

Advanced Magnetometry

Dirk Sander

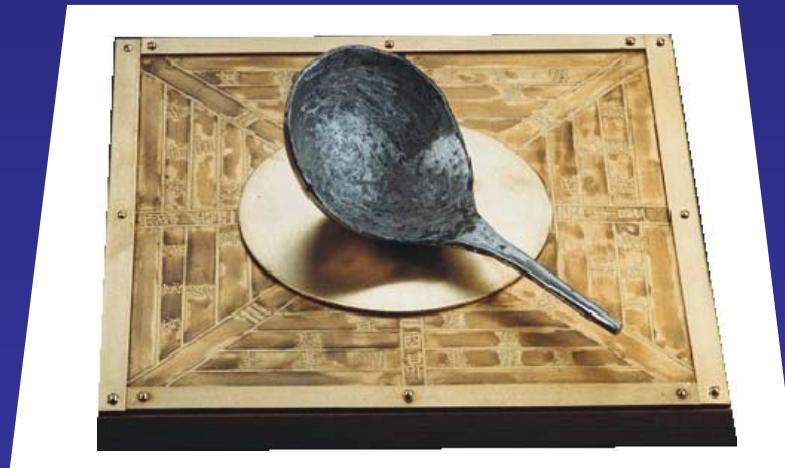
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www.mpi-halle.de



$$\vec{T} = \vec{m} \times \vec{B}$$

compass, Han dynasty 200 AC – 200 AD

What will be presented?

- interest in magnetometry of nanoscale objects
- UNITS, required sensitivity and accuracy
- overview of established techniques
VSM, SQUID, AGM, torque magnetometer
- magnetometry for nanoscale objects
SQUID, torque magnetometry, micromechanical sensors
- application and outlook
monolayer magnetometry and single spin detection

Novel magnetic properties at the nanoscale I

modified magnetization in monolayers and at interfaces

theory and experiment:

single layers:

enhanced magnetic moment

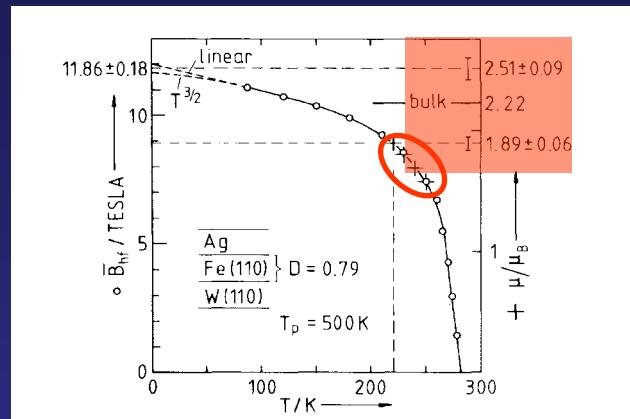
1 ML Fe / W(110): +14 %

extrapolated, NOT measured
(TOM)

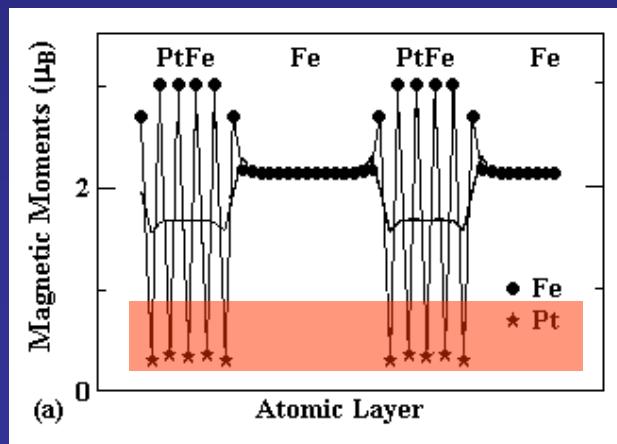
induced magnetic moment:
e.g. Pt in Co / Pt or Fe / Pt

Pt: 0.2 μ_{Bohr}

magnetic resonant-SXRD
at ESRF, beamline ID-03



Elmers, Liu, Gradmann, PRL 63(1989)566.



Skomski, JPCM15(2003)R841.

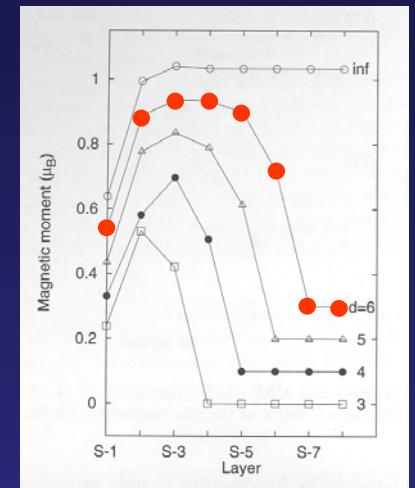
Novel magnetic properties at the nanoscale II

adsorbate-induced reduction of magnetic moment

H / Ni n / Cu(001)

theory: reduction by ~30 % at both interfaces

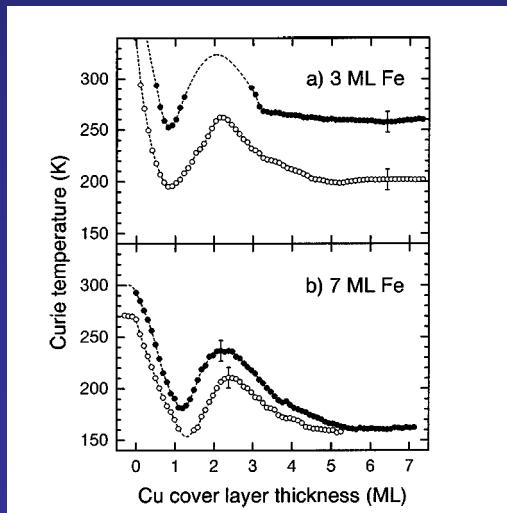
Maca, Shick, Redinger, Podlucky, Weinberger
Czech. J. Phys. 53(2003)33.



caplayer-induced reduction of T_{Curie}

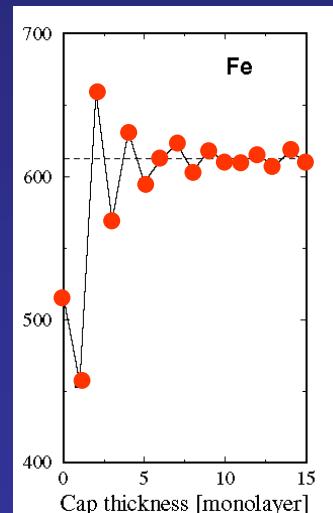
Cu n / Fe / Cu(001)

experiment



theory

oscillatory T_C



Volmer, vanDijken, Schleberger, Kirschner,
PRB 61(2000)1303.

Pajda, Kudrnovsky, Turek, Drchal, Bruno,
PRL 85(2000)5424.

Magnetometry and magnetic anisotropy

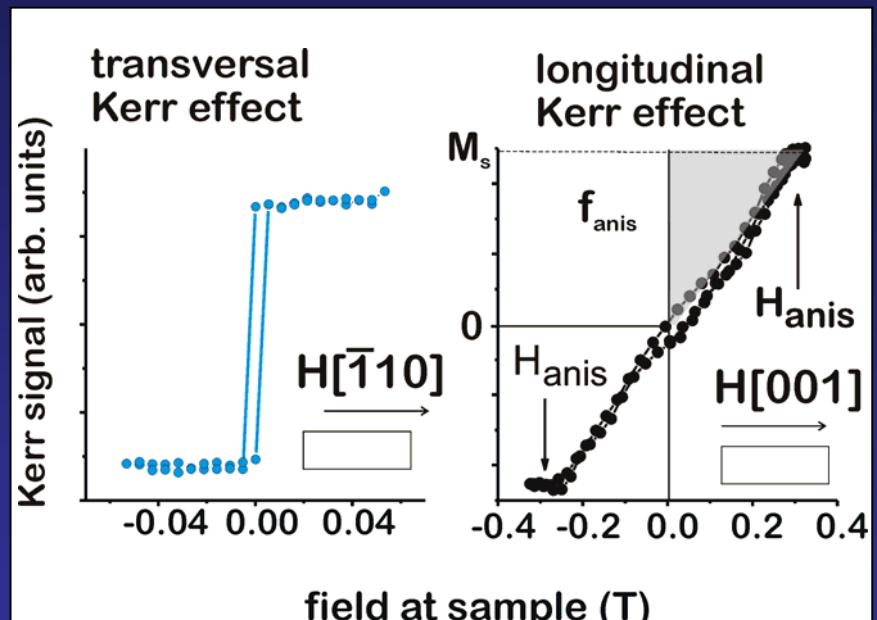
strain, interfaces and atomic coordination:
modified magnetic anisotropy

in-plane magnetic anisotropy:
1.7 nm Fe / W(110)

easy magnetization along [-110],
NOT [001] (like bulk Fe)

magnetization along “hard” axis

$$f_{\text{anis}} = \frac{1}{2} \mu_0 M_s H_{\text{anis}}$$
$$= 0.26 \text{ MJ/m}^3 = 19 \text{ } \mu\text{eV/atom}$$



Sander, JPCM16(2004)R603.

here: relative M_s from MOKE,
better: magnetometry

Units in magnetism

Correlation between electric current and magnetic field



deflection of compass needle

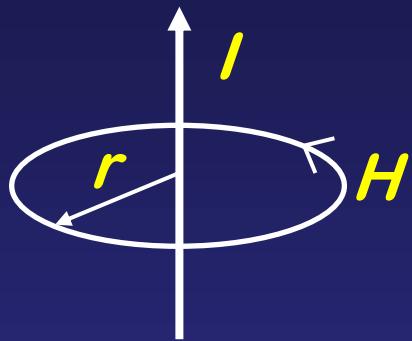
Chr. Oersted
(1777 – 1851)



forces between currents and
Ampère's law

A.M. Ampère
(1775 – 1836)

Magnetic field H due to a current I :



$$\oint \vec{H} d\vec{s} = \iint_A \vec{j} d\vec{A} \quad (\text{Ampère's law})$$

$$H = \frac{I}{2\pi r} \left[\frac{A}{m} \right]$$

what about Tesla [T]? $\text{rot } \vec{B} = \mu_0 \vec{j}$

B [T]: magnetic induction
 $\mu_0 = 4\pi 10^{-7}$ [T m /A]
permeability of free space

$$B = \frac{\mu_0 I}{2\pi r} \quad [\text{T}]$$

and Oersted [Oe]? $1 \text{ T} = 10^4 \text{ Oe} = 0.796 \frac{\text{MA}}{\text{m}}$

1 T is a large field..., 100 A in 1 cm: ONLY 2mT

Magnetization M and magnetic moment m

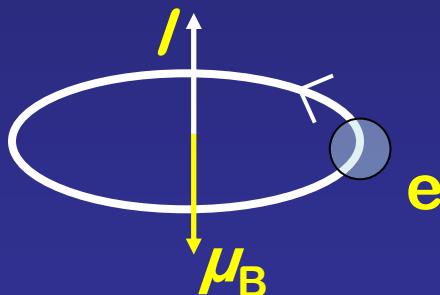
$$\vec{B} = \mu_0 (\vec{H} + \vec{M})$$

Sommerfeld convention

$$\vec{M} = \frac{N}{V} \vec{m}$$

total magnetic moment per volume,
N: number of magnetic moments
V: volume

atomic magnetic moment: Bohr magneton μ_B



classical picture
-WRONG-

$$\mu_B = \frac{e \hbar}{2 m_e} = 9.274 \times 10^{-24} \text{ A m}^2 \quad [\text{J/T}]$$

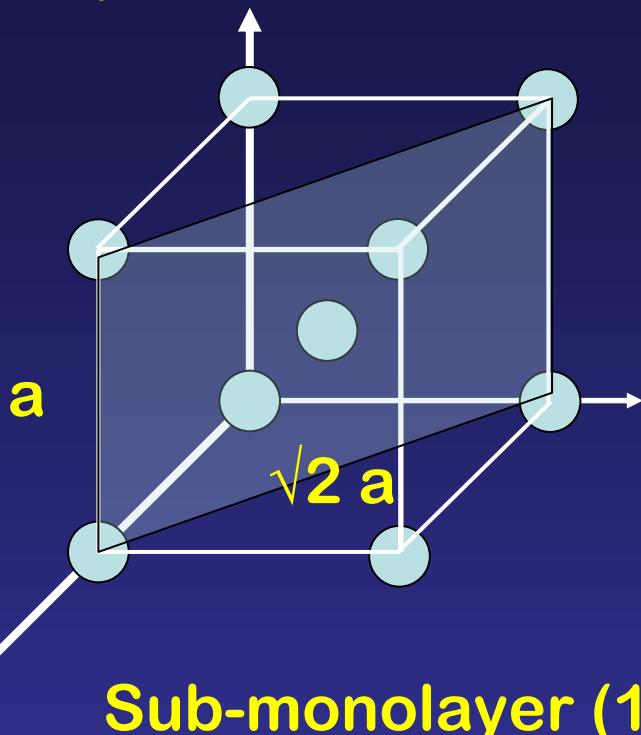
1 μ_B : magnetic moment of 1 electron spin

$$(1 \text{ emu} = 10^{20} \mu_B = 10^{-3} \text{ Am}^2)$$

Spontaneous magnetization M_s of bulk elements

	bcc-Fe 286 K	hcp-Co 287 K	fcc-Ni 287 K
[kA / m]	1717	1447	493
[T]	2.16	1.82	0.62
[μ_B]	2.18	1.74	0.58

Required sensitivity for nanoscale magnetometry



Example:

Fe / W(110), bcc (110),
 $a = 3.16 \text{ \AA}$

$$n_{W(110)} = 1.42 \times 10^{15} \text{ cm}^{-2}$$

Sub-monolayer (1% ML) sensitivity requires: $10^{13} \mu_B$

$$10^{-10} \text{ J / T}$$

$$10^{-6} \text{ A cm}^2$$

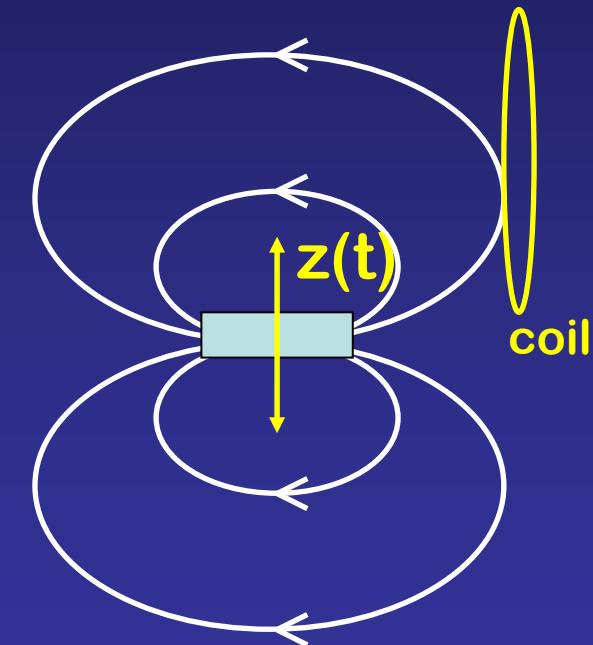
accurate magnetization data can only be derived for known amounts of deposited materials (e.g. thickness calibration)

Vibrating sample magnetometer (VSM) I

S. Foner, Rev. Sci. Instr. 30(1959)548; JAP 79(1996)4740.

a moving magnetized sample induces a voltage V in a pick-up coil

change of flux Φ is induced by the stray field B of the sample,
which is approximated by a dipolar field

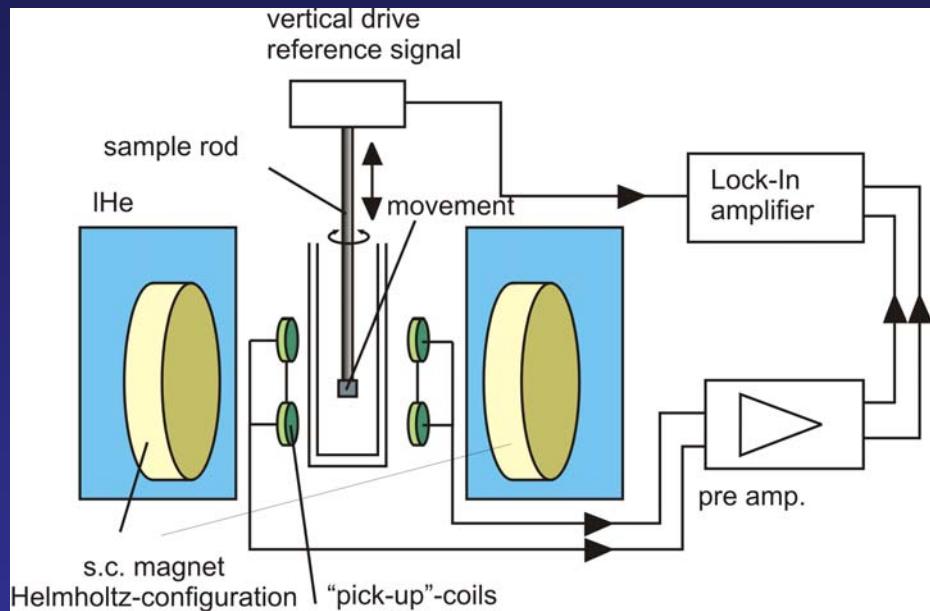


$$\Phi(t) = \iint_{\text{coil}} B_x(x_{\text{coil}}, y, z(t)) dy dz$$
$$V \sim \frac{d\Phi}{dt} \quad (\sim m_{\text{total}, x})$$

calibration: comparison to a moving Ni sphere

Vibrating sample magnetometer (VSM) II

experimental set-up



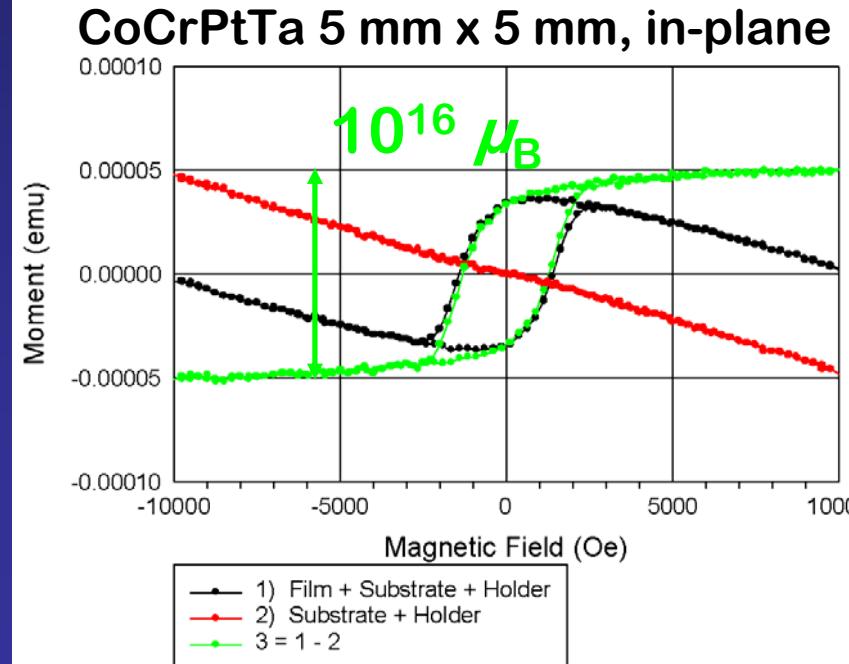
also: vector VSM

2 sets of orthogonal pick-up coils
for anisotropy measurements

noise < 1 μemu ($10^{14} \mu_B$)

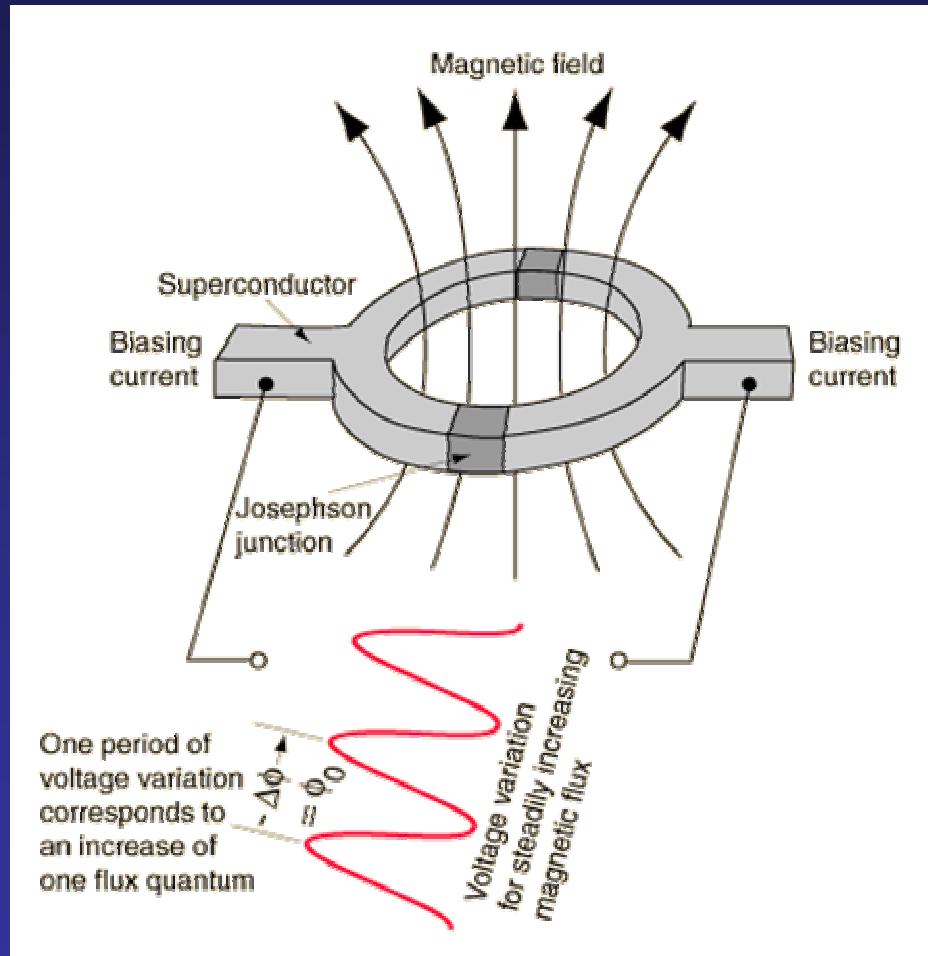
background effect:

Figure 1: $M(H)$ for CoCrPtTa HD film. $M(H)$ for VSM sample holder and substrate are also shown.



SQUID magnetometry I

super-conducting quantum interference device

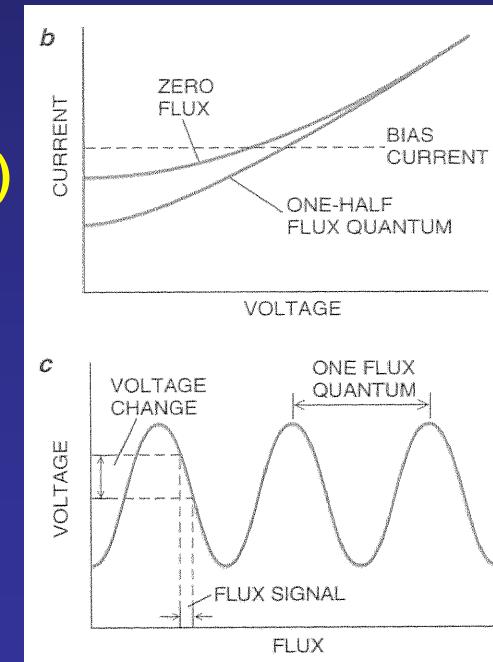


signal detection:

feedback cancels flux change, V constant

superconductivity
Josephson junction ($2x$)
flux quantization
($\Omega_0 = h/2e = 2 \times 10^{-15} \text{ Tm}^2$)
flux-to-voltage converter

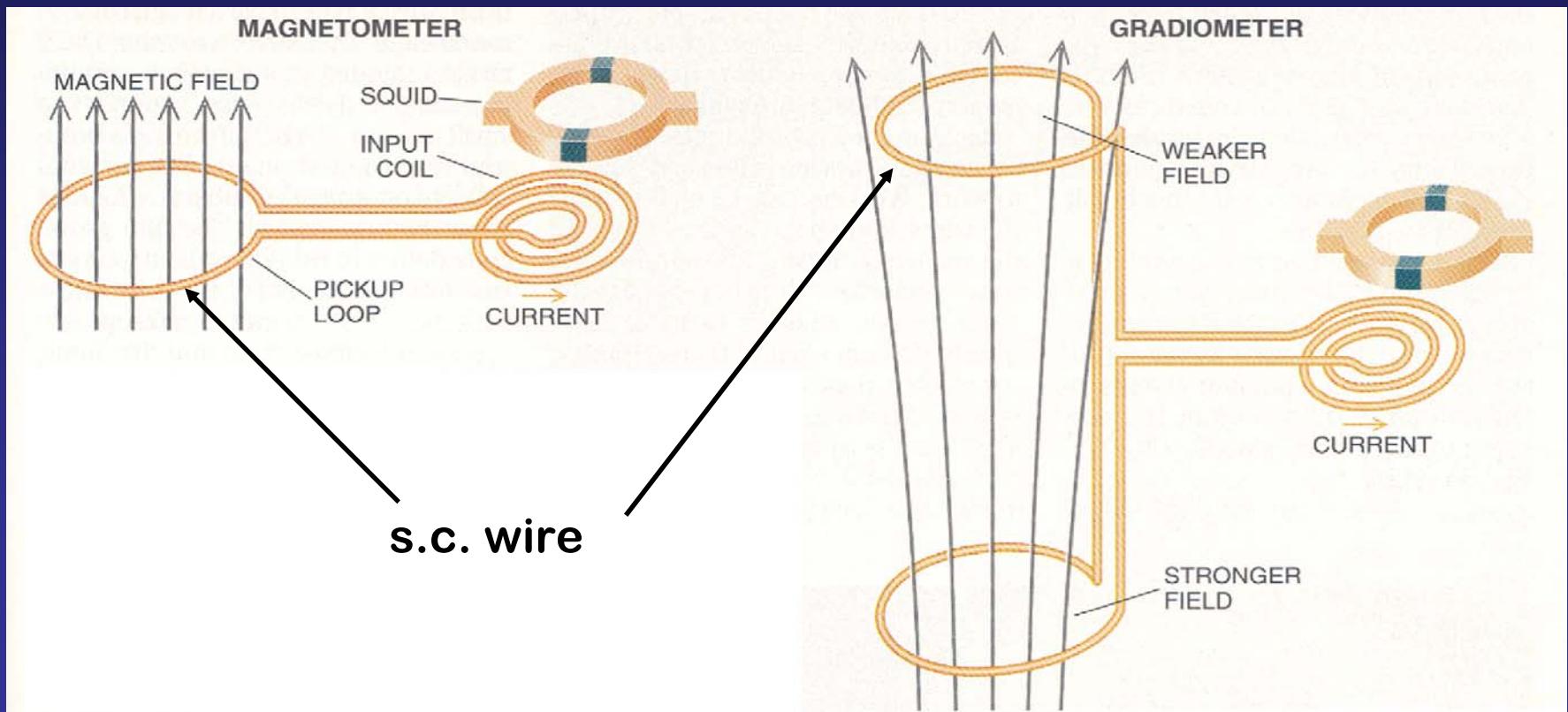
dc-SQUID
(direct-current)



J. Clarke, Sci. Am. 271(1994)36.

SQUID magnetometry II

flux transformers and gradient coils
pick-up loops for larger flux-sensitive areas
 cm^2 vs μm^2



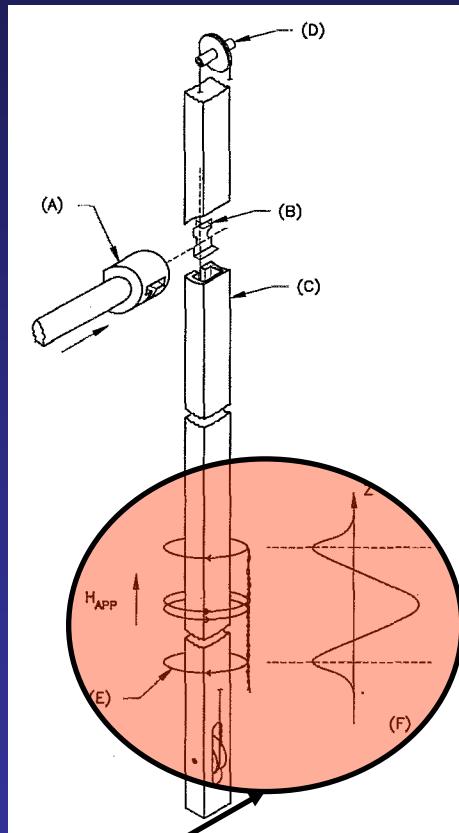
sensitivity range: $10^{12} \mu_B - 10^{20} \mu_B$
background signal (sample holder, substrate)

SQUID magnetometry III

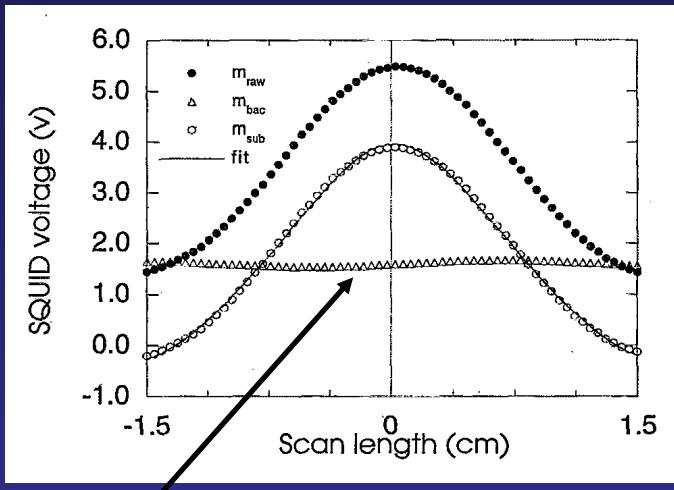
UHV-SQUID

Spagna, Sager, Maple RSI 66(1995)5570.

in UHV:

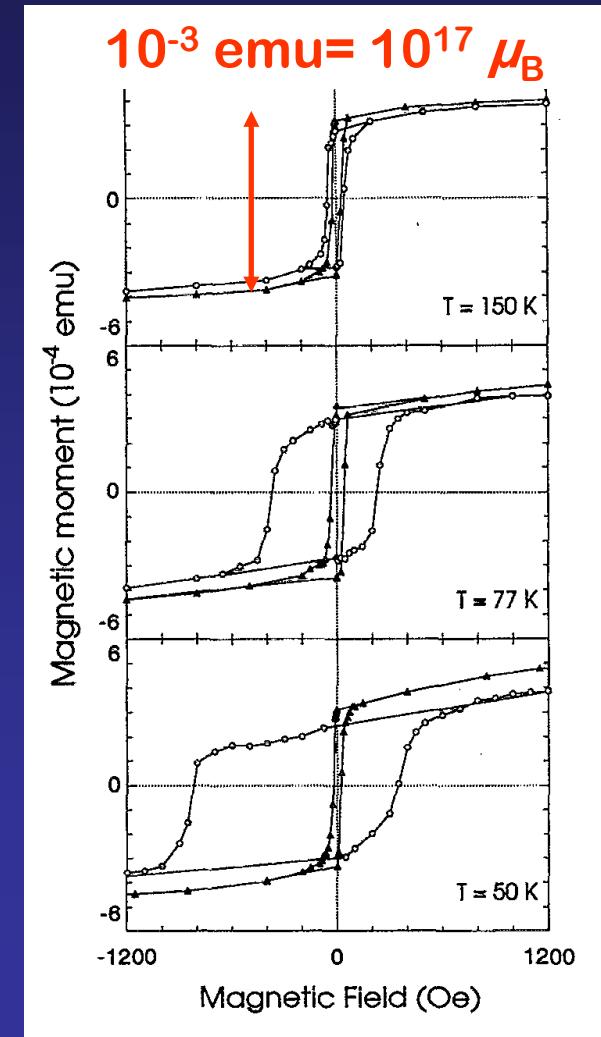


gradient coil
ideal point-dipole signal



significant background

67 Å CoO/Co/Si(110):
before and after oxidation
exchange bias



micro SQUID (μ -SQUID)

see: previous summer school

<http://lab-neel.grenoble.cnrs.fr/euronanomag/2003-brasov/program.html>

and Wernsdorfer's group at

<http://lab-neel.grenoble.cnrs.fr/themes/nano/>

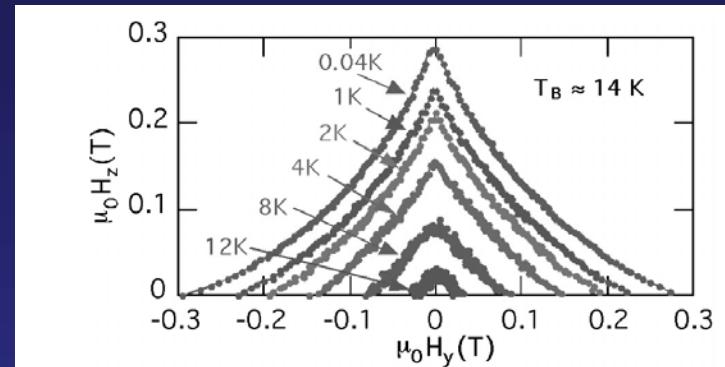
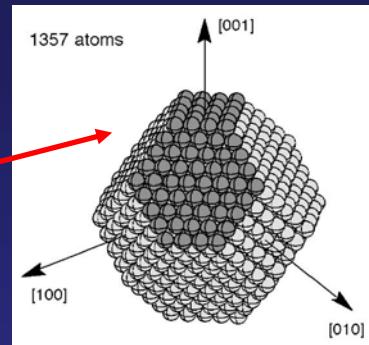
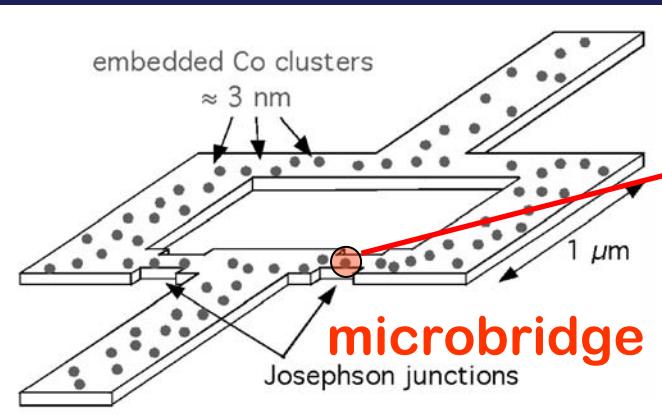


FIG. 4. Temperature dependence of the switching field measured in the H_y - H_z plane in Fig. 3. An extrapolation of the switching fields to zero gives the blocking temperature $T_B = 14$ K [22].

trick:
embedded Co clusters
in Nb-SQUID
only clusters in microbridge
contribute
(co-deposition of Co and Nb)

Co cluster:
diameter 3 nm
appr. 1400 atoms

switching fields of
single clusters
anisotropy of single clusters
is derived

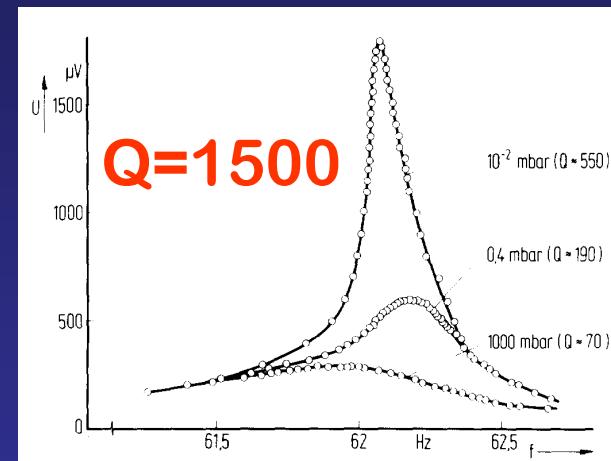
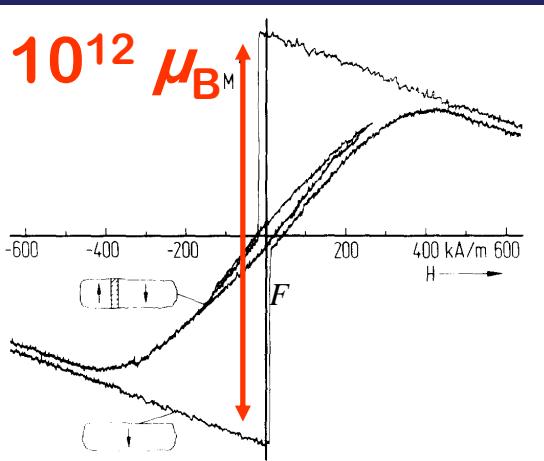
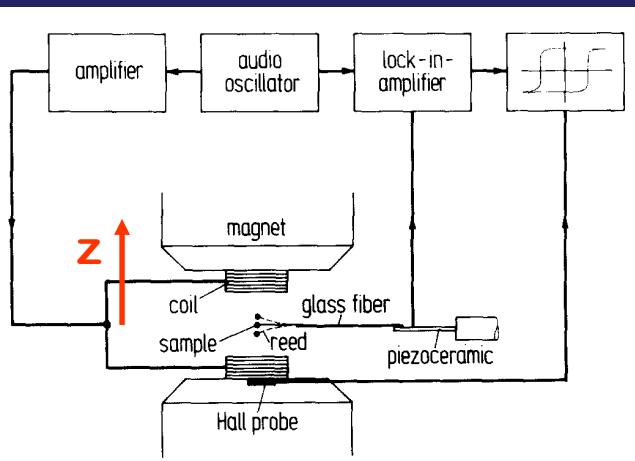
Alternating gradient magnetometry (AGM)

force due to a magnetic field gradient

$$F_z = m_z(B_z) \frac{\partial b_z}{\partial z}$$

m: total magnetic moment
B: magnetizing field
b: gradient field

benefit: NO geometric factors



gradient coils
piezoelectric detection

diamagnetic moment
of Au superimposed

resonance gives larger
vibration amplitude

sensitivity $10^{10} \mu_B$ is possible

5 μm sample -18 μm Au wire-glass fiber-piezo

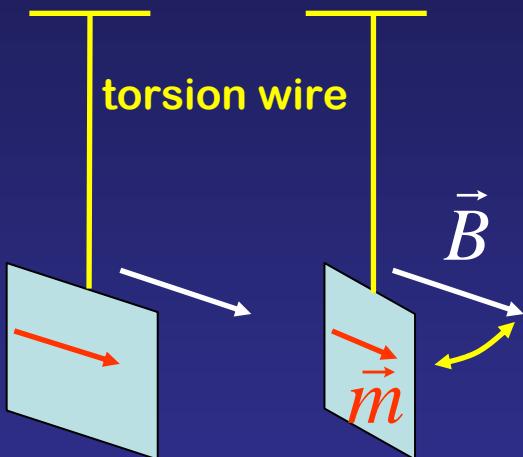
Roos, Hempel, Voigt, Dederichs, Schippan RSI 51(1980)612.

Torque magnetometry I

$$\vec{T} = \vec{m} \times \vec{B}$$

benefit: quantitative m

torsion-oscillation magnetometry (TOM)



deflection:

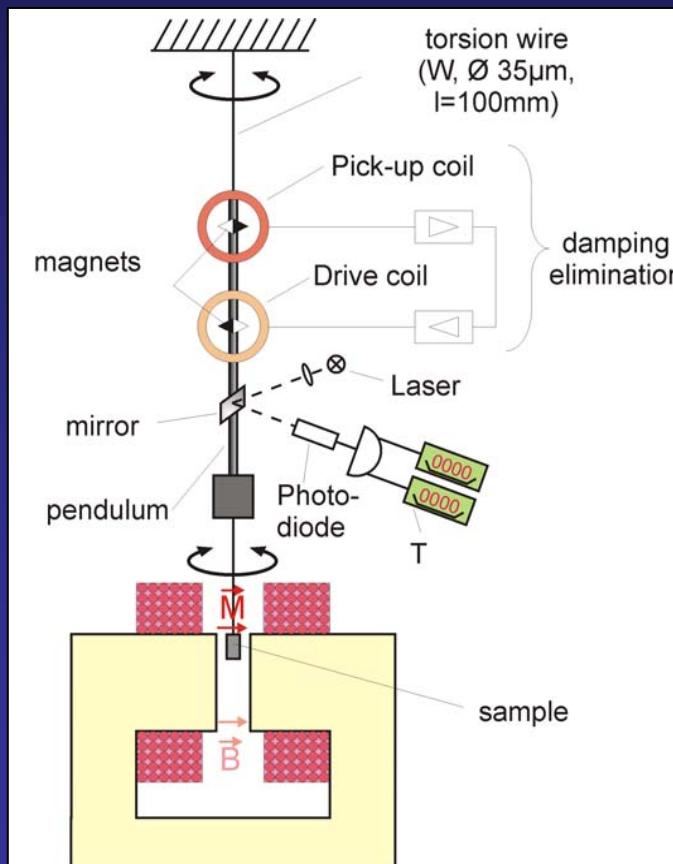
m based directional moment
measure modified $T(B=0)$ vs $T(B)$

$$T_0 = 3 \text{ s}$$

$$\Delta T = 75 \mu\text{s}$$

sensitivity: $10^{13} \mu\text{B}$

anisotropy studies



Bergholz, Elmers, Gradmann

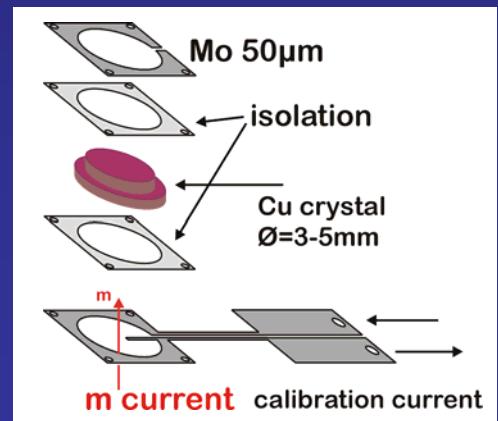
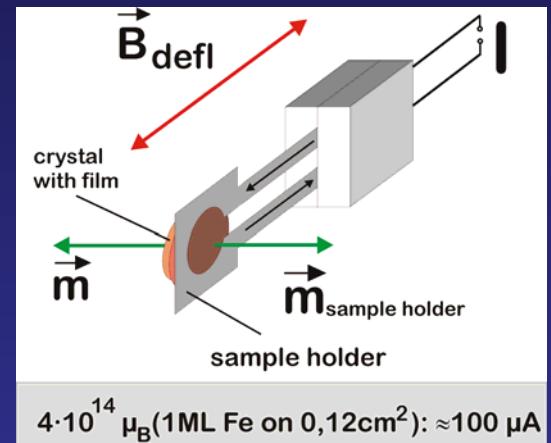
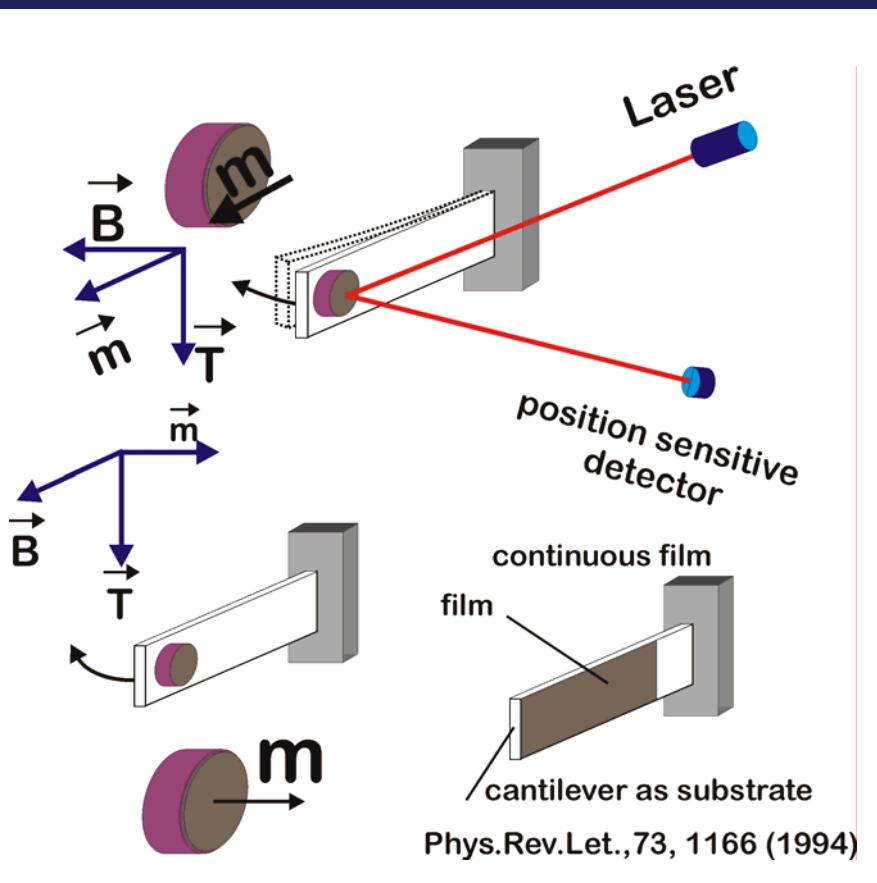
PRL 63(1989)566, Appl. Phys. A 51(1990)255.

Torque magnetometry II

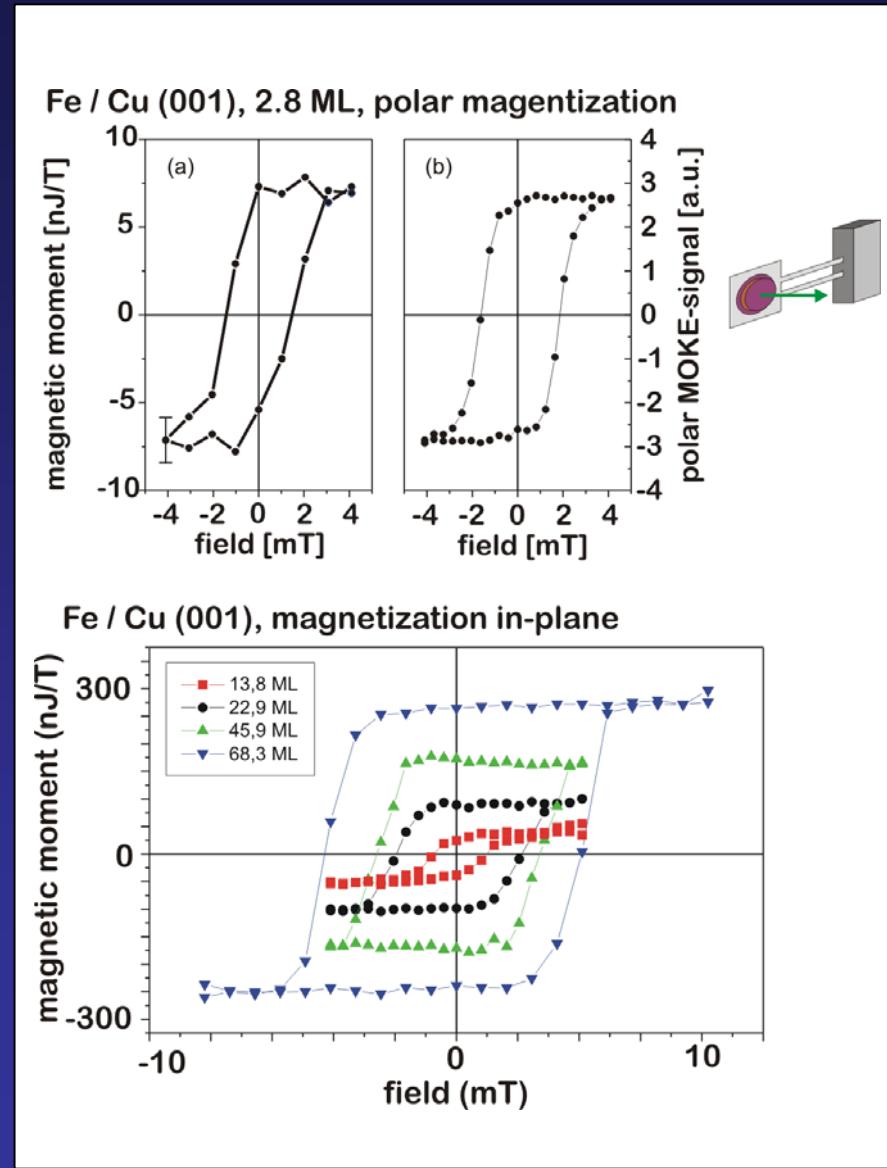
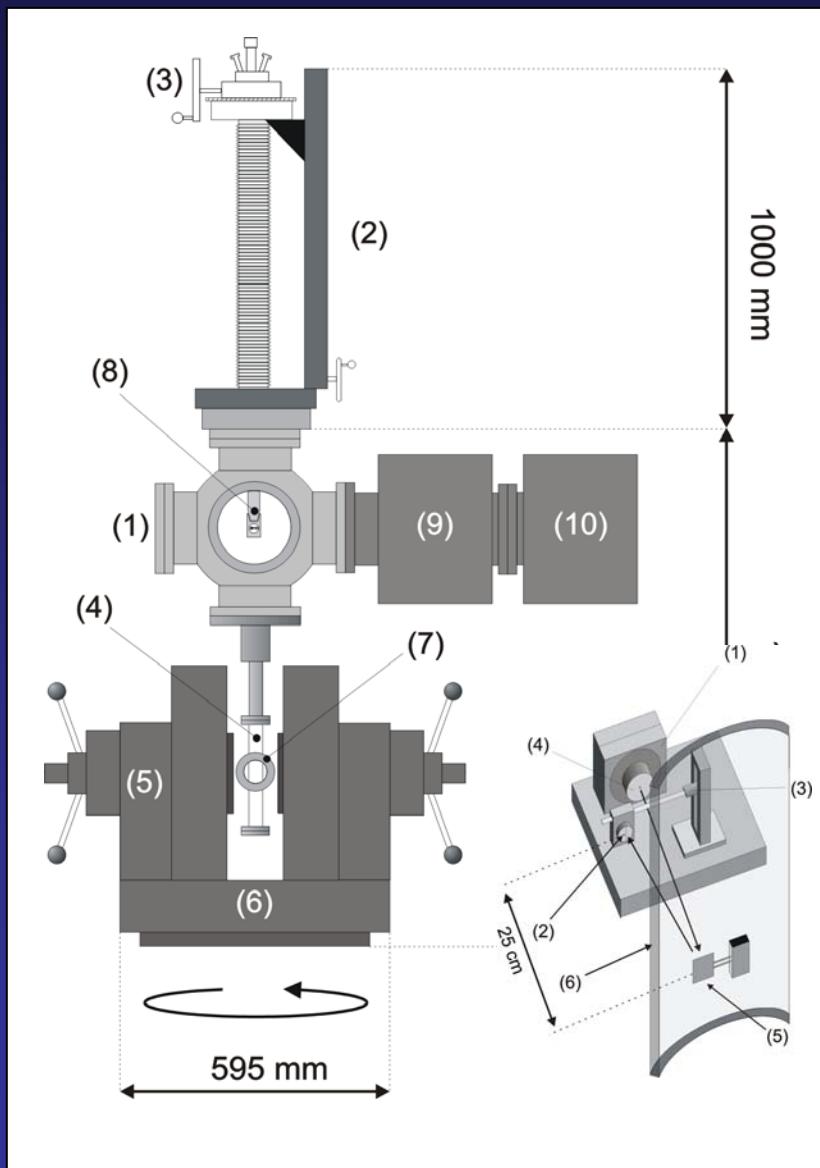
$$\vec{T} = \vec{m} \times \vec{B}$$

cantilever magnetometry

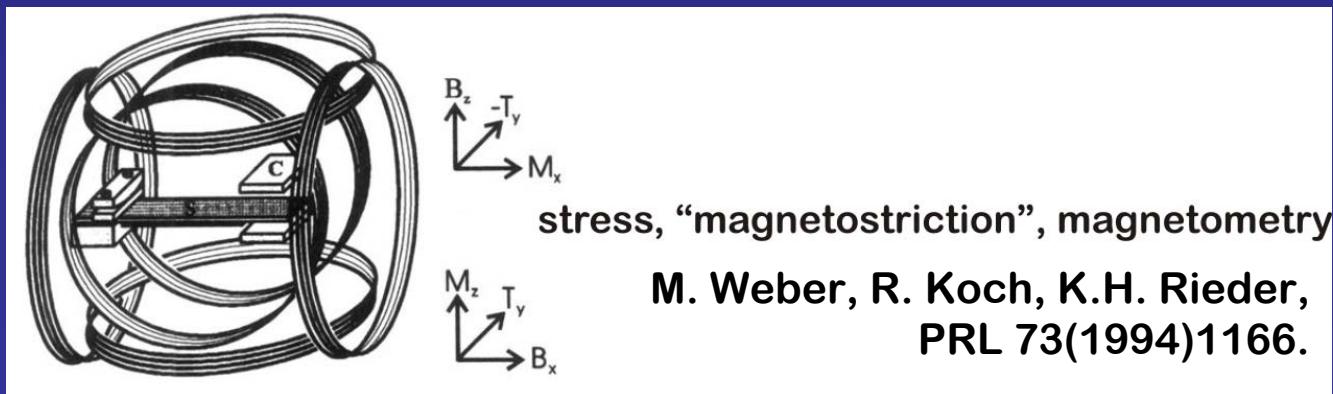
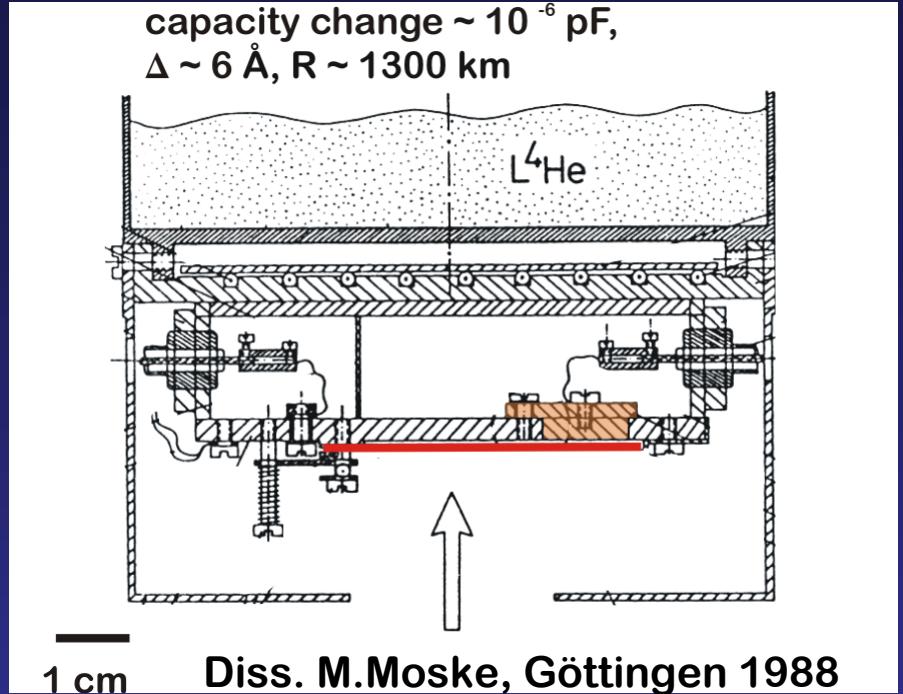
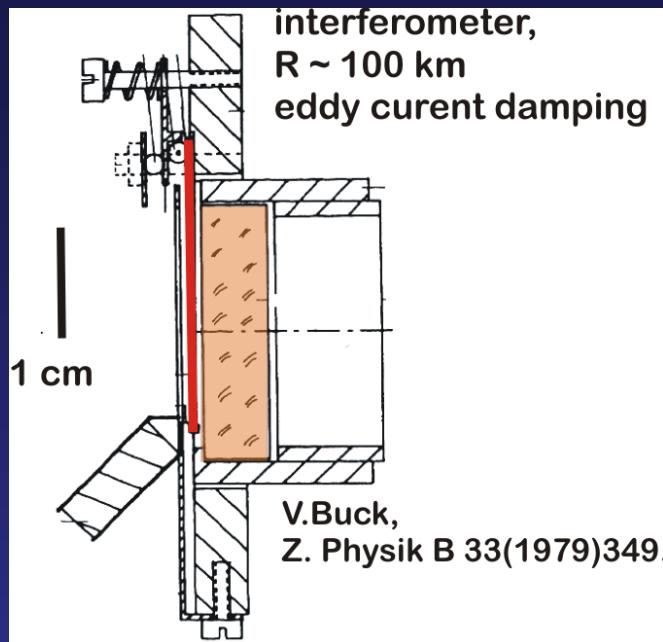
built-in calibration:



Torque magnetometry of atomic layers

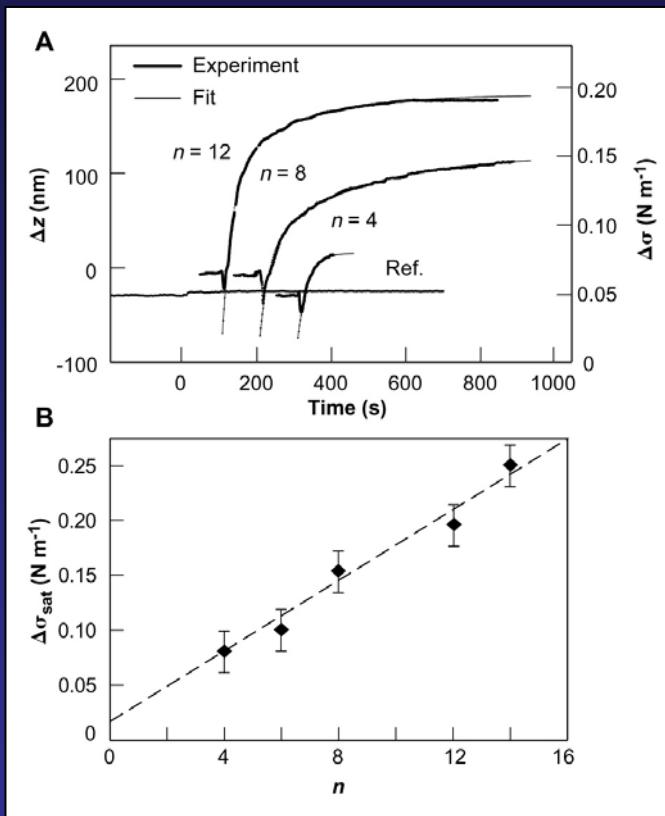
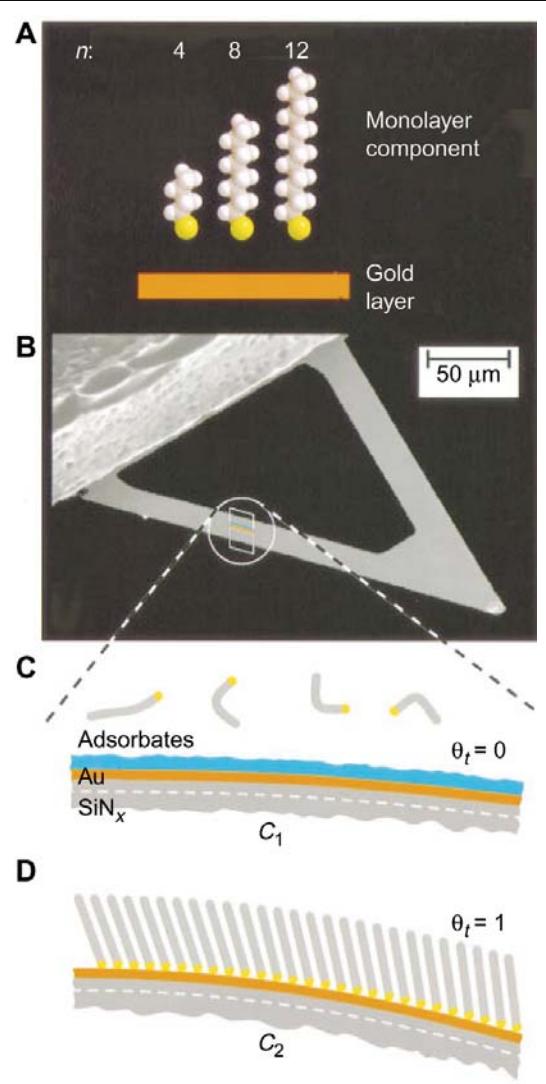


Optical and capacitive detection of cantilever deflection

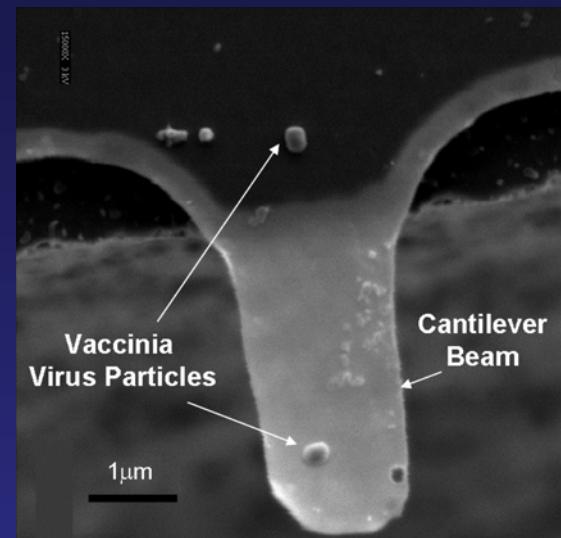


Micro-cantilevers

AFM sensors



μ -Si sensor



$1 \mu\text{m} \times 4 \mu\text{m} \times 30 \text{ nm}$

$f_0 = 2 \text{ MHz}$

$\Delta f = 16 \text{ kHz}$

scale for one virus

$m = 1 \text{ fg}$

Bashir et al.,
APL March 8, 2004

dipolar repulsive forces
between Alkanethiols on Au

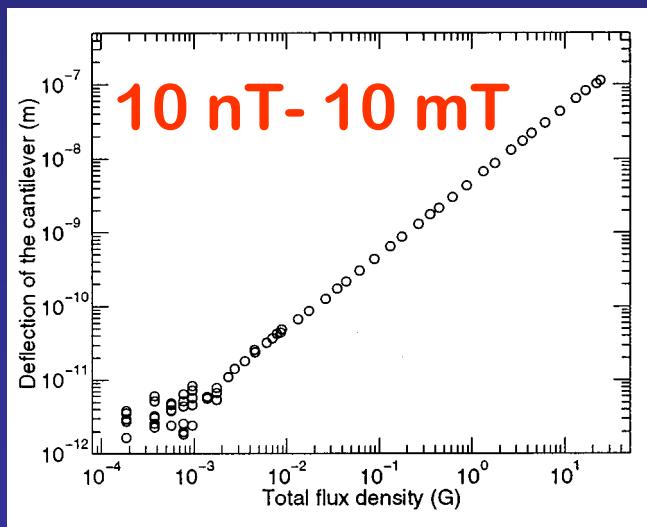
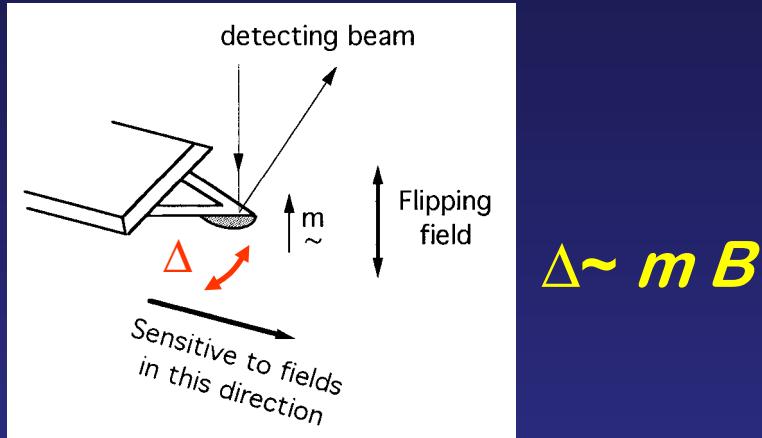
microelectromechanical systems (MEMS)

AFM tip with f.m. particle

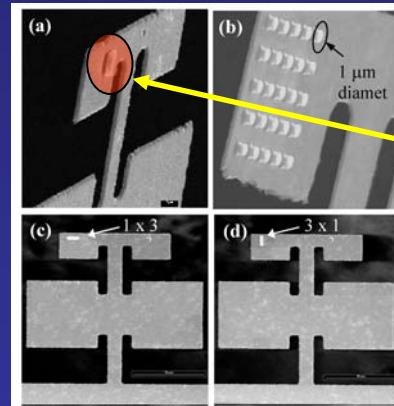
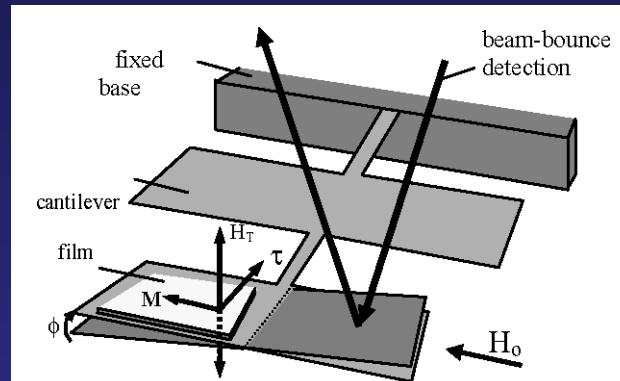
Cowburn, Moulin, Weland APL71(1997)2202.

microcantilever magnetometry

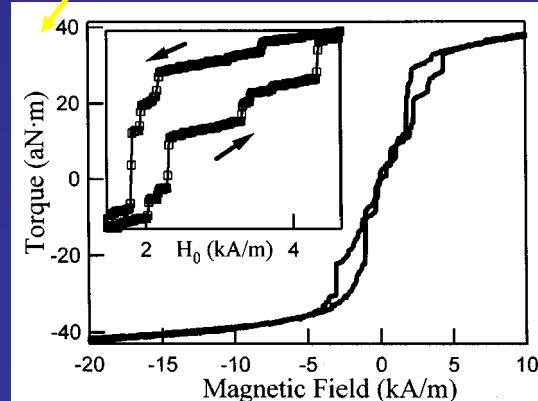
Chabot, Moreland JAP93(2003)7897.



high dynamic range magnetic field sensor

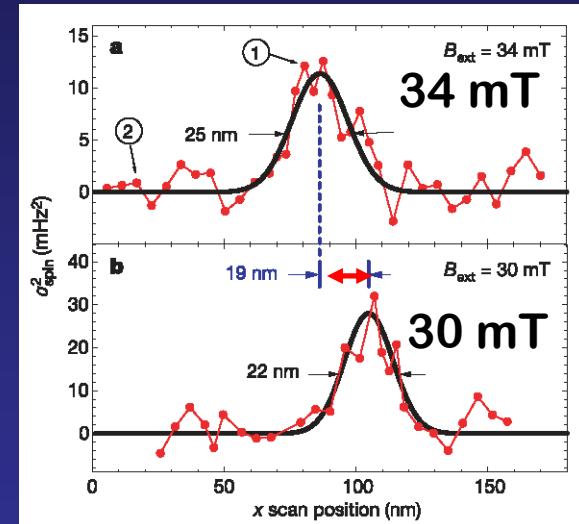
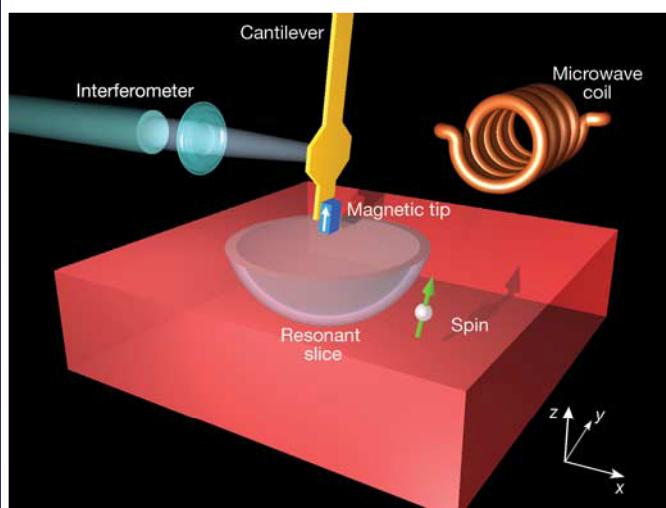
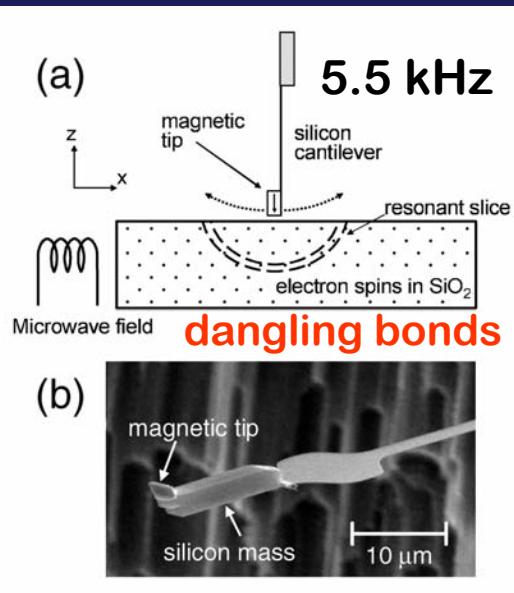


sensitivity:
 $10^8 \mu_B$



Magnetic Resonance Force Microscopy (MRFM)

single spin detection
(below surface, nm spatial resolution)



$$B_0(x, y, z) = \omega / \gamma$$

$\delta f \sim m_{\text{eff}}$ (mHz, averaging 13 h per point)

smaller external field
resonance slice shrinks
shift of peak

Mamin, Budakian, Chui, Rugar, PRL 91(2003)20604.

Nature 430(2004)329.

IBM Almaden Research Center:

http://www.almaden.ibm.com/st/nanoscale_science/asms/mrfm/

Conclusion

quantitative magnetometry with true nanoscale sensitivity ($10^{13} \mu_B$) is experimentally demanding

induction methods (SQUID, VSM) give the resolution, but suffer from the need for calibration

force (AGM) and torque methods give quantitative results, but may require special substrates

...the topic remains challenging...