Submicron Magnetometers and their Applications to the Study of Nanomagnetism and Biosensing

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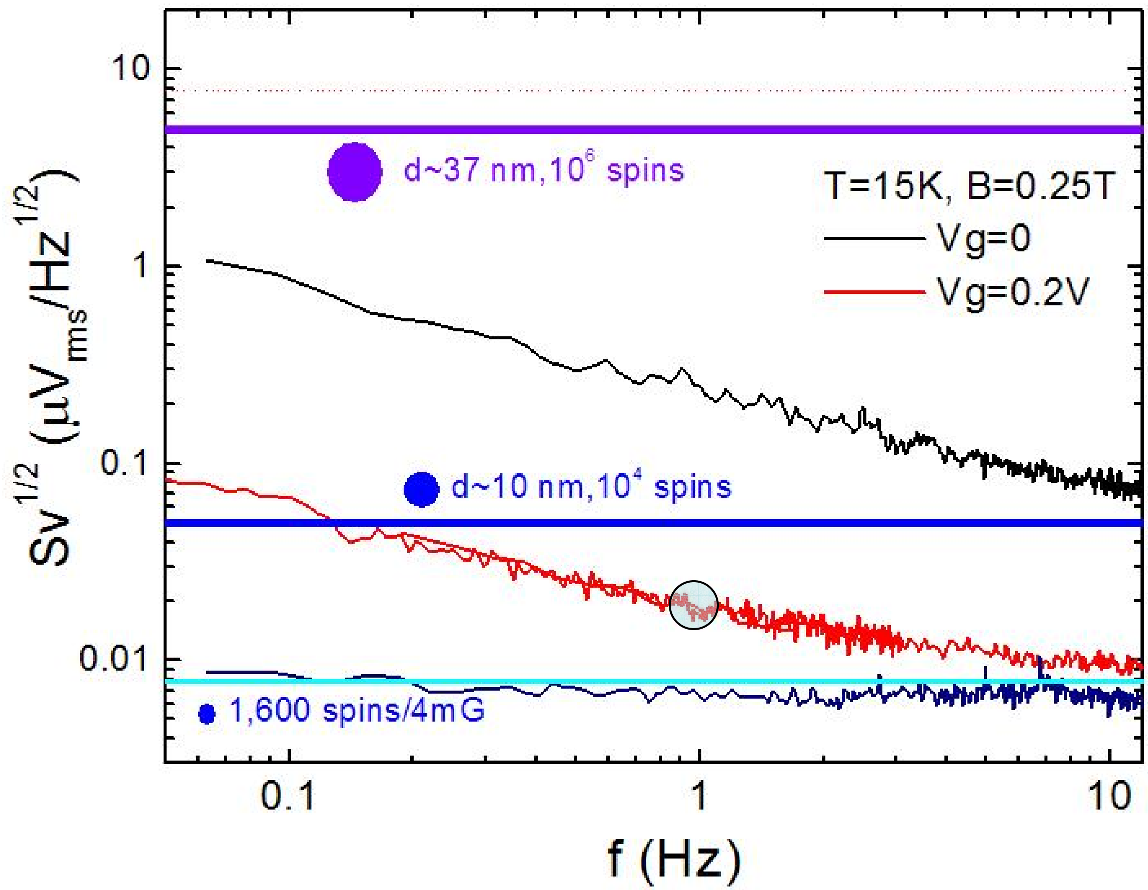
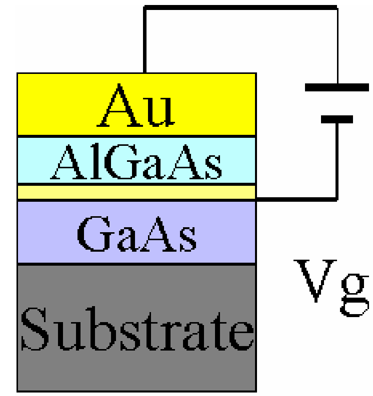
- Jens Müller, MARTECH

- Hideo Ohno & Keita Ohtani, Tohoku University
- Mark Field & Gerard J. Sullivan, Rockwell Scientific Company LLC

Sensitivity of a Submicron Hall Device





Moment sensitivity:

$\sim 10^4\ \mu_B/\sqrt{Hz}$

$\sim 10^{-16}$ emu

@ B=0.25 T

Estimated for a dipole placed in the center of a Hall cross of physical size of $0.7X0.7\mu m^2$ and active area of $\sim 0.5X0.5\ \mu m^2$

Kent, von Molnár, Gider, and Awschalom, J. Appl. Phys. (1994).
Li et al., PRL (2004)

Outline

I. Interaction effects at small scales

II. Noise in submicron Hall devices

II. Magnetic Biosensors

Outline

I. Interaction effects at small scales

II. Noise in submicron Hall devices

III. Magnetic Biosensors

Jens Müller

Materials by:

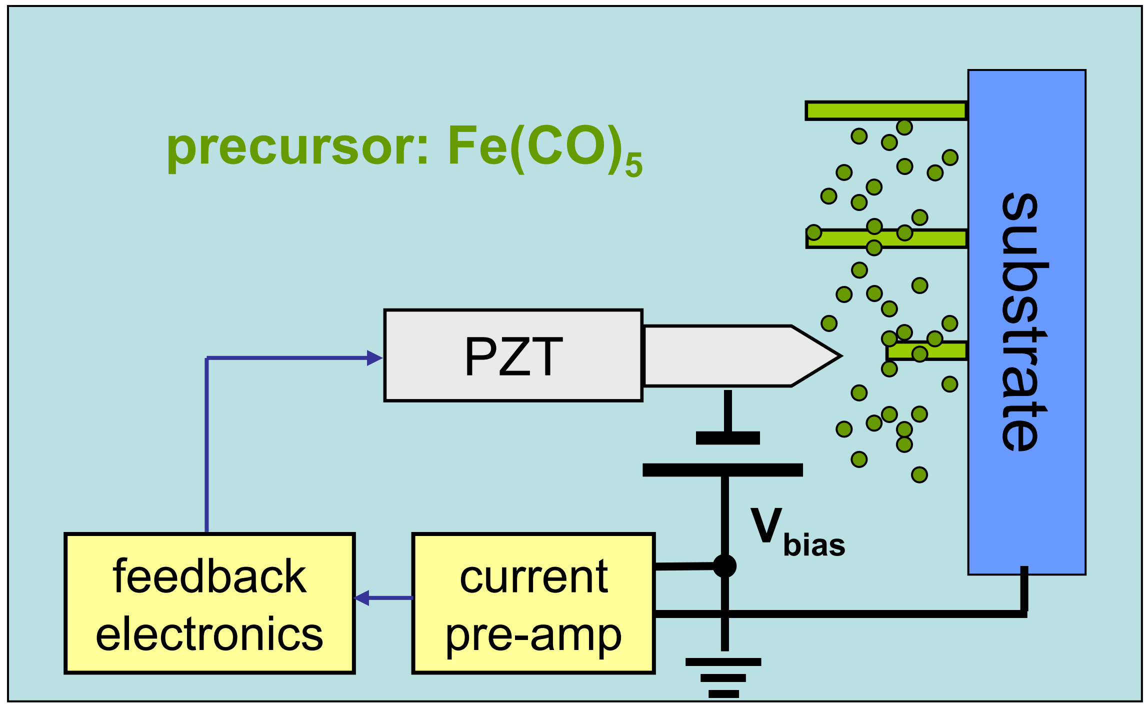
Hideo Ohno, Keita Ohtani (Tohoku University),

Nano-scale magnetic particles

- testing of theoretical models
- technological applications → high-density information storage
  → spin electronic devices

- growth by STM assisted CVD

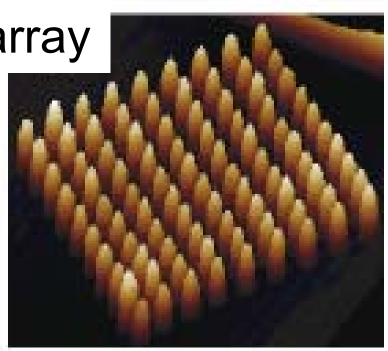
  → exact positioning
  → d ~ 5 – 20 nm
  h ~ 80 – 250 nm
  a ≥ 80 nm



shape anisotropy: EMD along cylinder axis

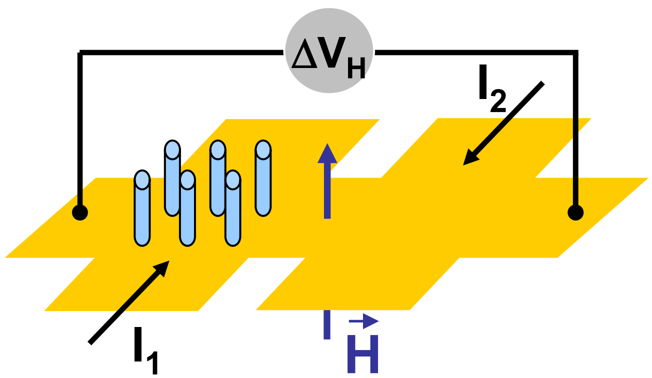
9 × 10 array

AFM



McCord and Awschalom, APL, (1990)
Kent, Shaw, von Molnár, and Awschalom, Science, (1993)

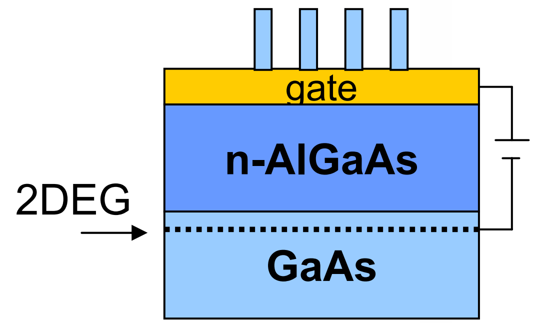
Micro-Hall magnetometry



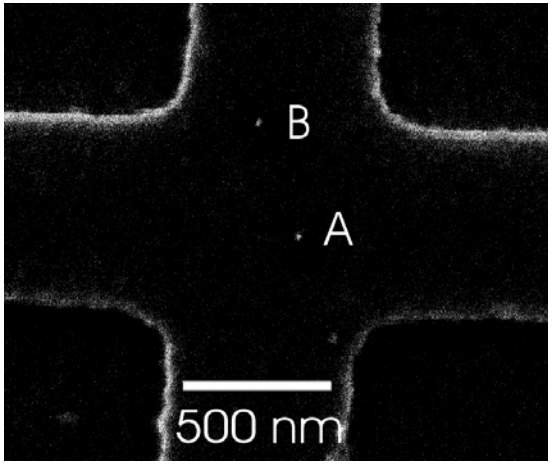
- Hall magnetometers based on 2DES in gated GaAs/$Al_xGa_{1-x}As$

  → moment sensitivity
  ~ **10^4** $\mu_B/\sqrt{Hz}$ @ 1 Hz

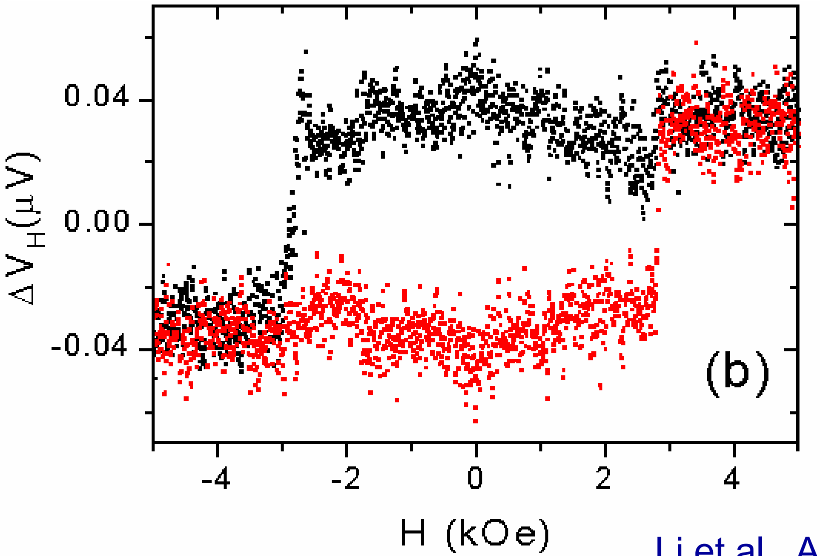
  Li et al., PRL (2004)



- measuring $\langle B_z \rangle$ → magnetization reversal of *individual* non-interacting particles grown on Au



$d \sim 5$ nm, $h \sim 120$ nm, $m \sim 5 \times 10^5 \mu_B$

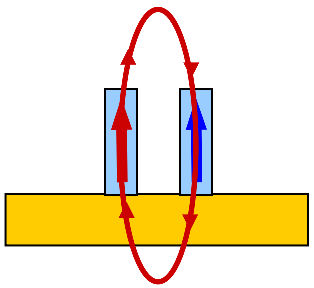


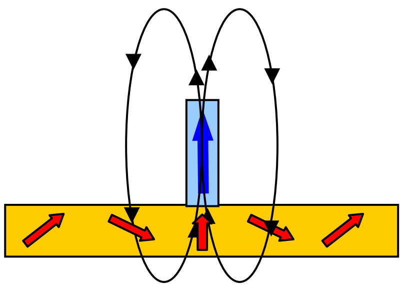
Li et al., APL (2002)

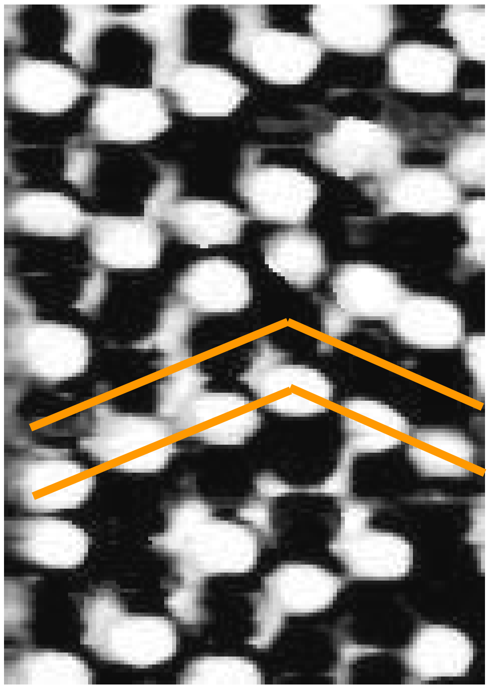
Interaction effects

Magnetic nanoparticles grown onto magnetic thin film:

- particle-particle interaction
- particle-thin film interaction
  → magnetostatic, exchange





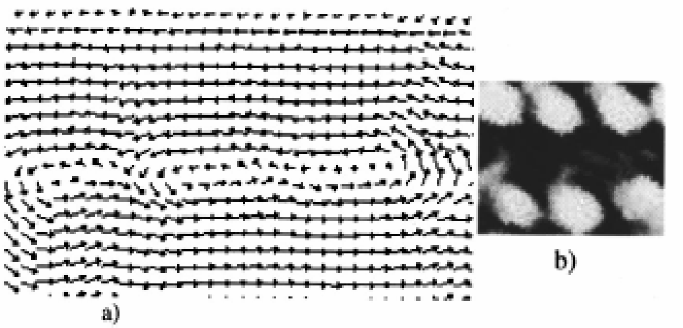


Enhanced interactions in particle array grown onto Permalloy

→ **simultaneous switching events**

→ **metastable "stripe state"**

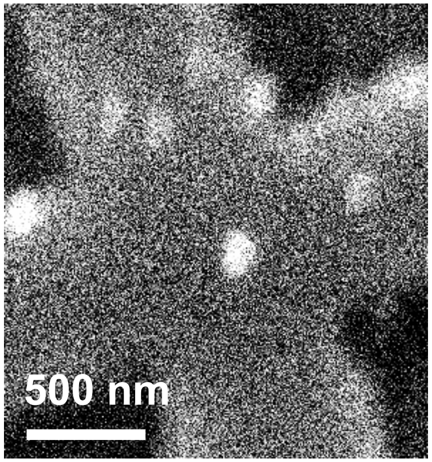
→ **magnetic domains in Permalloy**



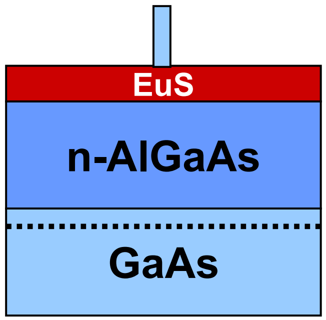
Wirth and von Molnár 2000, Christoph et al. 2001

"Simple" test system

sample 1



Single magnetic Fe particle grown onto EuS



EuS –

concentrated magnetic semiconductor

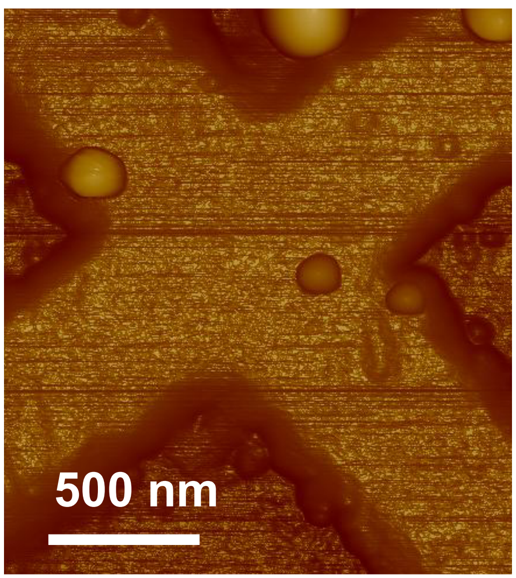
S = 7/2

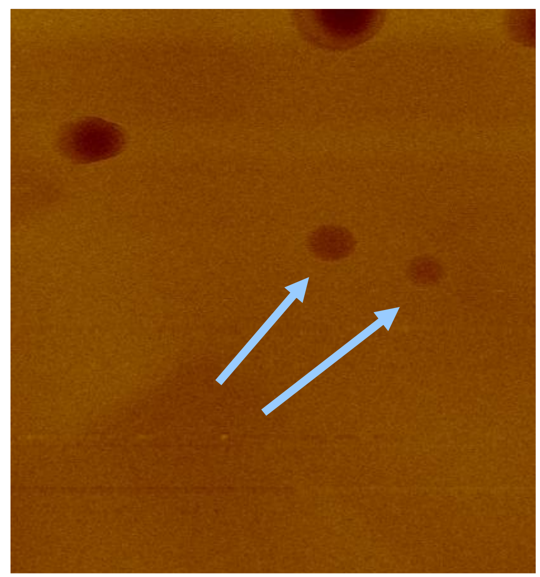
T_C ~ 17 K (insulating), ~ 25 K (conducting)

magnetization switching in MFM

sample 2

AFM



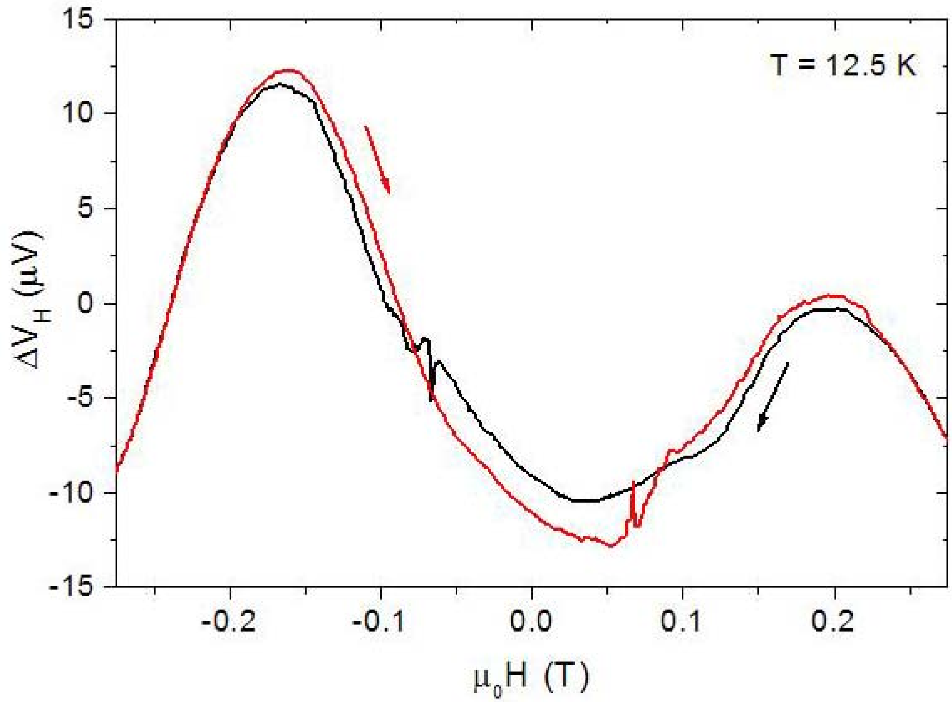


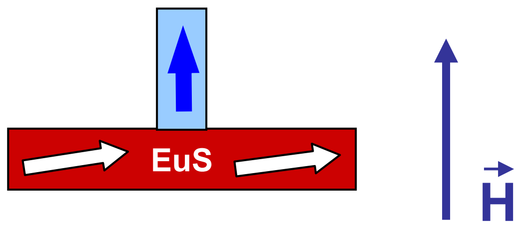
MFM

⊗ $\vec{H}$

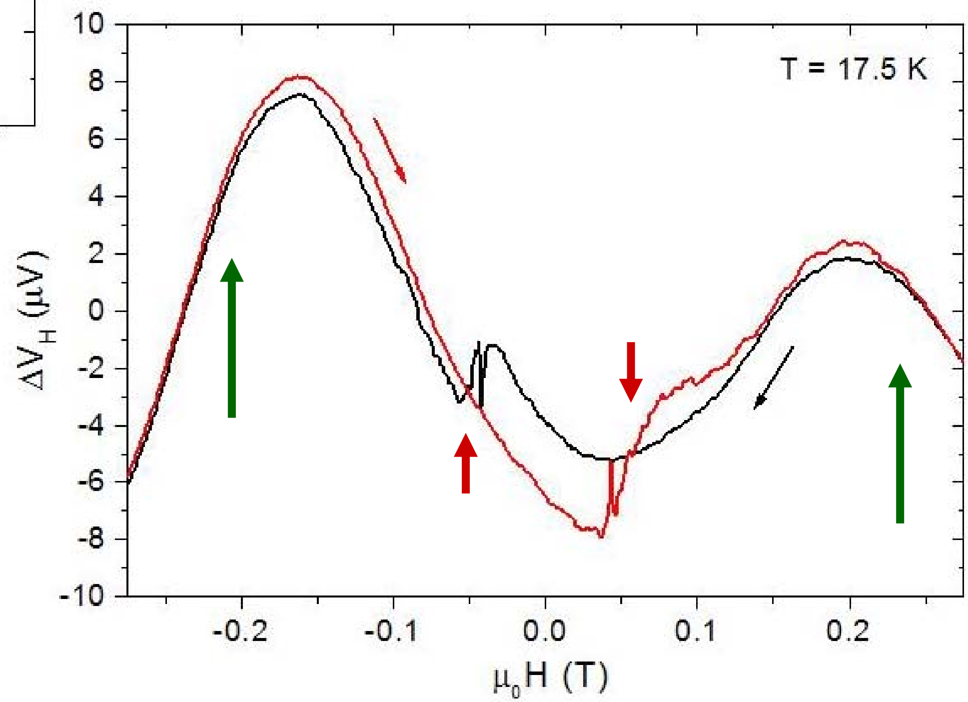
field pulse

Single Fe particle on EuS



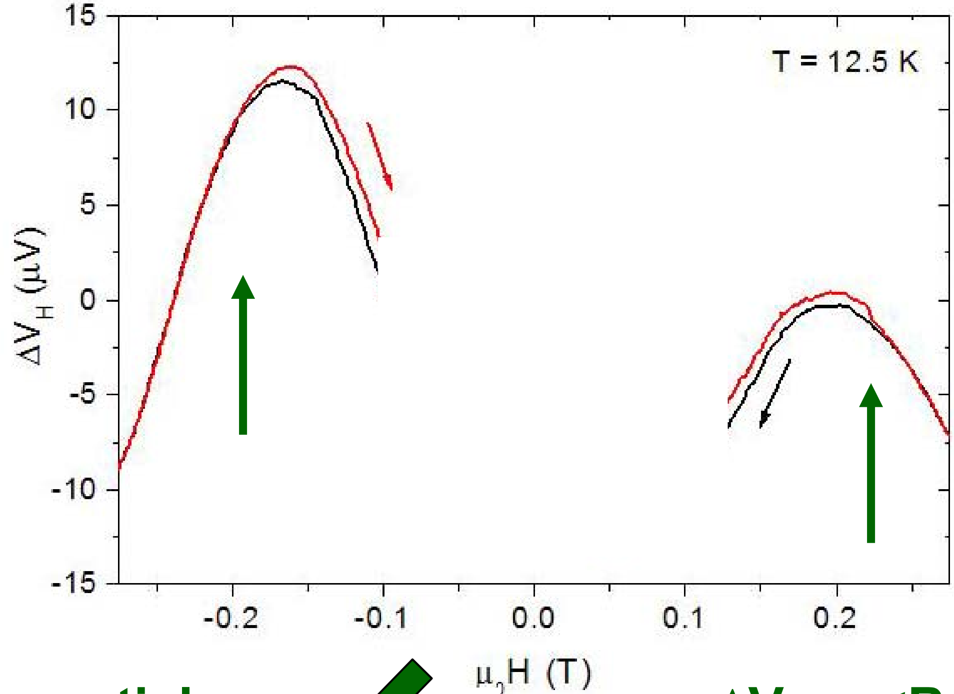


• switching of Fe particle



• switching in EuS

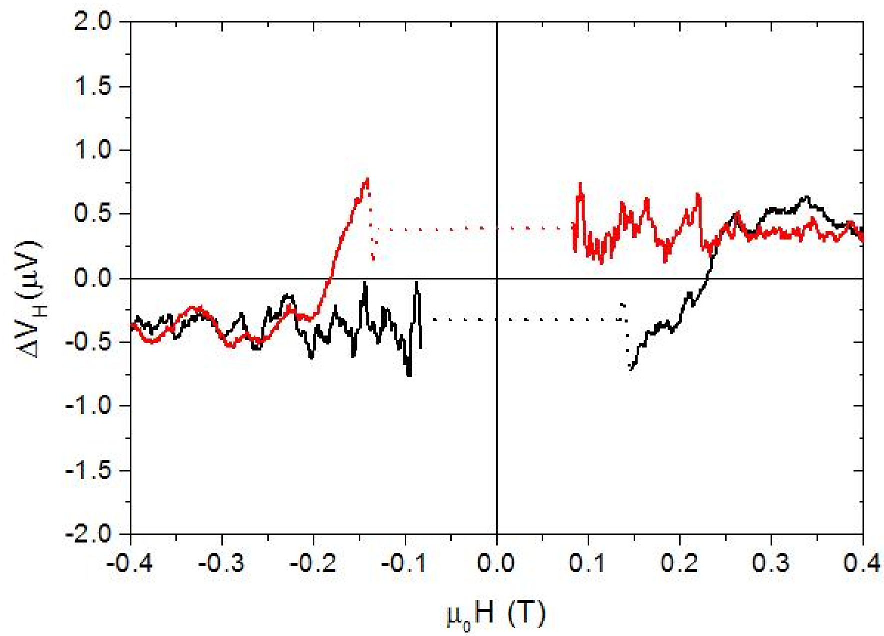
sample 1

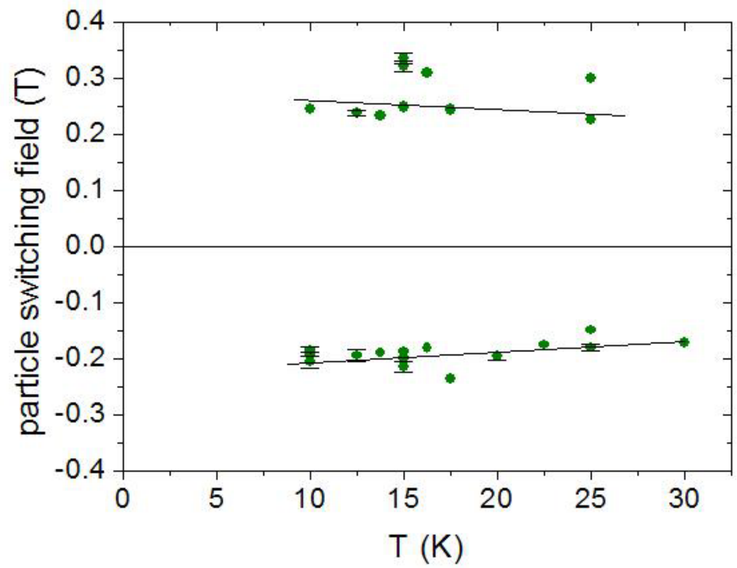


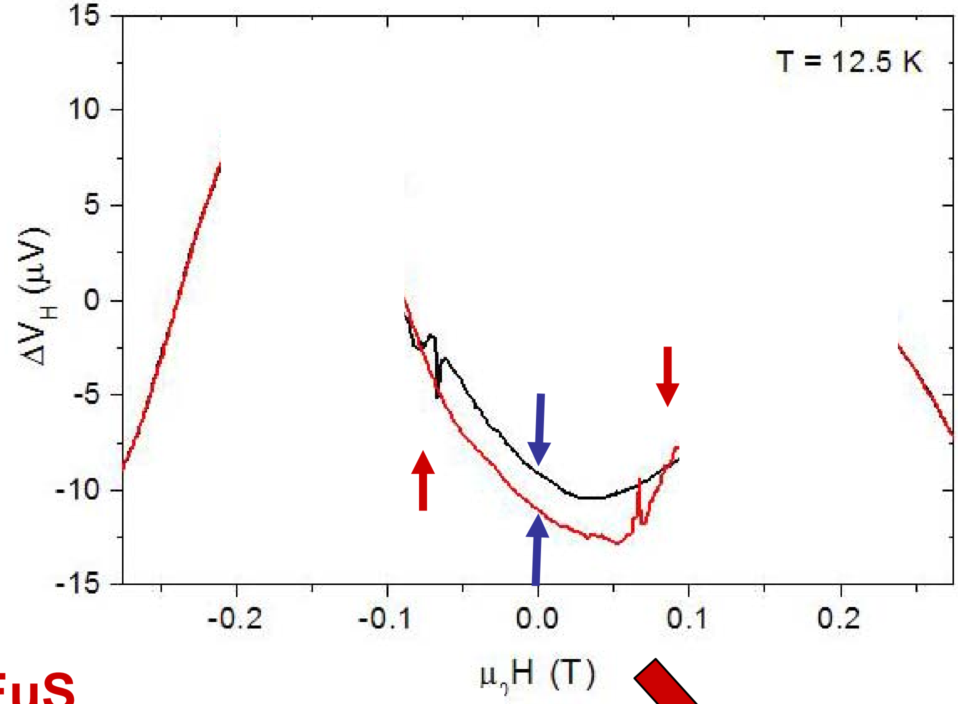
- **switching of Fe particle**

$\Delta V_H \propto \langle B_z \rangle \Rightarrow$ d ~ 40 nm

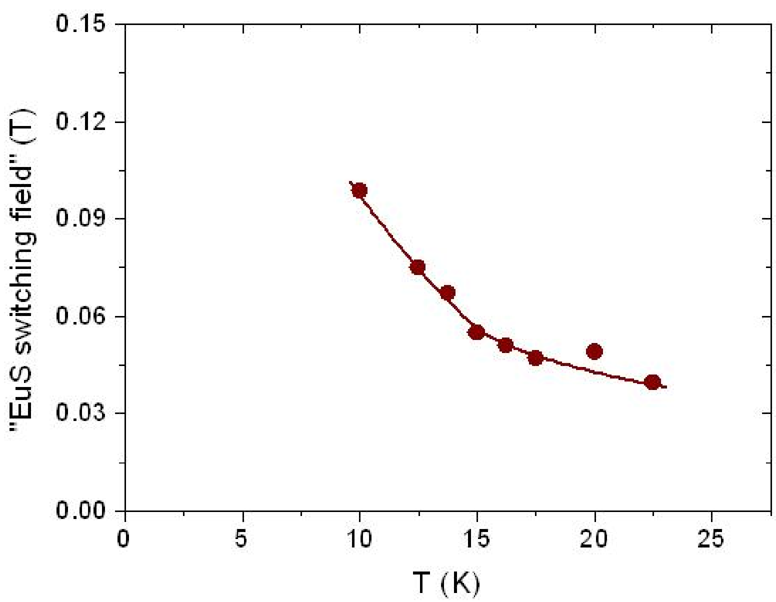
→ not single domain

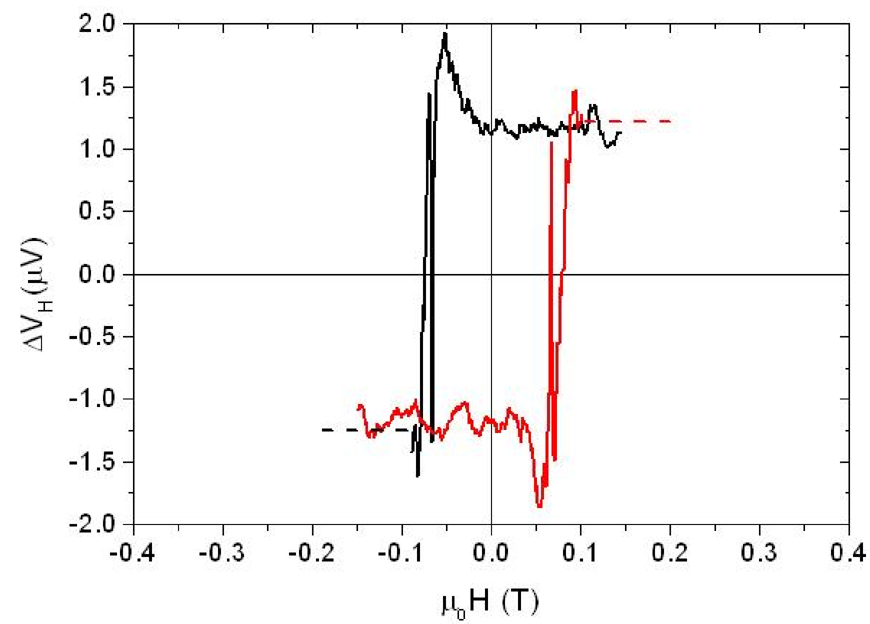




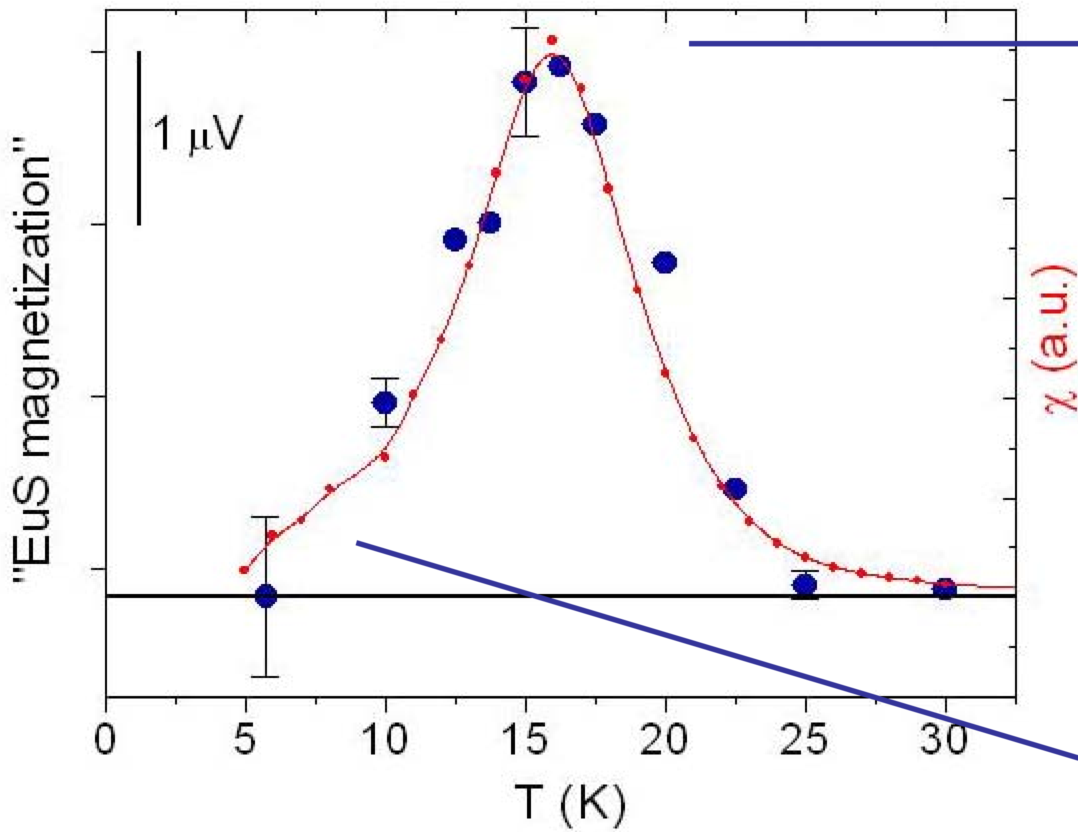


- **switching in EuS**





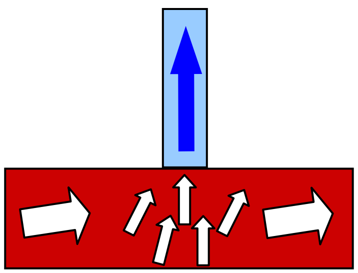
Single Fe particle on EuS

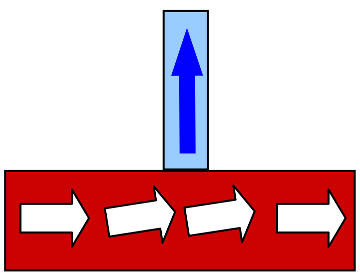


EuS volume that switches:

$\Delta V_H \propto \langle B_z \rangle \Rightarrow$ **d ~ 100 nm**

d (particle) ~ 40 nm

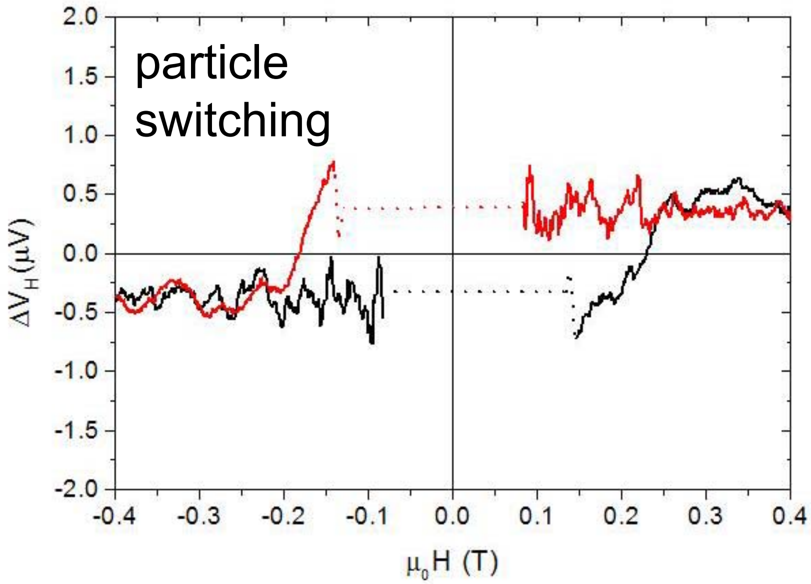


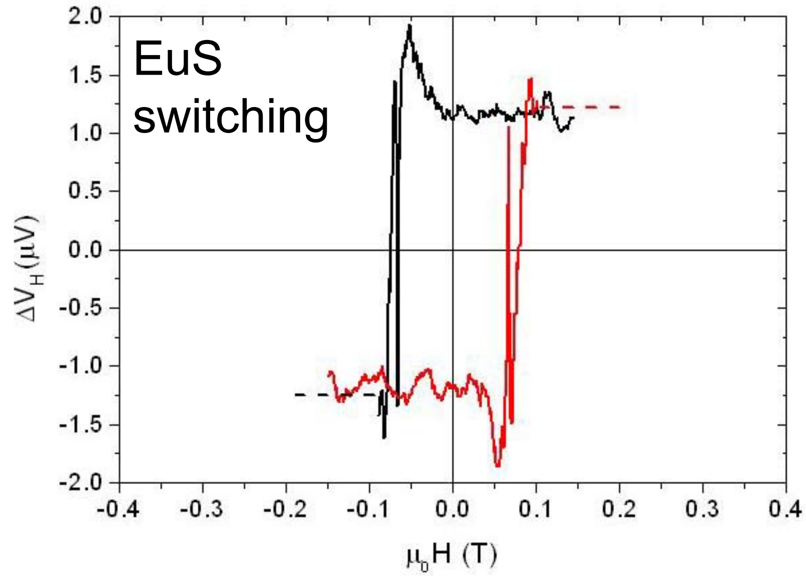


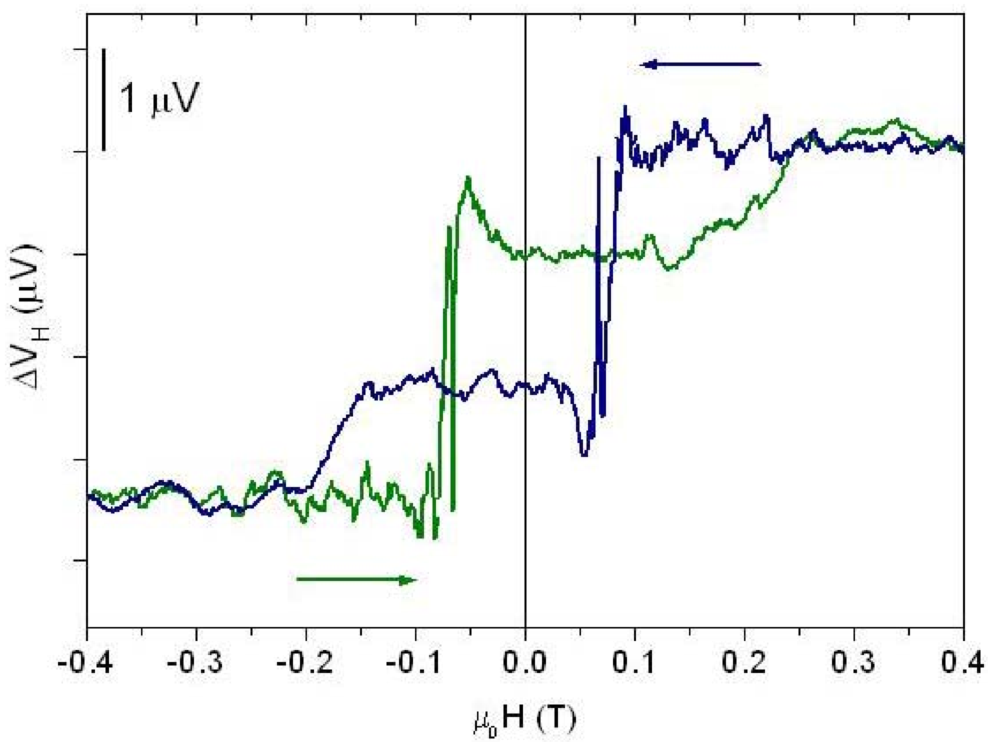
- **susceptibility-like behavior**

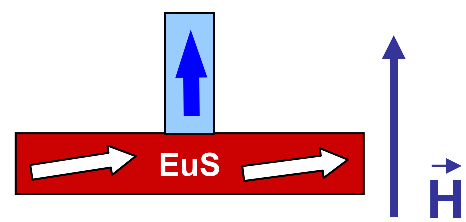
  → competing interactions:

  particle – EuS ←→ exchange in EuS









- **switching contributions of nano-scale Fe particle and EuS thin film + interaction effects**

- **complex magnetization behavior**

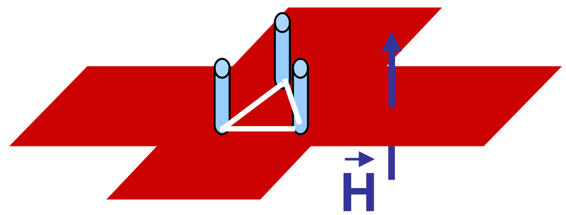
Comments

- Single Fe particle on EuS study has shown that:

  → Fe particle induces magnetization changes in EuS

  → there exist complex competing magnetic interactions,

  i.e. EuS-EuS vs. Fe-EuS, also Fe-EuS-Fe

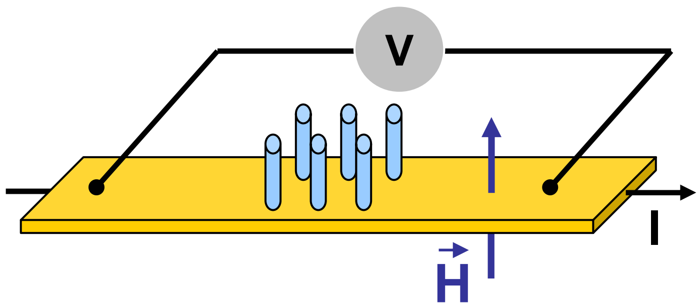


- Magnetic: interactions between particles

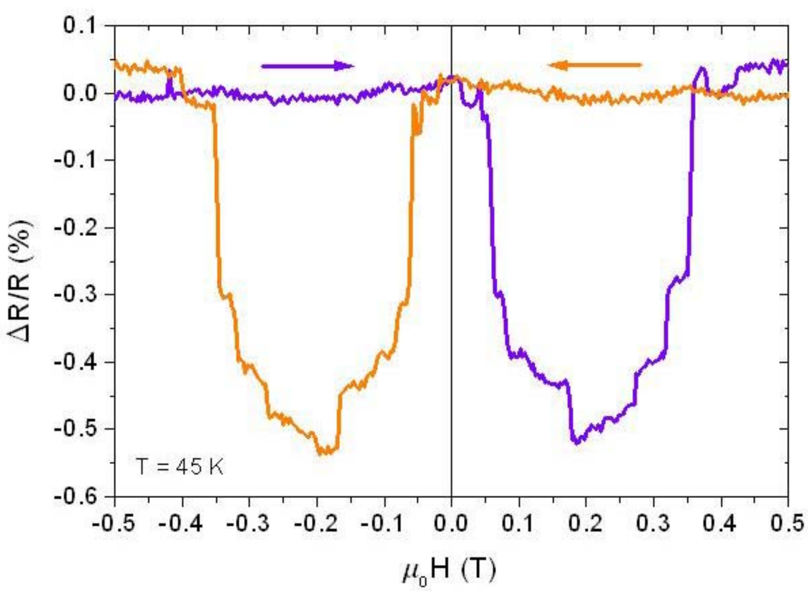
  → *e.g.* frustration on triangular lattic

- Transport: in substrate due to interactions

Transport

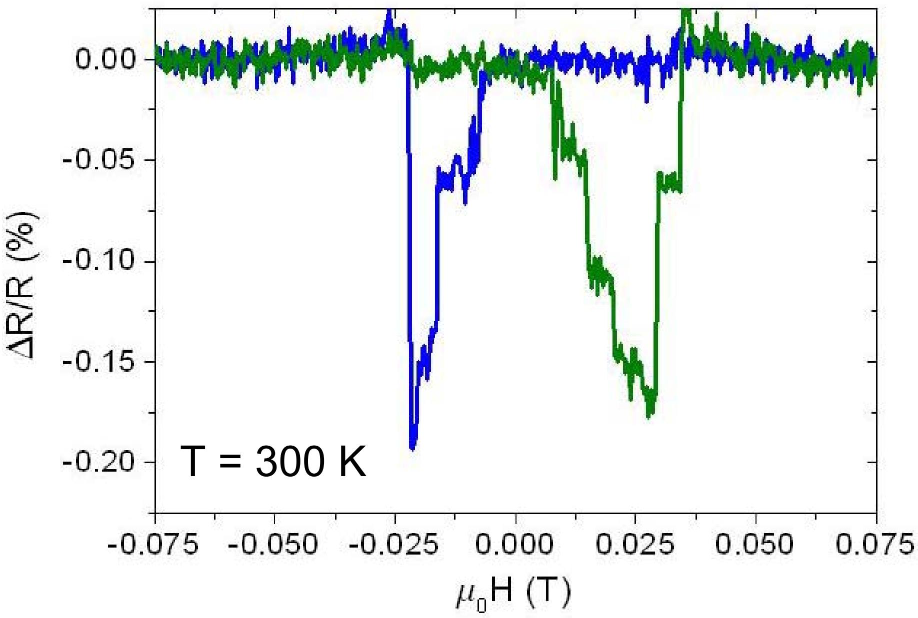


- modulation of transport in Py by particle's magnetization up to RT

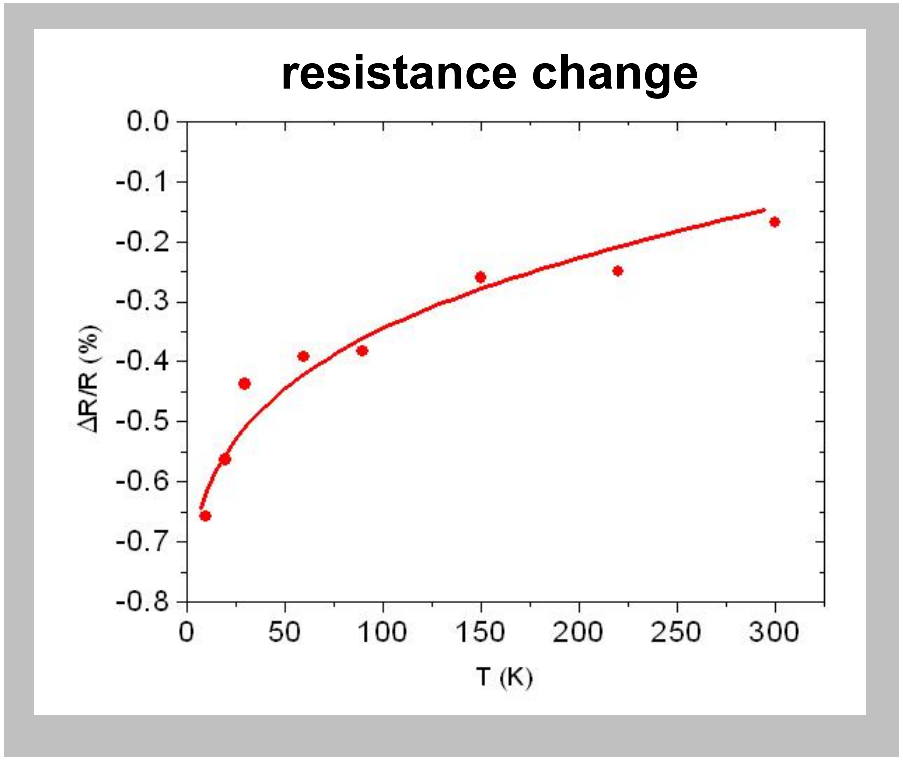


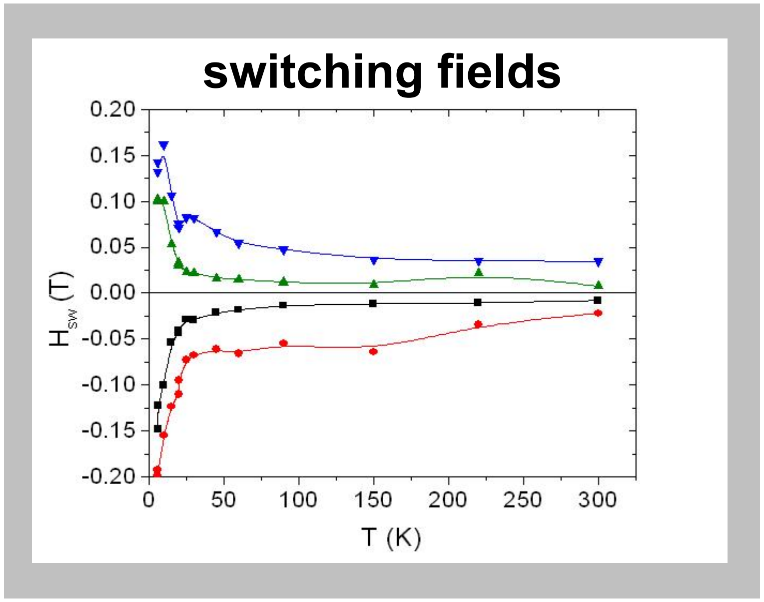
- engineering of transport properties of micro/nano-structured magnetic films using small and local magnetic flux sources

Transport of particle-permalloy heterostructure



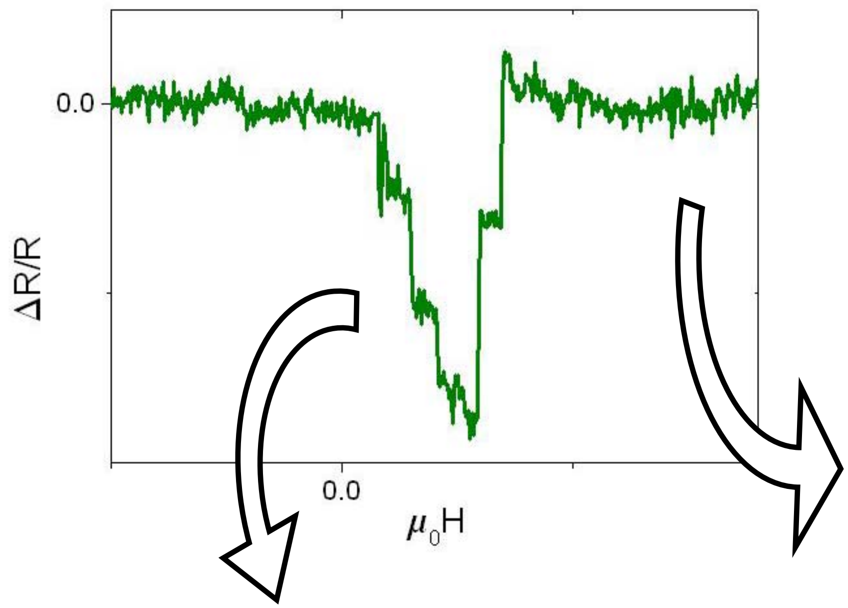
Temperature dependence



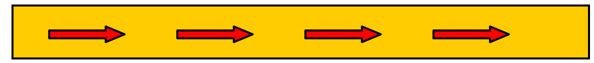


effect persists up to RT !

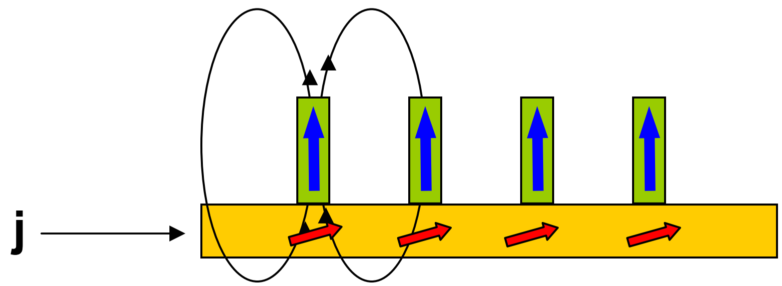
Explanation in terms of AMR ?

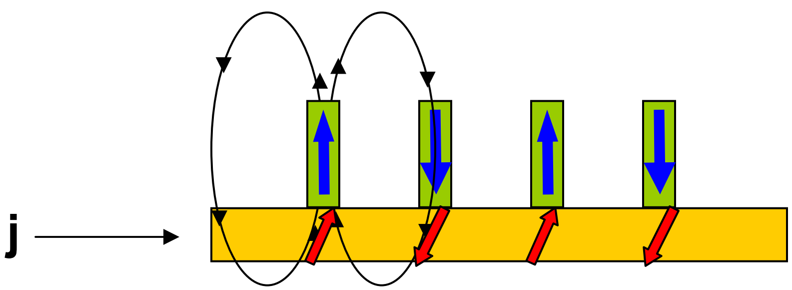


without particles



magnetization in plane





larger component of out-of-plane magnetization

→

lower resistance

also:

domain wall formation in Permalloy ?!

cf. Christoph et al., JAP (2001)

Future work

→ **new material: (Ga,Mn)As**

→ **particles on constriction**

Outline

I. Interaction effects at small scales

II. **Noise in submicron Hall devices**

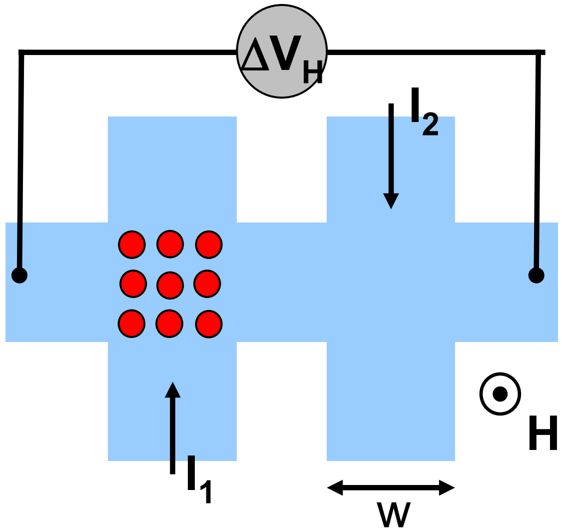
III. Magnetic Biosensors

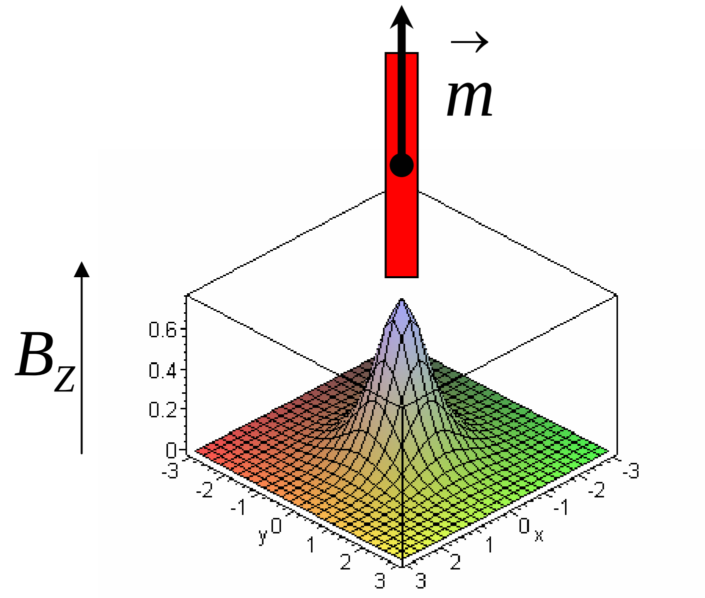
Jens Müller

Materials by:

Hideo Ohno, Keita Ohtani (Tohoku University),

Improve moment sensitivity by miniaturization

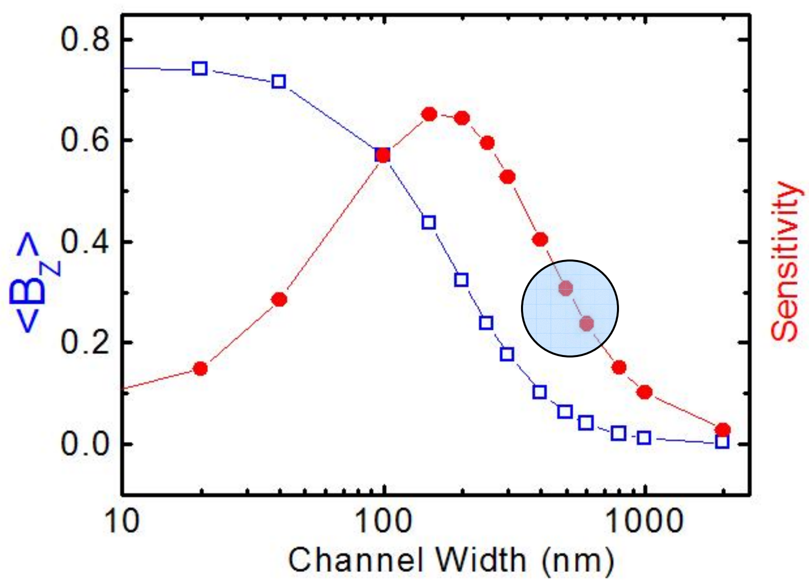




moment sensitivity: $m_{min} = C^{-1} \cdot B_{min}$

- **field sensitivity:** $\mathbf{B_{min} \propto w^{-1}}$
- **coupling coefficient:** $C = \langle B_Z \rangle / m$

⇒ **miniaturization**



However:

- mesoscopic effects
- 1/f noise and telegraph noise

⇒ *systematic* noise studies

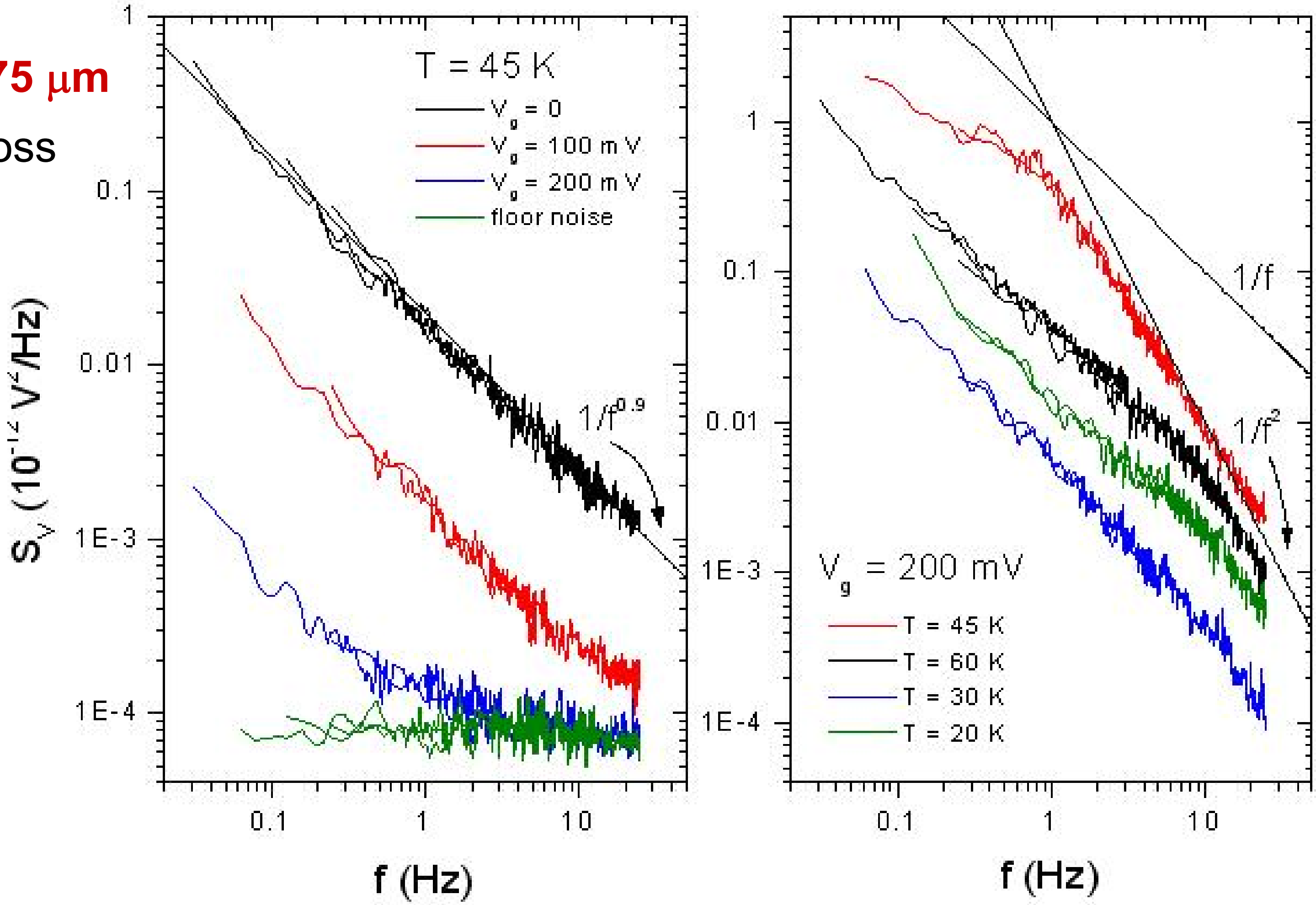
Noise in submicron AlGaAs/GaAs Hall devices

w = 0.75 μm

Hall cross

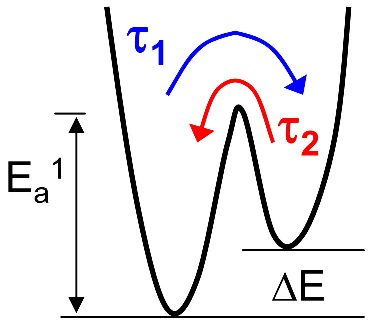
w = 0.45 μm

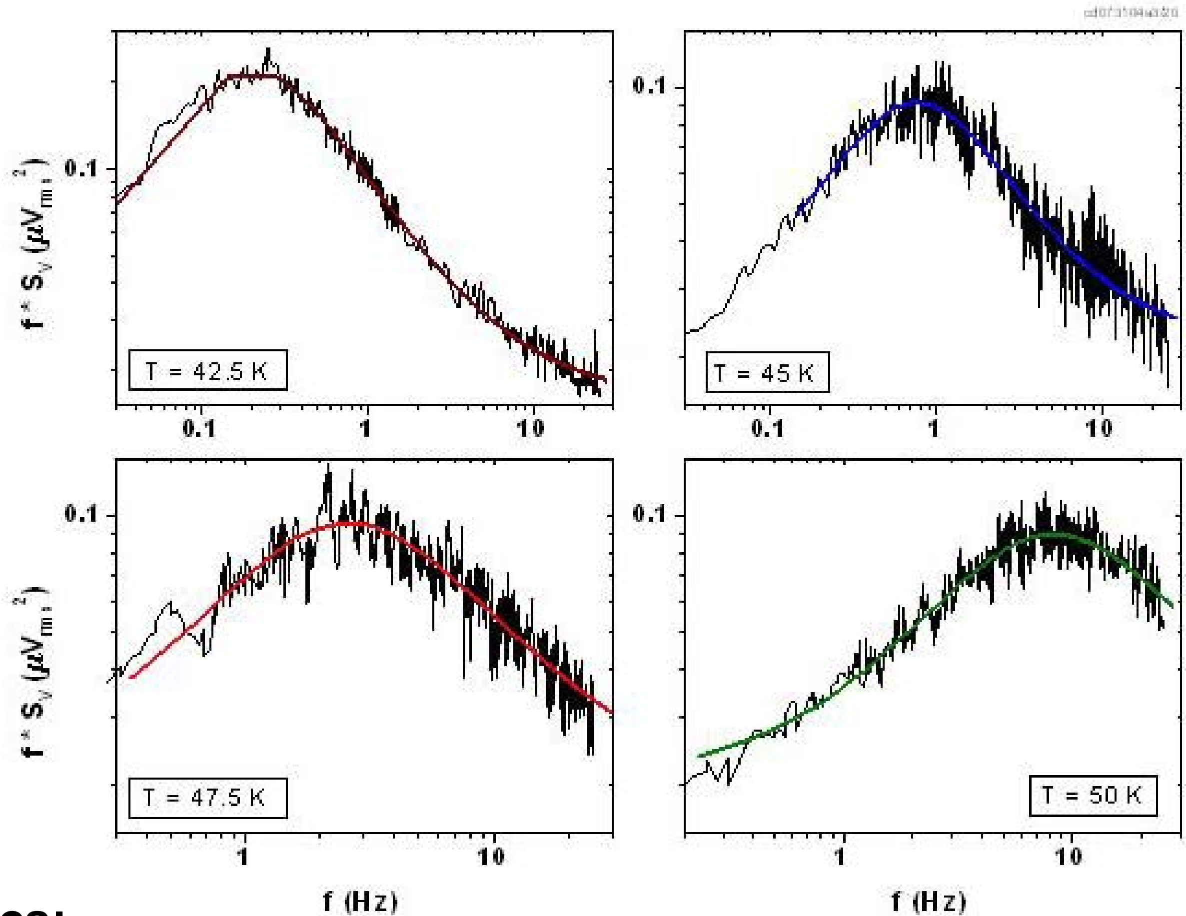
Hall cross



- large suppression of 1/f noise by gating
- **moment sensitivity** > 10^4 $\mu_B/\sqrt{Hz}$ at 1 Hz and B = 0.25 T (10^{-16} emu)
- non-monotonic T dependence
- deviations from 1/f
  → Lorentzian-type spectra

Decomposition of 1/f noise





→ analyze **f x S(f)**

$\Rightarrow f_p,\ f_p^2 \cdot S(f_p)$

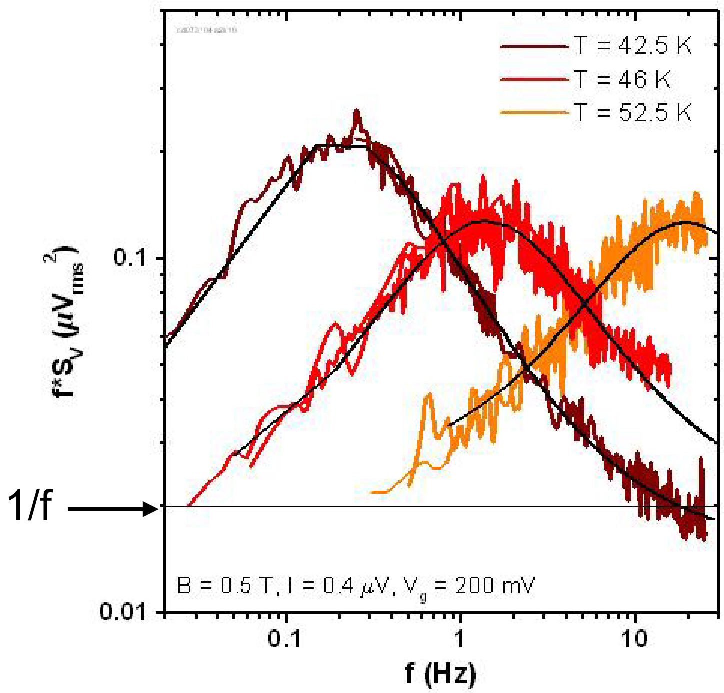
Kirtley et al.,
J. Appl. Phys. (1988)

Two-rate fluctuator kinetics:

$$S(f) = \frac{4(\Delta V)^2}{\tau_1 + \tau_2} \cdot \left(\frac{1}{(1/\tau_p)^2 + (2\pi f)^2} \right)$$

$$1/\tau_p = 2\pi f_p = 1/\tau_1 + 1/\tau_2$$

Machlup, J. Appl. Phys. (1954)

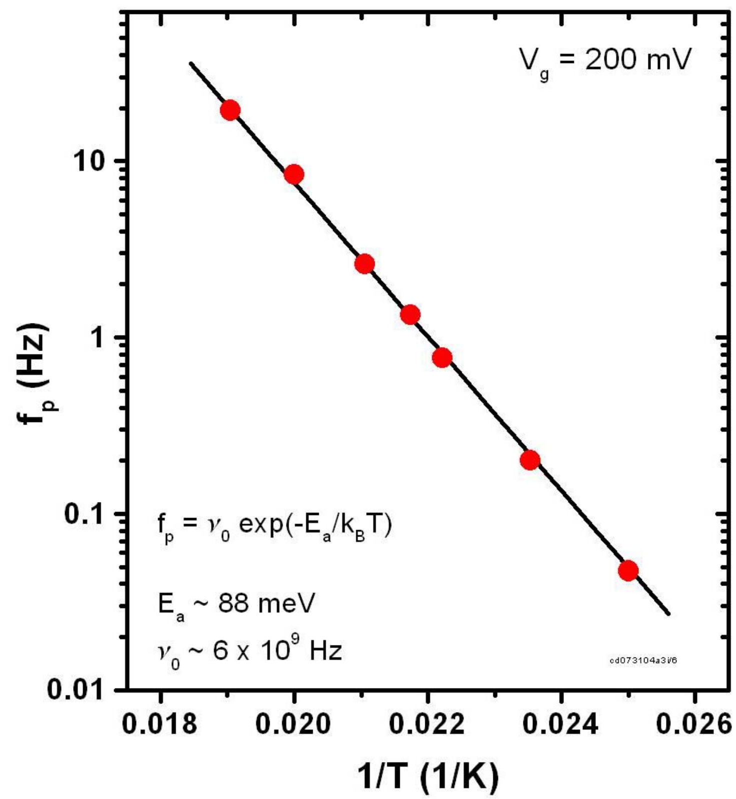


- single fluctuator + (small) 1/f background
- thermally activated behavior

$$\tau_i = \nu_{0,i}^{-1} \cdot \exp\left(E_{a,i} / k_B T\right)$$

- electron trapping / emission:

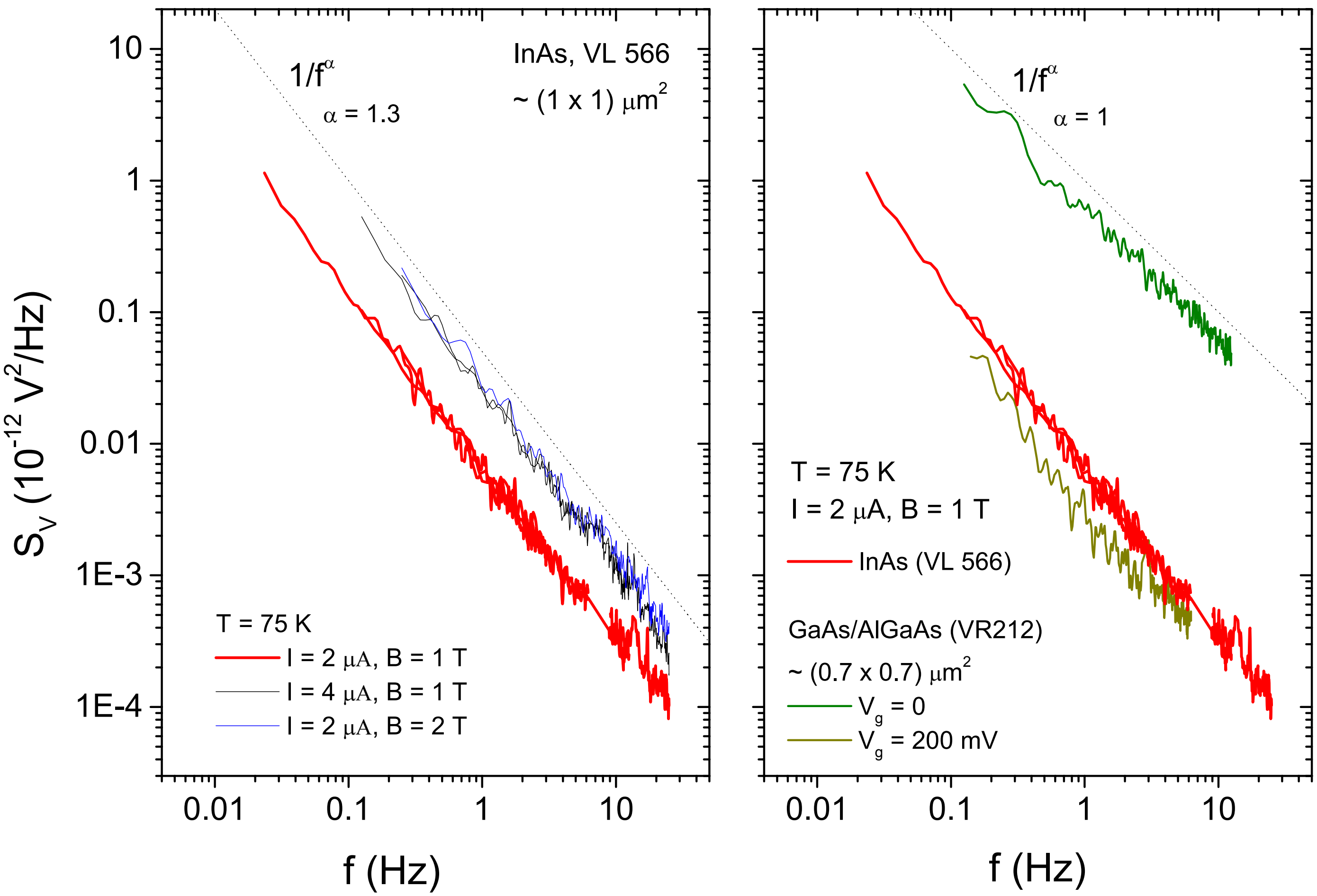
$$E_a \sim 88 \text{ meV}, \;\; \nu_0 \sim 6 \times 10^9 \text{ Hz}$$



Conclusions:

- **gated submicron Hall devices excellent probes to study fluctuations in GaAs/$Al_xGa_{1-x}As$ heterostructures**
- random telegraph noise
  → limits device miniaturization
  → **restricts temperature range to below 100 K** ***(trapping/detrapping of electrons from DX centers)***

Hall devices from alternative semiconductors: InAs/AlSb quantum well heterostructures



Noise level of *ungated* InAs device similarly low to that of $Al_xGa_{1-x}As/GaAs$ devices where noise has been substantially suppressed by gating

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III. **Magnetic Biosensors**

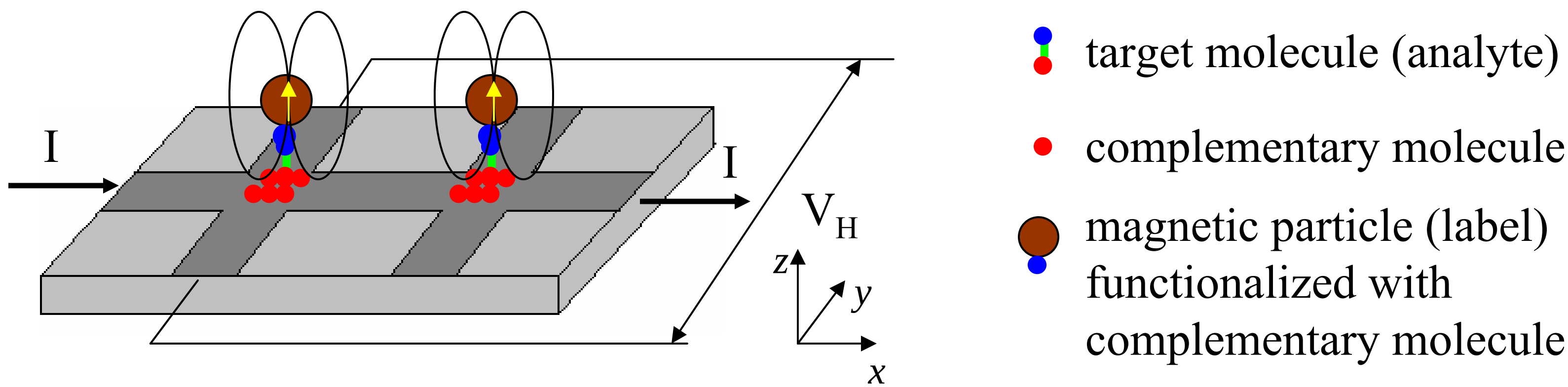
Goran Mihajlović, Pradeep Manandhar

Materials by:

Hideo Ohno & Keita Ohtani (Tohoku University),

Mark Field & Gerard J. Sullivan (Rockwell Scientific)

Hall sensor biological sensing scheme



Magnetic labels should:

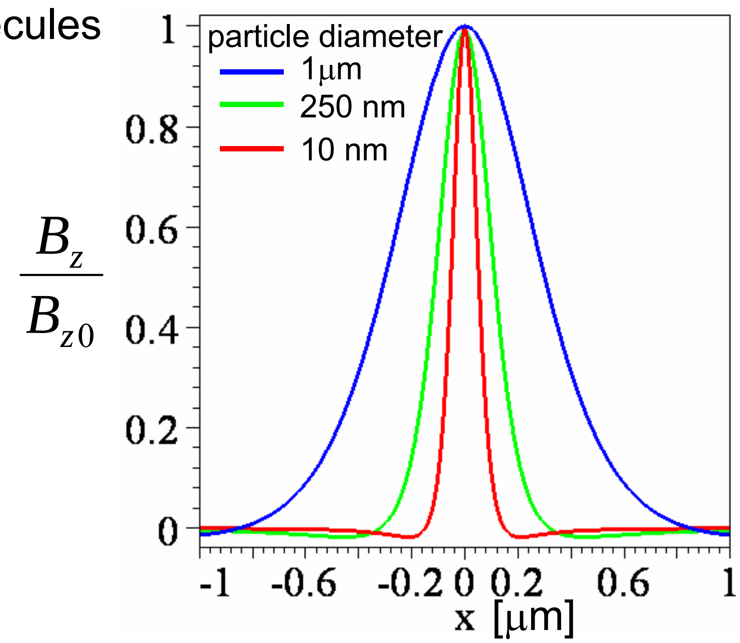
- be superparamagnetic to avoid aggregation in a sample solution
- have sizes comparable to the size of the target biomolecules

viruses: 20 – 450 nm
proteins: 5 - 50 nm
genes: 2nm × 10 – 100 nm

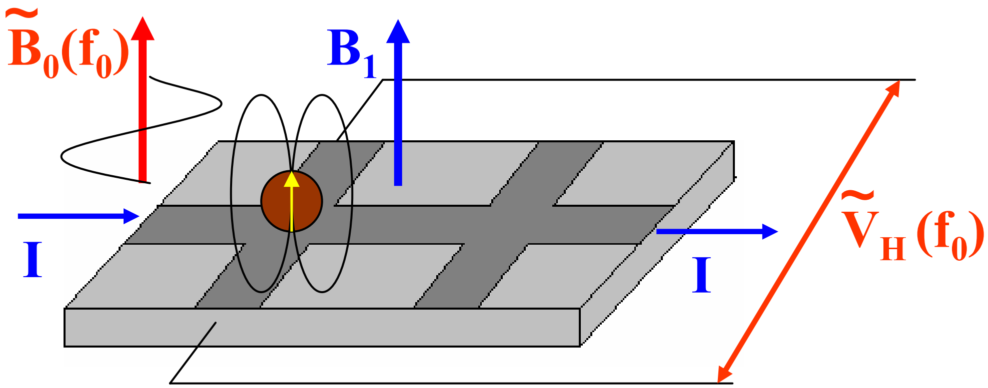
Q. A. Pankhurst et al., J. Phys. D **36**, R167 (2003)

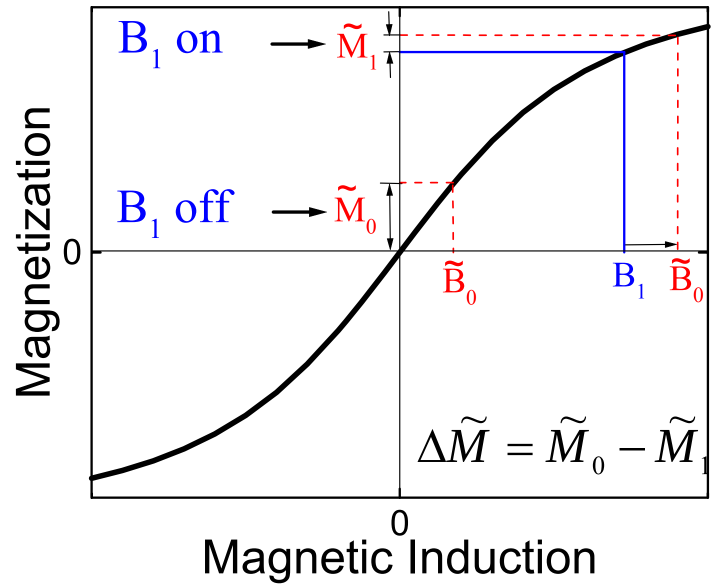
$$V_{\mathrm{H}} \propto \frac{1}{A}\int_A B_z dS$$

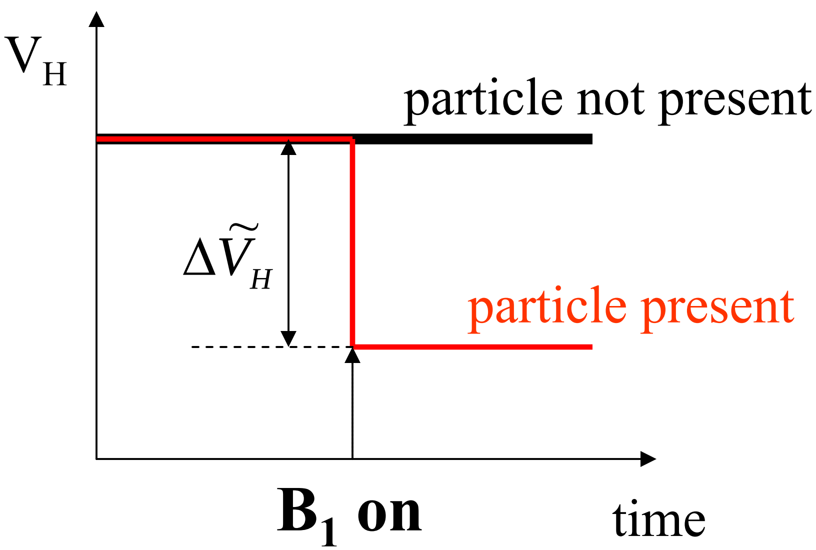
⇒ minimize *A* to maximize the signal !



Detection method for superparamagnetic particles

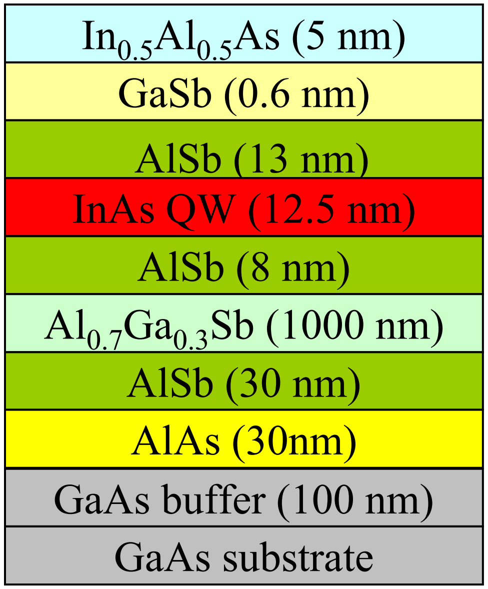


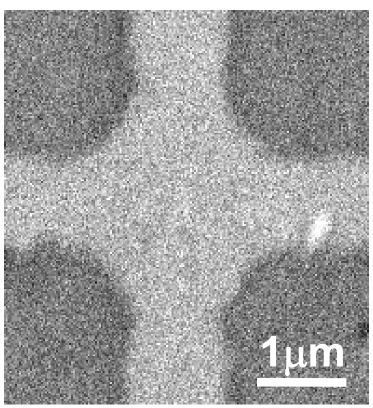


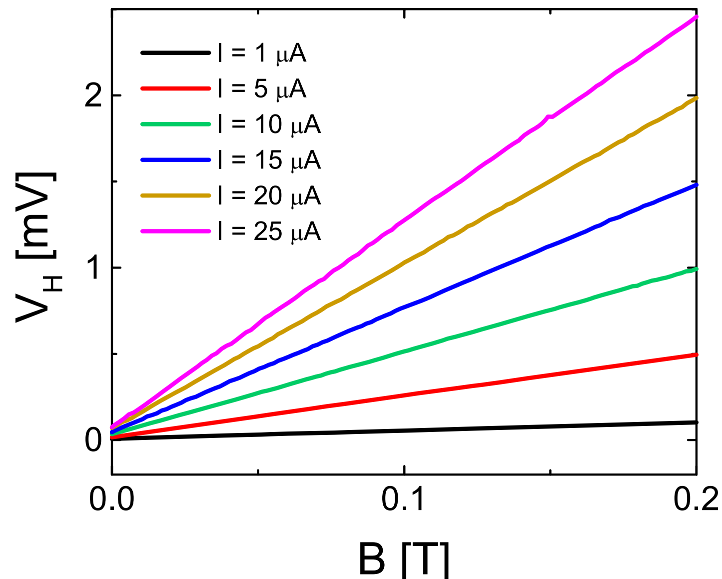


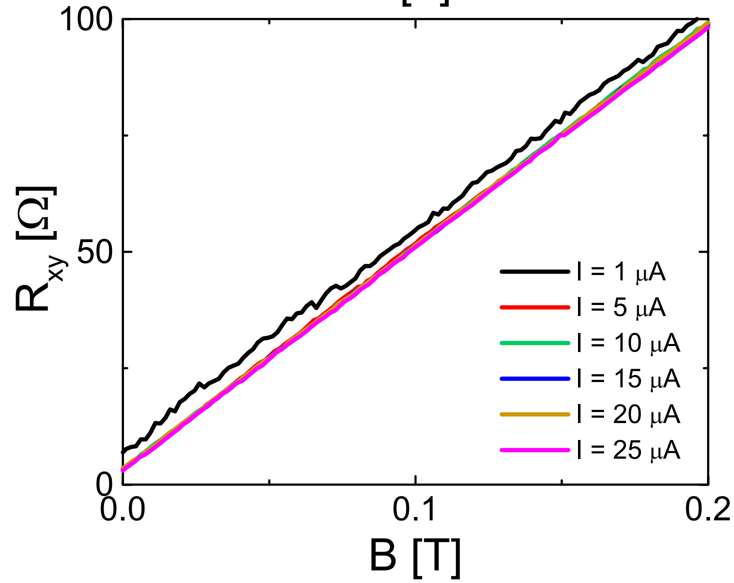
- **linear sensor output necessary to obtain definite information from one measurement**
- $\Delta\tilde{M} = f\left(\tilde{B}_0, B_1\right) \Rightarrow$ possibility for tuning the the signal to noise ratio by the applied fields

Micro-Hall sensors from InAs/AlSb quantum well heterostructures





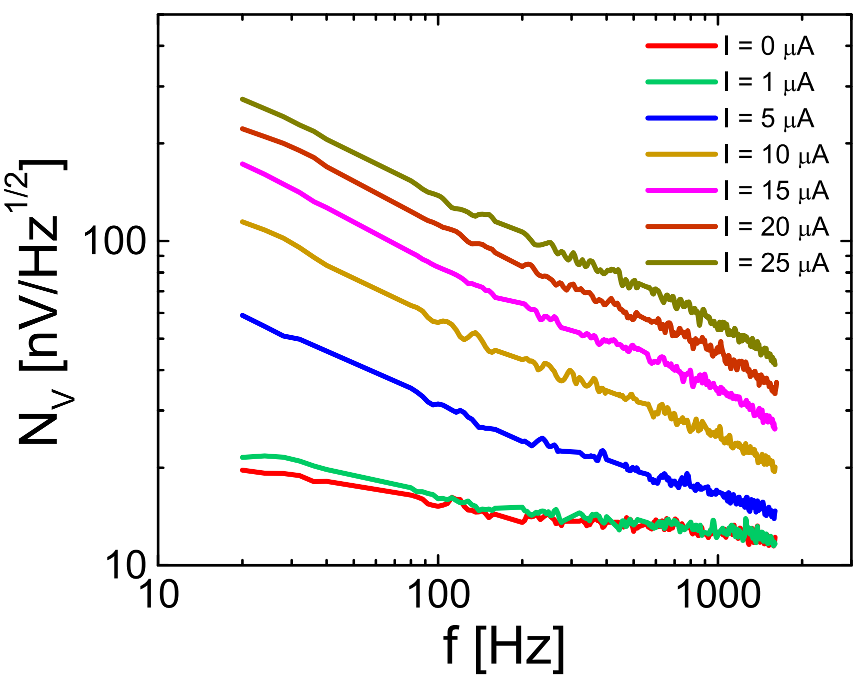


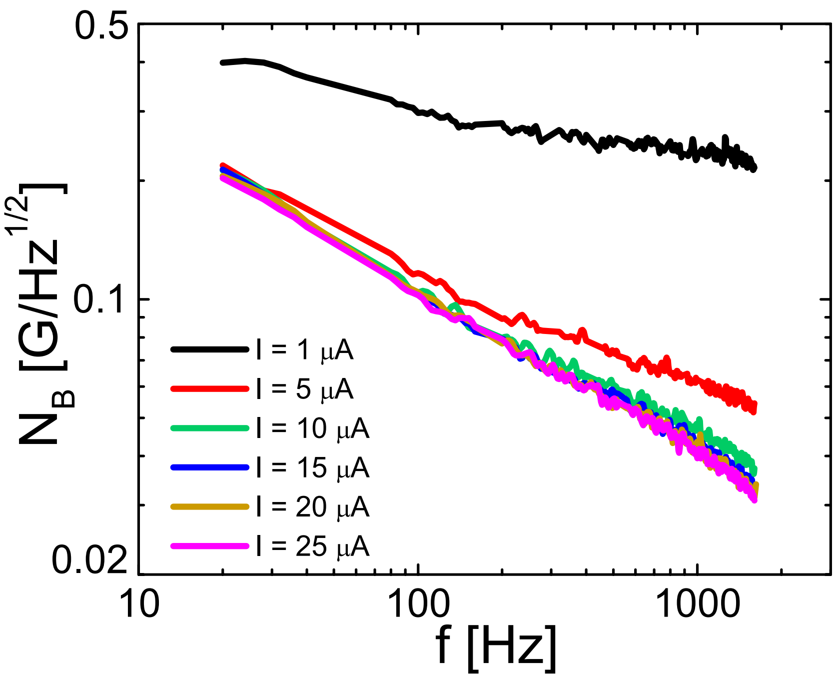


470 Ω/T < R_H < 620 Ω/T

Magnetic field resolution of the micro-Hall sensors

- minimum uniform magnetic field that can be detected by the device
- ultimately limited by the device noise level at a maximum bias current $B_{min} = \dfrac{V_{HN}}{R_H I_{max}}$
- $V_{HN} = N_V \sqrt{\Delta f} \quad \Rightarrow \quad B_{min} = N_B \sqrt{\Delta f}$

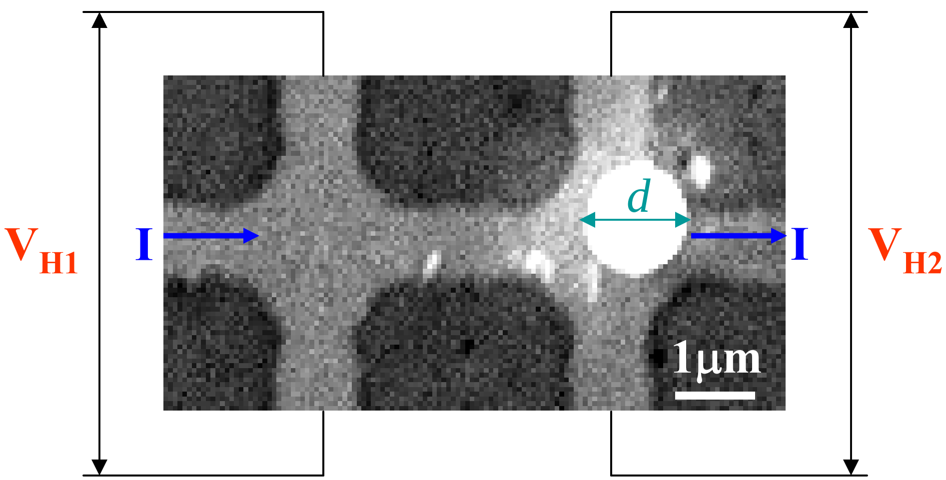


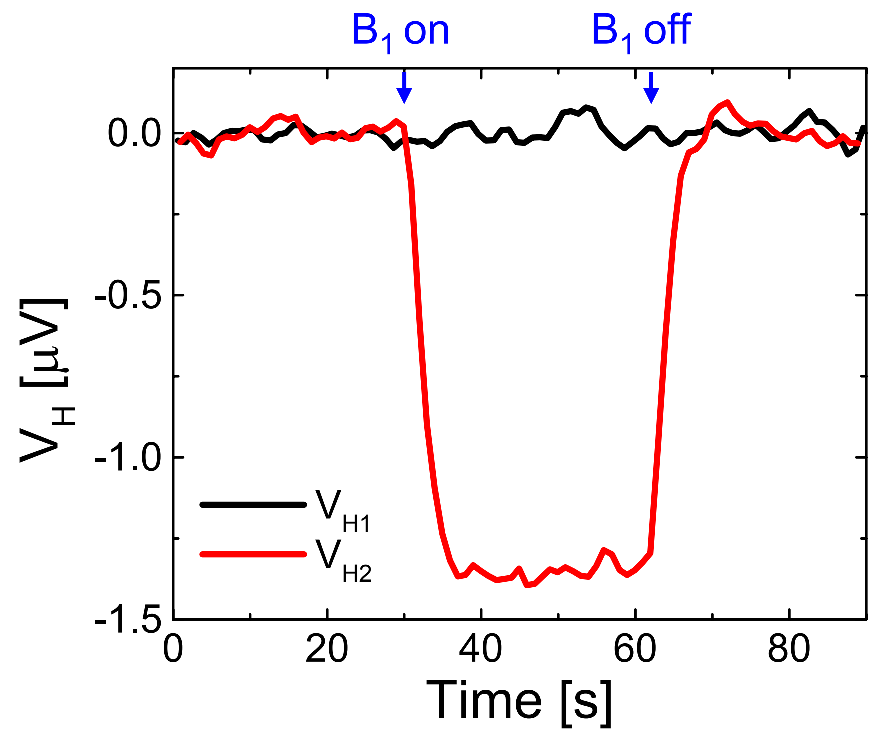


$\Rightarrow$ magnetic field resolution limited by 1/f noise !

Detection of Single 1.2 μm Superparamagnetic Bead

G. Mihajlović et al., Appl. Phys. Lett. **87**, 112502 (2005)





<u>superparamagnetic bead:</u> *d* ~ 1.2 μm

Fe_3O_4 nanoparticles in a spherical latex matrix

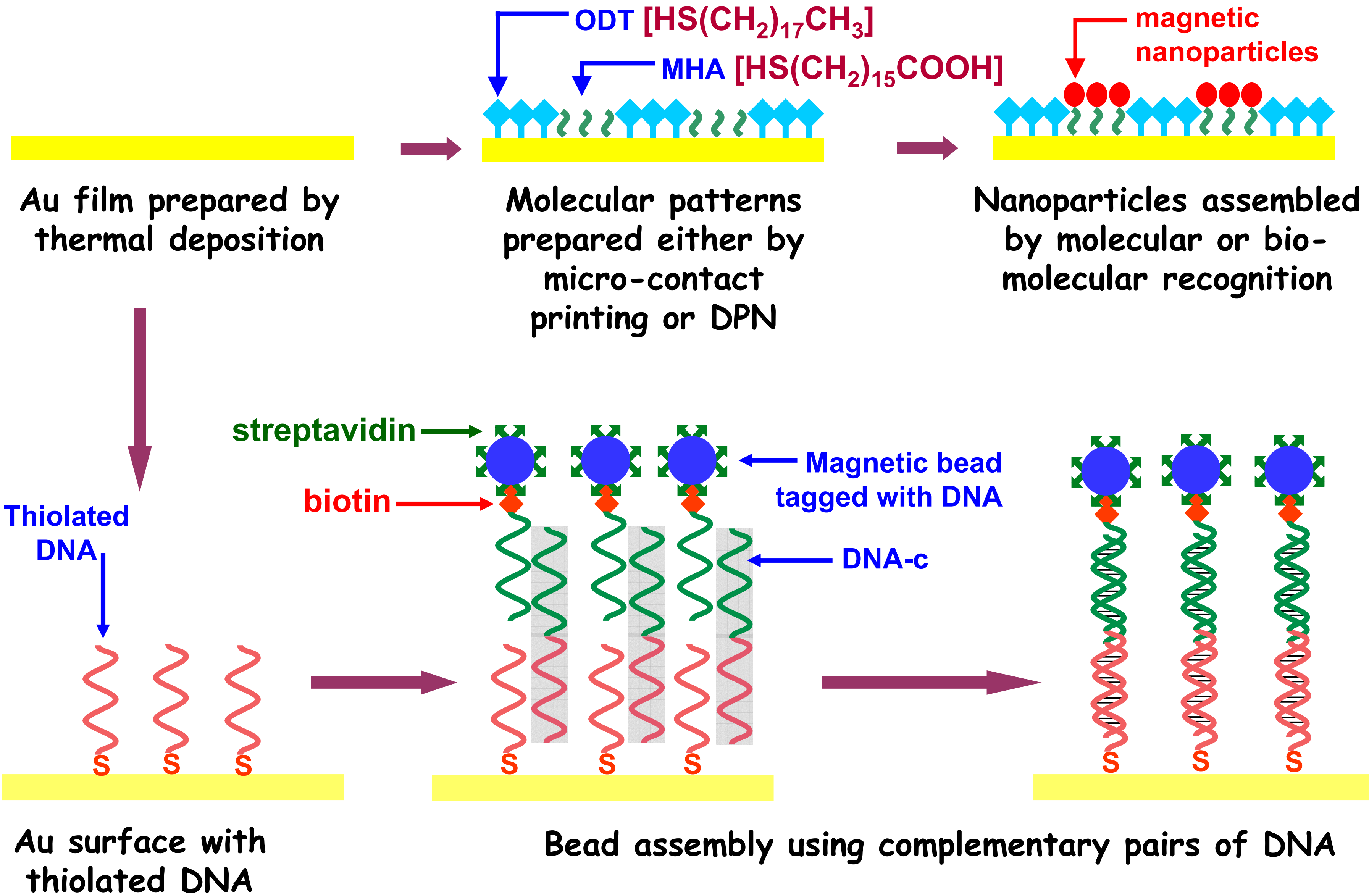
(Sigma Chemical CO)

Detection parameters: I = 10 μA, R_H = 616 Ω/T, B_0 = 26.3 G, B_1 = 470 G, f_0 = 83.7 Hz, τ = 1s

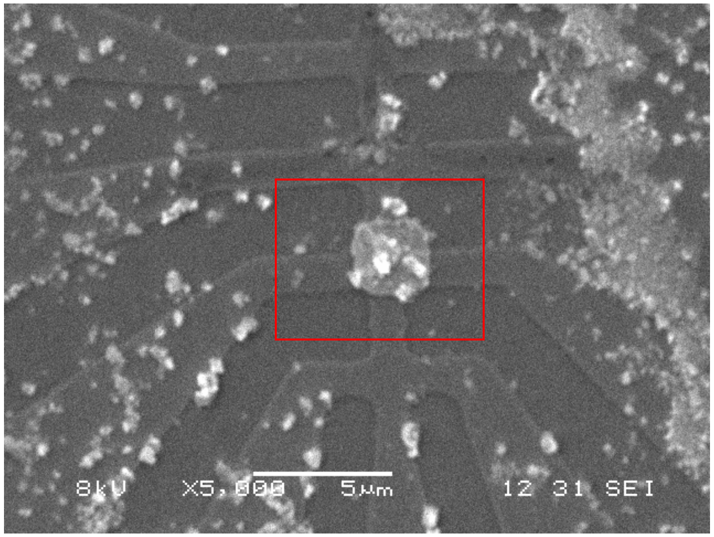
Detected signal and noise level: ΔV_H = 1.35 μV, V_{HN} = 29 nV, S/N = 33.3 dB (46.5)

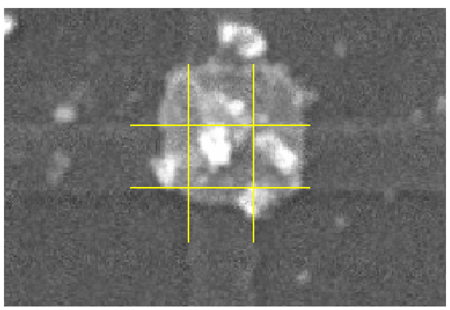
Detected change in the stray magnetic field: B_{det} = 2.2 G

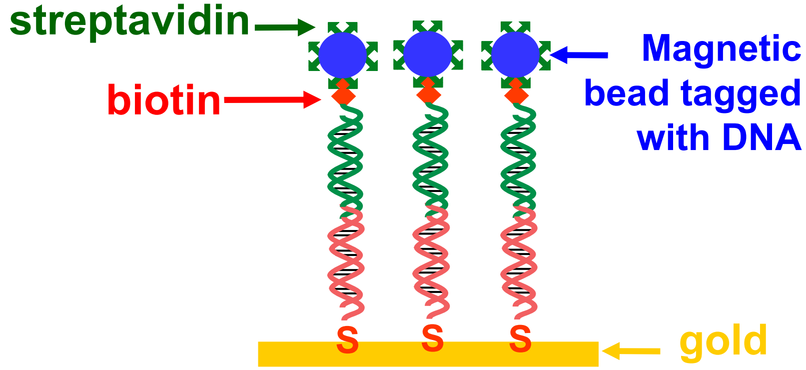
Scheme for Assembly of Nanoparticles and Magnetic Beads

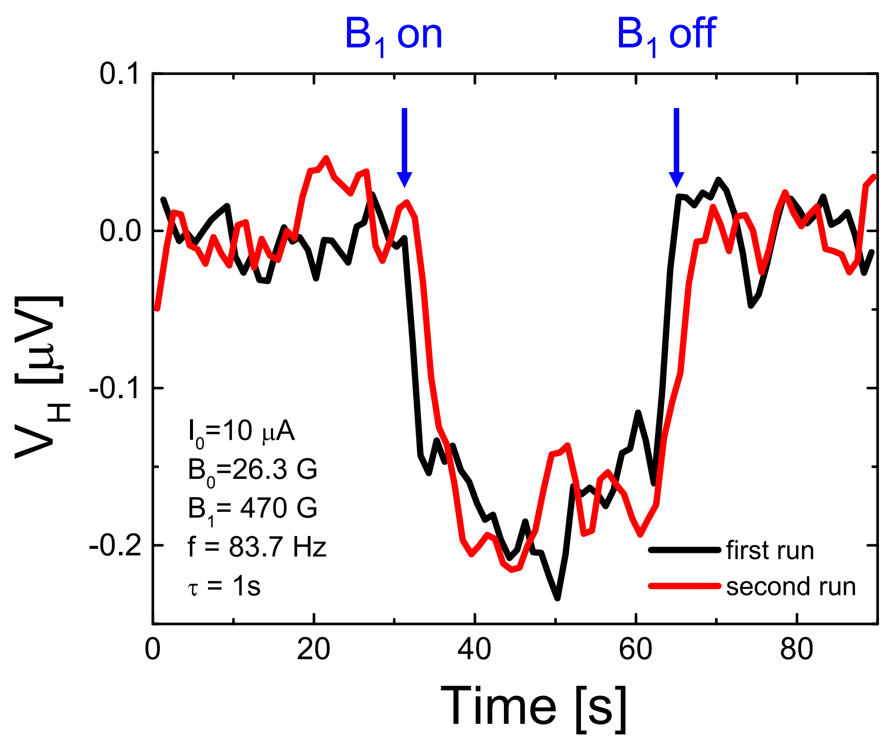


Detection of 250 nm Superparamagnetic Beads









$\Delta V_H = 0.18\ \mu V$

$V_{HN} = 23\ nV$

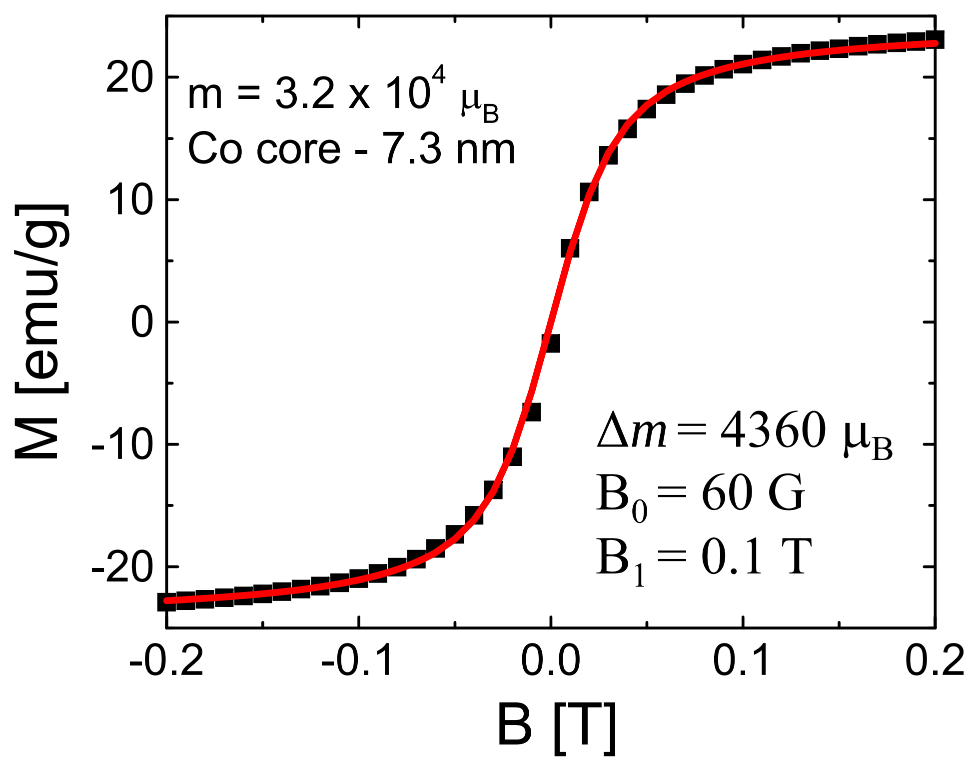
$S/N = 17.9\ dB\ (7.8)$

$B_{det} = 0.30\ G$

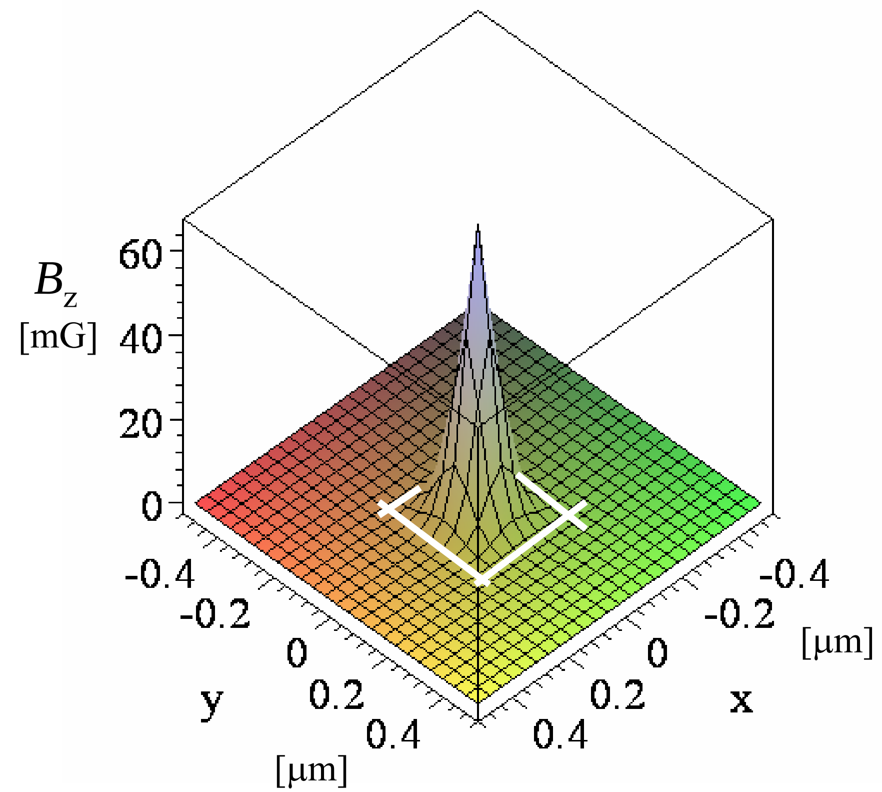
$\Rightarrow$ single nanobead sensitivity for 250 nm beads !

Are the smaller nanoparticles detectable?

Co nanoparticles



stray magnetic field distribution from a single Co nanoparticle



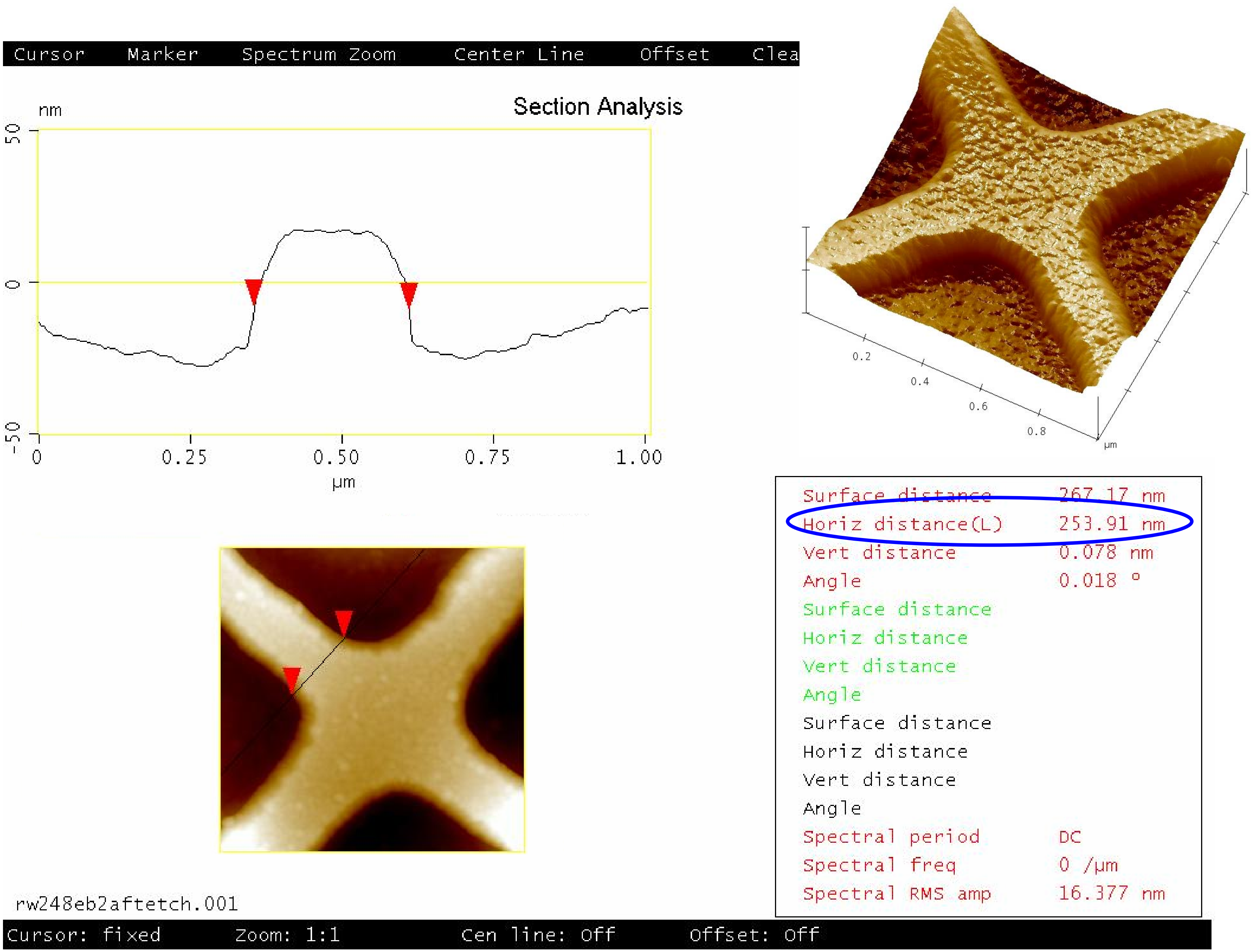
- average stray magnetic field flux from a single Co nanoparticle over the active area:

~ 0.2 mG for 1 μm × 1 μm Hall cross

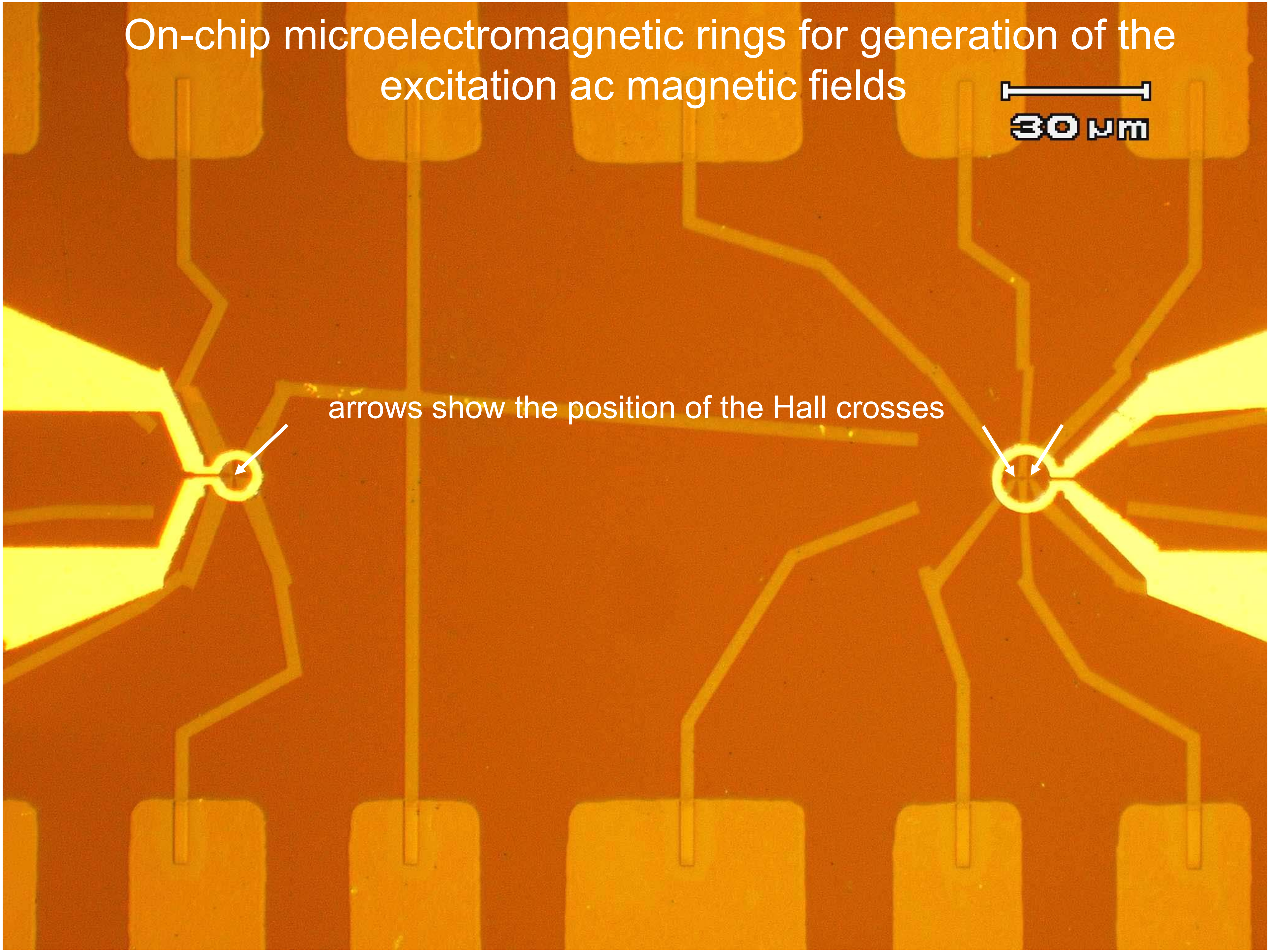
~ 10 mG for 300 nm × 300 nm Hall cross

⇒ submicrometer Hall sensors !

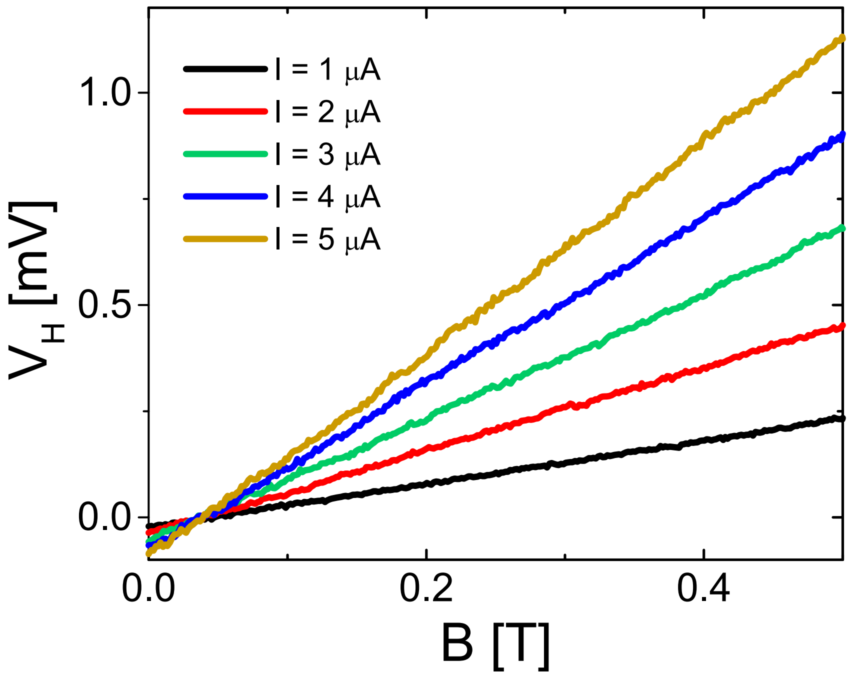
Fabrication of Submicrometer Hall sensors

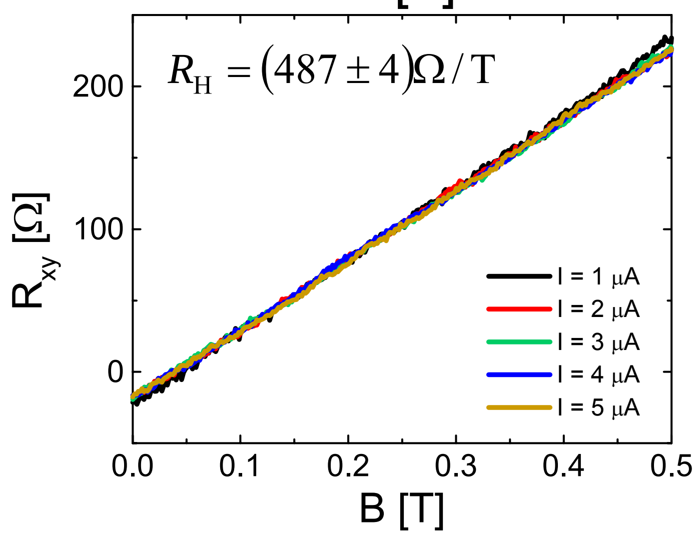


On-chip microelectromagnetic rings for generation of the excitation ac magnetic fields

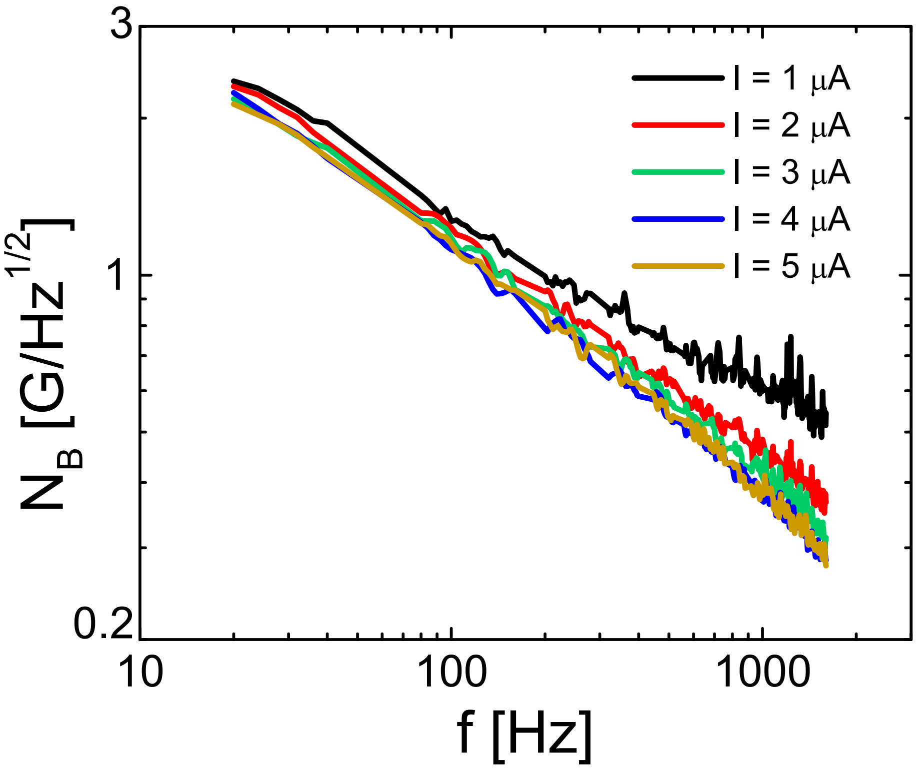


Functional submicrometer-Hall Sensors

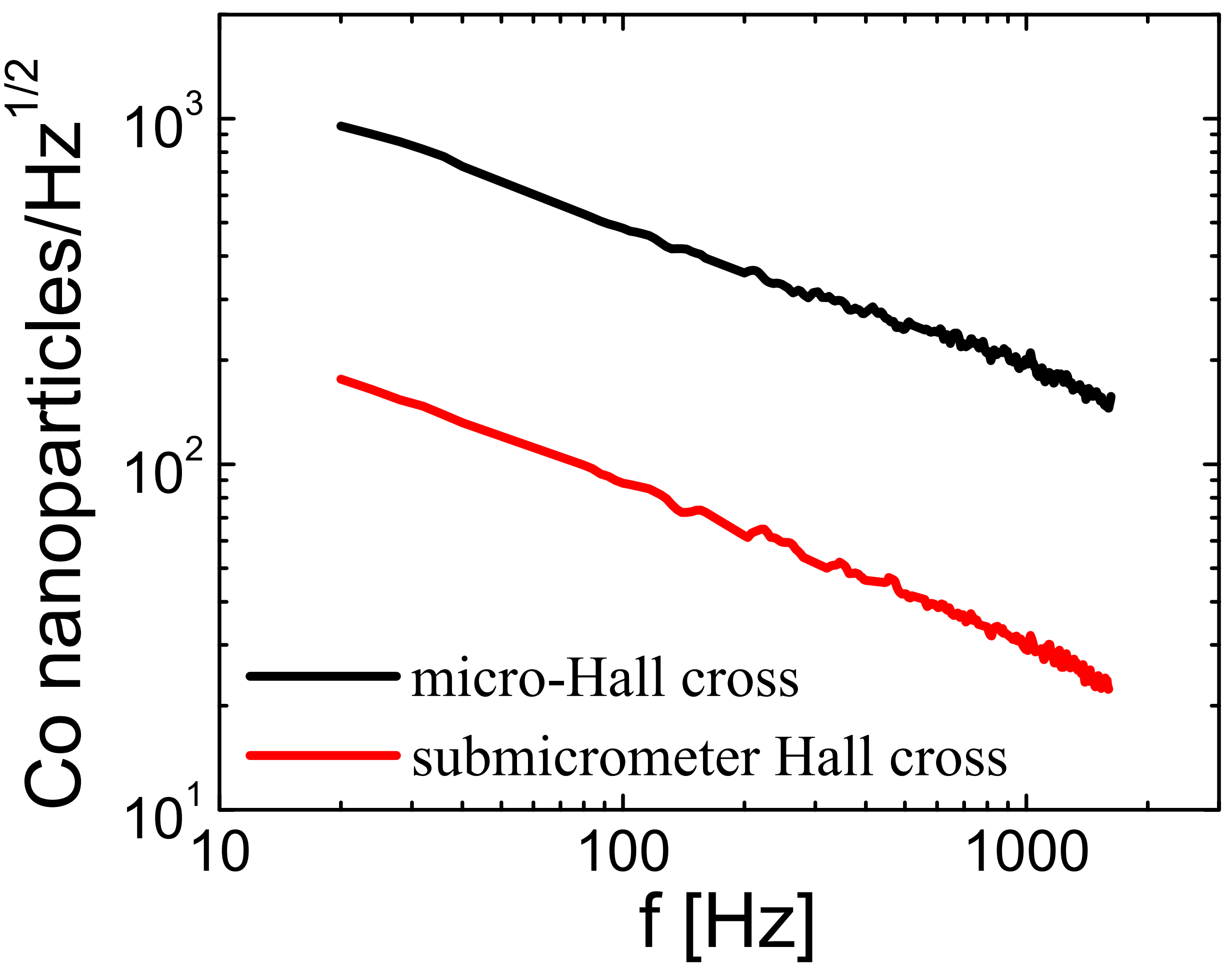




magnetic field resolution



Minimum detectable number of Co nanoparticles



100 Co nanoparticles = 4.36×10^5 μ_B !

Conclusions

• micron and submicron Hall sensors from GaAs/AlGaAs heterostructures are excellent probes for the study nanomagnetism, including interaction effects.

• micron and submicron Hall sensors from InAs/AlSb quantum well heterostructures are highly sensitive (moment sensitivities as much as $\sim 10^5\ \mu_B$ at room temperature) detectors of micro- and nanobeads that can be utilized in biomolecular sensing.