The ability to grow such structures on plastic films suggests the possibility of manufacturing flexible magnetoresistive heads for magnetic recording technology applications. A second important

[3] Parkin, et al., *Jpn. J. Appl. Phys.* **31**, 1246 (1992)

[4] Parkin, *Appl. Phys. Lett.* **69**, 3092 (1996)

Previous works

Y.F. Chen, et al. 2008
Mechanically tunable GMR[5]

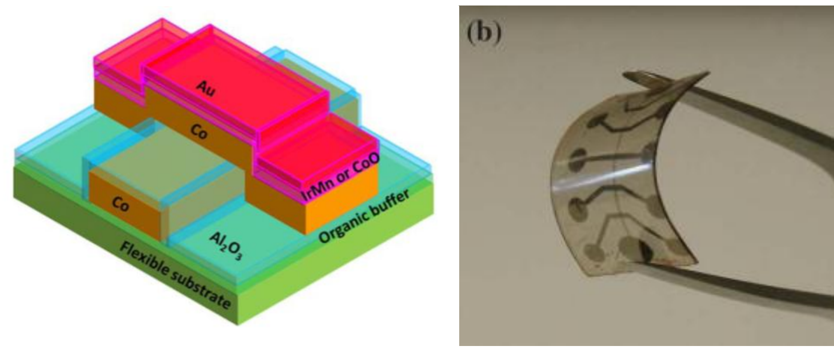


Co/Cu Multilayers on transparency

In-plane tensile strain reduces thickness of Cu spacer layers

→ Tuning the exchange coupling of the magnetic layers by stretching

C. Barraud, et al. 2010
MTJs on flexible substrates[6]



Magnetic tunnel junction (MTJ) on a flexible polymer sheet

TMR ratio of ≈ 20 %

Similar TMR magnitude and tunnel resistance before and after bending

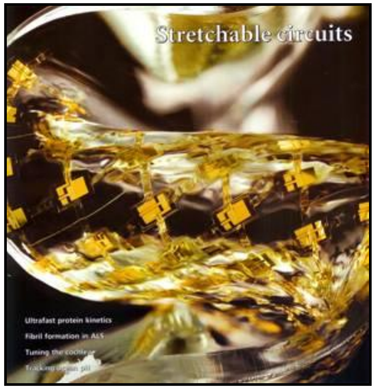
[5] Chen et al., *Adv. Mater.* **20**, 3224 (2008)

[6] Barraud et al., *Appl. Phys. Lett.* **96**, 072502 (2010)

Scope of our work

GMR elements on an elastic substrate (Rubber)

- Reversible application of tensile strain
- Elastic response of the GMR sensor
- Integration into stetchable electronic systems[7]



Enhancement of sensor performance on flexible and stretchable polymer substrates

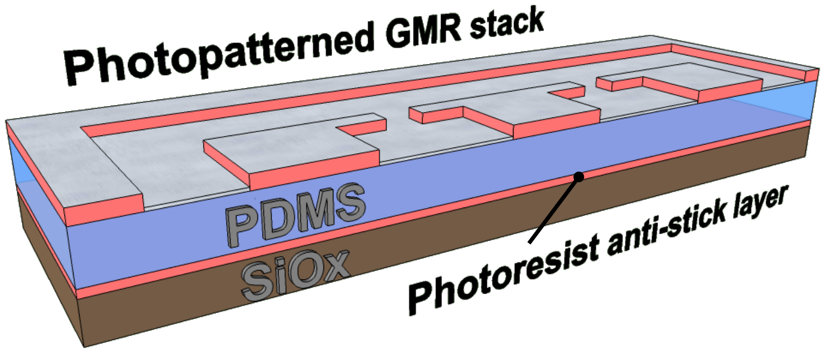
- Increase sensitivity for biosensor applications
- Increase GMR magnitude (comparable to sensors on rigid inorganic substrates)

[7] Kim et al., *PNAS* **105**, 18675 (2008)

Sample preparation

GMR layers on Poly(dimethylsiloxan) (PDMS)

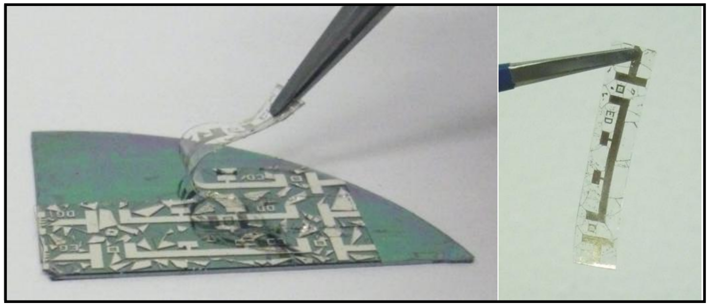
- by magnetron sputter deposition



Photolithographic patterning on the PDMS coated wafer

→ compatible to established micro-fabrication technologies

Four-point GMR measurement with current-in-plane (CIP) configuration



Pealing the rubber film from the rigid silicon support

- by means of the anti-stick layer

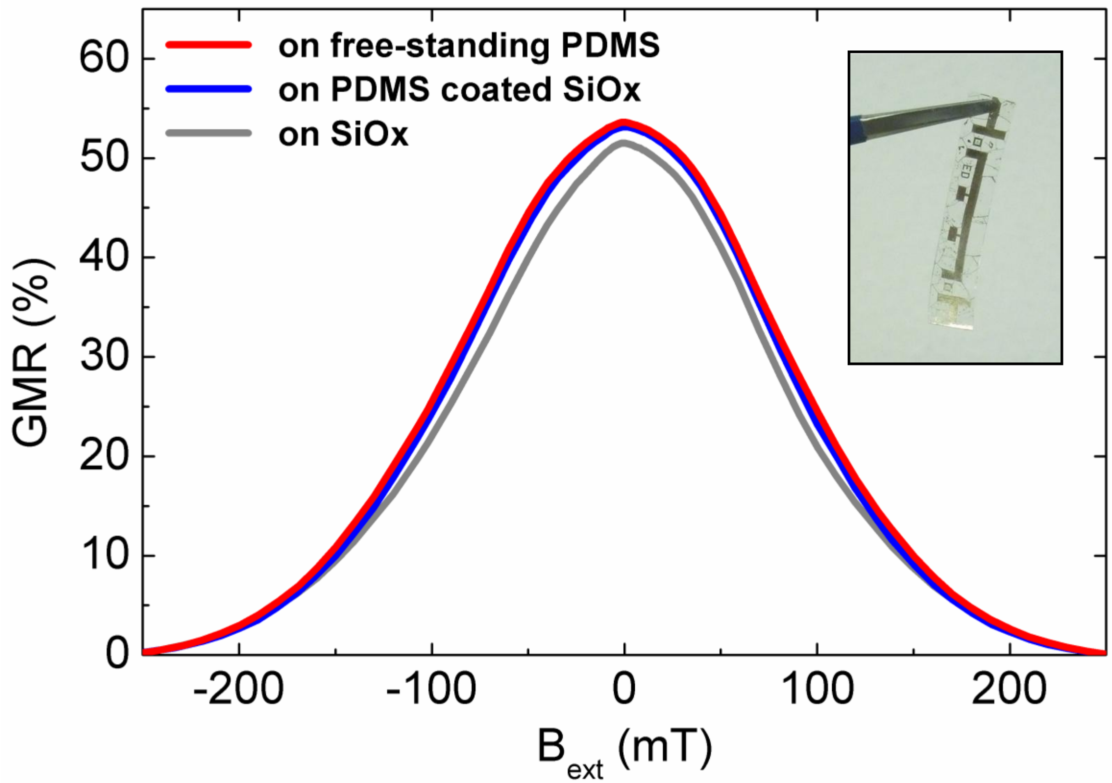
→ GMR layer on a free-standing elastic membrane

GMR measurements on free-standing films

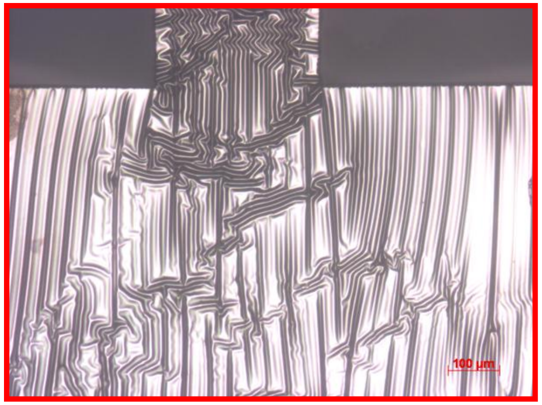
Field dependent magnetoresistance:

$$GMR(B) = [R(B) - R_{sat}] / R_{sat}$$

GMR of $[Co/Cu]_{50}$ multilayer stacks

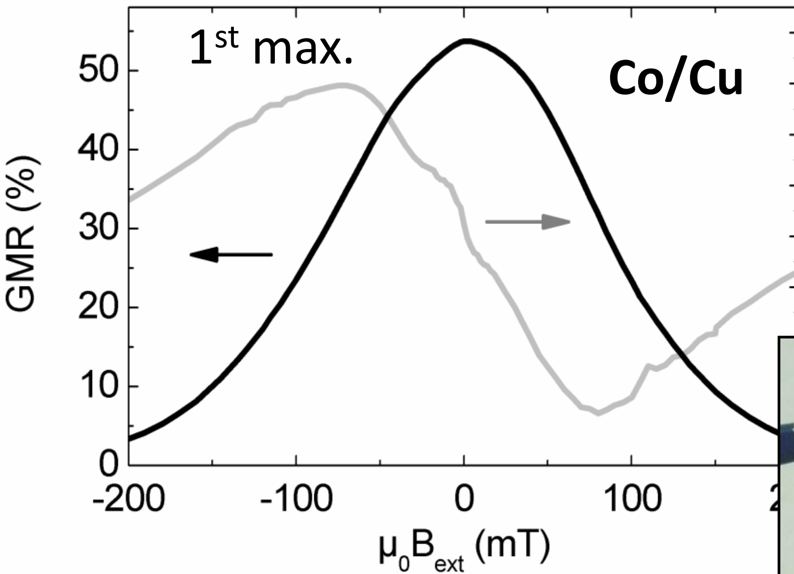


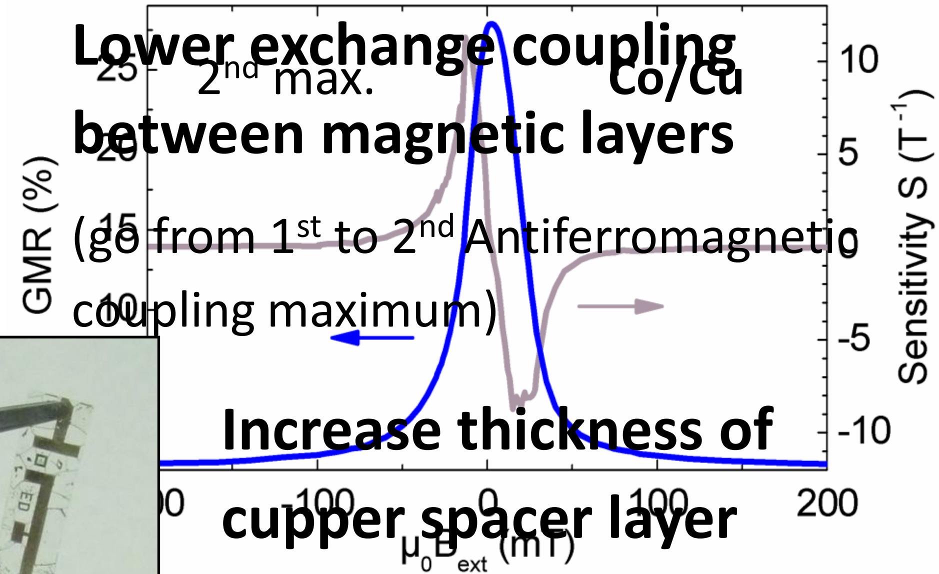
GMR layer before peel-off



GMR layer after peel-off

Sensitivity enhancement

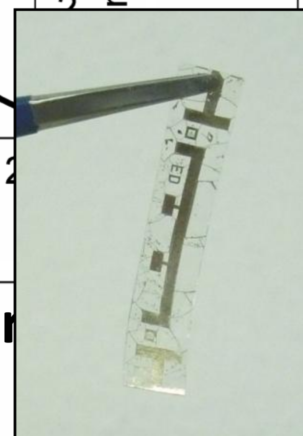


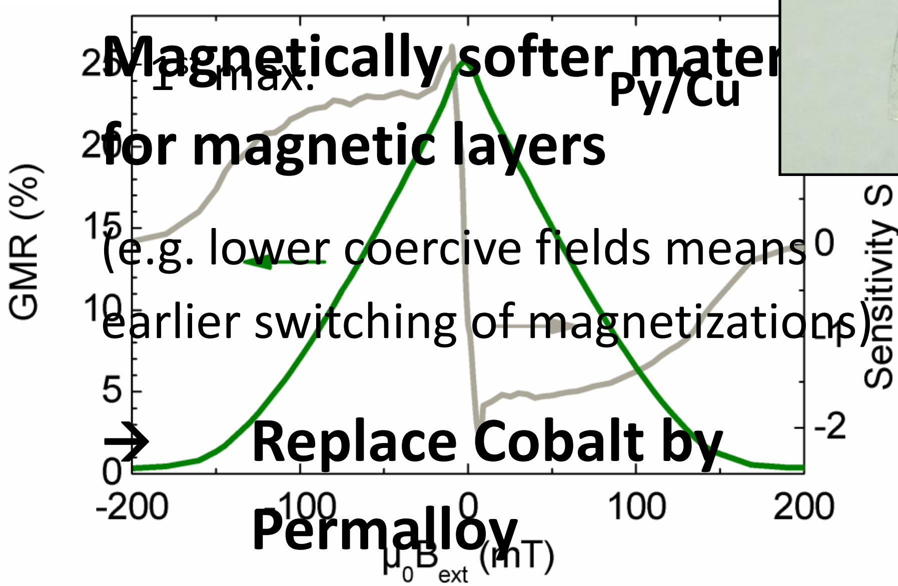


Lower exchange coupling between magnetic layers

(go from 1st to 2nd Antiferromagnetic coupling maximum)

Increase thickness of cupper spacer layer

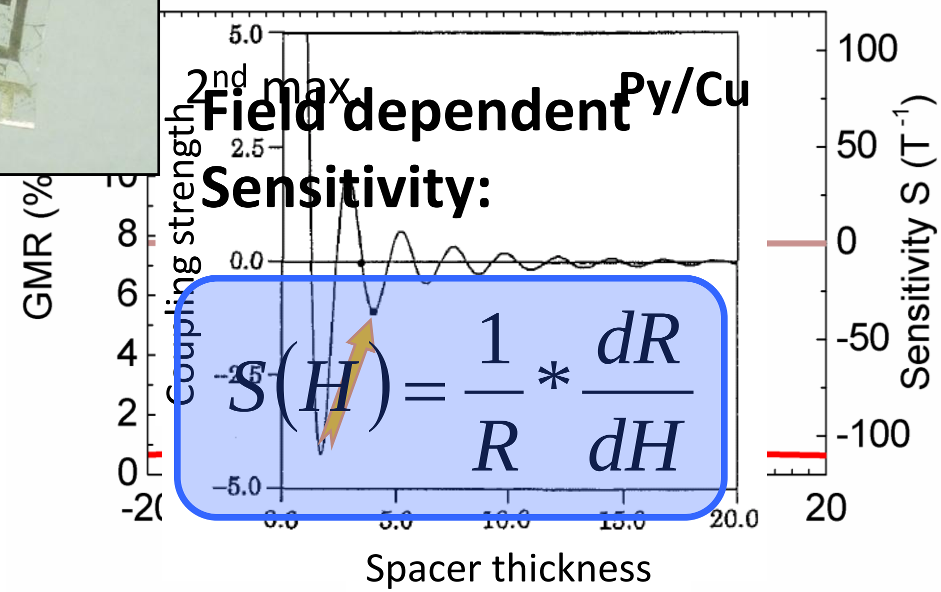




Magnetically softer material for magnetic layers

(e.g. lower coercive fields means earlier switching of magnetizations)

→ **Replace Cobalt by Permalloy**



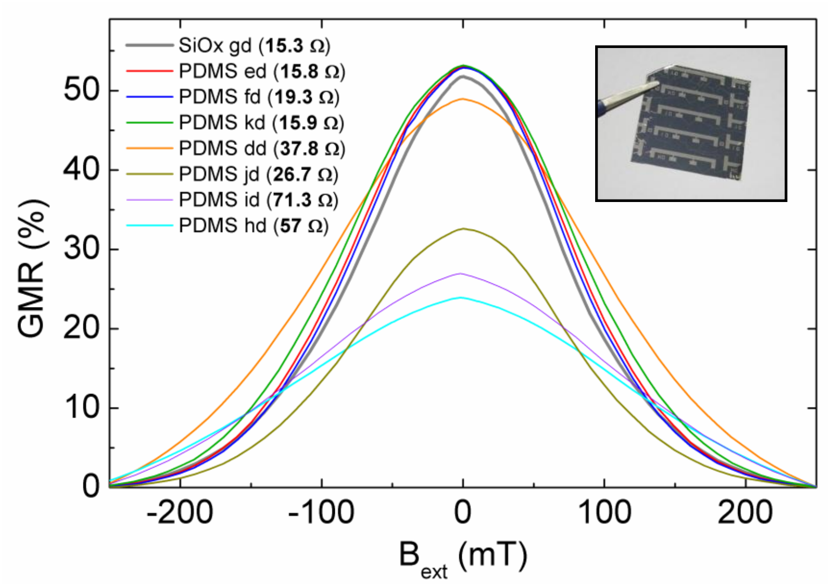
Field dependent Sensitivity:

$$S(H) = \frac{1}{R} * \frac{dR}{dH}$$

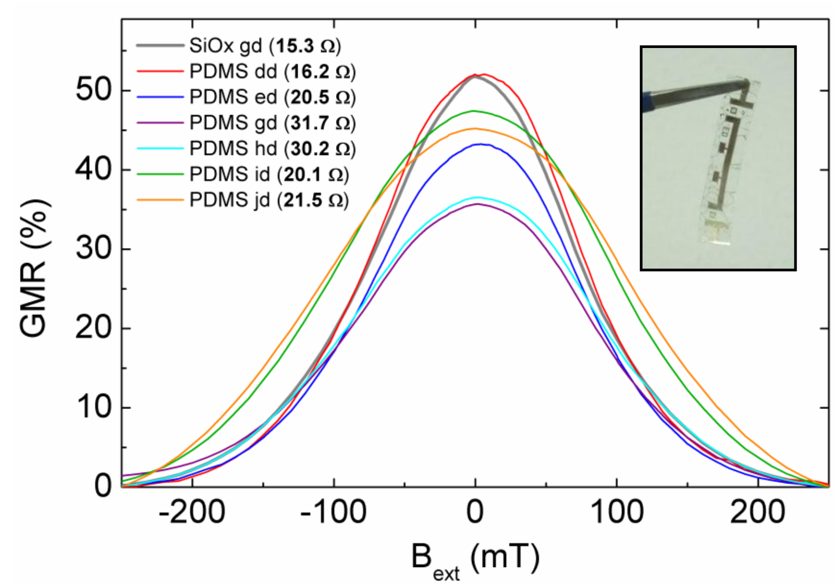
Parkin, *Annu. Rev. Matter. Sci.* **25**, 357 (1995)

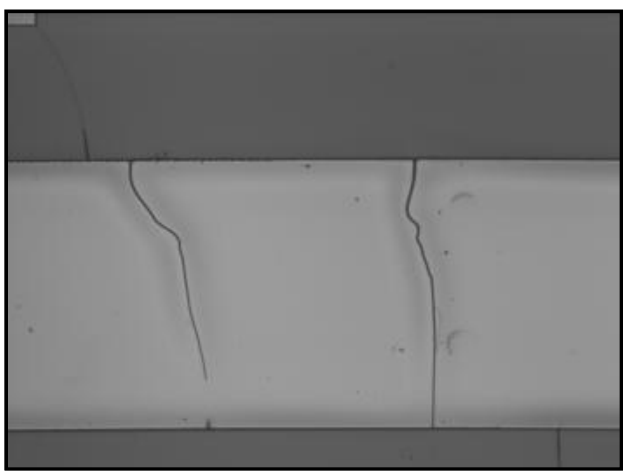
Self-healing effect on rubber membranes

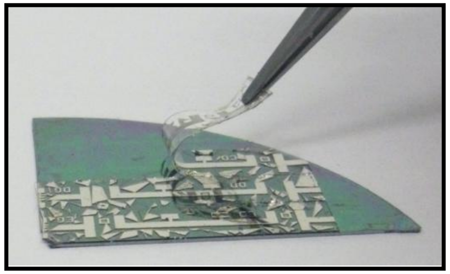
on PDMS coated silicon wafer

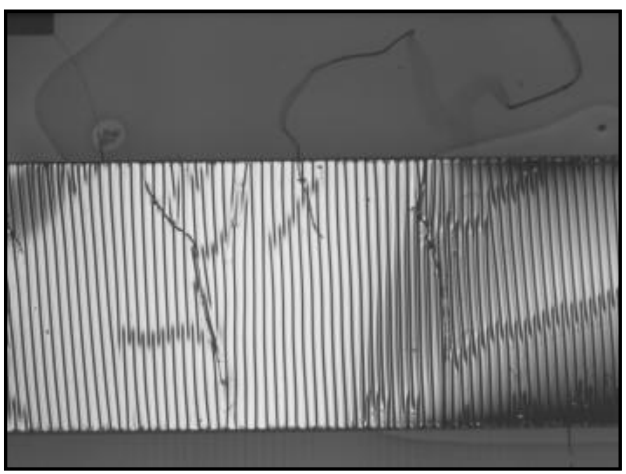


on free-standing PDMS membrane





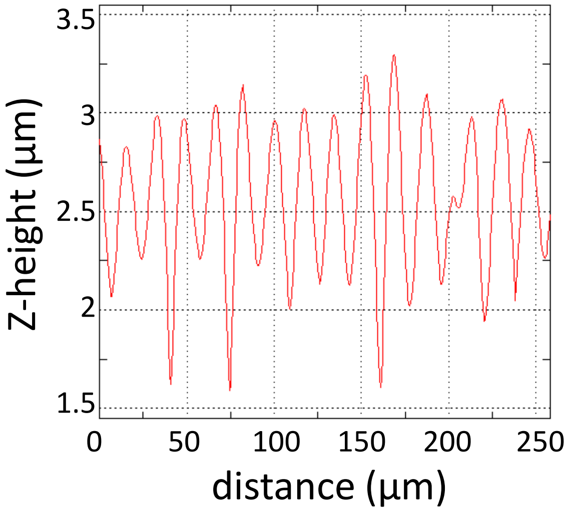


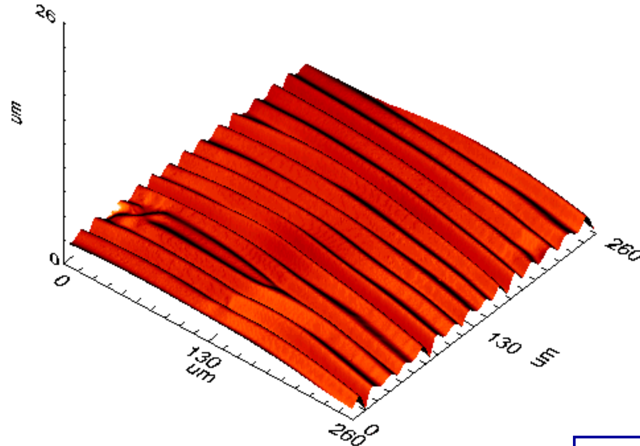


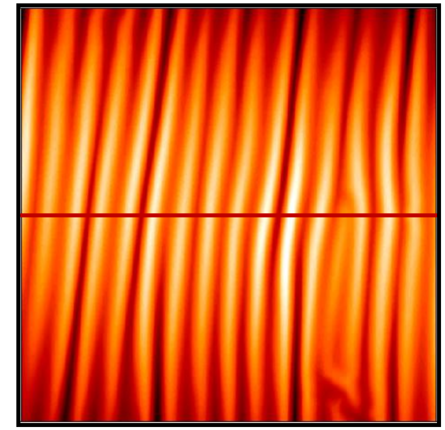
But, can we stretch this GMR device?

Wrinkling of GMR multilayers on rubber

Confocal Microscopy







- Spin-coating of PDMS
- Curing at 90°C (30 min)
- Compression suppressed
  → tensile stress in rubber
- Sputtering of GMR film
- Release from silicon wafer
- Compression of rubber
  → formation of wrinkles
- Stretchability of metal film[8]

E: Young's modulus
ν: Poisson ratio
d: Film thickness
M/P: metal film / polymer

→ Wavelength: λ ≈ 17 µm

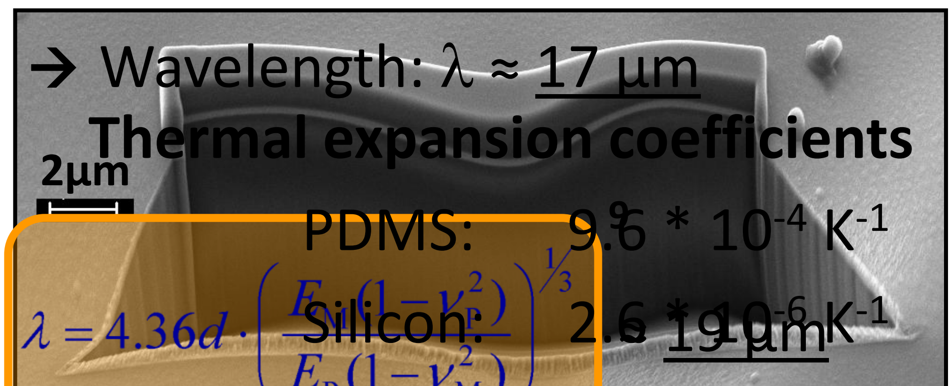
$$\lambda = 4.36d \cdot \left(\frac{E_M (1-\nu_P^2)}{E_P (1-\nu_M^2)} \right)^{1/3}$$

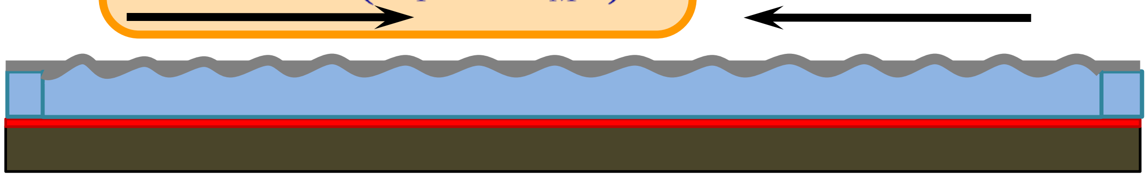
19 µm

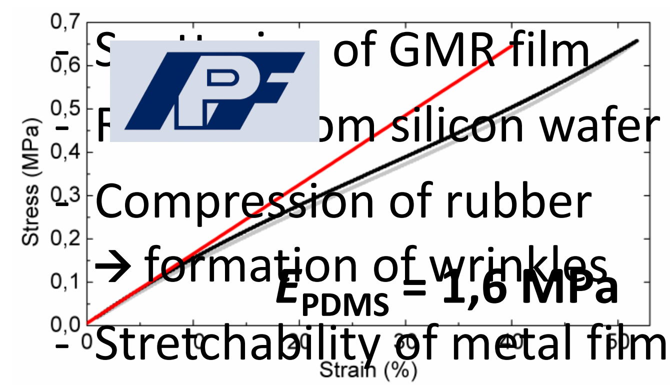
Thermal expansion coefficients

PDMS: 9.6 * 10^{-4} K^{-1}

Silicon: 2.6 * 10^{-6} K^{-1}





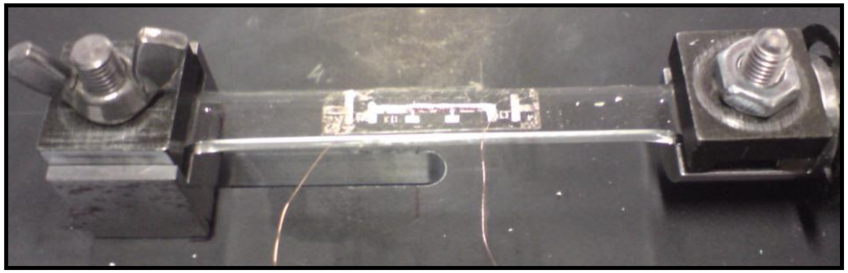


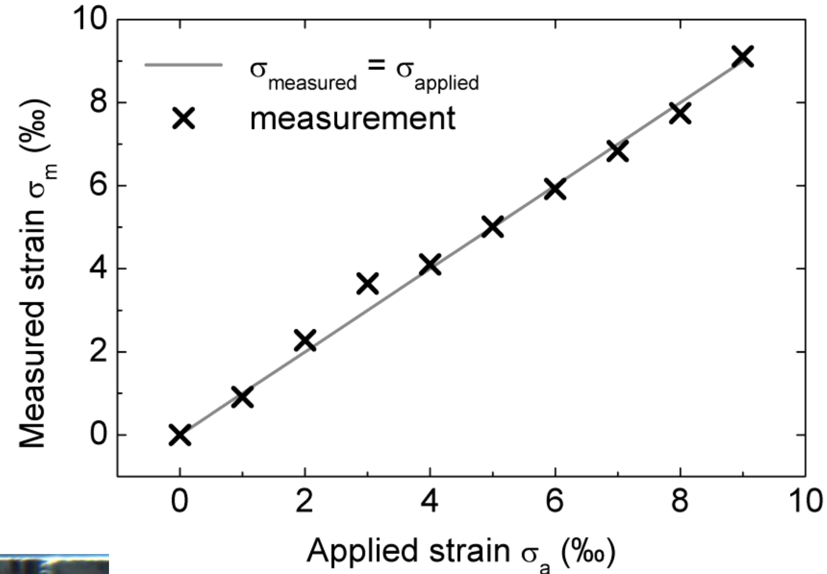
E_{PDMS} = 1,6 MPa

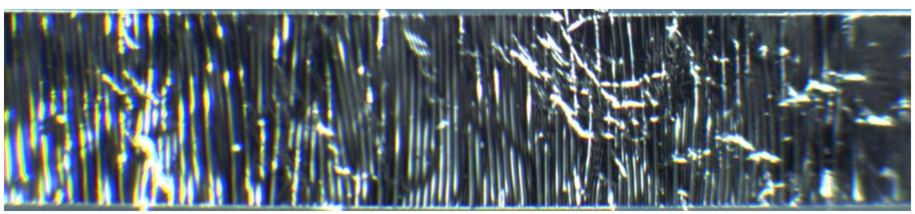
[8] Lacour et al., *Applied Physics Letters* **82**, 2404 (2003)

Stretching of wrinkled GMR films

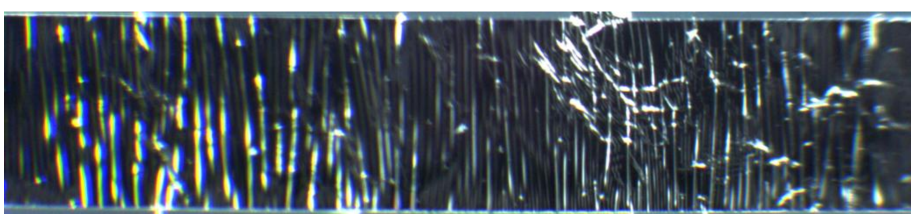
Piggyback setup for application of strain



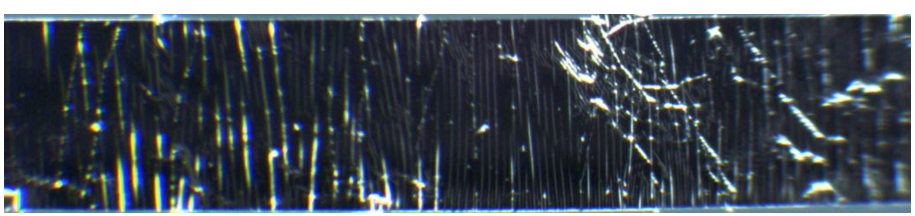




σ = 0 %

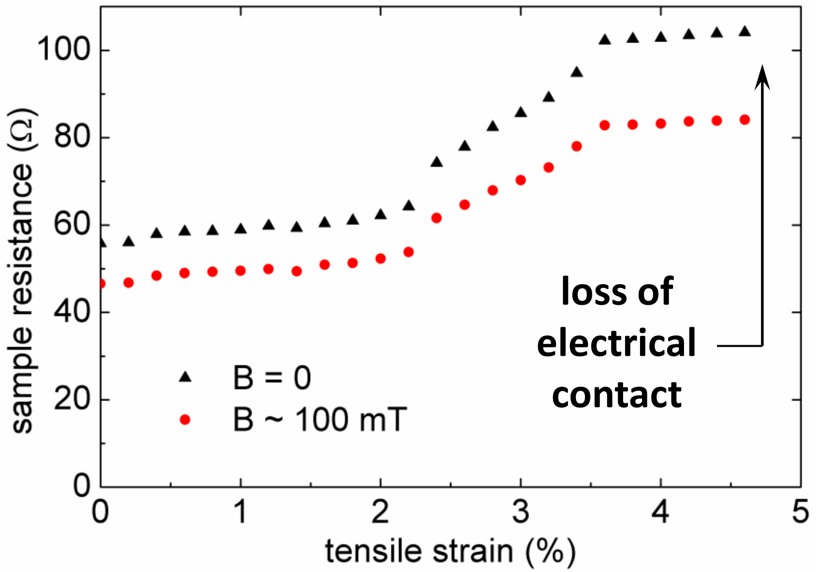


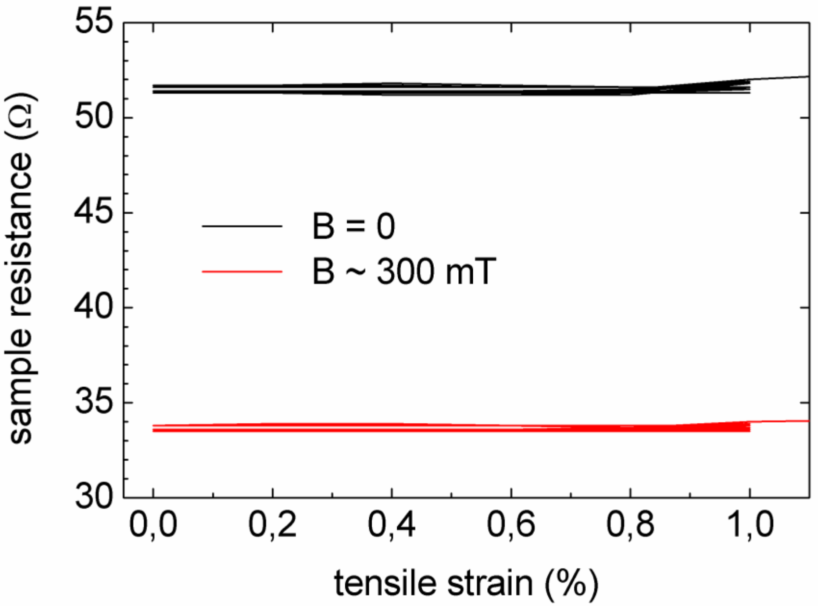
σ = 0.8 %



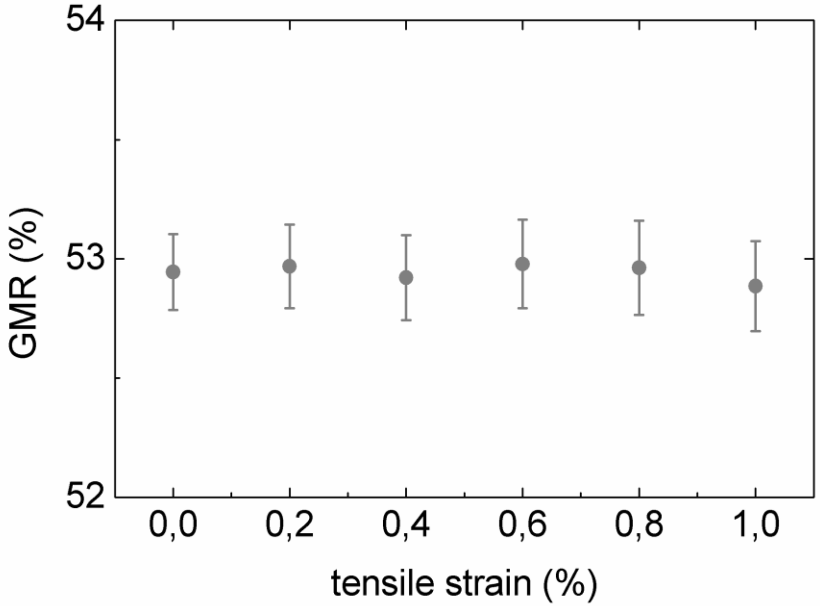
σ = 1.5 %

Stretching of wrinkled GMR films



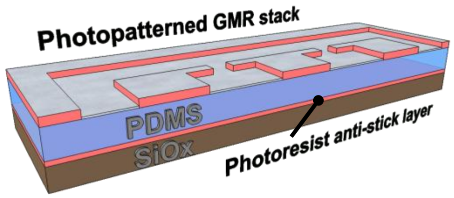


- GMR film remains conductive above 4% of uniaxial strain
- Resistance change under magnetic field remains stable
- Repeatability for lower strains
- GMR of >50% in saturation



Conclusion

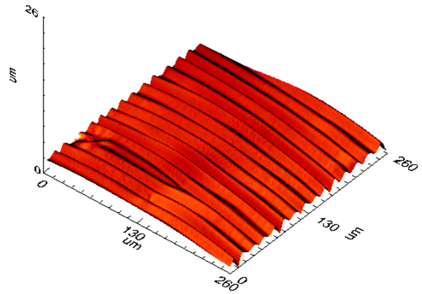
Fabrication of GMR multilayers on free-standing stretchable polymeric substrates



→ GMR characteristic is very similar to multilayers on rigid substrates

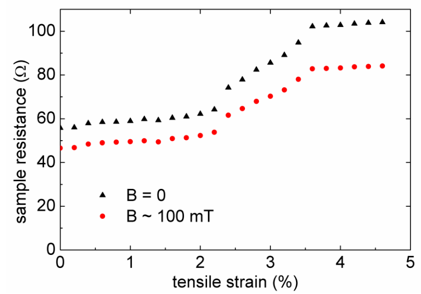
→ Self healing effect

Thermally induced wrinkling of GMR films on elastic membranes



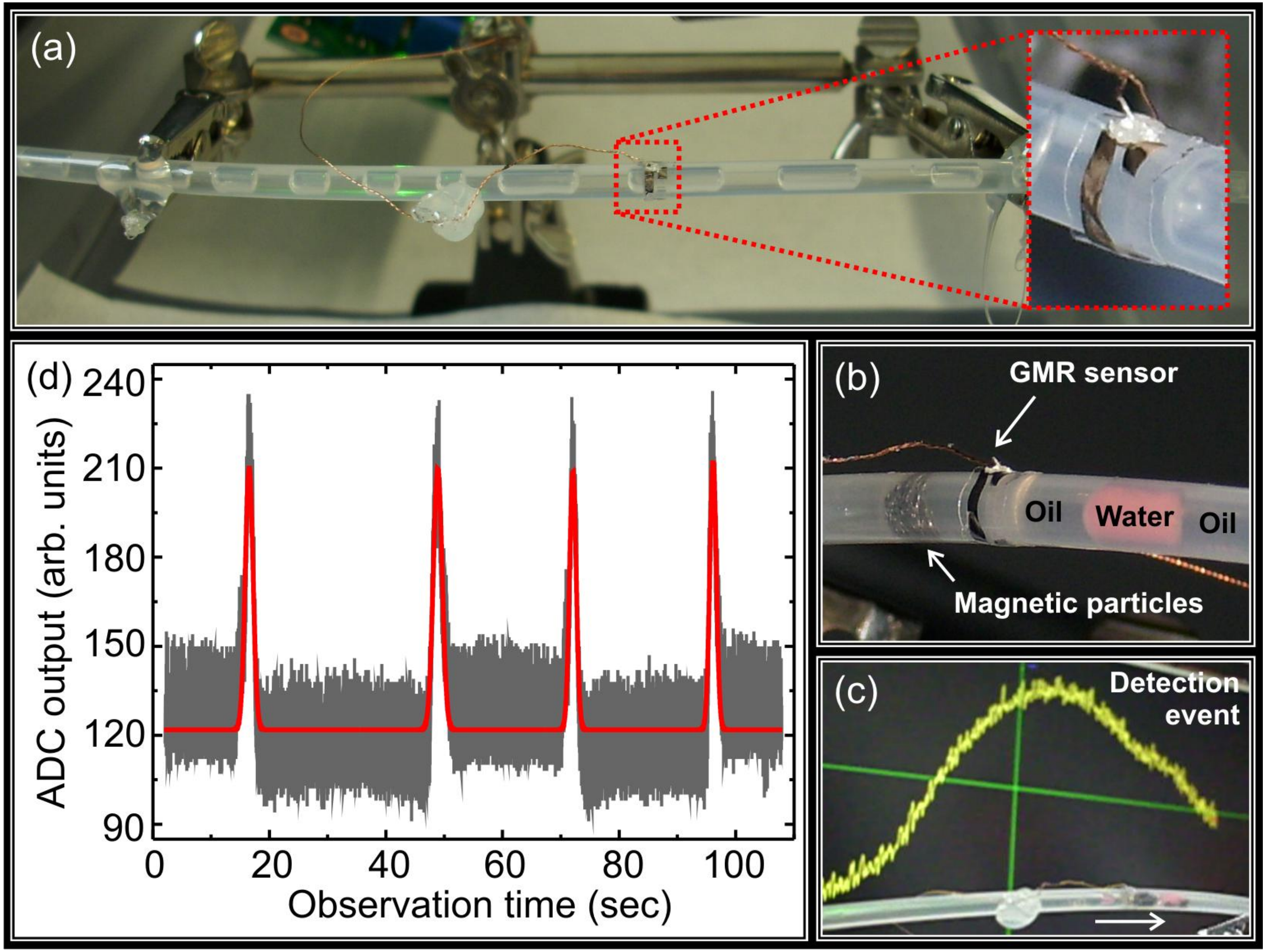
→ Allows rubber-like stretchability

Functional GMR multilayers under tensile strain



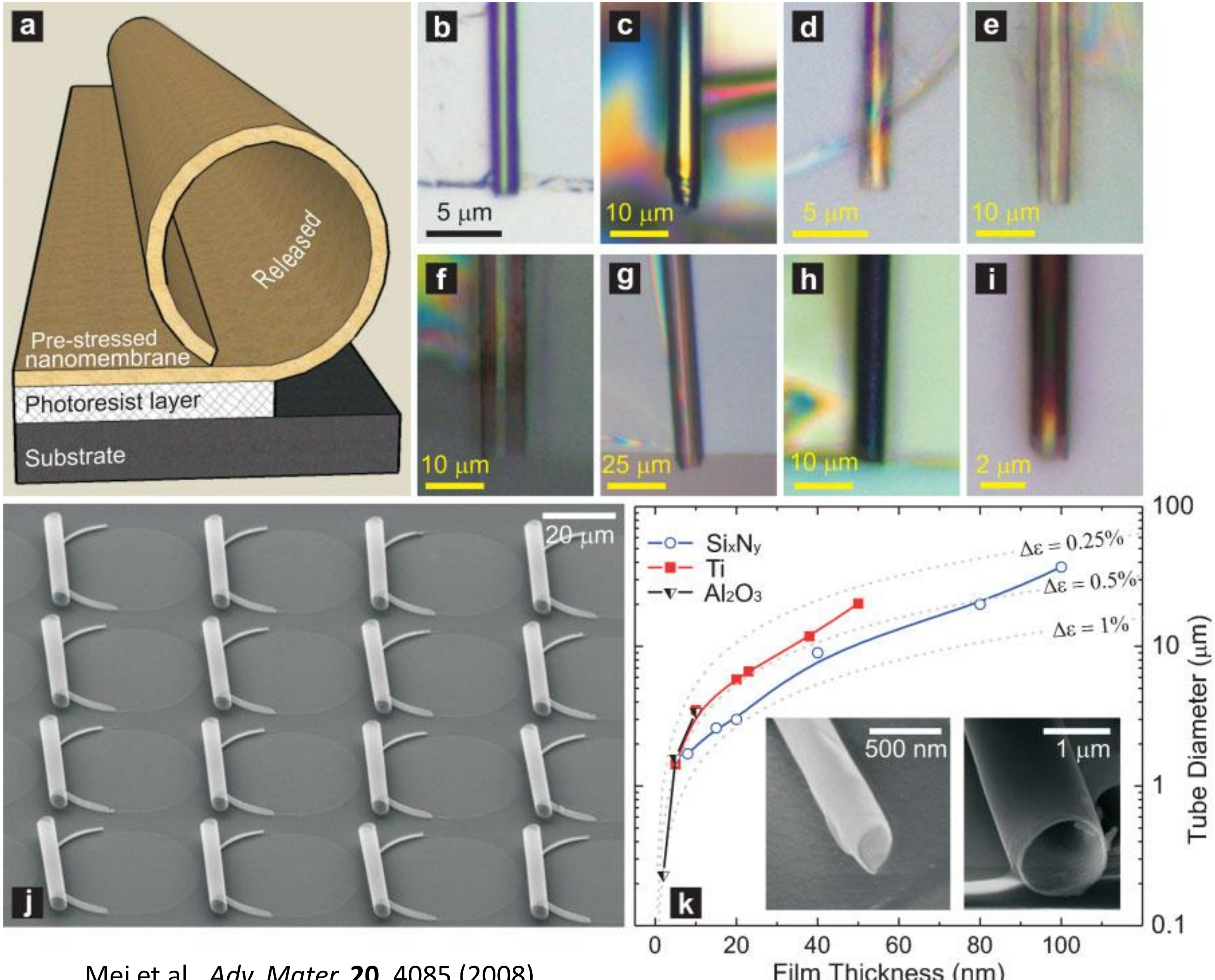
→ Repeatability upon cyclic loading

Elastic GMR sensor for fluidics applications



Rolled-up GMR sensor

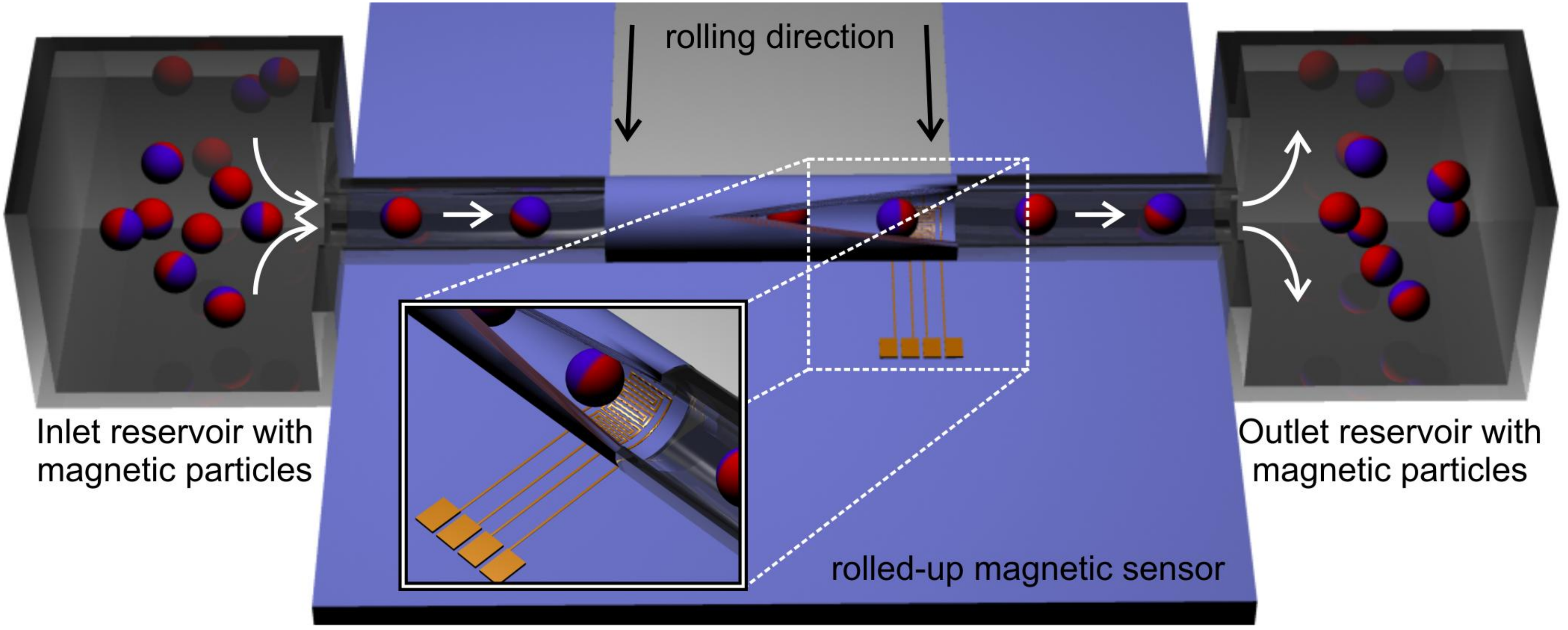
Rolled-up technology



Mei et al., *Adv. Mater.* **20**, 4085 (2008)

Concept: rolled-up GMR sensor in micro-fluidic channel

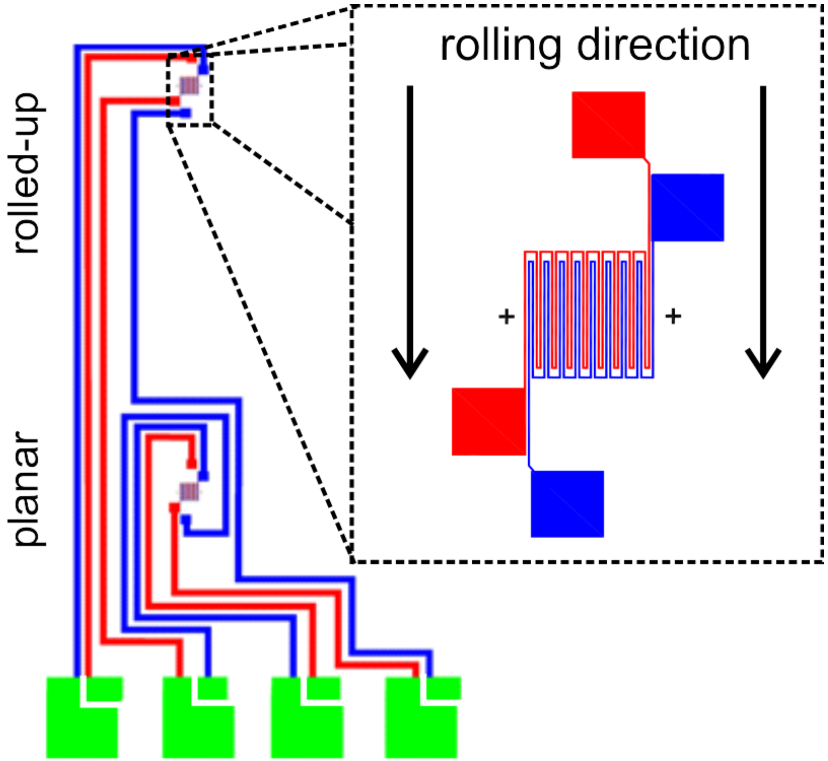
- Size of the sensor has to be adjusted to the size of the object
- Integration of the magnetic sensor in a micro-fluidic channel
- Rolled-up technology can be applied

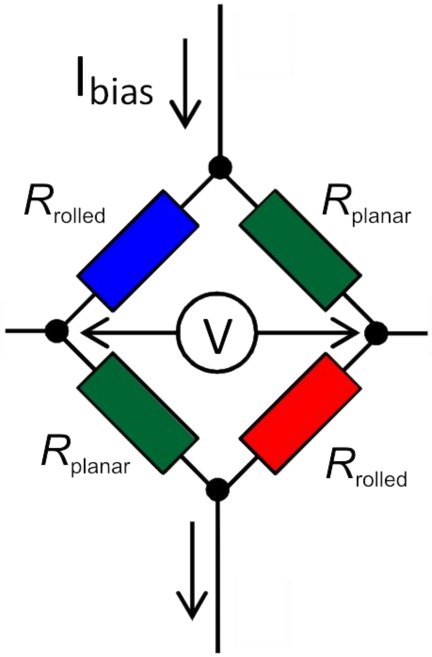


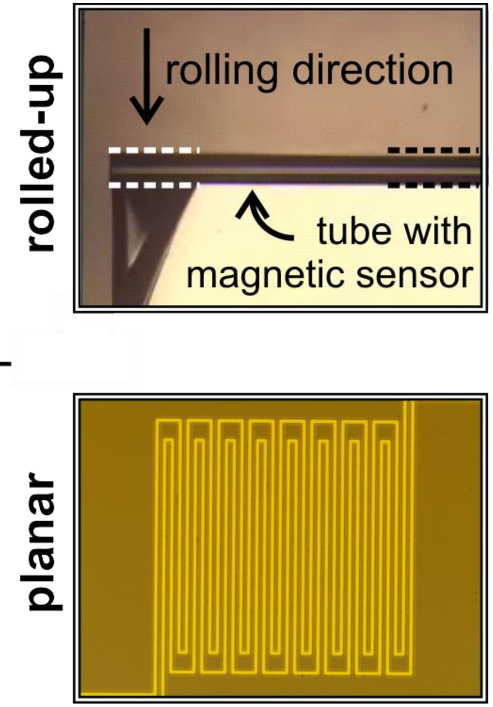
Electric connection of GMR sensors

Layer stack: [Py/Cu]x30 multilayers coupled in the 2nd antiferromagnetic maximum

- Sensors are connected in a bridge configuration
- Good thermal stability







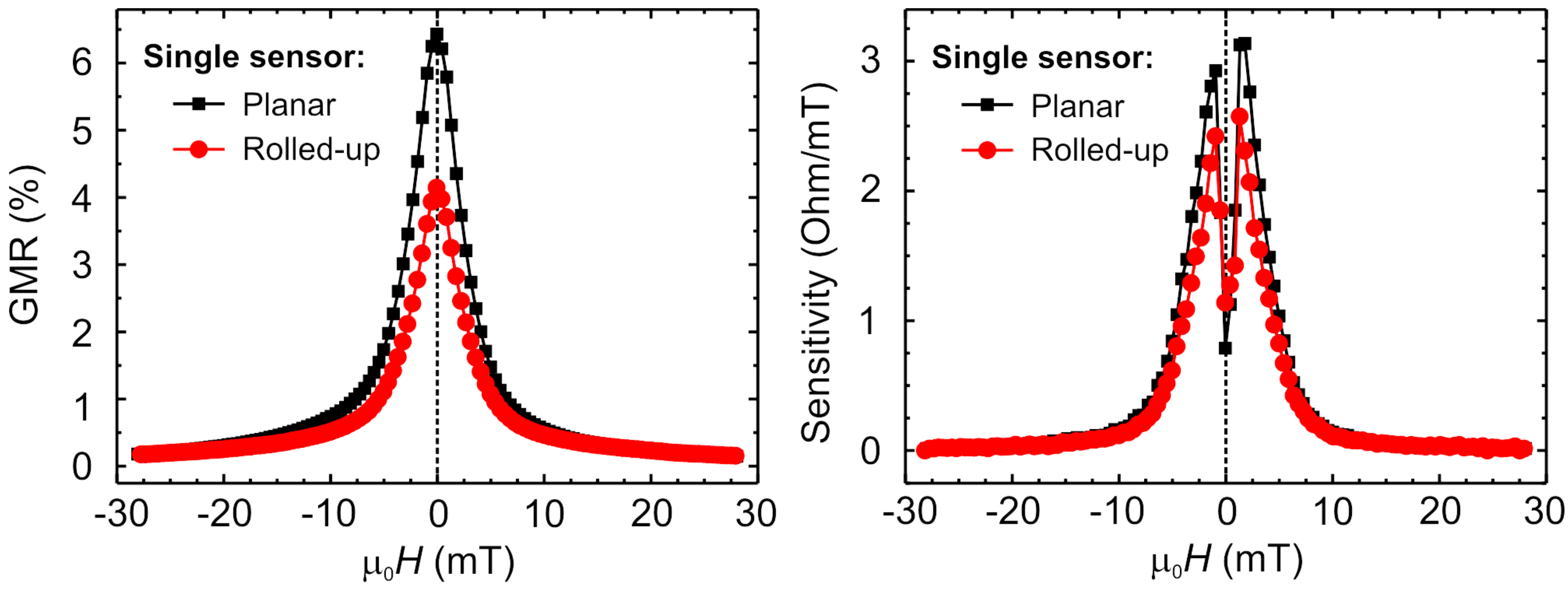
- Meander-like shape of sensor is used to increase resistance
- Two planar sensors act as reference
- Sensing using two rolled-up sensors

Planar vs. Rolled-up GMR sensor

Rolled-up sensor:

Diameter: 60 um

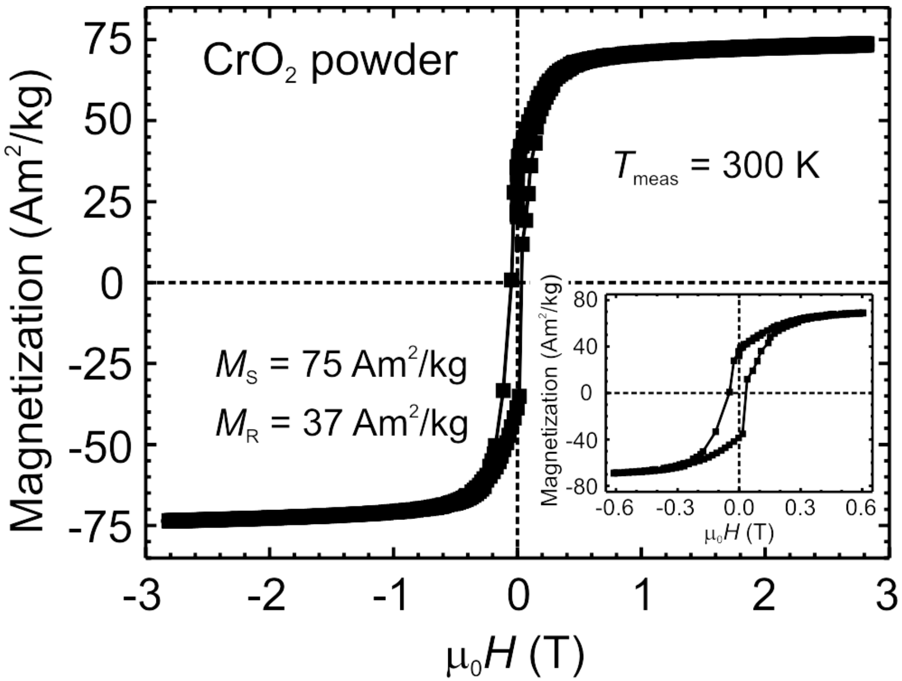
Length: 1000 um

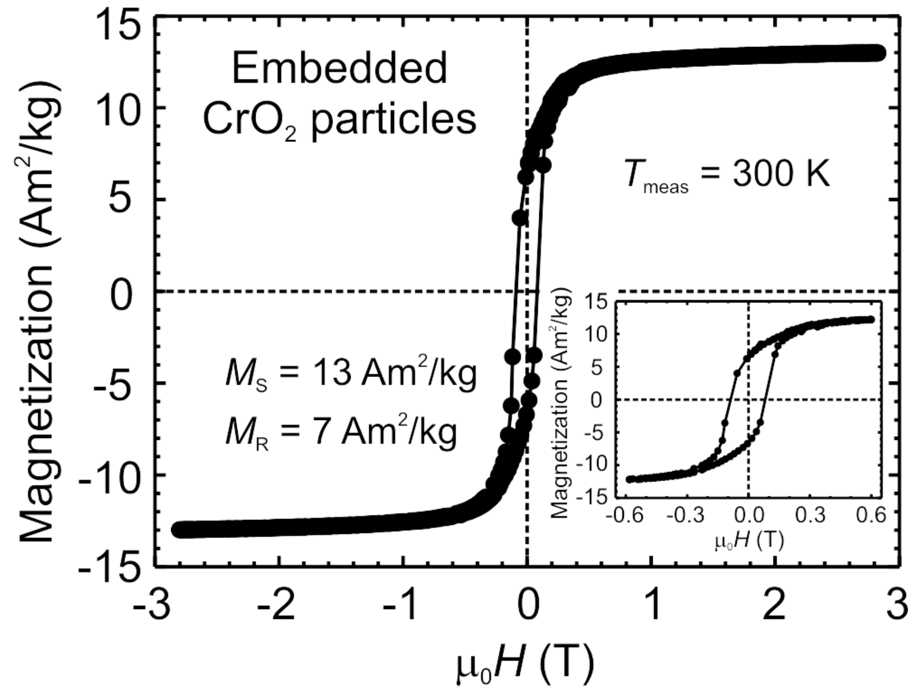


Single sensor elements are measured independently

- GMR ratio is slightly better for the planar sensor
- Sensitivity of the planar and rolled-up sensors is rather similar

Characterization of magnetic nanoparticles





Magnetic CrO_2 particles

Ferromagnetic particles

Elliptical shape: 300 x 30 nm^2

Defined easy axis of magnetization

Non-zero remanent magnetization

CrO_2 are in a hydrogel shell

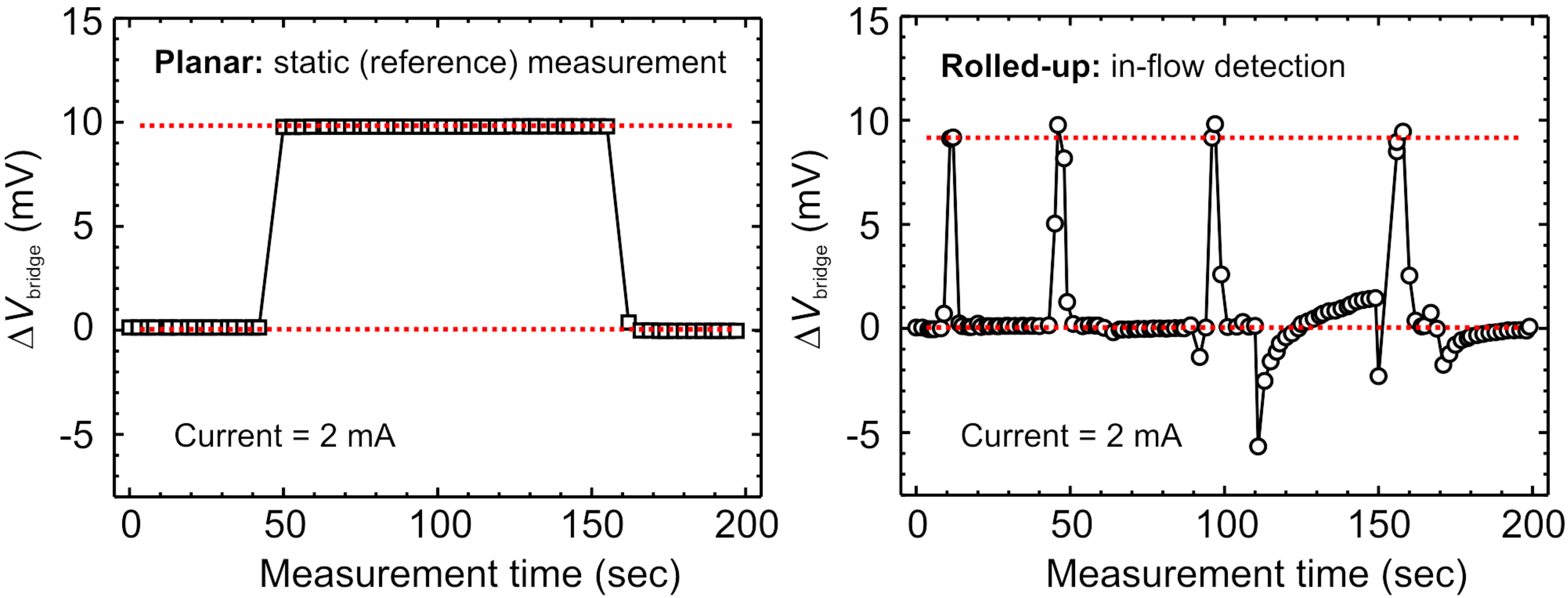
Hydrogel: 50 um diameter

Orientation of particles is fixed

Randomly oriented easy axis

$M_R = 0.5\ M_S$

In-flow detection of magnetic particles



- Signal level is similar with planar and rolled-up sensor
- Successful in-flow (dynamic) detection of magnetic particles
- Size of particle is adjusted to the size of the channel

  Hydrogel particle: 50 um

  Diameter of rolled-up tube: 60 um

Conclusion

Rolled-up technology was applied to fabricated integrated GMR sensor in micro-fluidic channel

→ Size of the rolled-up tube: 60 um

→ Size of the sensor is adjusted to the size of the object

Performance of planar and rolled-up sensors is similar

→ Sensors are connected in a bridge configuration

→ Improved temperature stability of the sensor

In-flow detection of magnetic micro-particles is successfully demonstrated

→ CrO_2 nanoparticles embedded in a hydrogel shell were detected

Acknowledgements

I would like to thank:

Larysa Baraban, Rainer Kaltofen, Stefan Baunack,
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Daniil Karnaushenko, Irina Fiering, Cornelia Krien

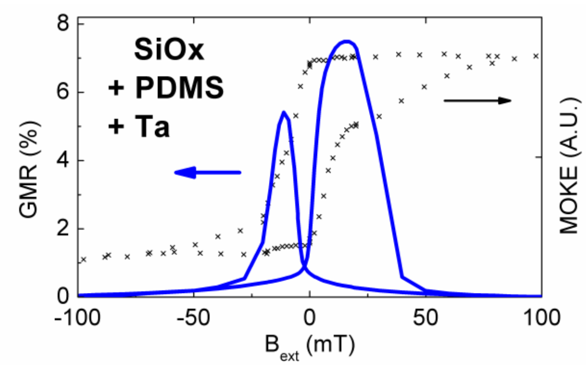
Alfredo Calvimontes (HighRes SDCM)
Konrad Schneider, Holger Scheibner (stress strain)

… and special thanks to YOU!

Outlook

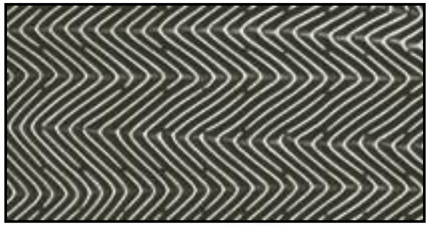
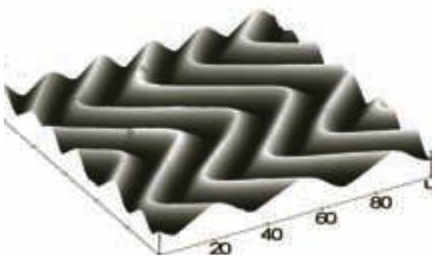
Stretching of different GMR systems:

- Py/Cu multilayers in 2nd maximum
- Spin valves (magnetic data storage)



Enhancement of stretchability

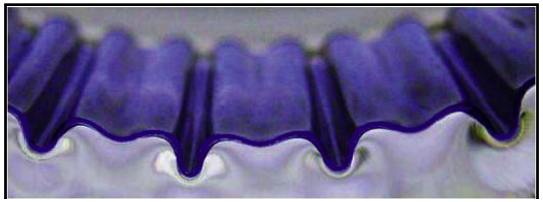
- Mechanical induced prestrain
- Biaxial strechability

J.A. Rodgers et al., Science 2010

Fundamental investigations

- Wrinkling of magnetic metal films on rubber substrates



F. Brau et al., Nature Physics 2011