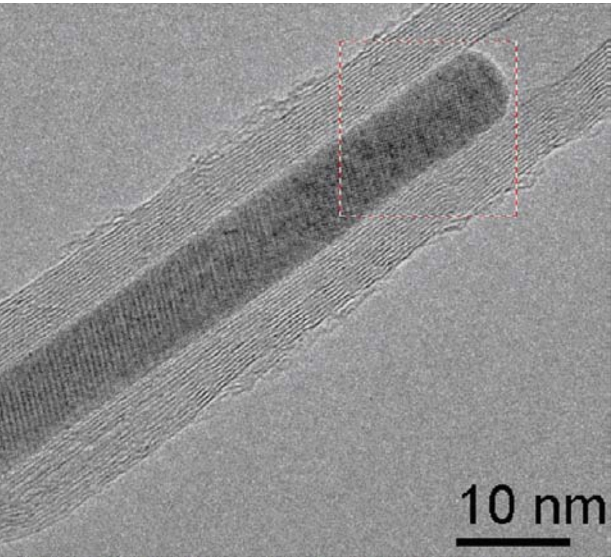
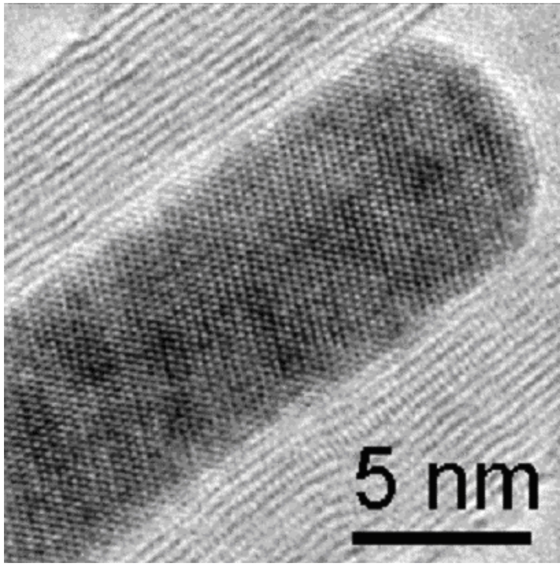
Leibniz Institute for Solid
State and Materials
Research IFW Dresden

Magnetic Nanowires inside Carbon Nanotubes

Magnetic force microscopy sensors using iron-filled carbon nanotubes



Thomas Mühl



Outline

Introduction and Motivation

Preparation of filled carbon nanotubes (CNTs) by CVD

Fe-filled CNTs

Fe_3C-filled CNTs

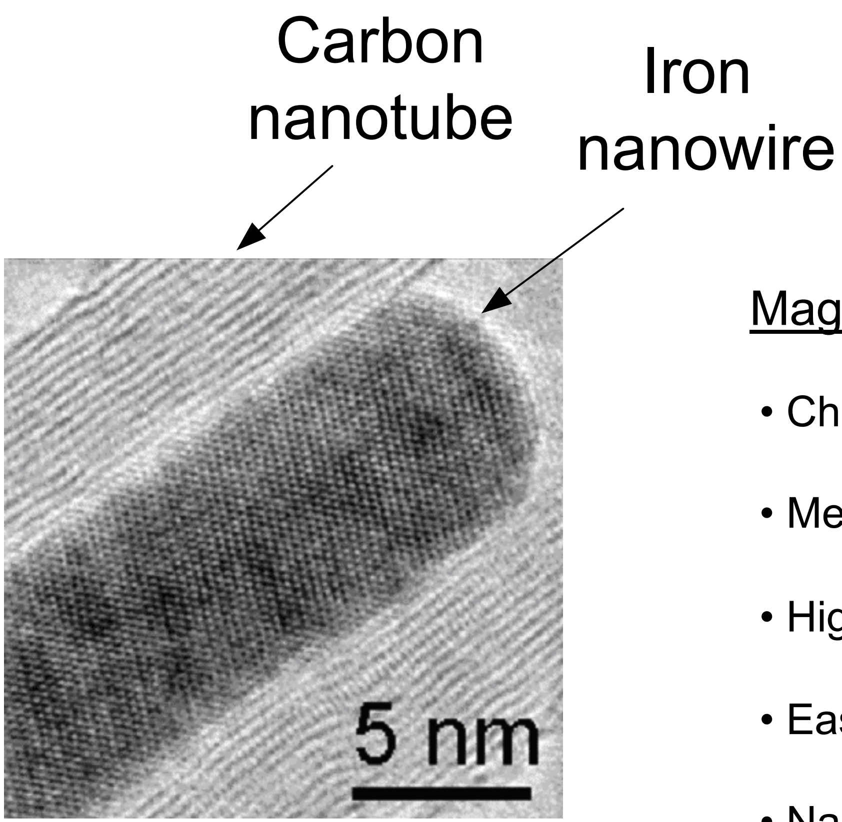
Manipulation of Fe-filled carbon nanotubes

Preparation of MFM probes using Fe-filled carbon nanotubes

Outlook

Summary

1. Introduction and motivation

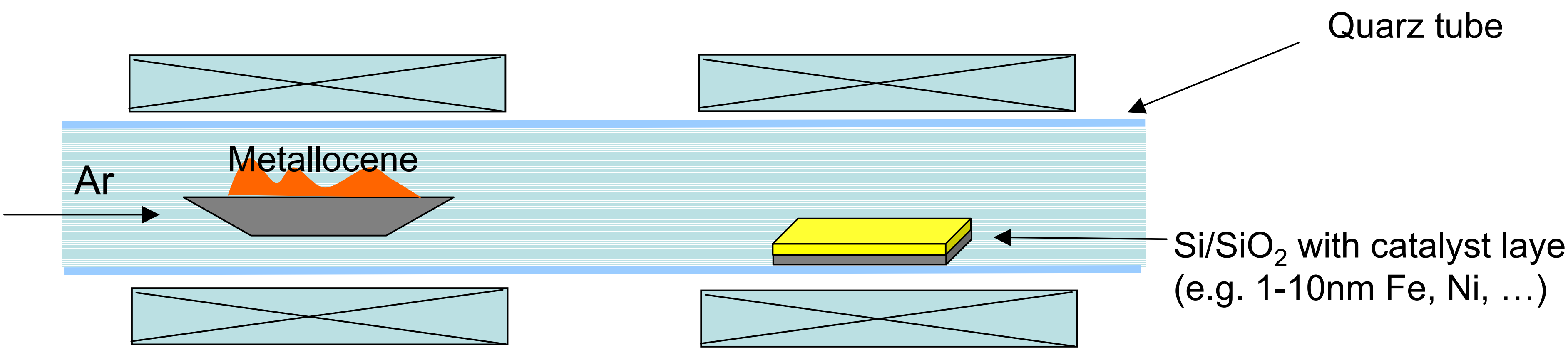


Magnetic nanowires inside carbon nanotubes

- Chemical stability
- Mechanical stability (elastic modulus E ~ 0.1-1 TPa)
- High aspect ratio
- Easy handling
- Nanowire material: Fe, Co, Ni, Fe_3C …

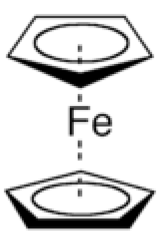
T. Mühl et al., J. Appl. Phys. ***93****, 7894 (2003)*
A. Leonhardt et al., J. Appl. Phys. ***98****, 74315 (2005)*
C. Müller, B. Büchner et al., J. Appl. Phys. ***103****, 34302 (2008)*
F. Wolny, U. Weißker, T. Mühl et al., J. Appl. Phys. ***104****, 064908 (2008)*

2. Preparation of filled CNTs by Chemical Vapor Deposition



<u>Heater 1:</u>
Metallocene sublimation
(180°C)

<u>Heater 2:</u>
Reaction temperature (800°C)



Metallocene:
Only source of metal and carbon for the filled nanotubes

C. Müller, A. Leonhardt, B. Büchner et al., Carbon ***44****, 1746 (2006)*
A. Leonhardt, S. Hampel, B. Büchner et al., Chem. Vap. Dep. ***12****, 380 (2006)*

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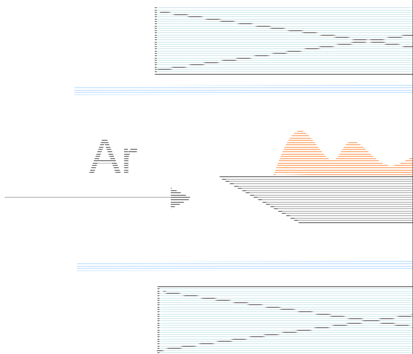
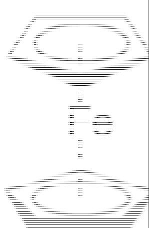
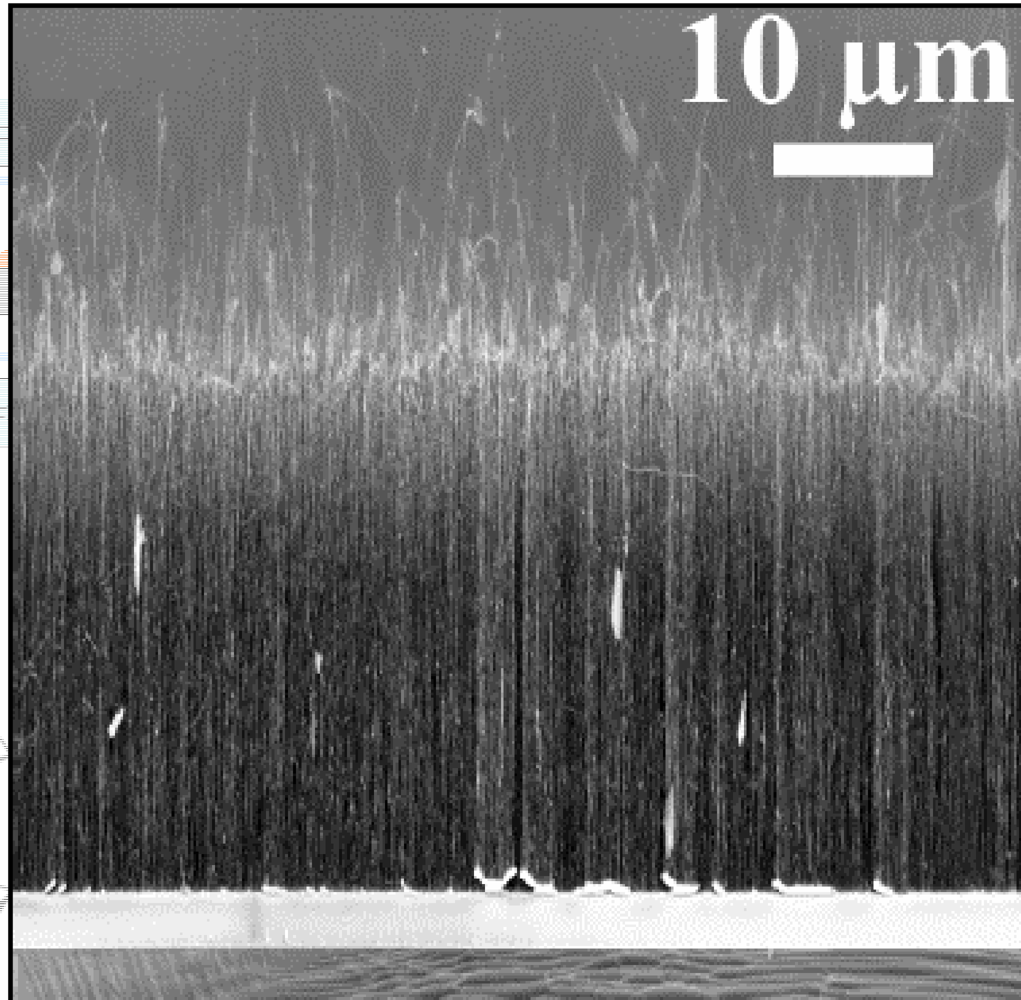


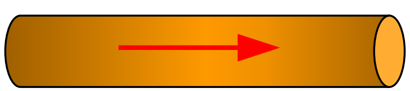


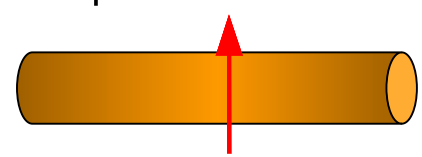


Metallocene:
Only source of metal and carbon for the filled nanotubes

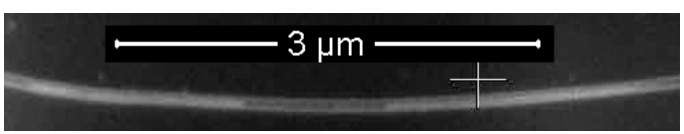
3. Fe-filled vs. Fe_3C-filled carbon nanotubes

Fe-filled		Fe_3C-filled
Precursor: solid ferrocene	**Preparation by thermal CVD**	Precursor: ferrocene dissolved in 1,2 dichlorobenzene
Body-centered cubic	**Crystal structure**	Orthorhombic
Single domain ferromagnet	**Magnetic structure**	Single domain ferromagnet
Parallel to the wire axis	**Magnetic easy axis**	Perpendicular to the wire axis

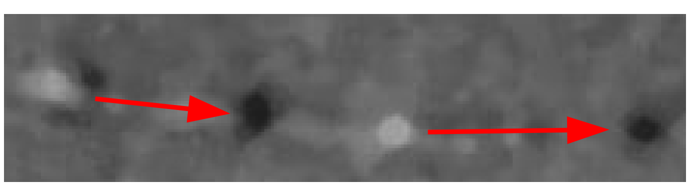


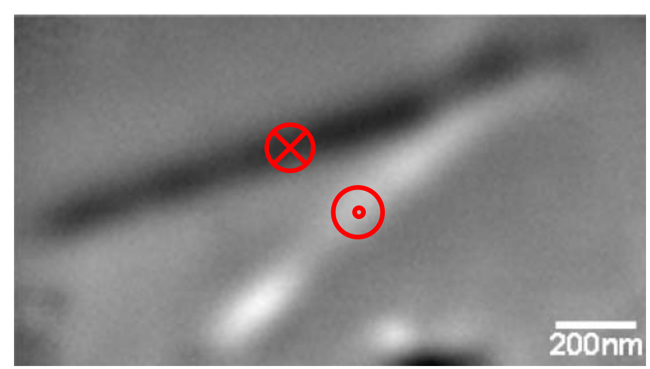


SEM



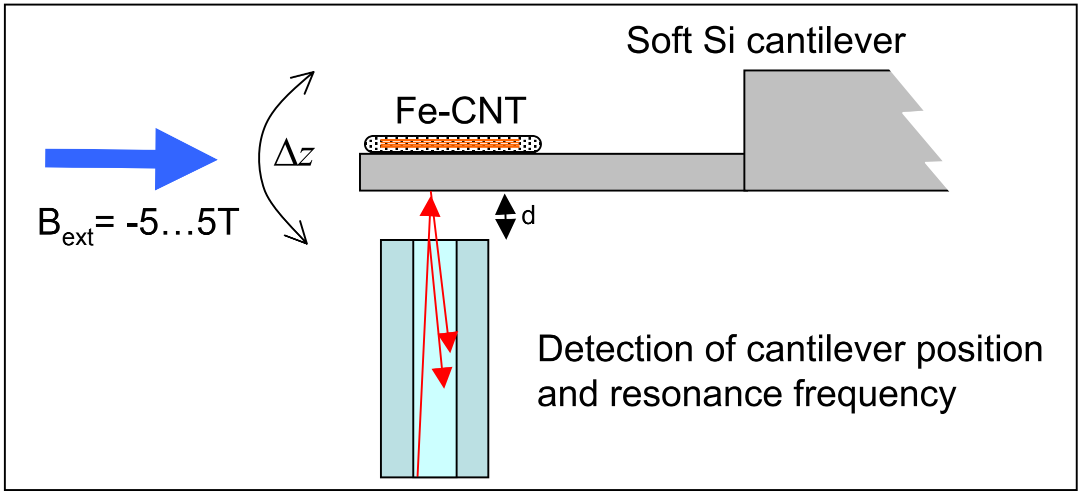
MFM



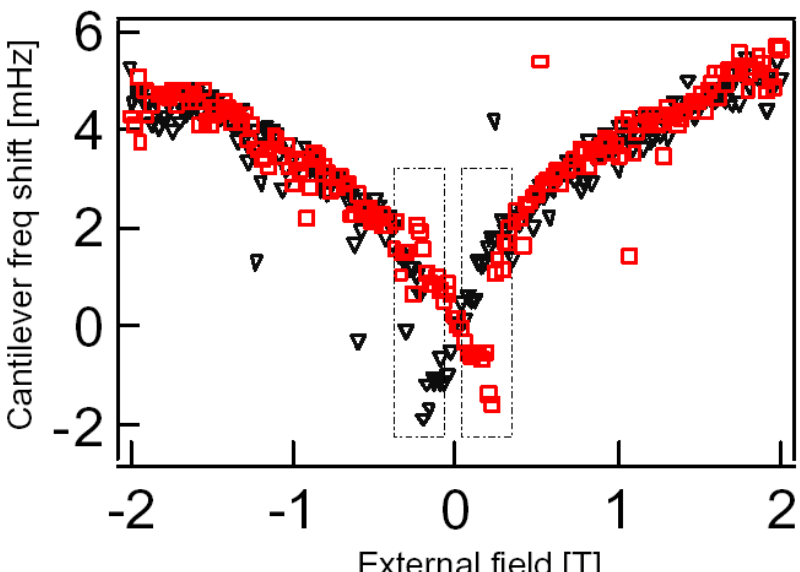


MFM

Cantilever magnetometry of a single Fe-filled CNT



Collaboration with Chris Hammel
(Ohio State University)



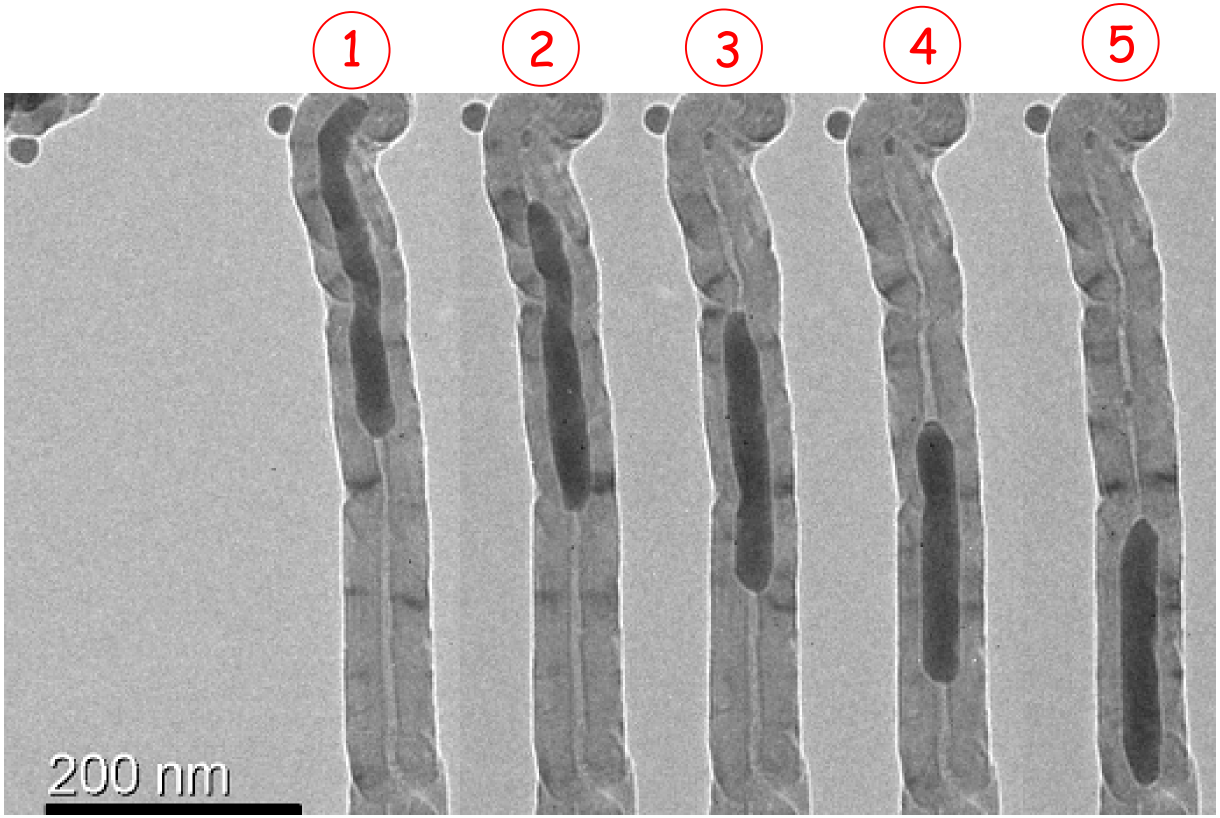
$m = 2 * 10^{-14}\ Am^2$

$H_k = 0.992$ T

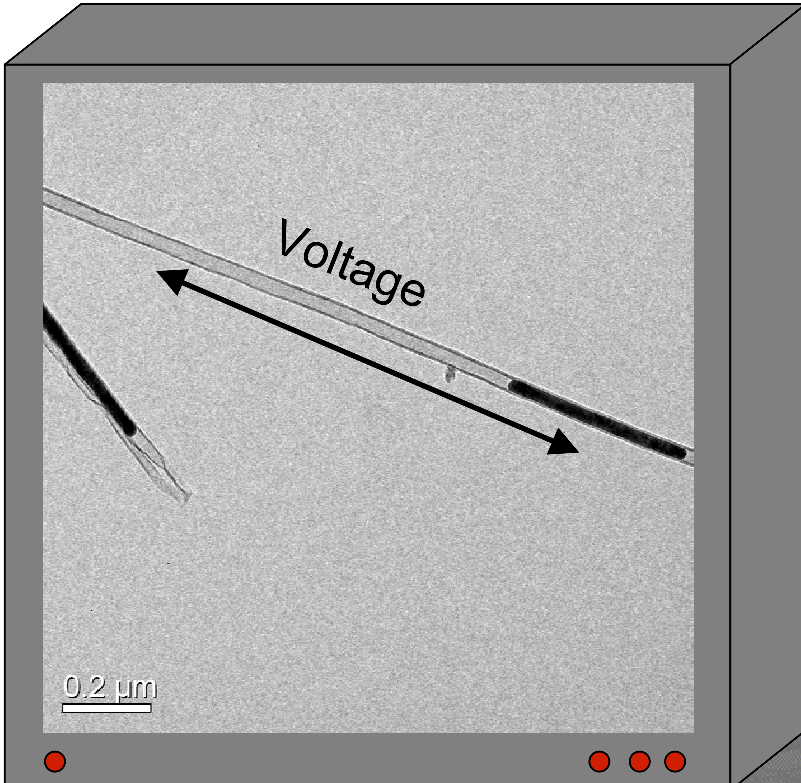
$H_{switching} = 0.220$ T

4. Manipulation of Fe-filled carbon nanotubes

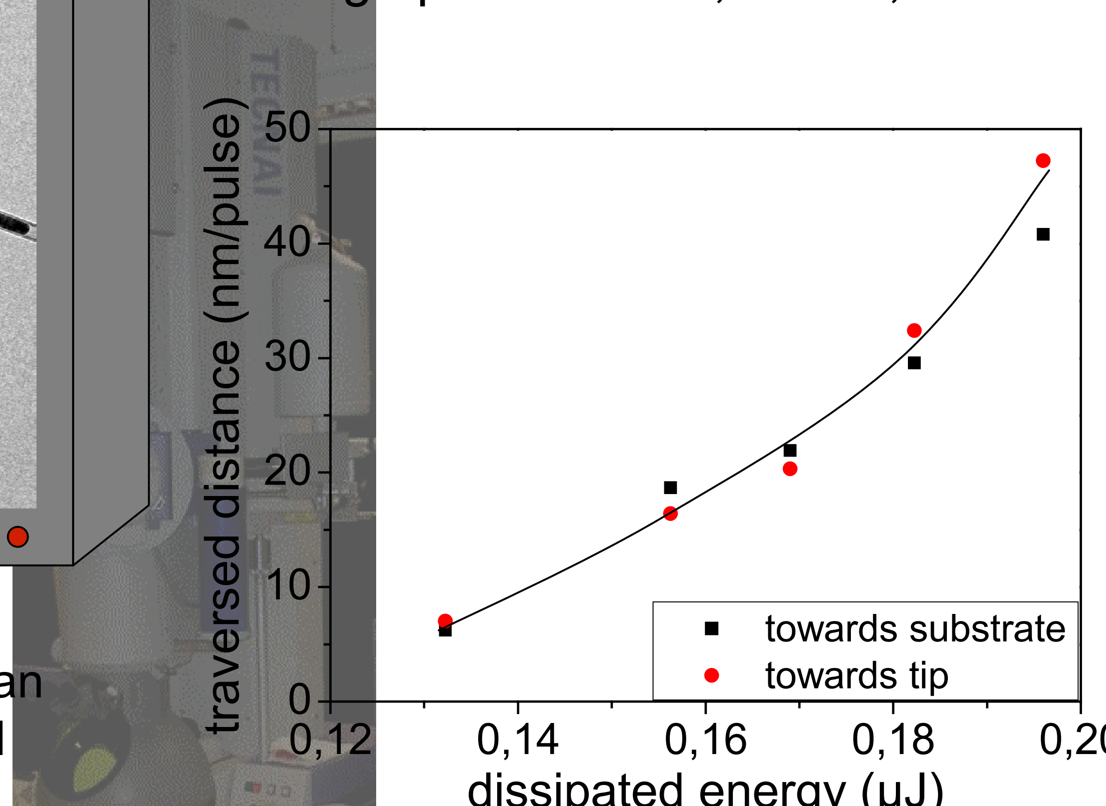
- The position of Fe nanowires inside CNTs can be tailored by electromigration experiments (application of voltage pulses).
- The direction of motion depends on the voltage polarity, i.e., back and forth motion is possible.



TEM picture sequence (application of 3.5 V pulses)

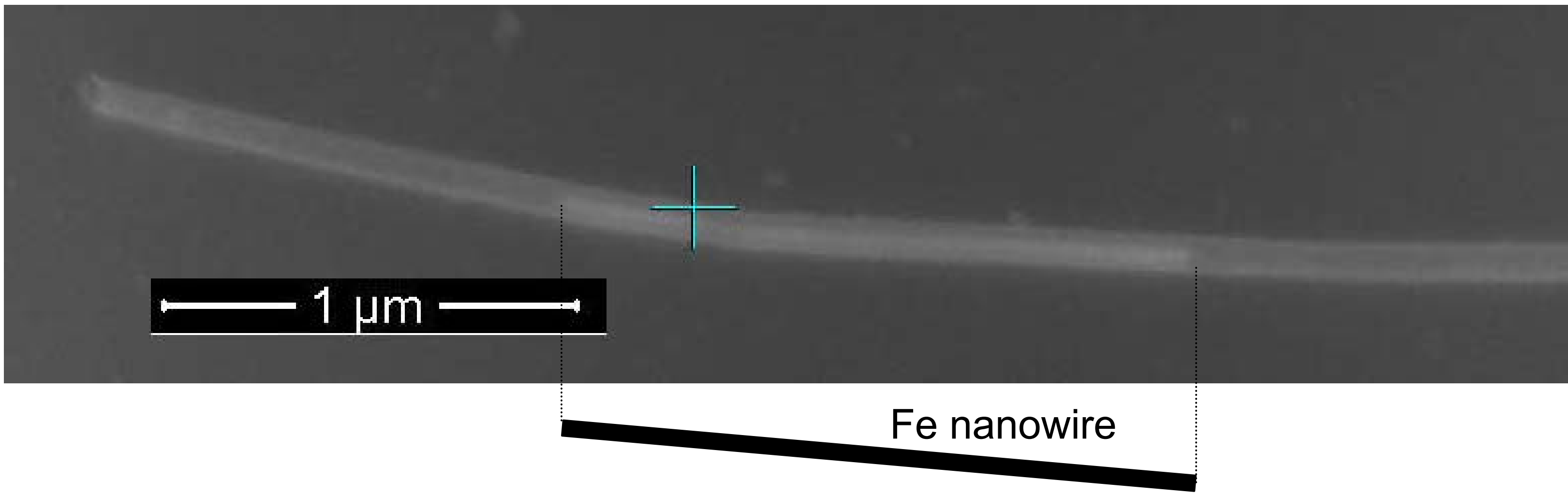


Video:
Voltage pulse: ±2.8V, 0.5ms; R = 42kΩ

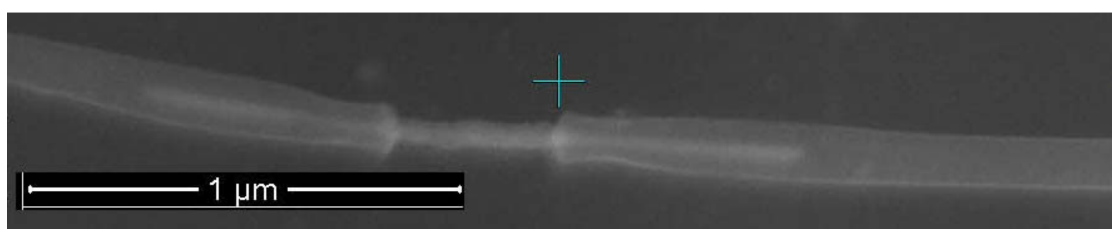


- Switching distance/speed can be influenced by the applied voltage pulses
- No degradation of the switch visible after ~60min

4. Manipulation of Fe-filled carbon nanotubes



After local carbon removal (by e-beam assisted oxidation)

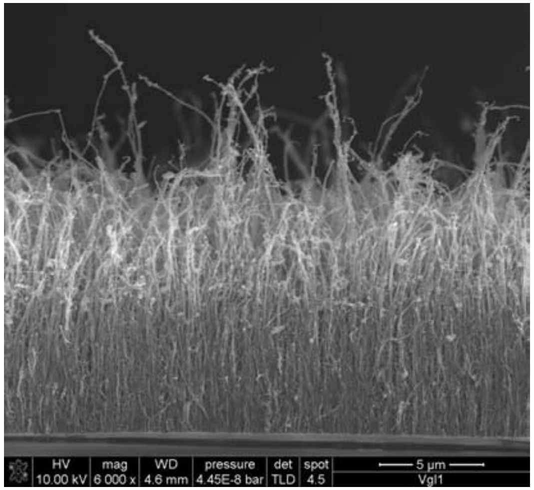


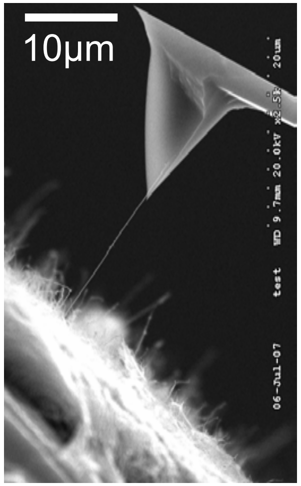
5. Preparation of MFM probes using Fe-filled carbon nanotubes

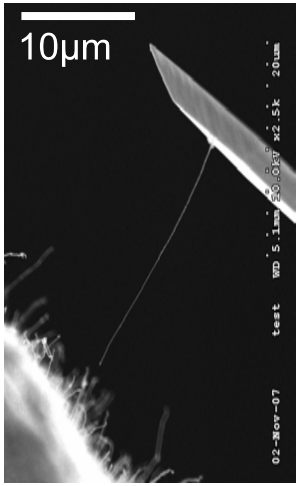
Initial goal: direct growth of filled nanotube on cantilever tip
But: many experiments failed; too many parameters, not controlable
…alternative solution?...

Procedure:

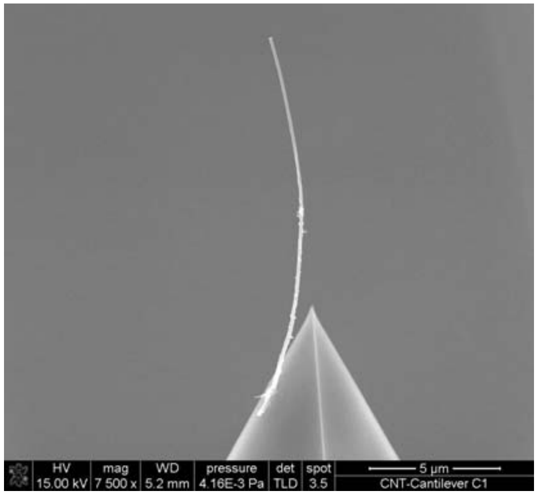
Production of Fe-CNTs by CVD on a silicon substrate → Attach Fe-CNTs to cantilever tips via nanomanipulation and carbon contamination in the SEM

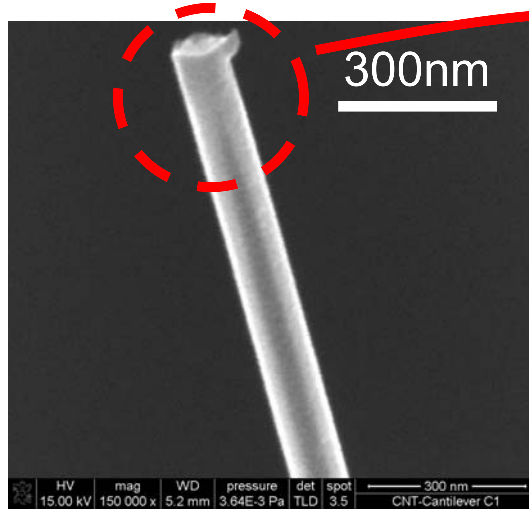


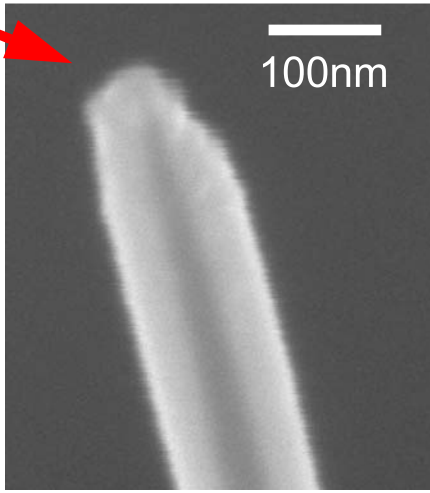


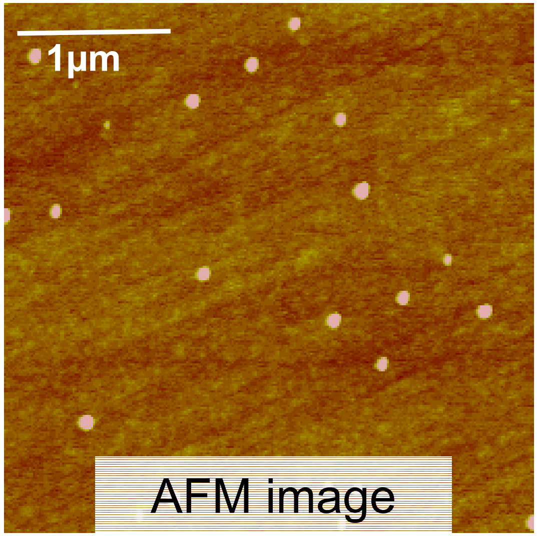


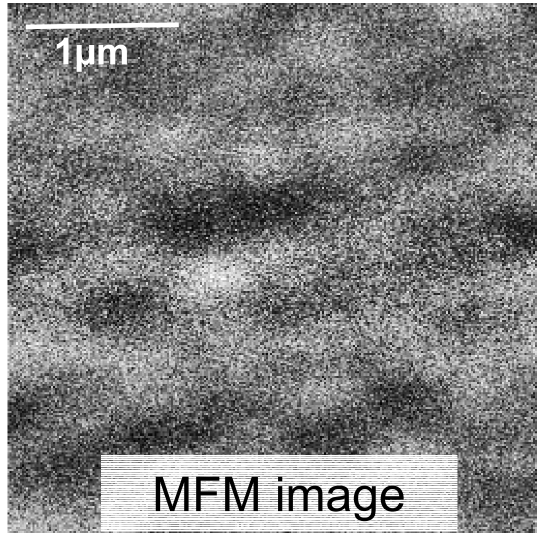
5. Preparation of MFM probes using Fe-filled carbon nanotubes

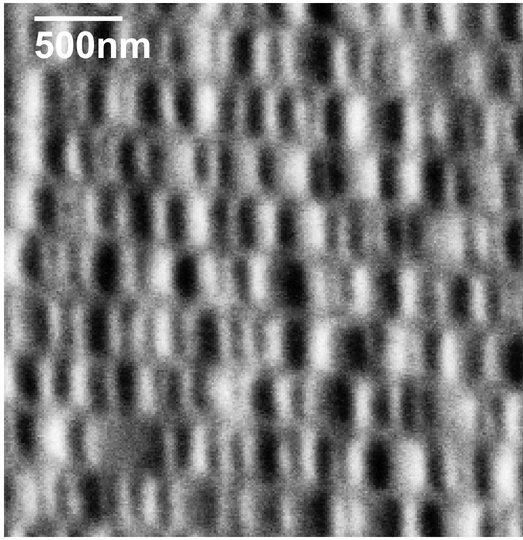






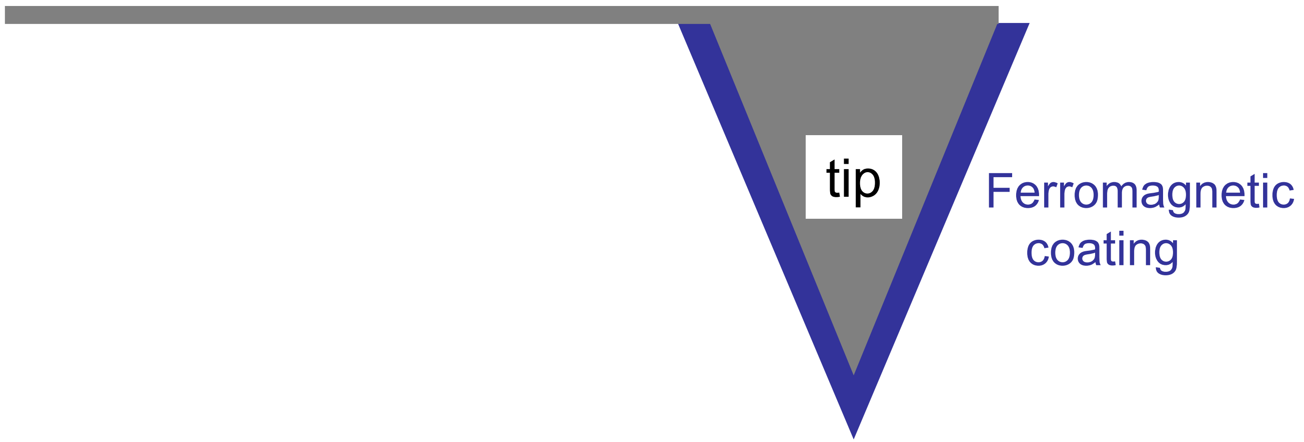






Advantage of CNT-MFM probe??

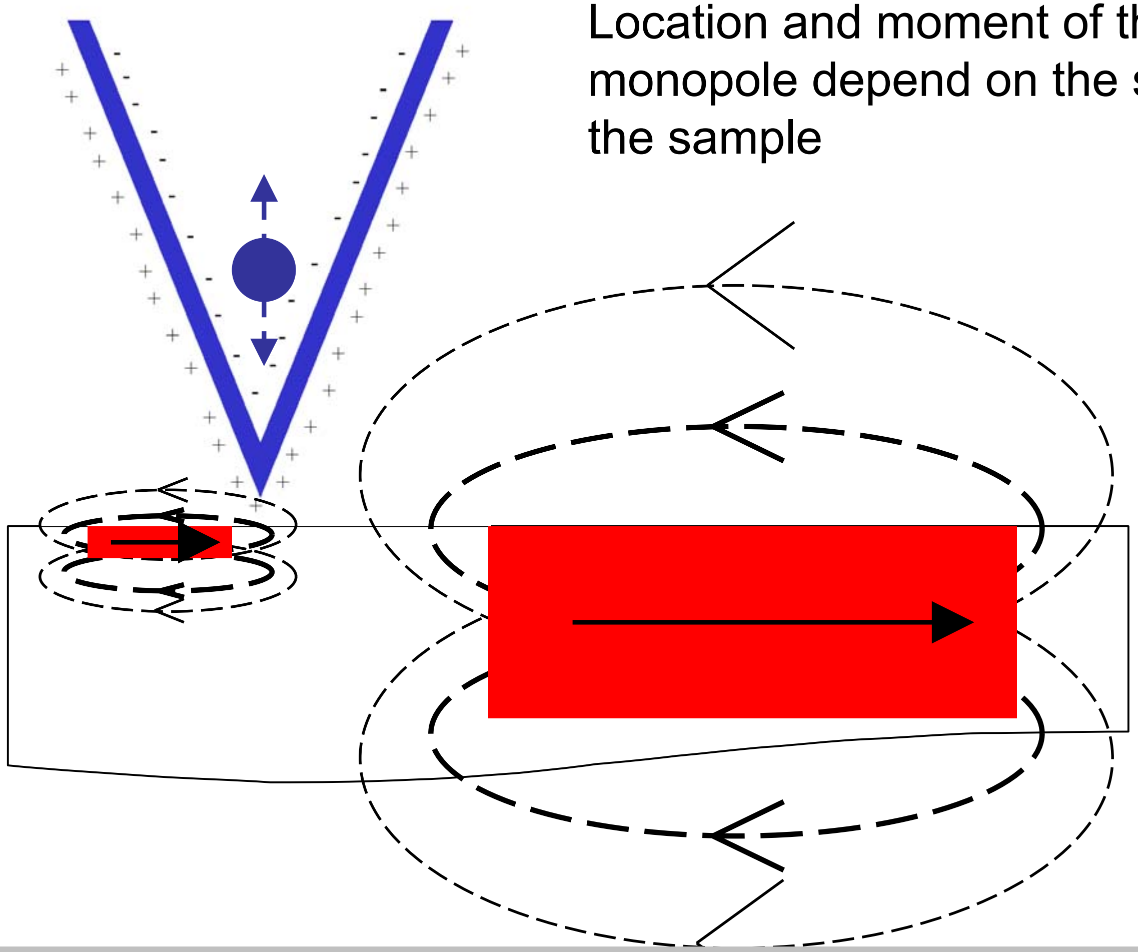
Conventional MFM probe



Advantage of CNT-MFM probe??

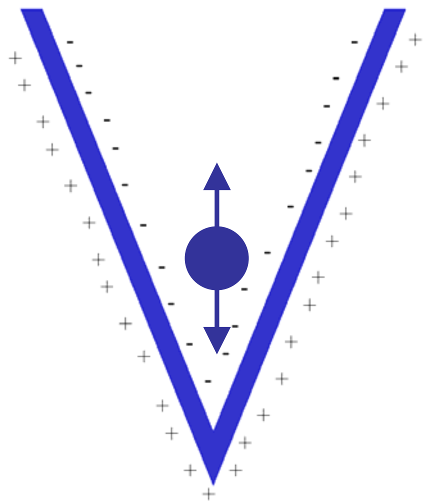
Conventional MFM probe

Location and moment of the effective dipole / monopole depend on the stray field geometry of the sample



Advantage of CNT-MFM probe??

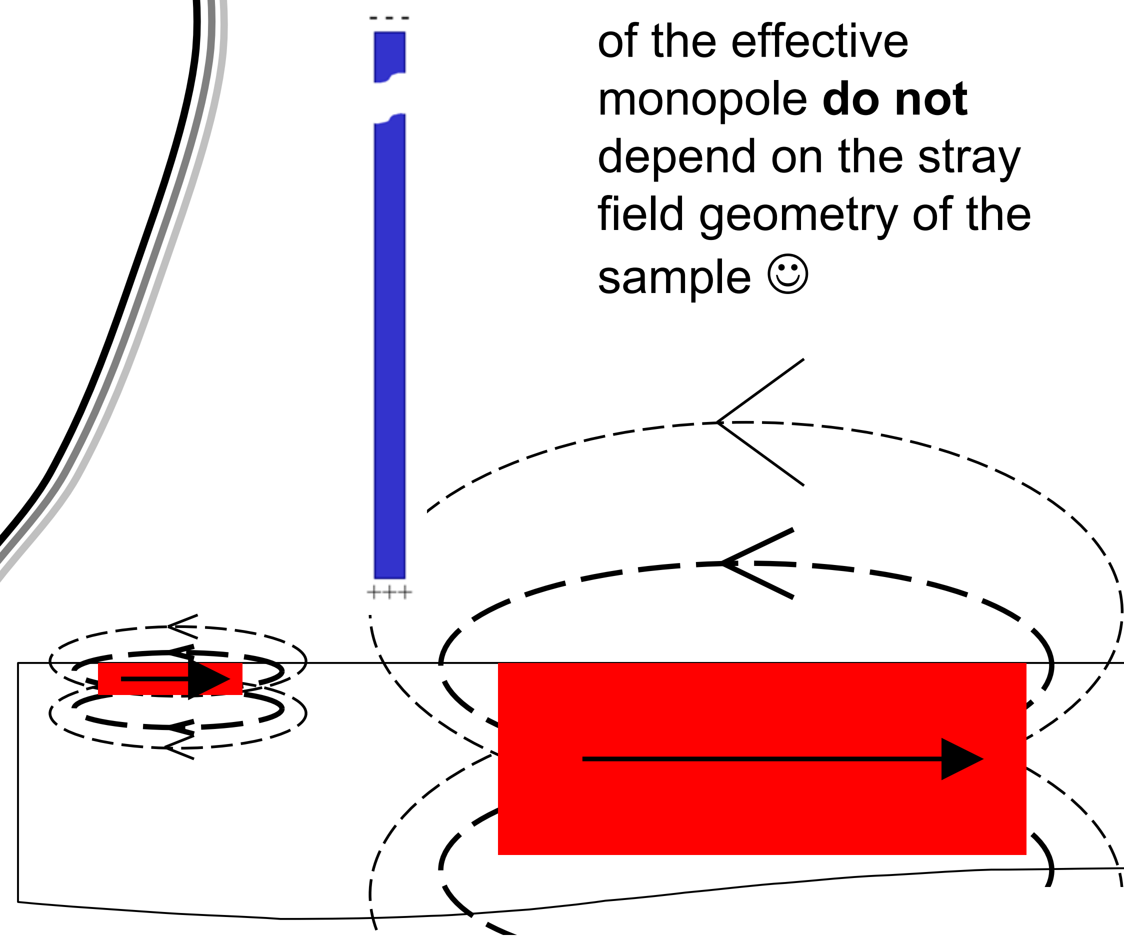
Conventional MFM probe



Location and moment of the effective dipole / monopole depend on the stray field geometry of the sample

CNT MFM probe

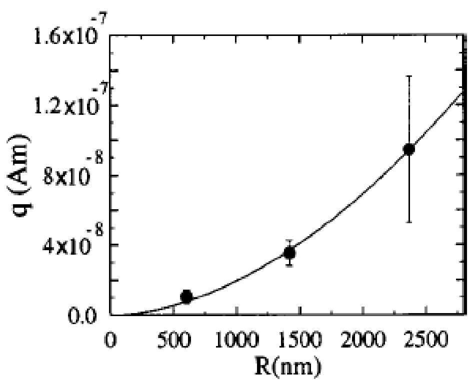
Location and moment of the effective monopole **do not** depend on the stray field geometry of the sample ☺

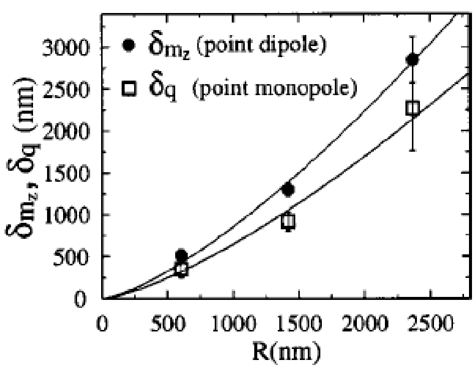


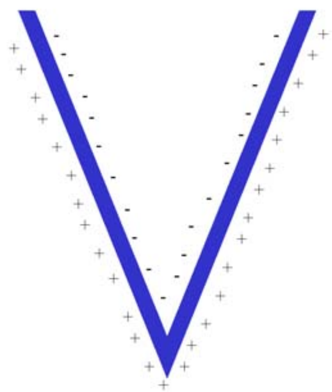
Advantage of CNT-MFM probe??

Conventional MFM probe

Location and moment of the effective dipole / monopole depend on the stray field geometry of the sample



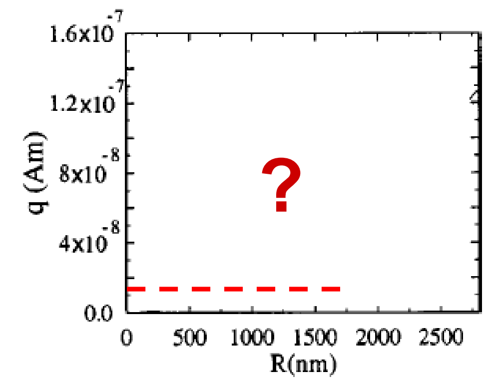


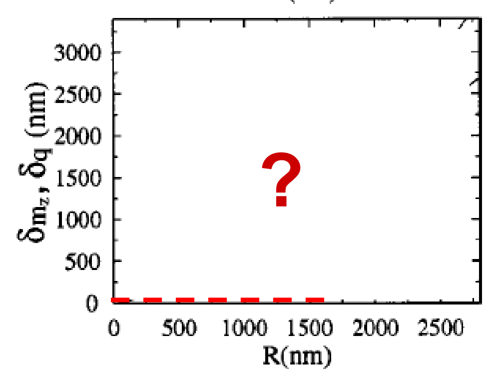


Lohau, Carl et al., JAP 86, 3410 (1999)

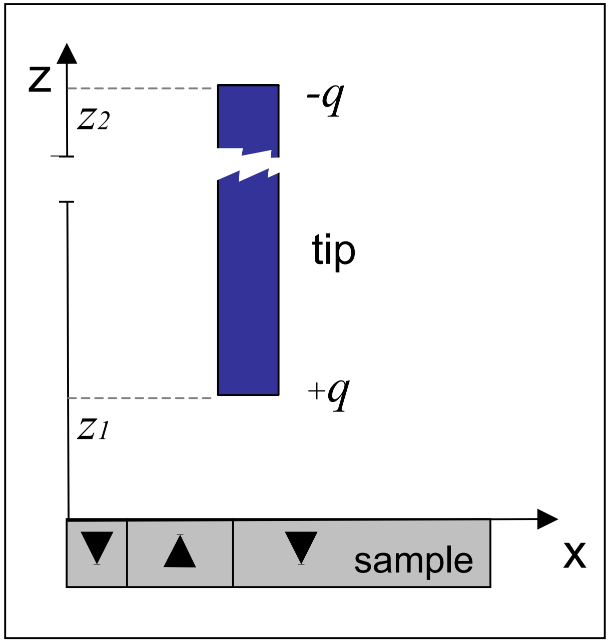
CNT MFM probe

Location and moment of the effective monopole **do not** depend on the stray field geometry of the sample ☺ … Has to be proved by experiments





Quantitative data analysis



Phase shift of the tip vibration due to the magnetic field (second derivative of the perpendicular stray field):

$$\Delta\Phi \propto \int_{Fe-cylinder} -q \frac{\partial^2 H_z}{\partial z^2} dz$$

$$\propto -q\left(\left[\frac{\partial H_z}{\partial z}\right]_{z2} - \left[\frac{\partial H_z}{\partial z}\right]_{z1}\right)$$

$\Delta\phi$	phase shift
H_z	z component of the sample stray field
q	magnetic monopole of the tip

(approx. for thin nanowire probes with constant magnetisation)

In case of a long nanowire probe :

$$\Delta\Phi \propto q\left[\frac{\partial H_z}{\partial z}\right]_{z1}$$

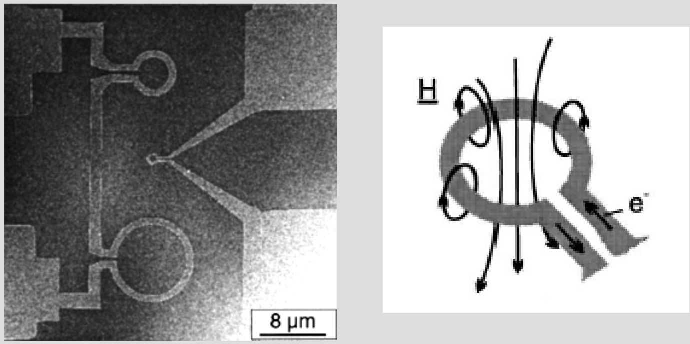
→ quantitative measurements of the first derivative of the sample's stray field z-component

J. Lohau, S. Kirsch, J. Appl. Phys. **86**, 3410 (1999)
Kebe, Carl, J. Appl. Phys. **95**, 775 (2004)
A. Winkler, T. Mühl et al., J. Appl. Phys. **99**, 104905 (2006)
F. Wolny, U. Weißker, T. Mühl et al., J. Appl. Phys. **104**, 064908 (2008)

Quantitative MFM probe analysis

Microstructured current carrying rings or lines (EBL) of defined geometry
→ produce a well defined magnetic stray field

$$H_z \propto \frac{IR^2}{(z^2+R^2)^{3/2}}$$



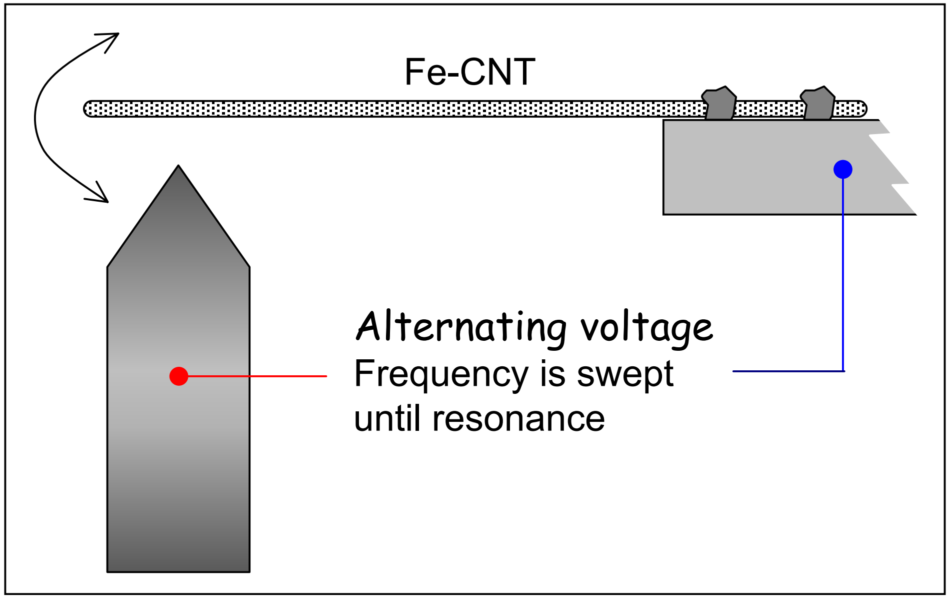
J. Lohau, S. Kirsch, J. Appl. Phys. 86, 3410 (1999)

→ MFM-scan of these rings with the Fe-CNT tip

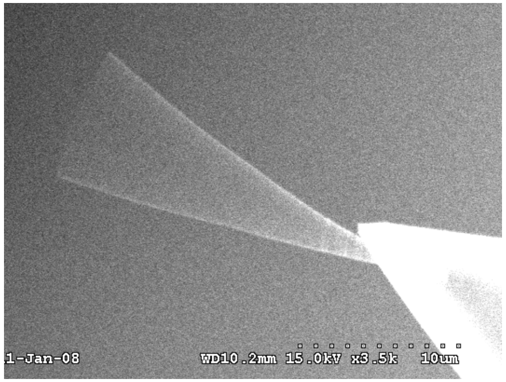
→ analysis of the image contrast as a function of the magnetic stray field and lift height allows the quantitative determination of the effective magnetic moments of the tip

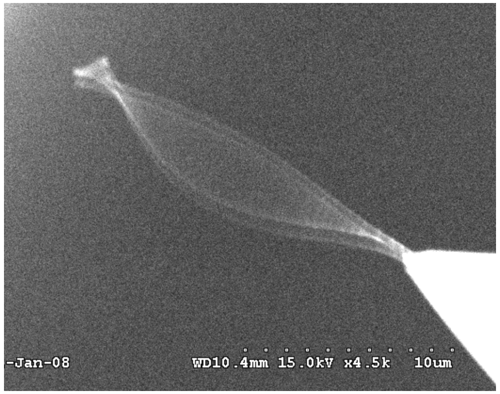
Outlook – Mechanical measurements

1.



$$f_0^{\,2} \sim \frac{k}{l \cdot r^2} \qquad\qquad k \sim E$$



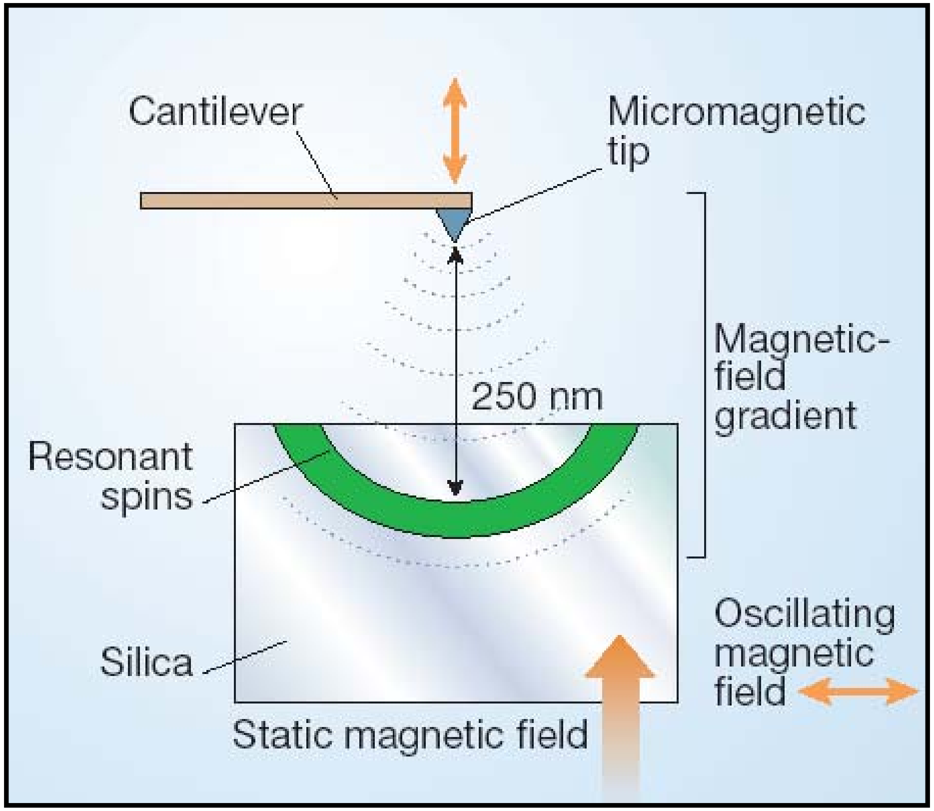


2.

Recently developed by M. Löffler (IFW Dresden):
New method using the bending of CNTs in external magnetic fields due to the Lorentz force.

Outlook – magnetic resonance force microscopy

Single electron spins already detected.
Detection of single nuclear spins requires ultrahigh gradient micromagnetic probe tips



Collaboration with Chris Hammel
(Ohio State University)

Thanks to:

- Franziska Wolny
- Uhland Weißker
- Markus Löffler
- Albrecht Leonhardt
- Matthias Lutz
- Kamil Lipert
- Andreas Winkler
- Siegfried Menzel
- Silke Hampel
- Rüdiger Klingeler
- Christian Müller
- Bernd Büchner

Funding:

Ferromagnetisch gefüllte Kohlenstoff-Nanoröhren als Sonden für die Magnetkraftmikroskopie,
DFG, 2006-2009

Materials World Network: Scanned Probe Studies of FMR Driven Spin Injection in Individual Fe-filled Carbon,
DFG/NSF, 2008-2011

Thank you for your attention!