# Scanning Probe Microscopy

L. J. Heyderman

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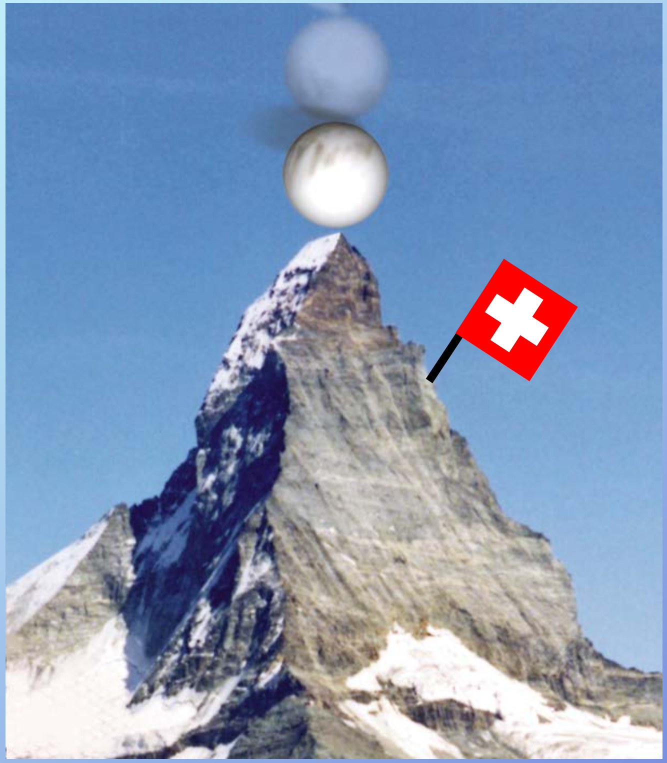

***If an atom was as large as a ping-pong ball…***

***…the tip would have the size of the Matterhorn!***

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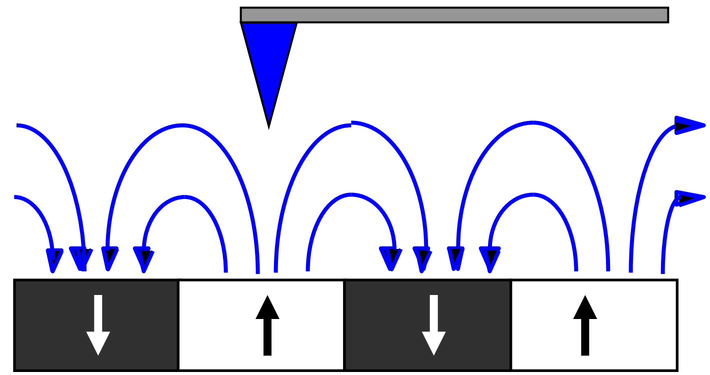
# Magnetic Force Microscopy



- Stray field interaction between film and magnetic tip
- Forces are on the order of $10^{-10}$ N
- Employ a cantilever (CL) "spring"
- The force sensing carried out in two ways:
  - Static force sensing: CL brought near to surface and bends down or up (interaction attractive or repulsive). But CL might "snap" onto the surface.
  - Dynamic force sensing: CL is oscillated at a certain frequency, typically at its resonance frequency or a bit off (5%)

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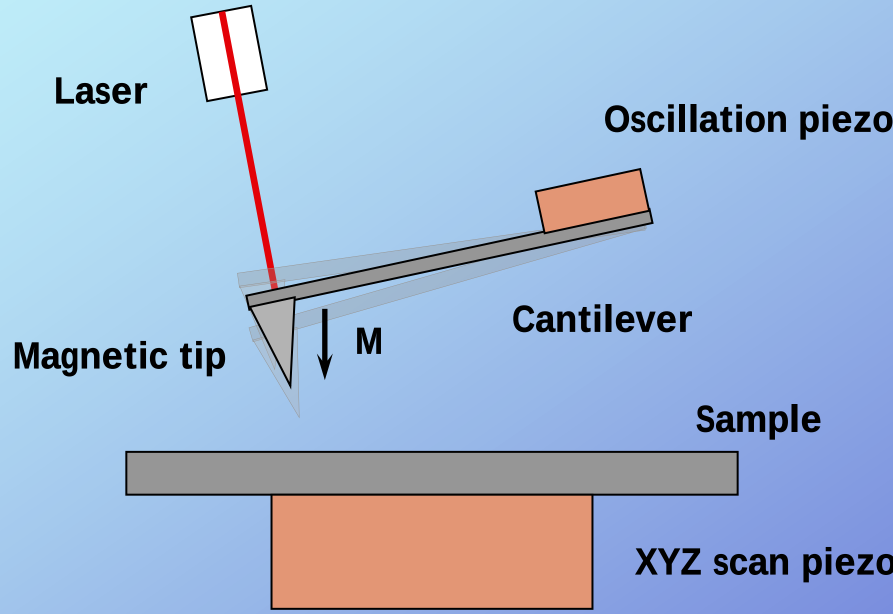
# Non Contact Dynamic MFM

Schematic drawing:




- The **cantilever** is oscillated with a fixed amplitude (nm).
- The **sample** is scanned by the XYZ scan piezo.
- The **measurement** signal is the *frequency shift* (shift of cantilever's resonance frequency), measured with a quadrant diode detector or laser interferometer.

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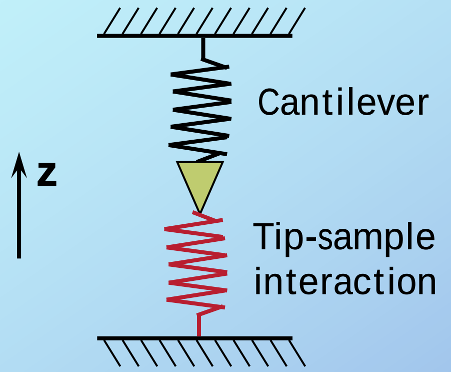
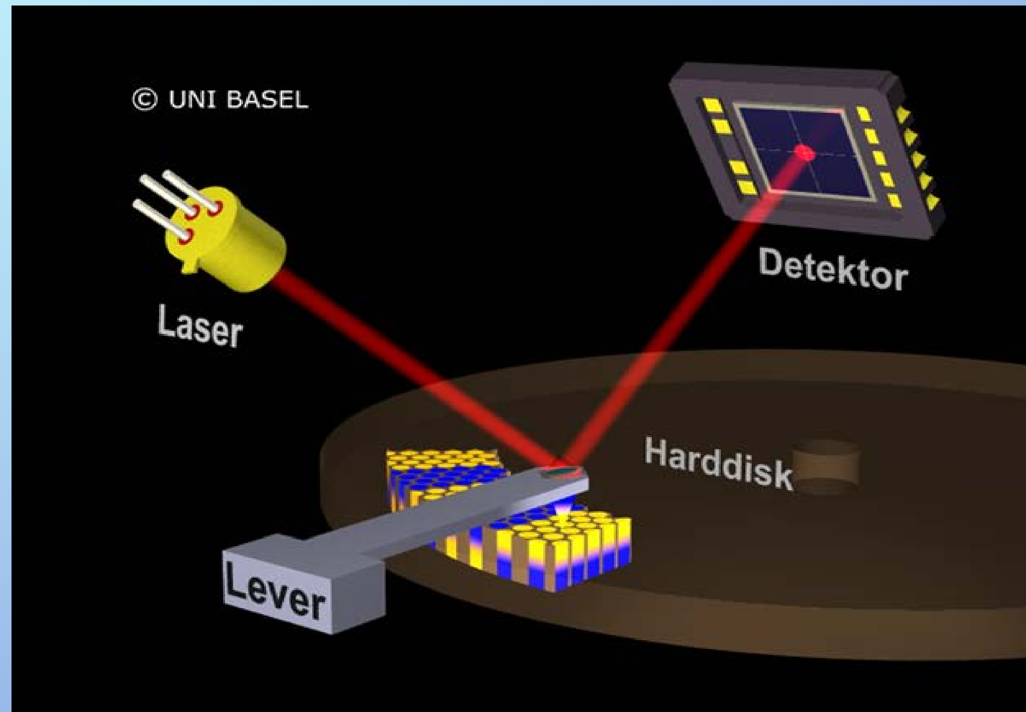
# SFM Dynamic Operation Modes

## Measurement Signal:

Massless spring system ➔ harmonic oscillator

Freq. $$f_0 = \frac{1}{2\pi}\sqrt{\frac{c_L}{m}}$$ spring constant ($c_L$), mass ($m$)




Linear part of Taylor Expansion

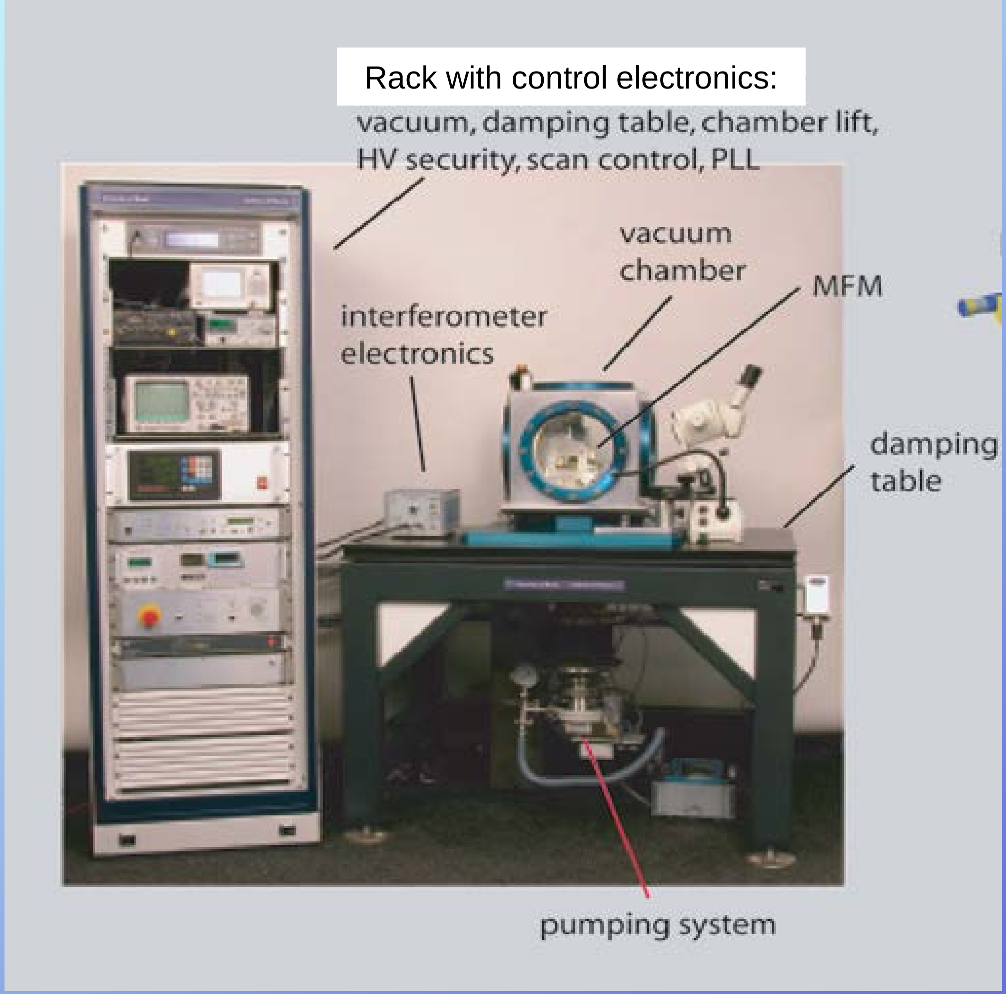
$$f_P = \frac{1}{2\pi}\sqrt{\frac{1}{m}\left(c_L - \frac{\partial F}{\partial z}\right)}$$

$$\delta f \equiv f_P - f_0 \approx -\frac{f_0}{2c_L}\frac{\partial F}{\partial z}$$

$\frac{\partial F}{\partial z}$ interaction force gradient

Attractive forces → lower resonance frequency → -ve freq. shift
Repulsive forces → higher resonance frequency → +ve freq. shift

# The High Resolution MFM

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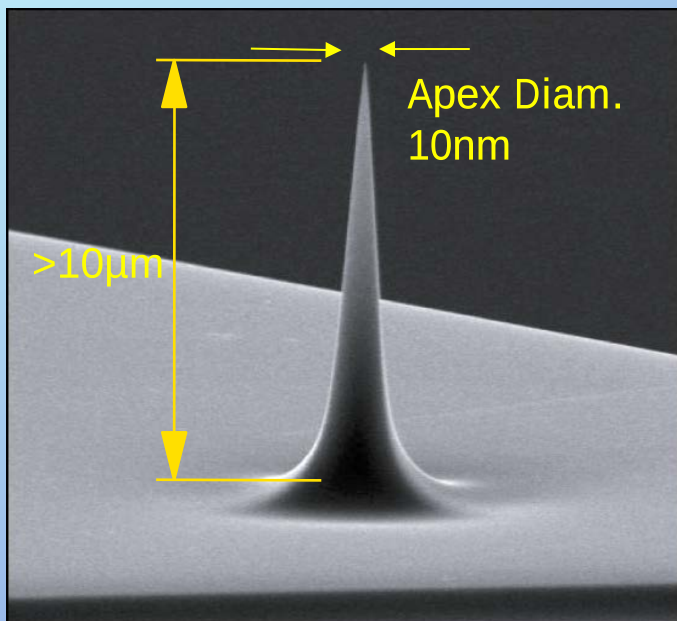
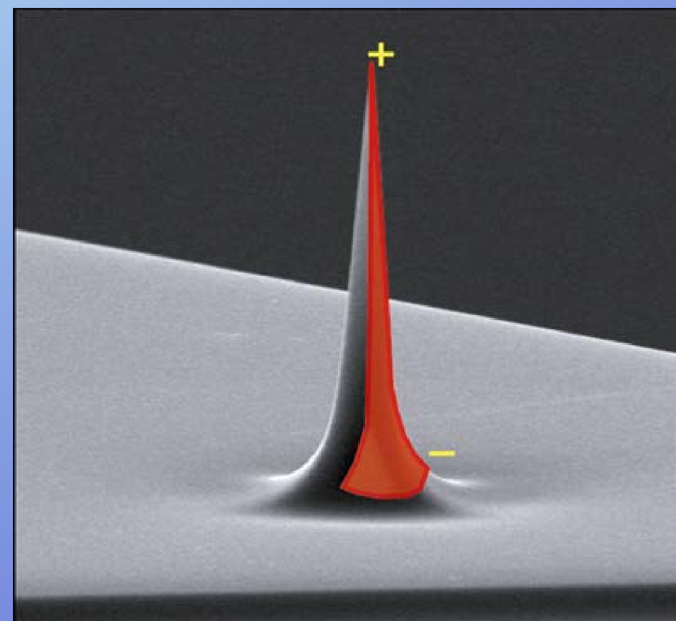
# High Resolution MFM: Requirements

- High aspect ratio tip with small apex diameter, small cone angle.
- Ultra-thin & smooth ferromagnetic coating (3-6 nm).
- High measurement sensitivity limited only by thermal noise of cantilever due to gas molecules hitting cantilever. Therefore need to go to vacuum (results in a large Q, i.e. a low damping).




T.R. Abrecht, J. Appl. Phys. **69**(2), p668 (1994)

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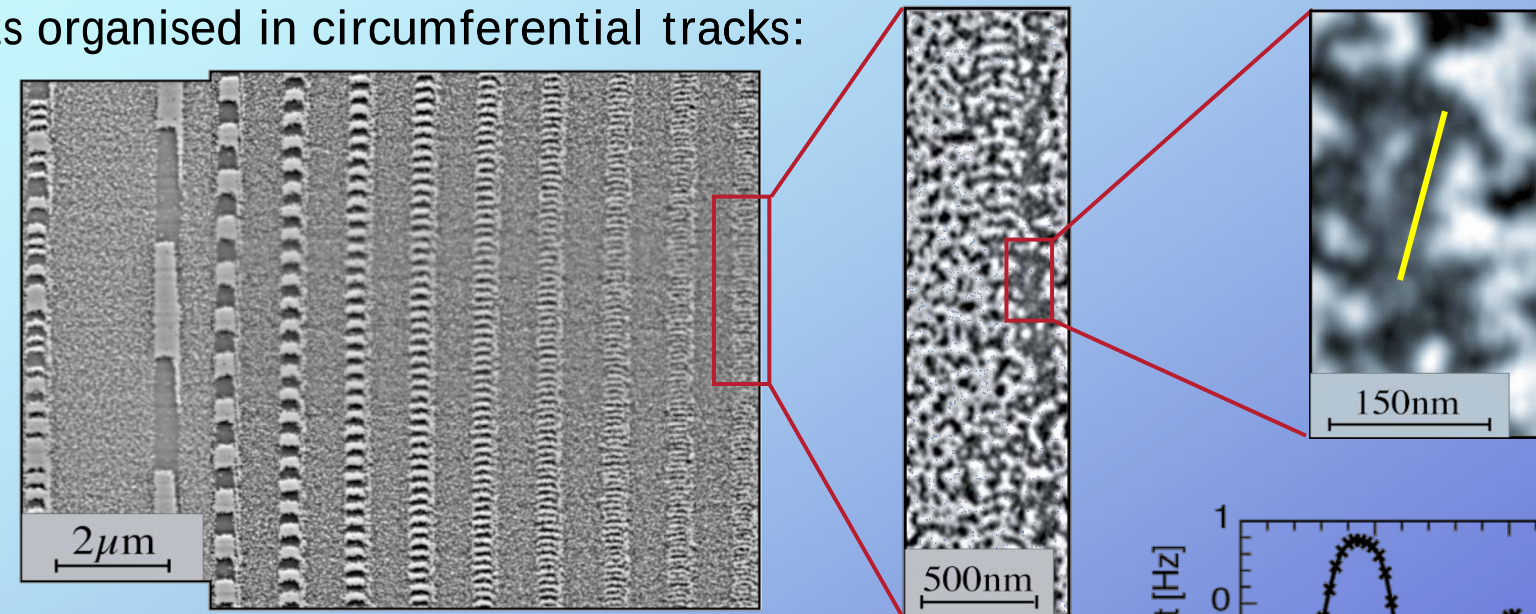
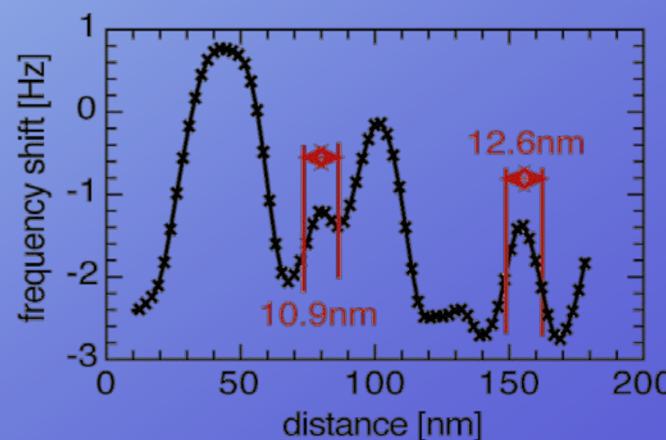
# High Resolution MFM: Example

High resolution MFM images of hard disk media (sample by Seagate Research):

Bits organised in circumferential tracks:




Increasing density / decreasing bit size




hr-MFM images important in HD research:

- detect defects in the bits
- measure media properties

A. Moser et al. J. Magn. Magn. Mater. (2005)

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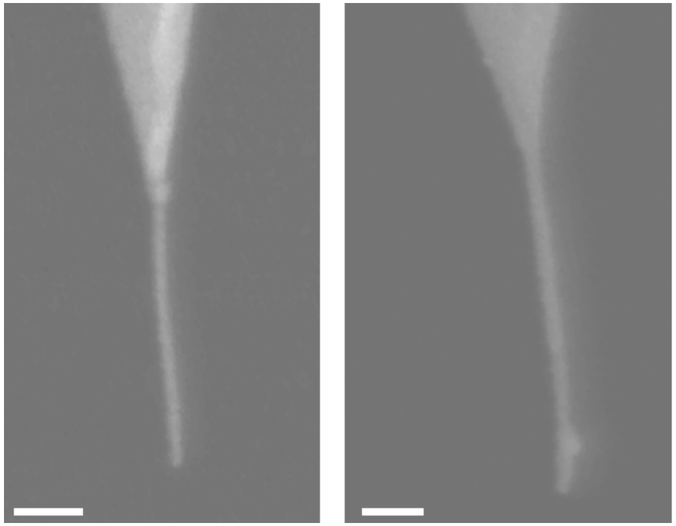
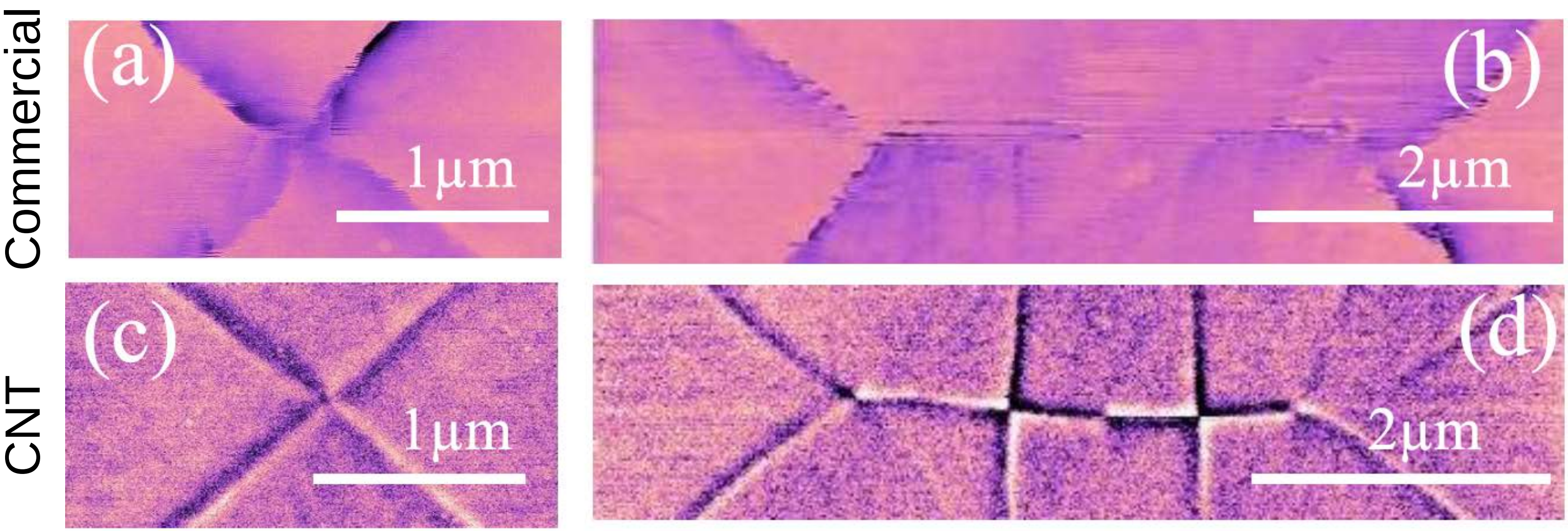
# In-Plane Structures with CNT Tip



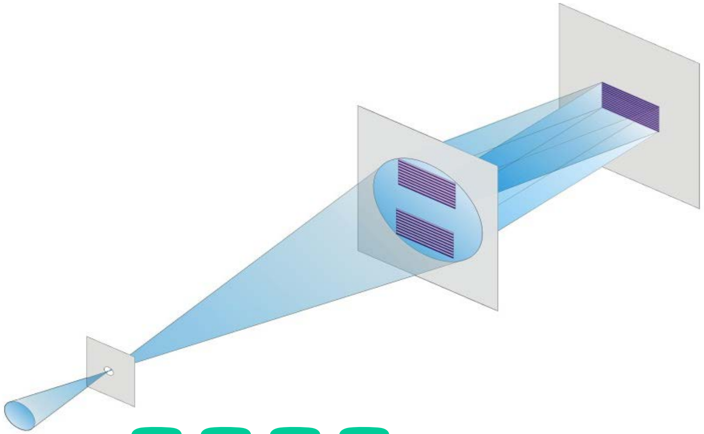
Y. Lisunova, J. Heidler, I. Levkivskyi,
I. Gaponenko, A. Weber, Ch. Caillier,
L.J. Heyderman, M. Kläui and P. Paruch
Nanotechnology (2013)

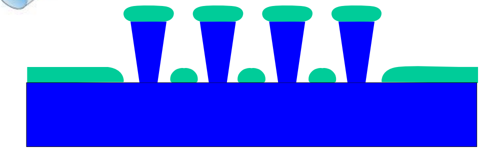
**High resolution with no vacuum!**

Scale Bar: 100 nm



# Magnetic Islands with EUV-IL





## Co/Pd Multilayer on $SiO_x$ Pillars

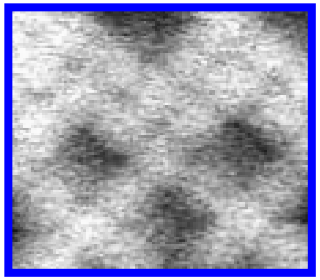
Period = 50 nm → 263 $Gbit/in^2$

Diameter = 28.4 nm, $\sigma$ = 5 %

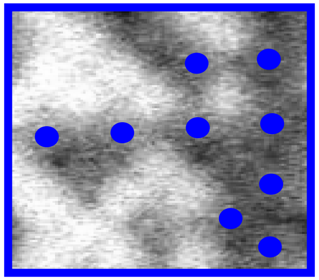
**MFM measurements**

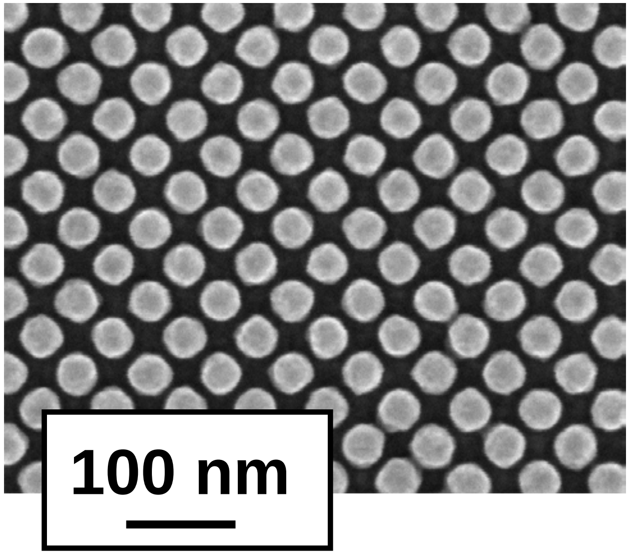
Switched Islands: •

H = -6.5 kOe



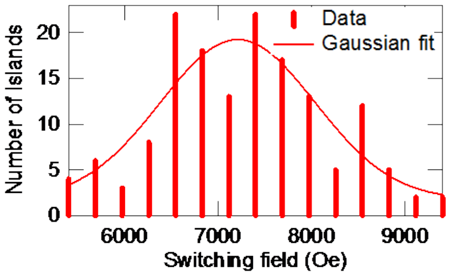
-7 kOe





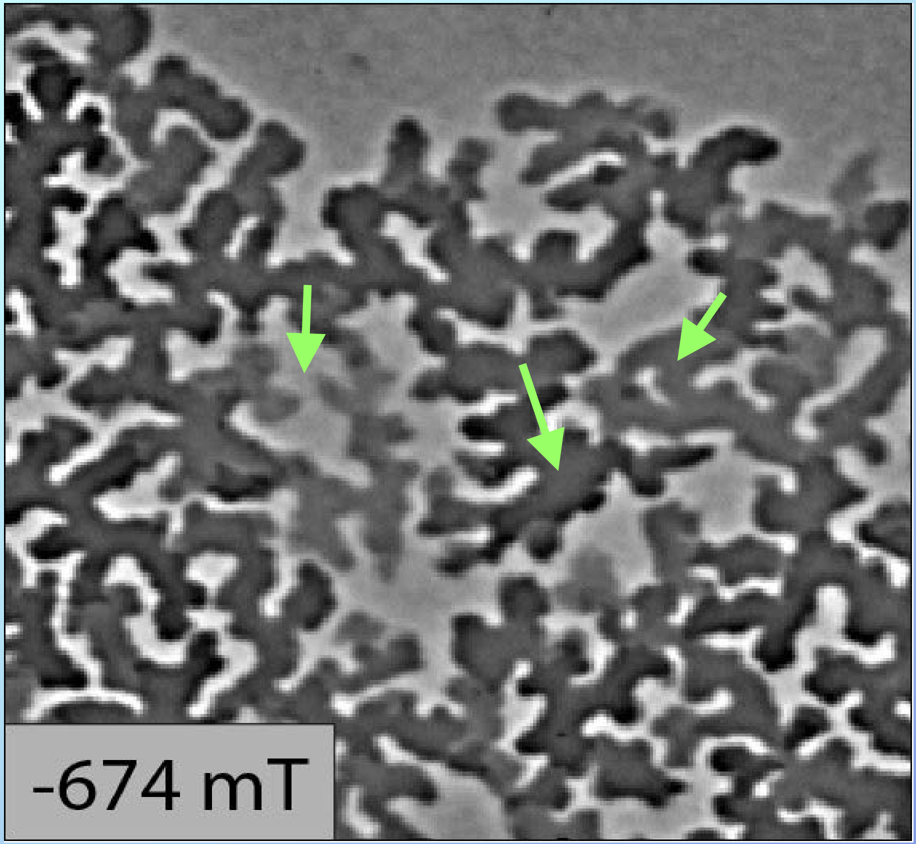

Mean switching field: 7200 Oe

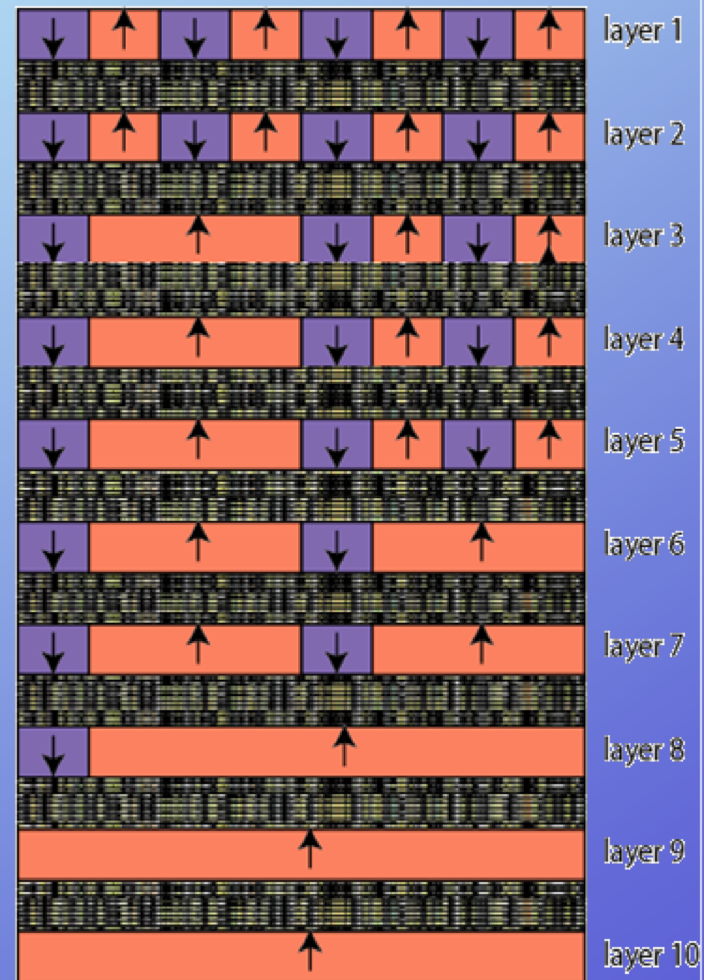
SFD ($\sigma$/mean) = 11.5 %




F. Luo, L. J. Heyderman, H. H. Solak, T.Thomson, M. E. Best APL (2008)

# CoPt Multilayer in Hysteresis Loop

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- Magnetization of layers from top to bottom.
- Which grey level corresponds to which layer?
- Take a calibrated tip and compare simulation with image.

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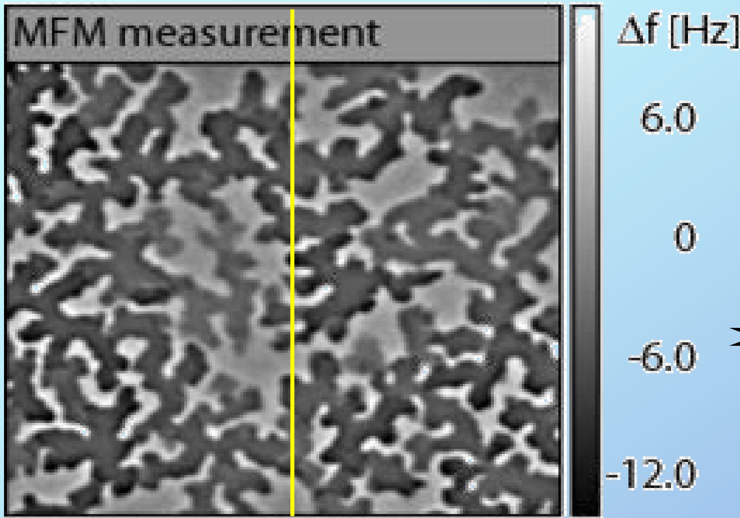
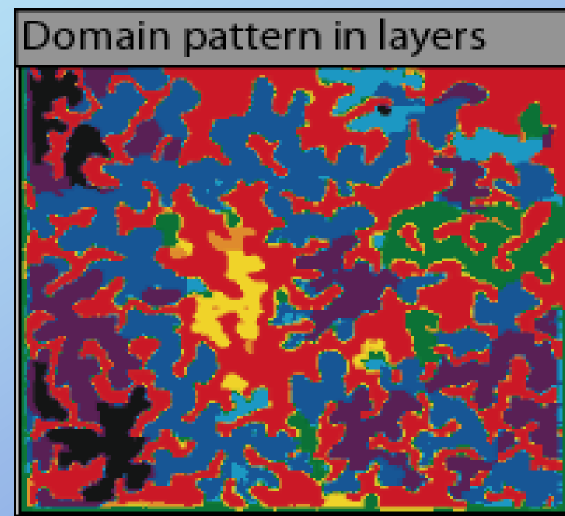
# Simulation of MFM Images

1



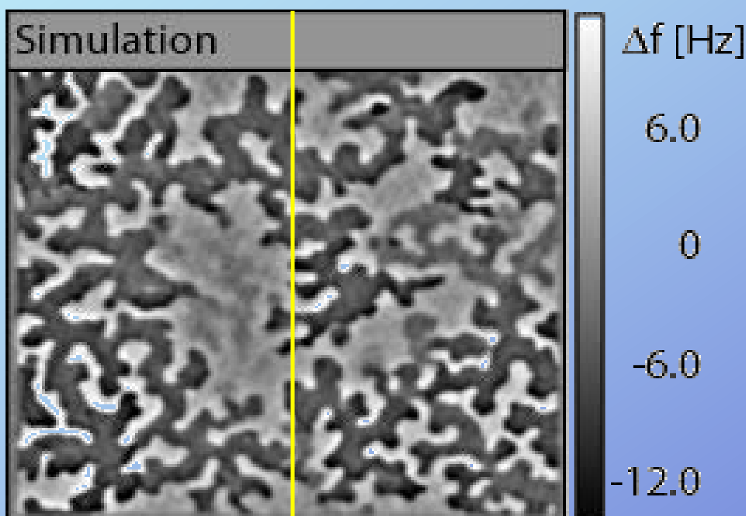

Guess

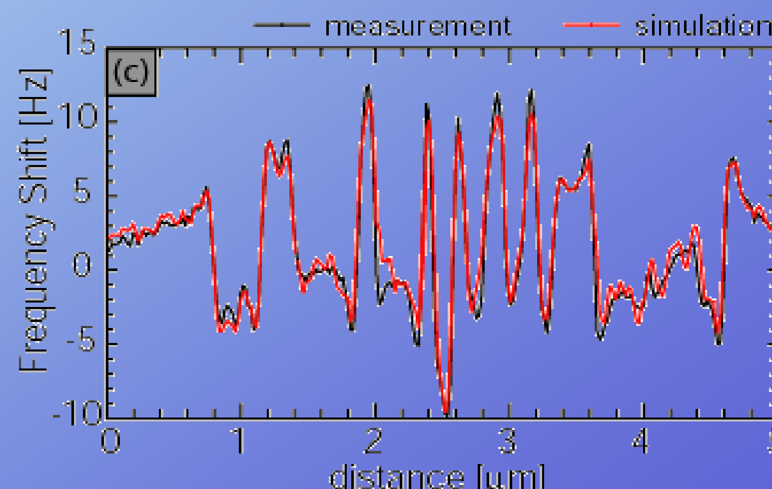
2




Colours: domains in different layers

3

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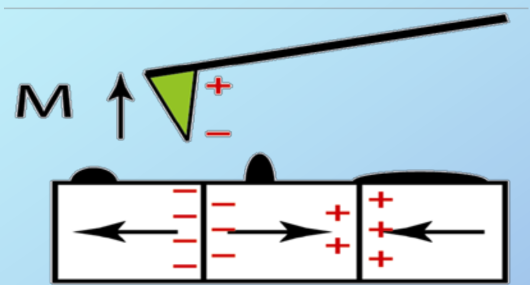
# Topography Separation

Magnetic contrast inverts when rotating the tip magnetization by 180°.
Topographic contrast remains (van der Waals is always attractive).

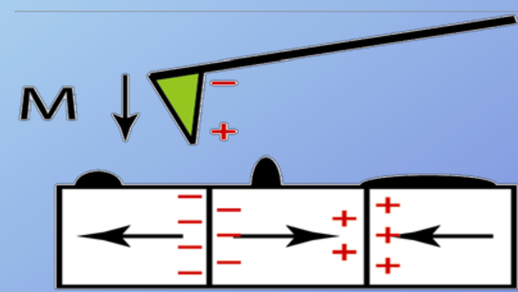
⇨ Acquire two images with opposite tip magnetization states.

A

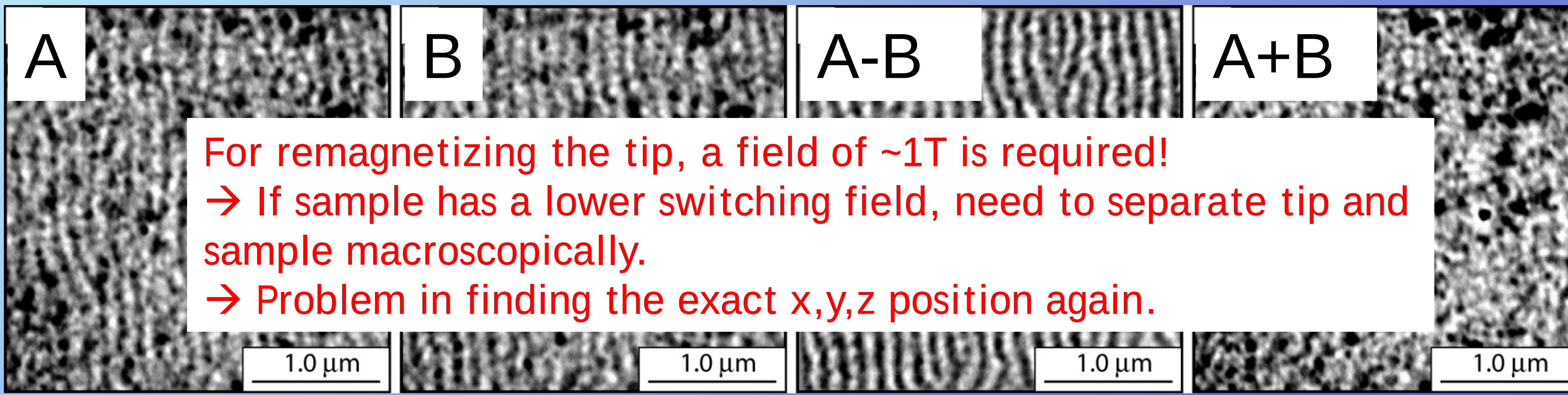



Tip magnetization up

B




Tip magnetization down




For remagnetizing the tip, a field of ~1T is required!
→ If sample has a lower switching field, need to separate tip and sample macroscopically.
→ Problem in finding the exact x,y,z position again.

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# MFM Summary

- Maps the magnetic stray field (or derivative)
- Resolution: typically 20-30 nm, high resolution: 10 nm
- Non-destructive
- Especially sensitive to z-component of stray field: ideal for perpendicular anisotropy materials (e.g.magnetic media) but can also image domain walls in in-plane samples
- Requires virtually no sample preparation
- Surface should be relatively flat
- Tip quality is critical
- Influence of tip: difficult to measure magnetically soft samples

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