Nano Magnetics
for *Biomimetic Cilia* Applications

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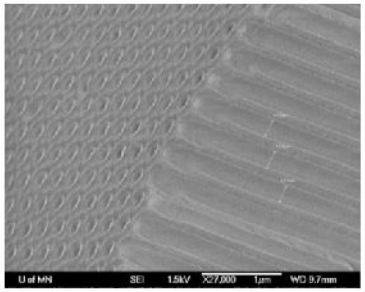
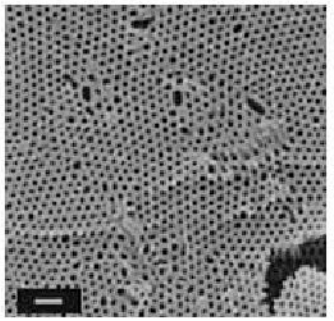
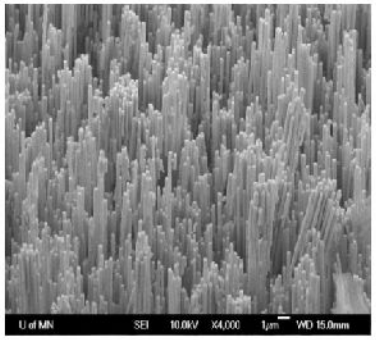
Applications

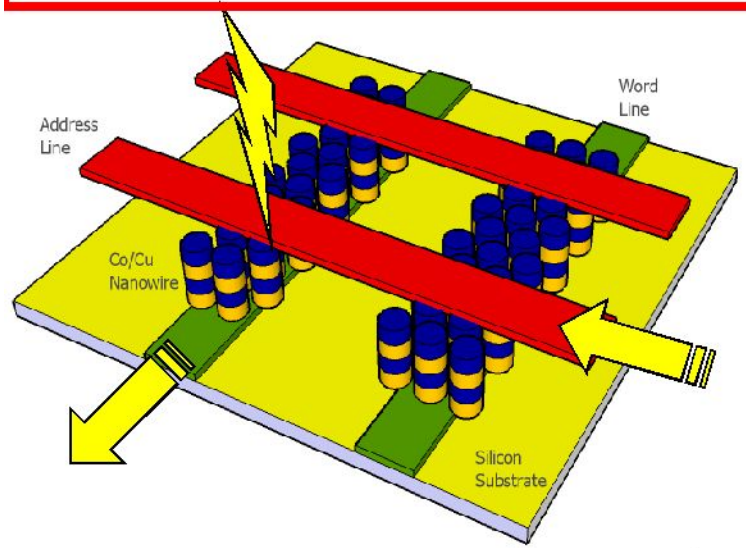
- Recording
  - Read Sensors
  - Bit patterned media (BPM)
- Random Access Memory (RAM)
- Cilia (NEMS)
- Biomagnetics

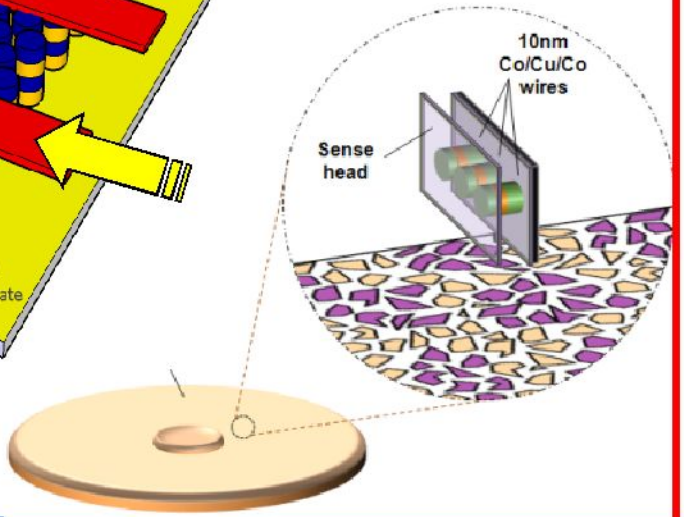


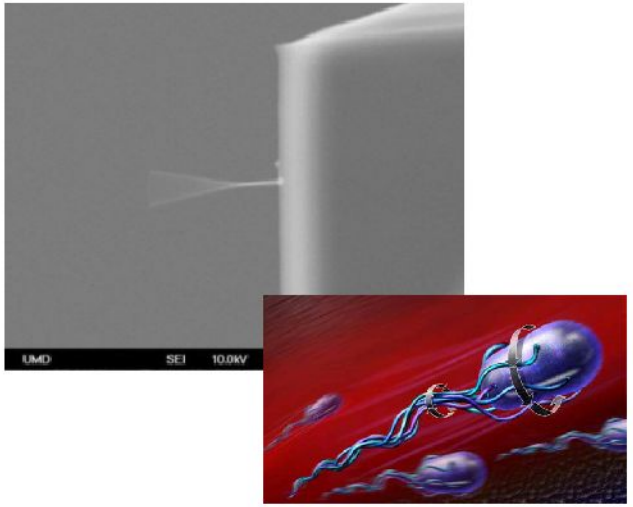




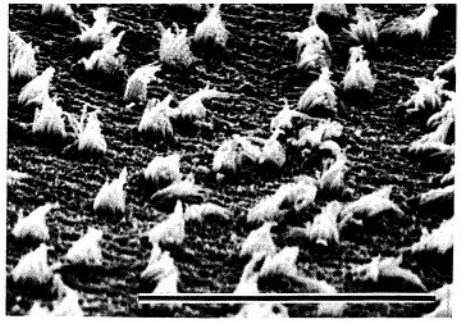
www.nano.umn.edu/omni/research



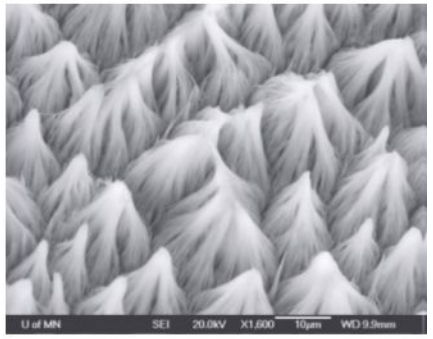


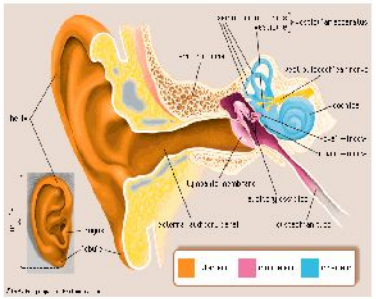


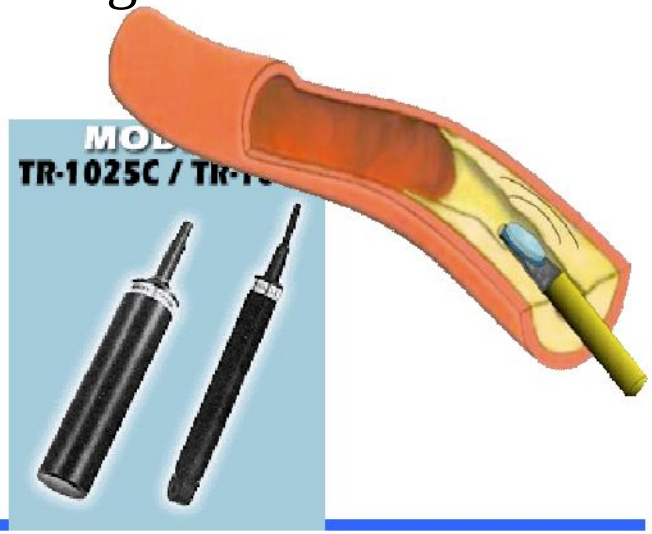
Outine



- Motivation: Artifical Cilia
- Magnetostrictive Galfenol
- Measuring Magnetic Multilayers
- Applications: flow and vibration sensing

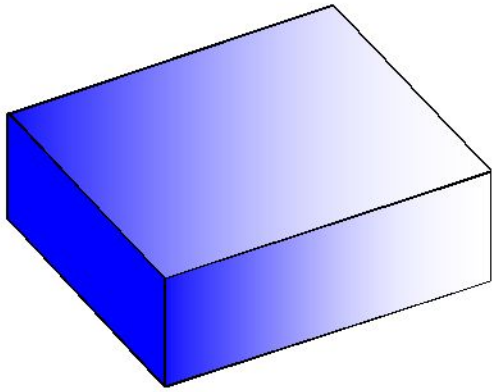




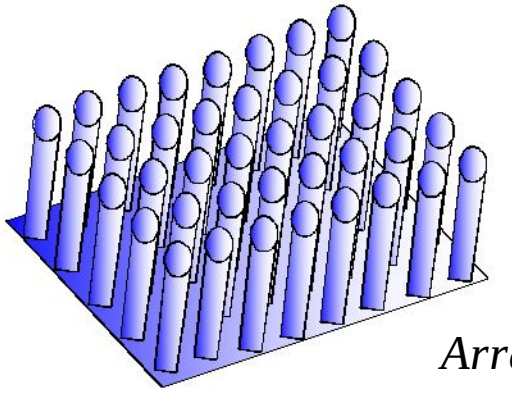


Overview- Advantages

- Nanosensors: increase in surface ~~area~~ area increase in the device sensitivity
  - Consider two sensing elements, both 1 m thick



Thin film

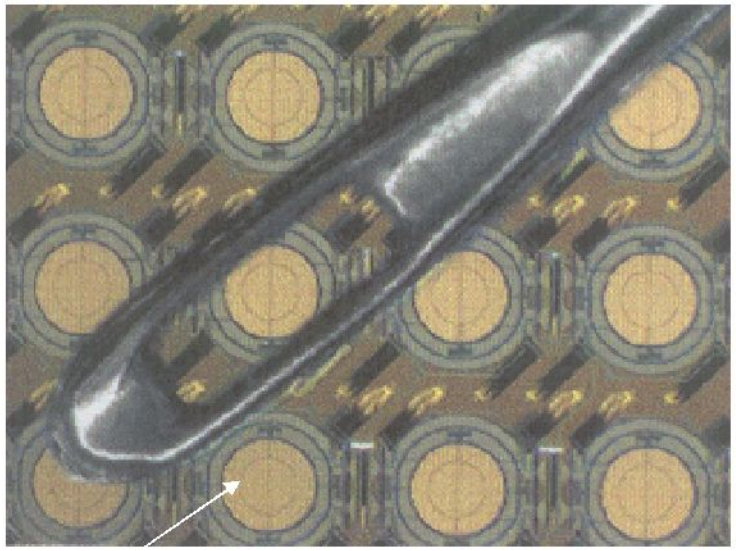


Array of nanowires with 100 nm diameters & 100nm interwire spacings

Advantages: NEMS

- Microelectromechanical Systems (MEMS)
  - Feynman "Plenty of Room at the Bottom" Dec 1959.
  - Newell, Science **161**, 1320 (1968).
- Why?
  - Reduce mass
  - Increase resonant frequency
  - Lower force constants
- Where?
  - Mirrors in optical communications
  - Flow control in ink-jet printers
  - Accelerometers in airbags
  - .. sensors, medical, displays, storage…

Lucent mirror array



Diameter ~.4mm

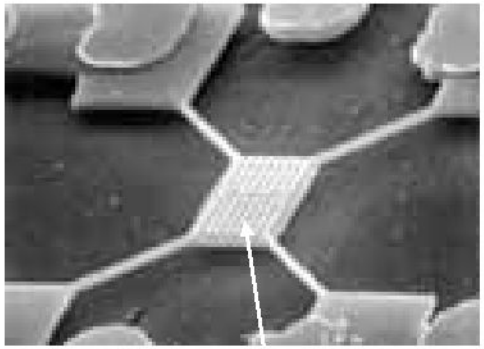
Engineering Structures

- "Machine" large numbers of integrated devices

- Planar Processing- *Top-Down*
  - Si processing follows microelectronics
  - New ion- and e-beam lithography (100nm)
  - New materials

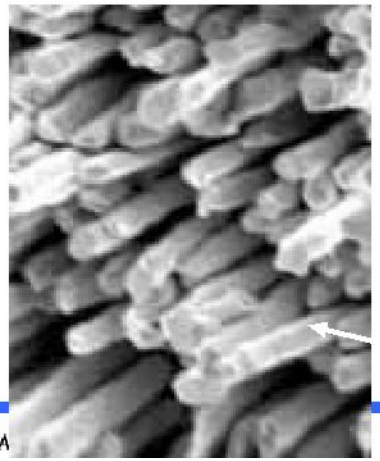
NEMS

Roukes, Caltech



3um x 3um

- Self Assembly- *Bottom-Up*



Stadler,
U Minnesota

20 nm

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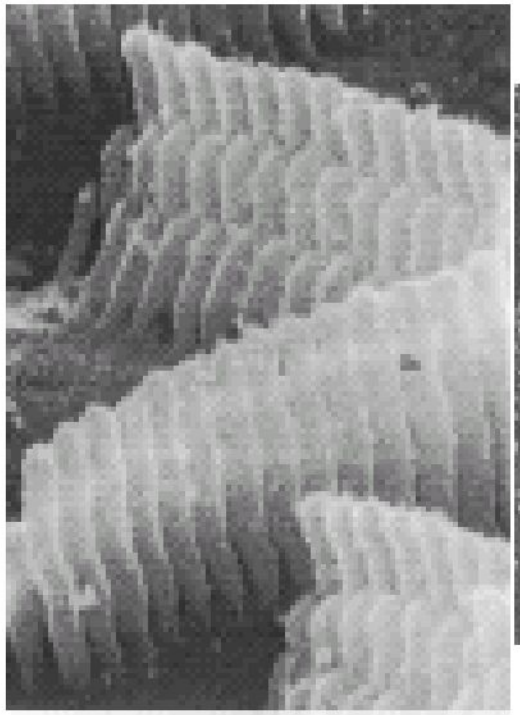
The Problems of Motion

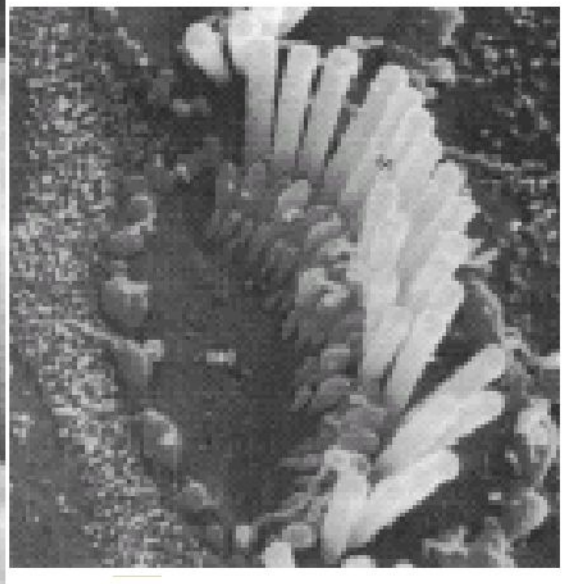
- How to induce motion?
  - Biomolecular motors
  - Electric fields
  - Thermal ($_{th}$)
  - Acoustic signals
  - Magnetic fields

- How to detect motion?
  - Electric fields
  - Optical methods- most common
  - Tunneling current
  - Magnetic fields
  - Acoustic signals

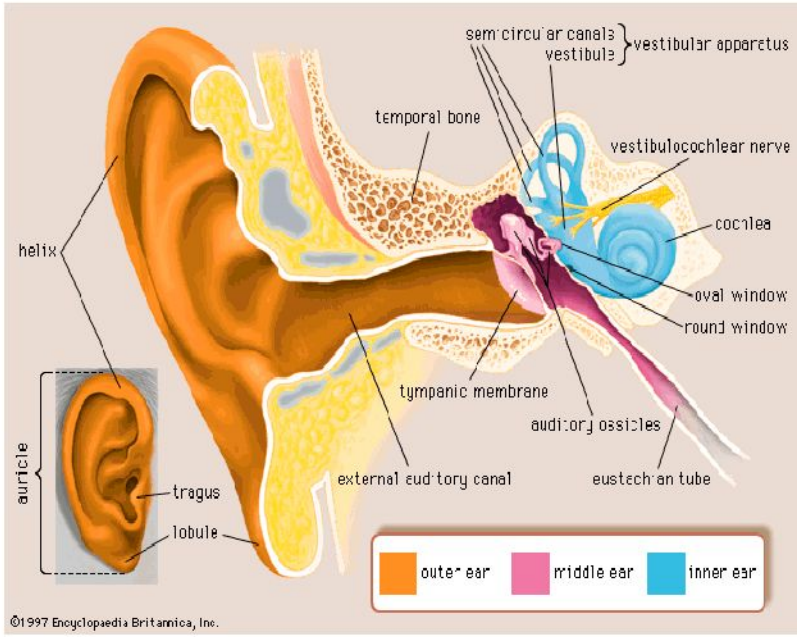
A Model Acoustic Sensor: *your ear!*



Cilia from outer ear cell



Cilia from inner ear cell



Cilia from our lab

Encyclopedia Britannica

Yost and Nelson
Fundamentals of Hearing

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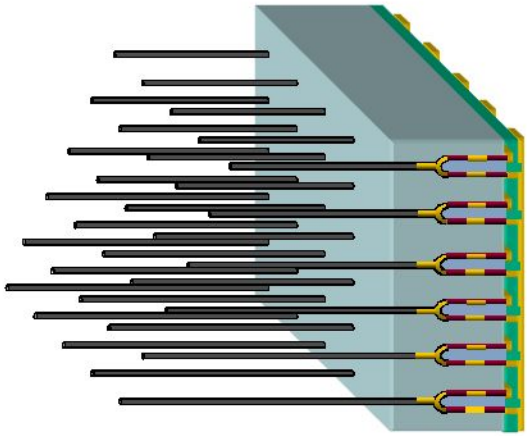
Artifical Cilia Sensors



Giant magnetoresistive nanowires (GMR)

Magnetostrictive nanowires

Mechanical stimulus → Magnetic Field → Voltage

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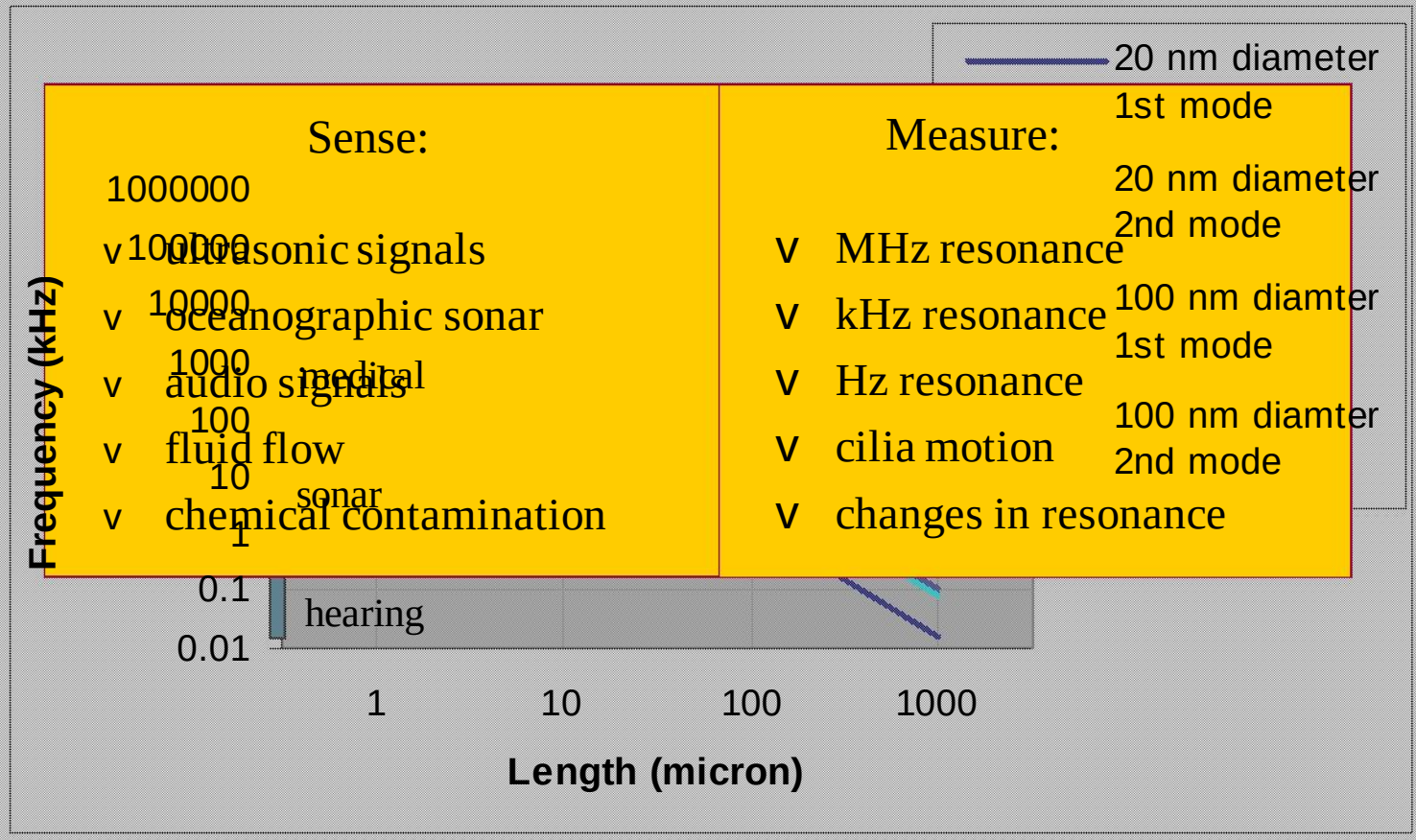
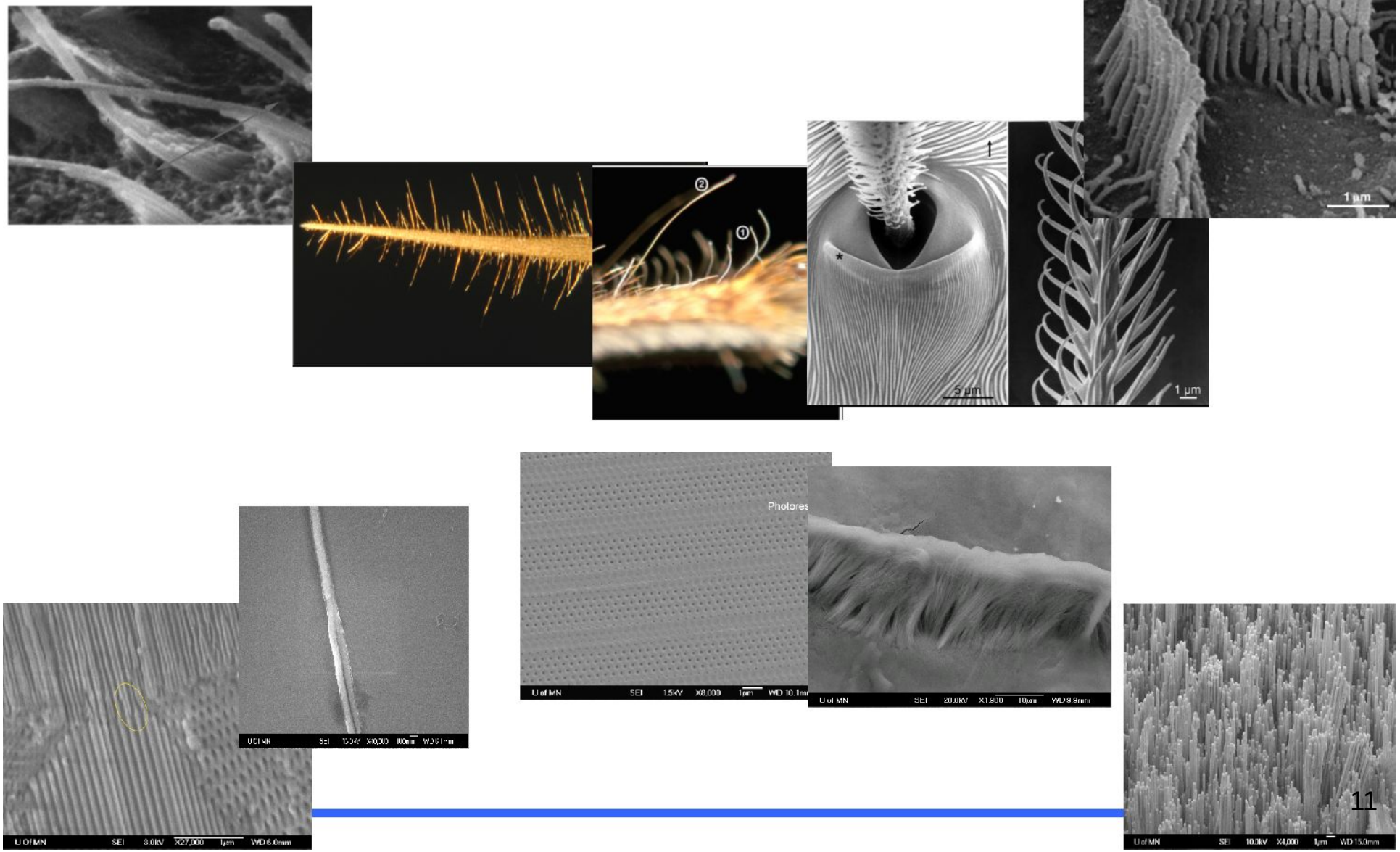
Artificial Cilia

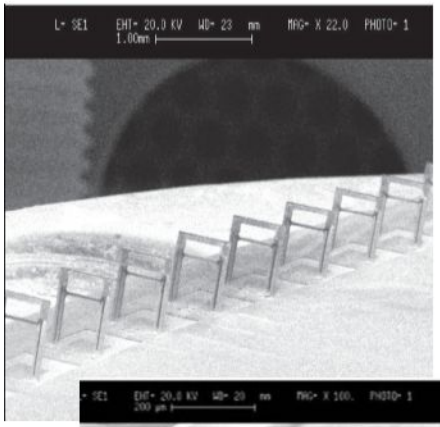


Cilia: Natural and Synthetic

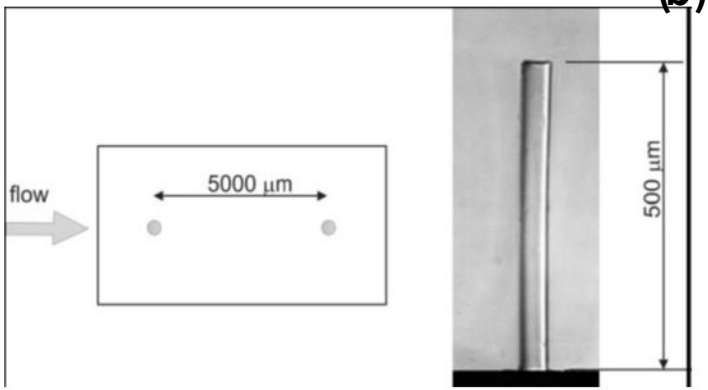


Yingchen Yang et al *Proceedings of the National Academy of Science,* published online Nov 28, 2006.
Boris P. Chagnaud et al *The Journal of Neuroscience,* (2008) V28(17) pp4479–4487.
Gijs J M Krijnen et al *Nanotechnology* 17 (2006) S84–S89
N. Izadi et al *DTIP of MEMS & MOEMS* (2007) Stresa, Italy.
Zhifang Fan et al *Journal of Micromechanics and Microengineering,* 12 (2002) 655-661.

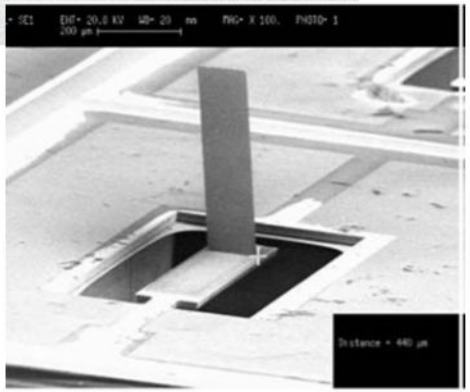
MEMS Cilia Review



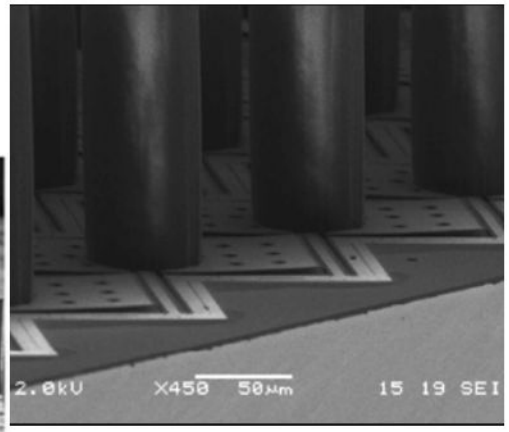
(a) mm-scale artificial lateral line sensors; [32]



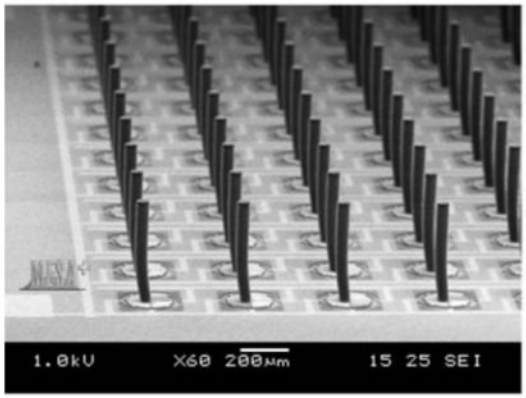
(b) flexible micropillar flow sensor; [33]



(c) 820mm tall, 100mm wide, 10 mm thick artificial hair cell cilium; [36]

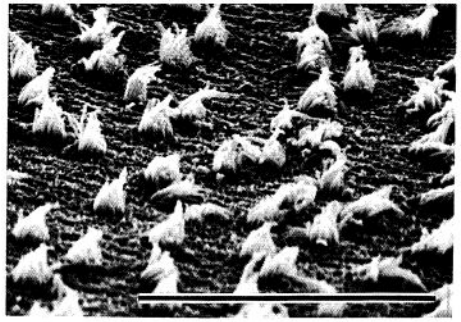


(d) SU-8 hairs with modified base structure for enhanced sensitivity; [35]



(e) Array of SU-8 epoxy-based polymer hairs 470mm long supported by SixNy membranes; [34]

Outine



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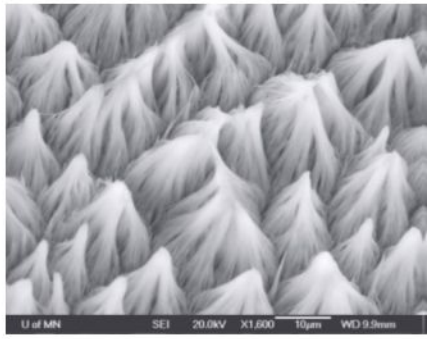
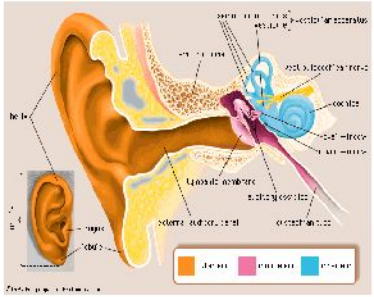
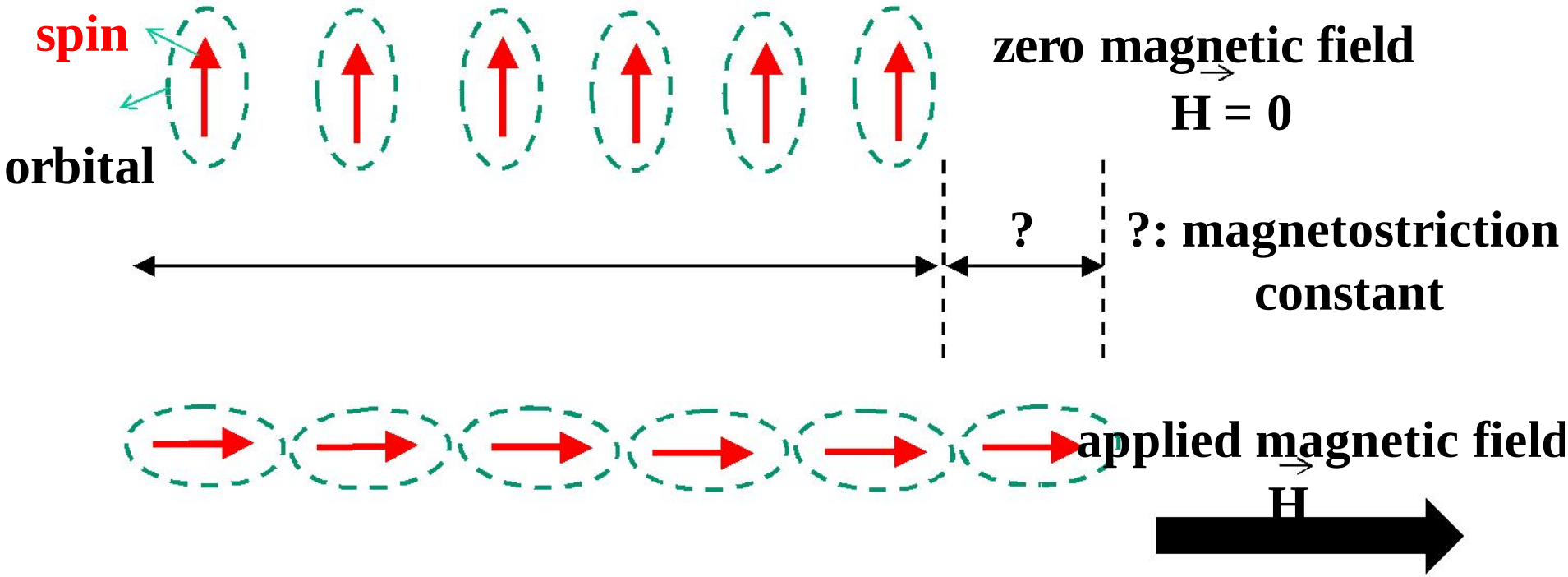


- Measuring Magnetic Multilayers
- Applications: flow and vibration sensing



Origin of Magnetostriction

Spin – Orbit coupling

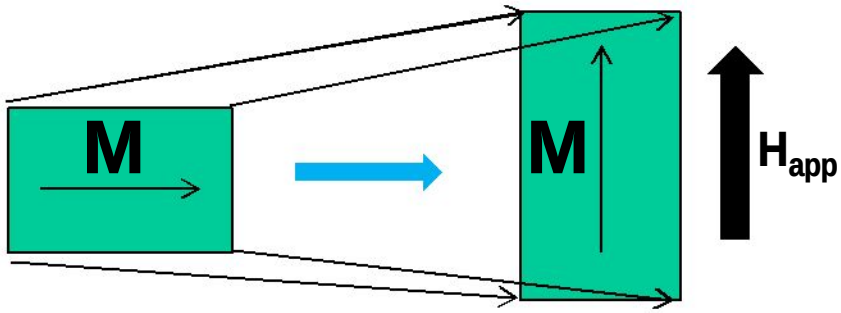


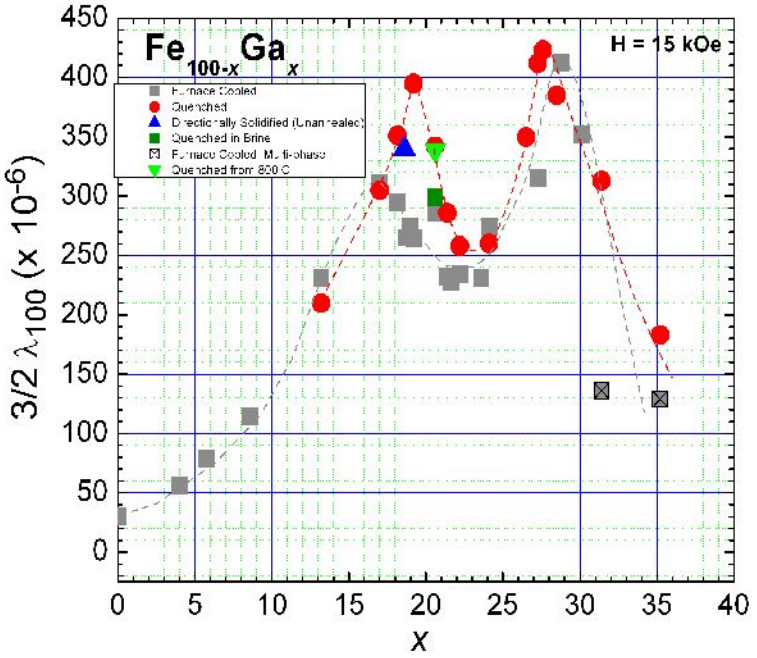
- Spin-orbit coupling very strong in Rare-Earth based alloys
- Hence, very large magnetostrictive constants in FeDy, FeTb and TbDyFe alloys.

MOTIVATION FOR FeGa ALLOYS

MAGNETOSTRICTION

No Magnetic Field Applied Magnetic Field

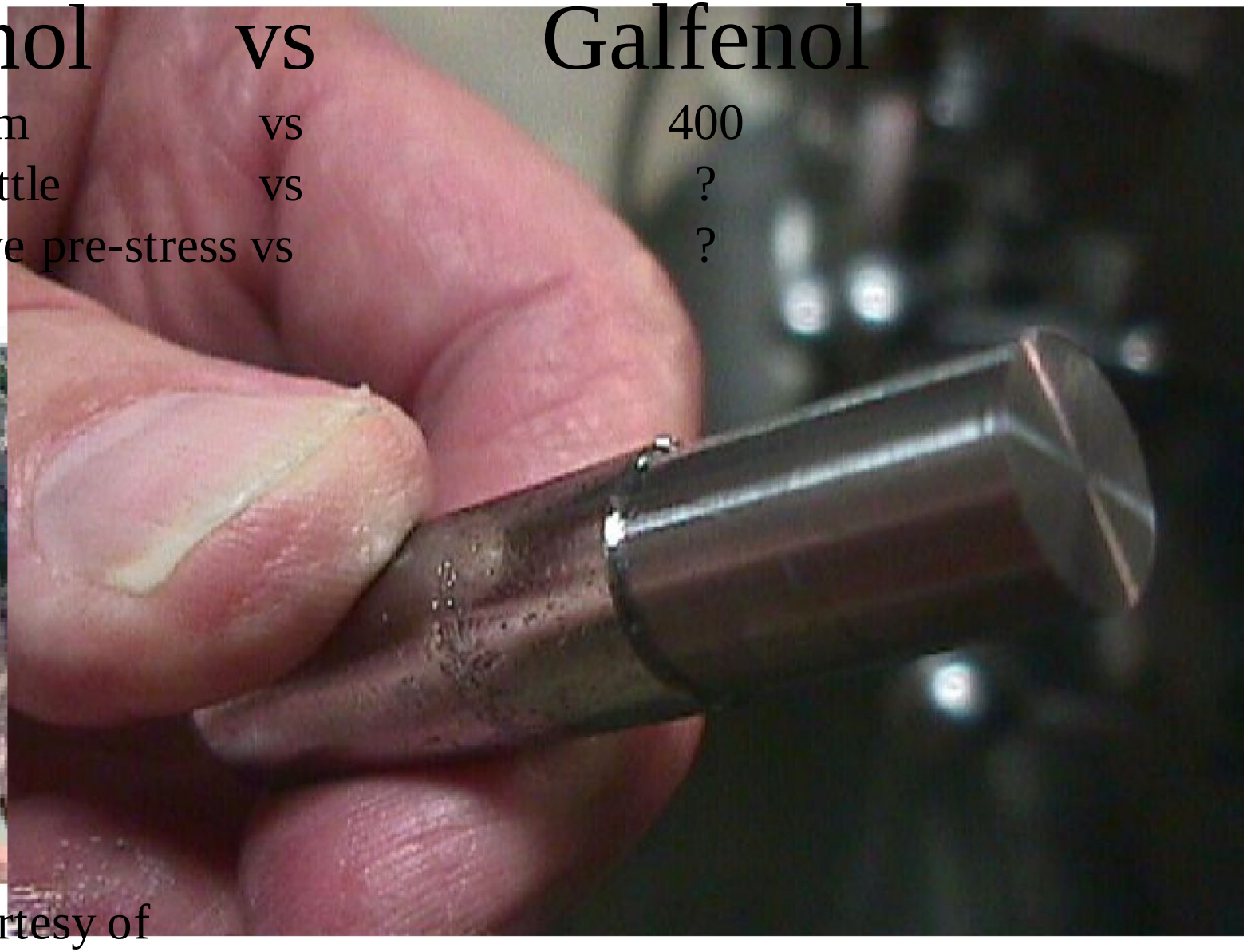




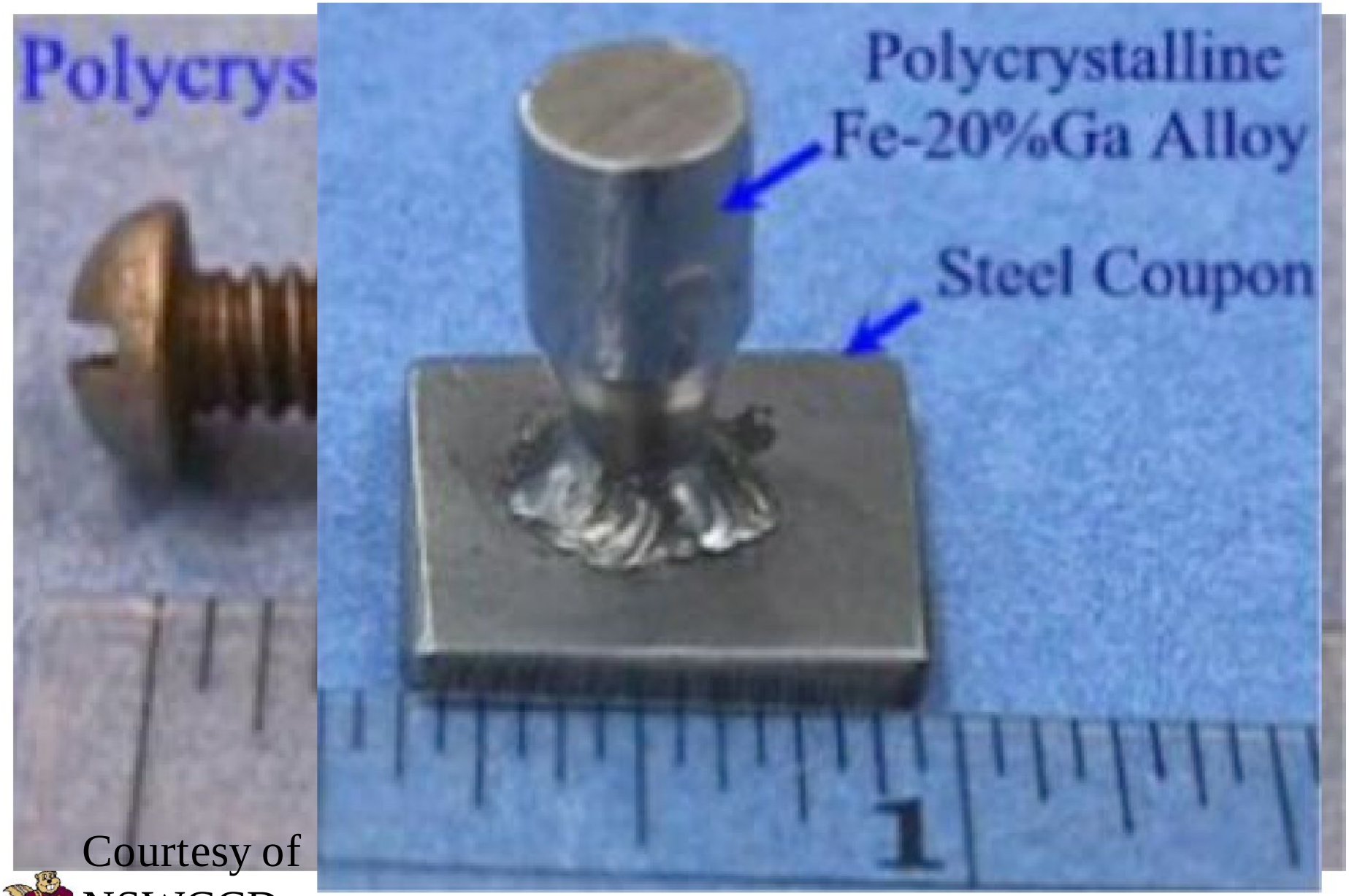
- Large Magnetostriction
- High Strength
- Use of these properties in nanowire forms

Terfenol vs Galfenol

1600ppm	vs	400
very brittle	vs	?
compressive pre-stress	vs	?

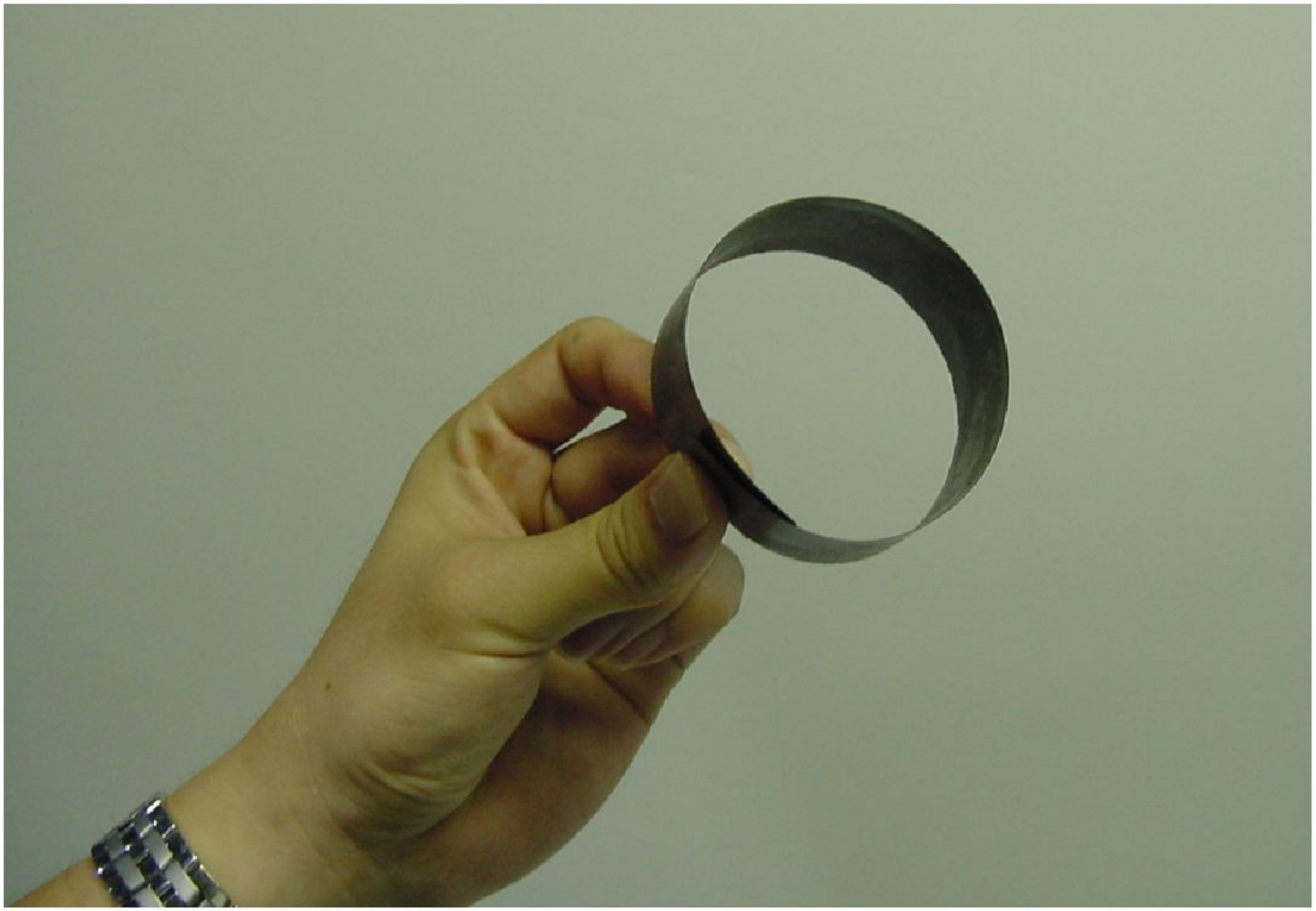


Courtesy of NSWCCD



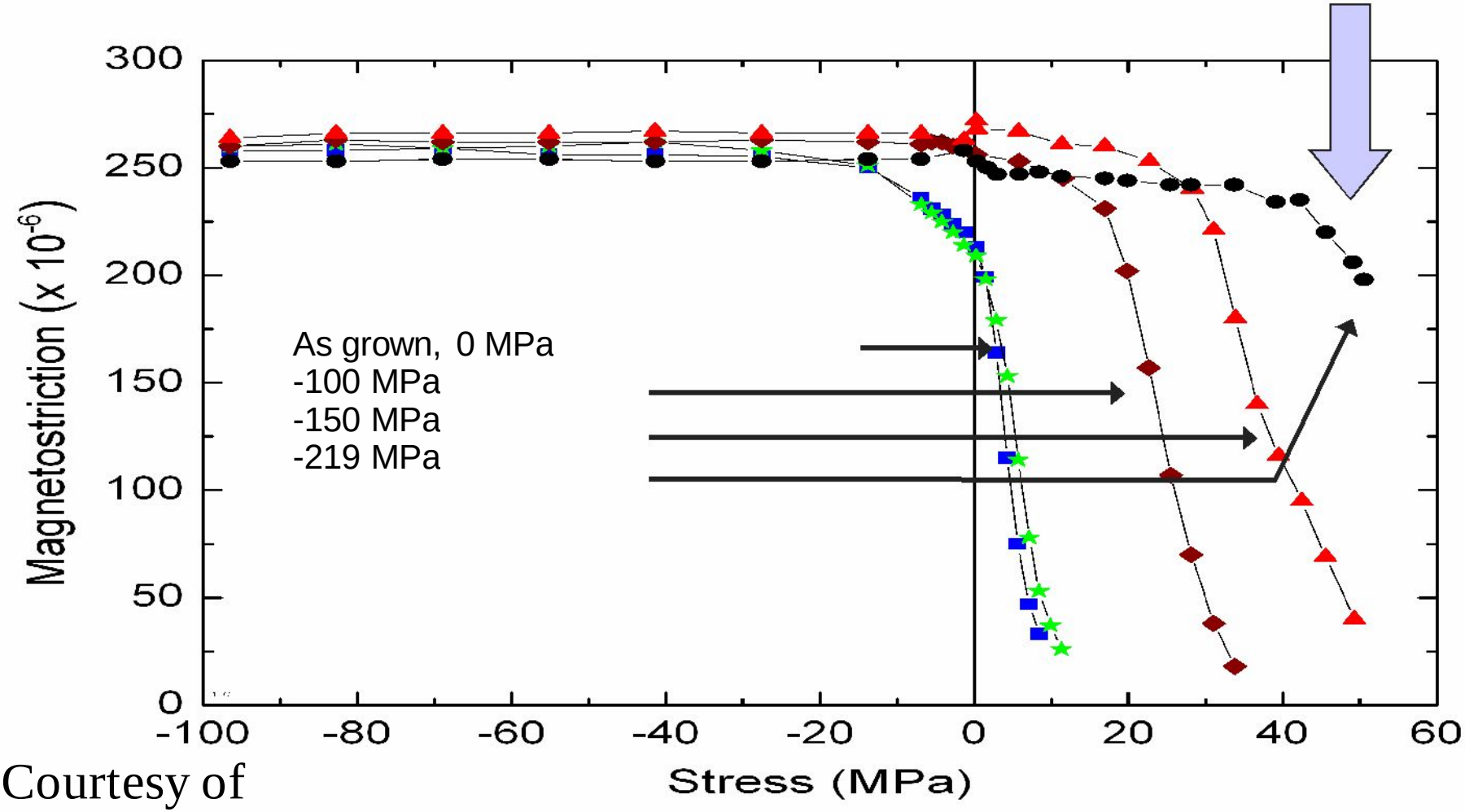
Courtesy of NSWCCD

Rolled Galfenol shows Flexibility



Building in a Uniaxial Anisotropy

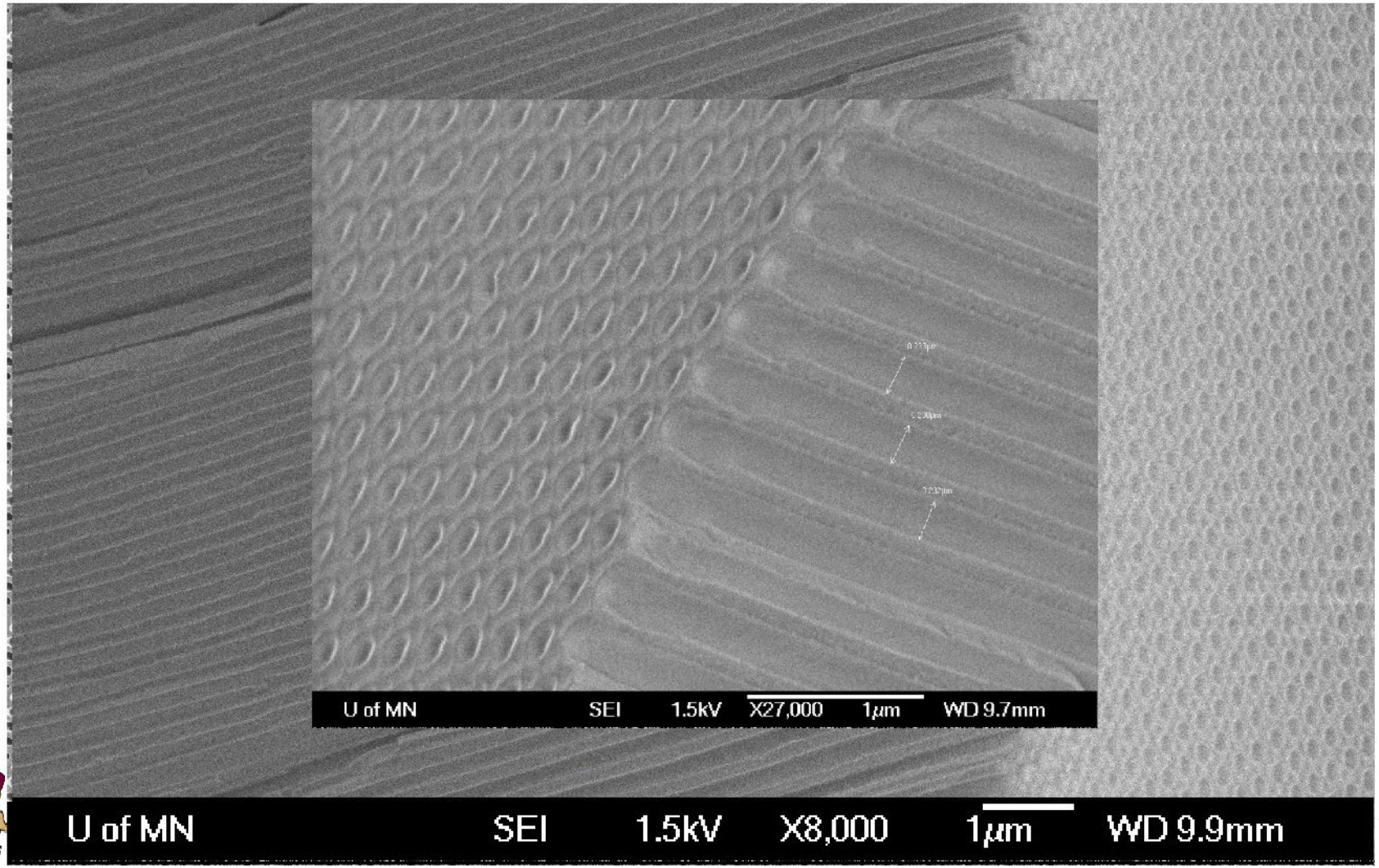
Full magnetostriction with 45 MPa tension!



Courtesy of NSWCCD

30 T/GPa sensing

Sides are Strictly parallel



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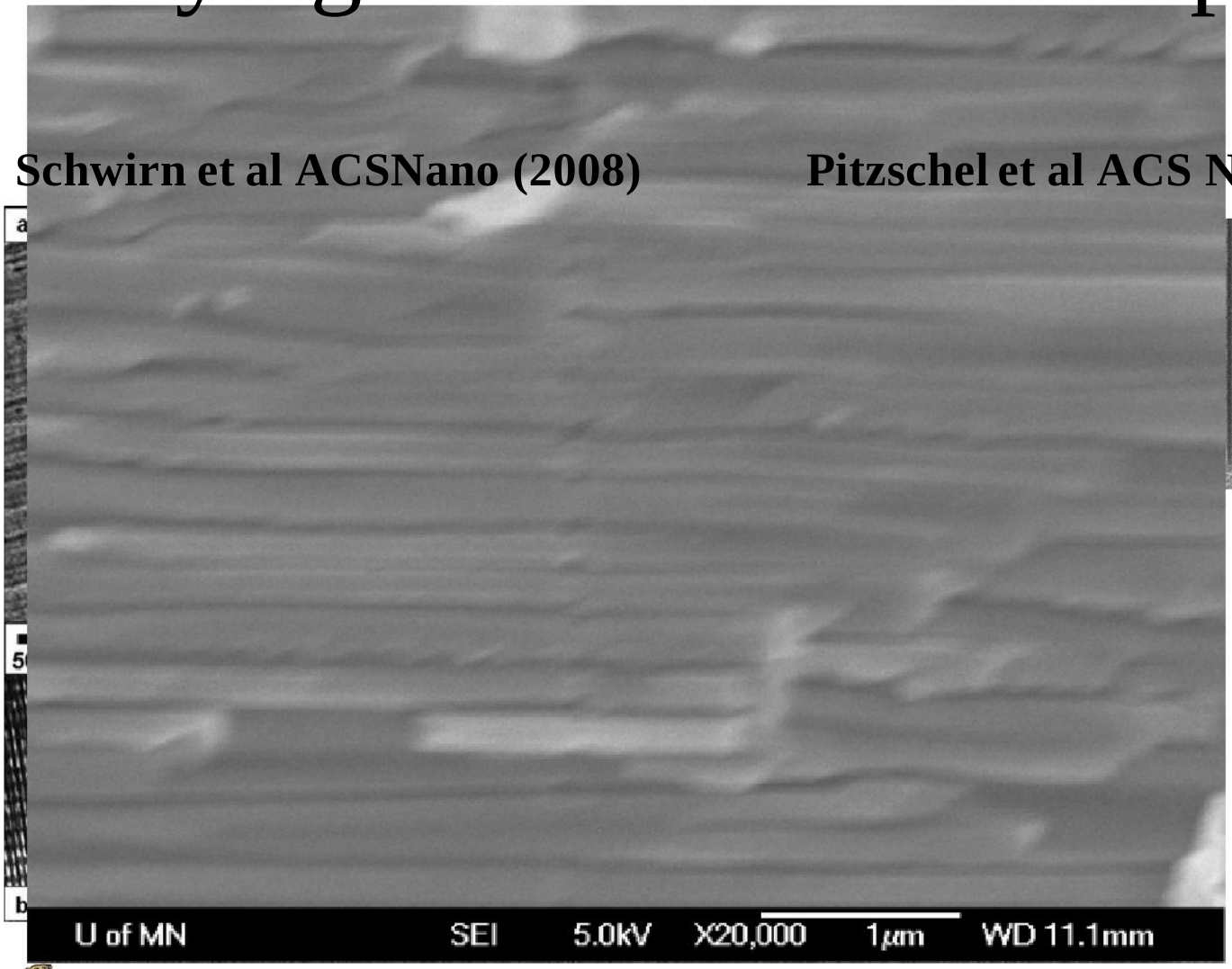
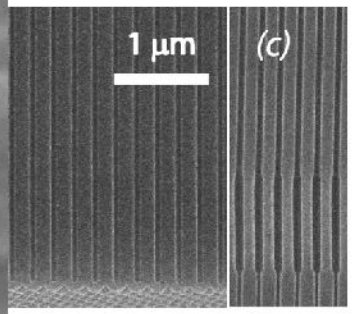
Varying Diameters of Nanopores

Schwirn et al ACSNano (2008)

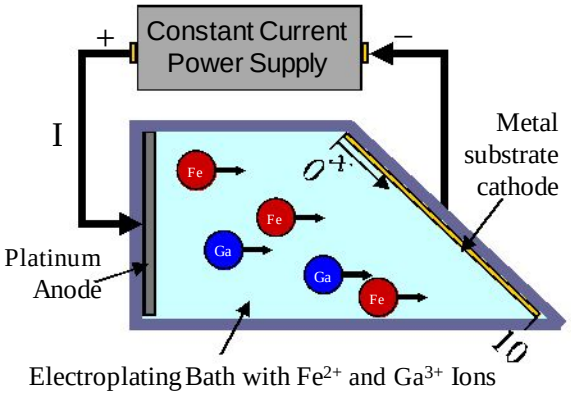


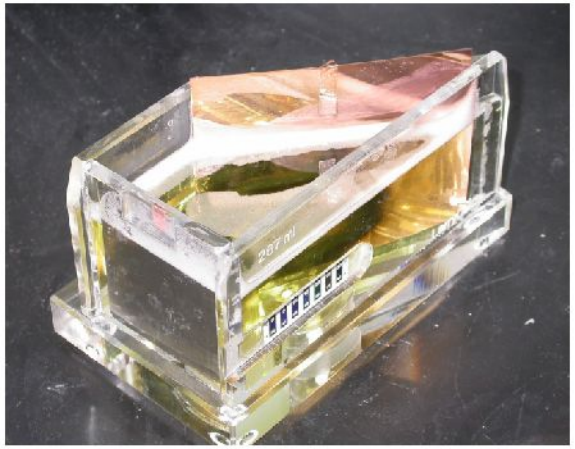
Pitzschel et al ACS Nano (2009)

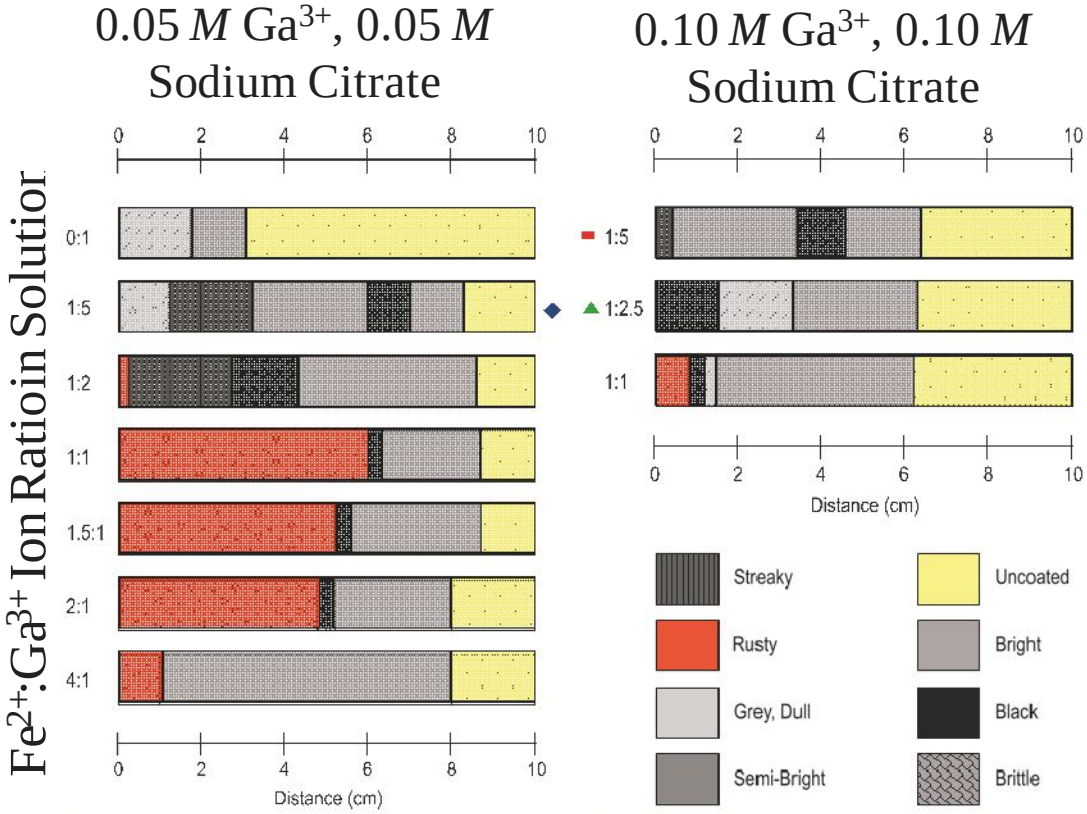


Norby and Stadler
UMN 2009
unpublished

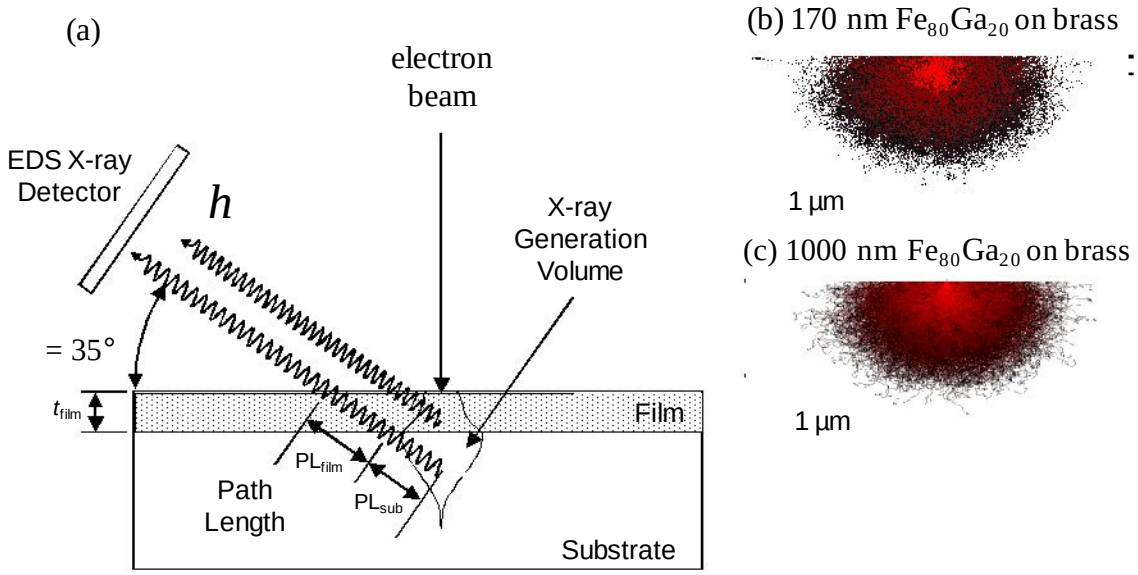
Refining Electroplating using Hull Cell





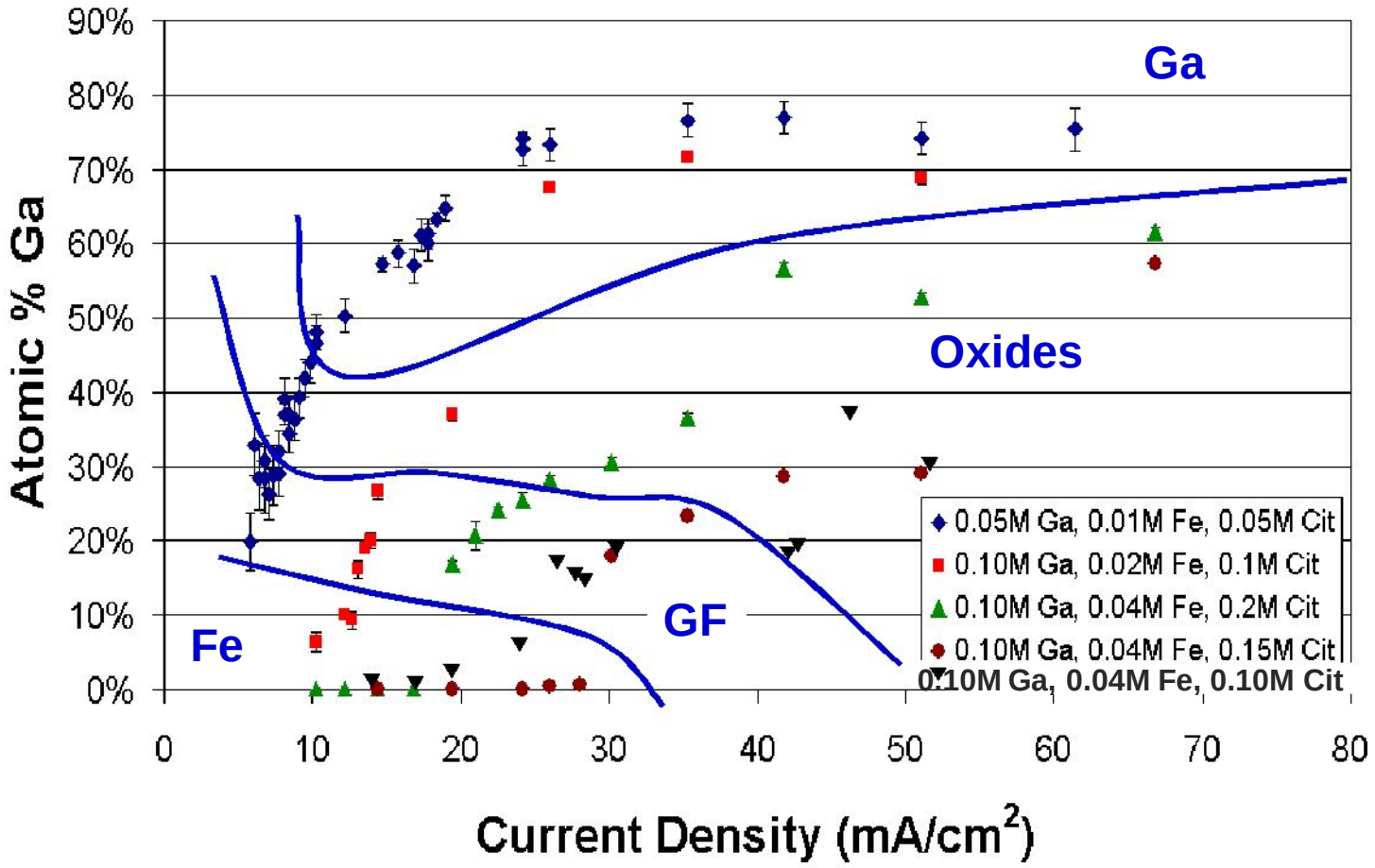


EDS Simulations for Thicknesses



Schematic of characteristic x-ray generation in specimen and collection in solid state detector, and Monte Carlo simulations of electron scattering trajectories vs. depth for (b) 170 nm $Fe_{80}Ga_{20}$ and (c) 1000 nm $Fe_{80}Ga_{20}$ films on a brass substrate with a beam energy E_0=20 keV

Phase Diagram of Electrochemical Galfenol



See Madhukar Reddy et al , Electrochemistry Comm 2012

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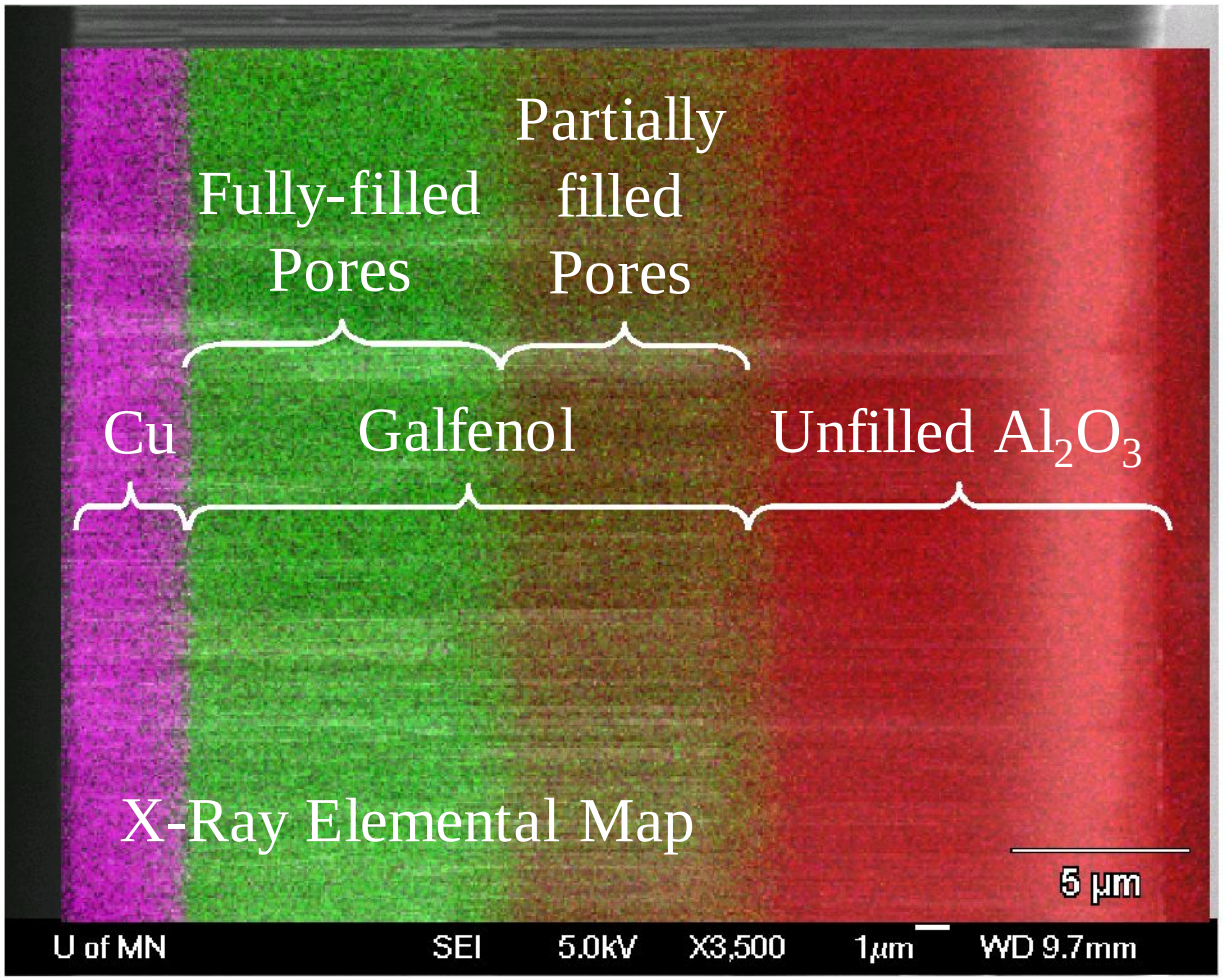
Nanowires in 40 nm Templates



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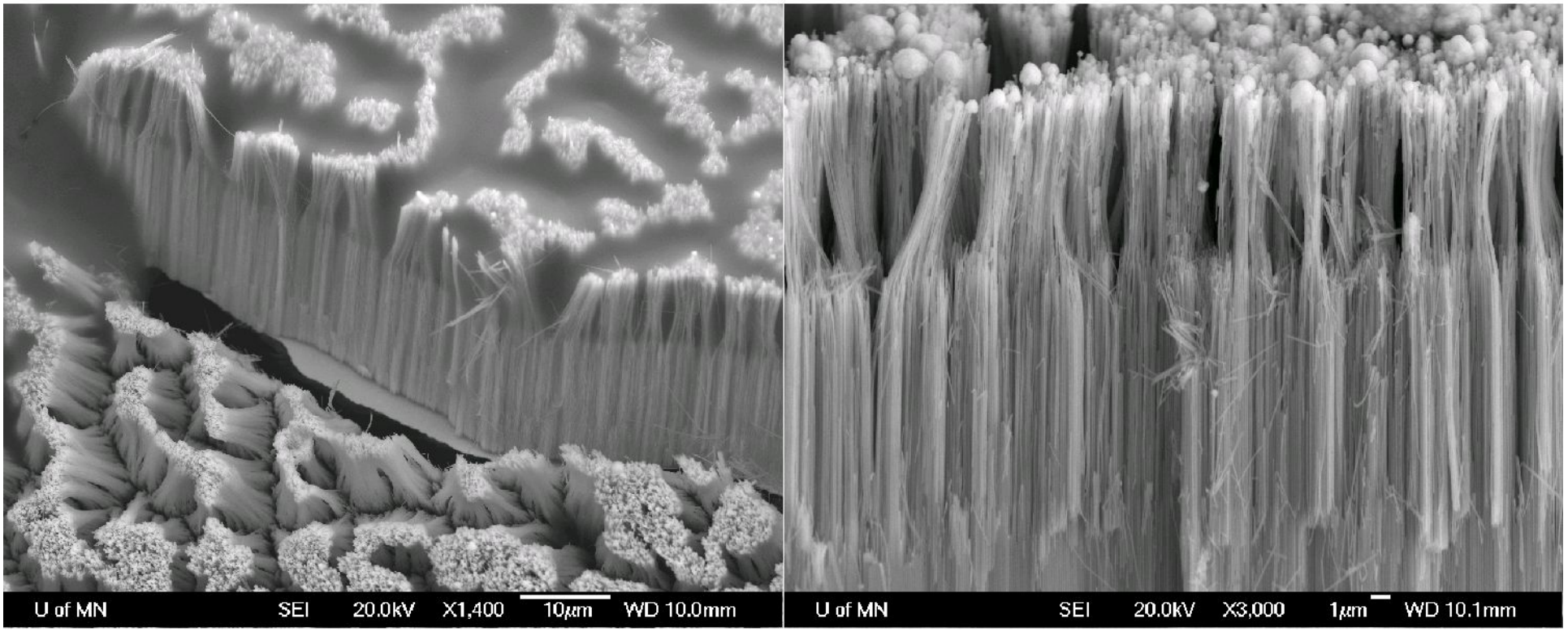
Exposed Galfenol Nanowire Arrays

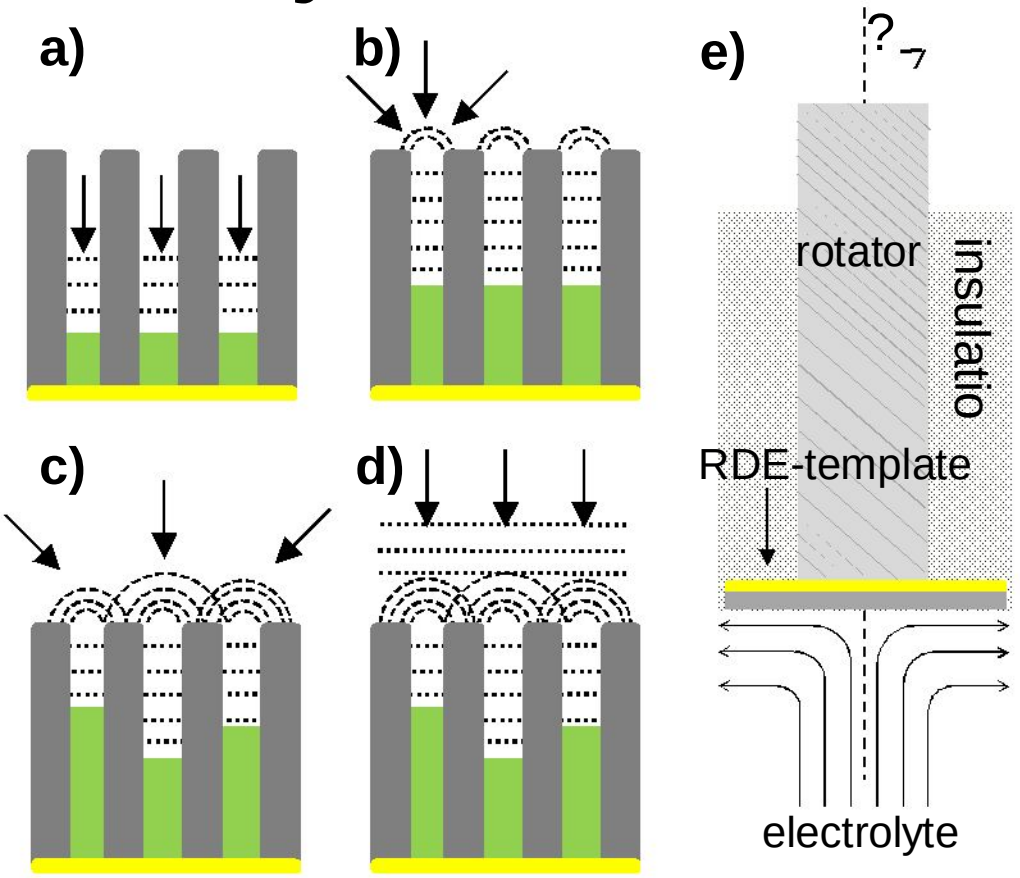


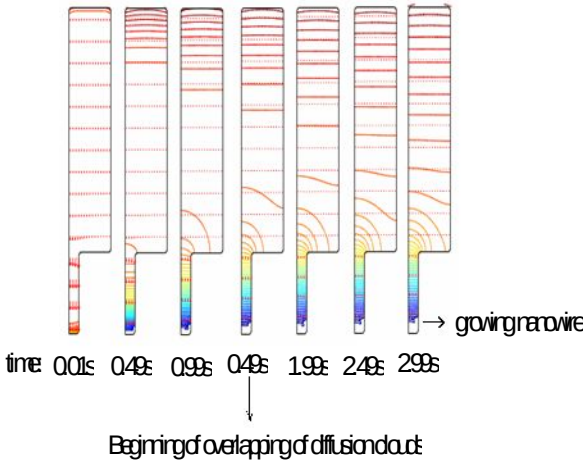
Non-uniformities Multiply

- Outgrowth blocks

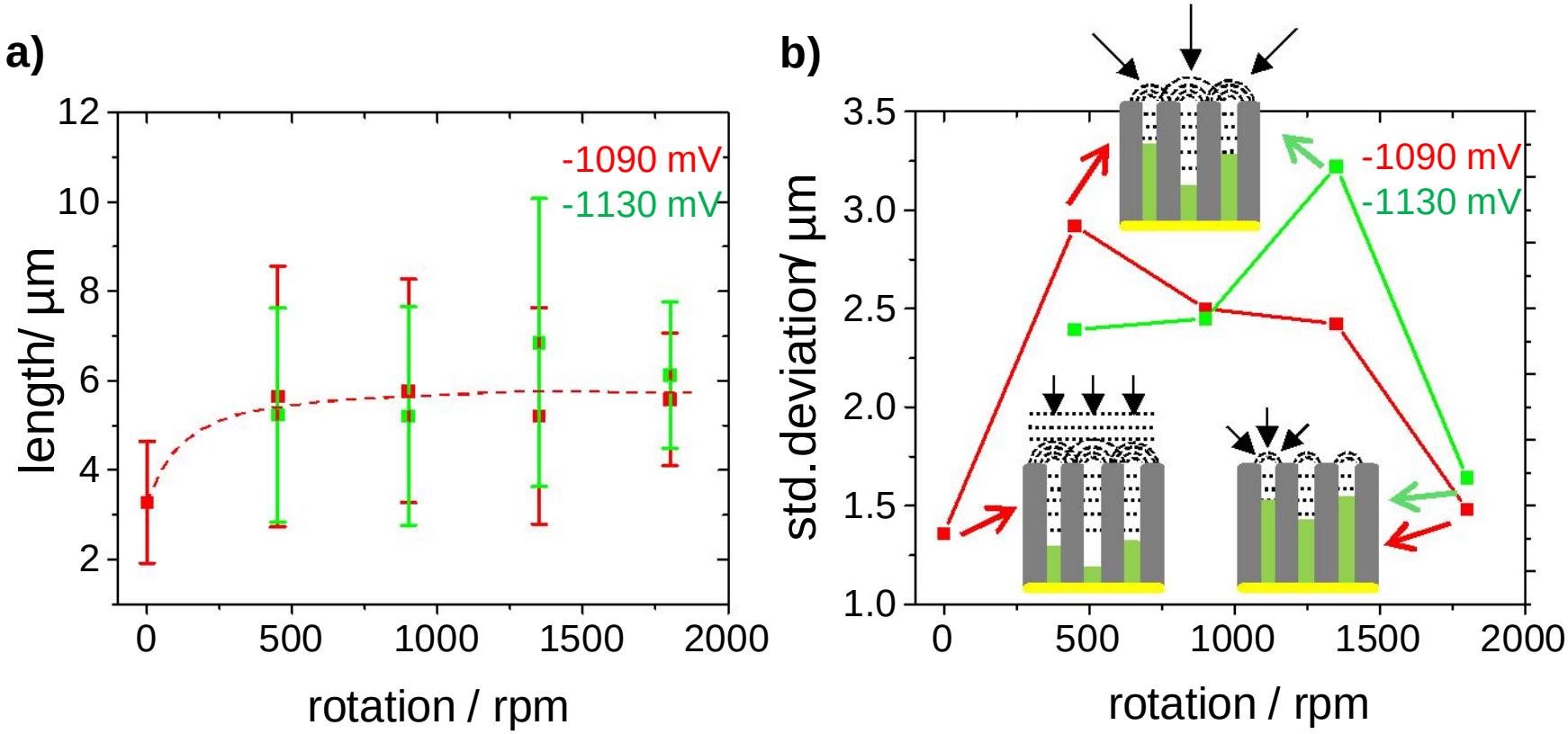
other wires

Why are few wires so long?





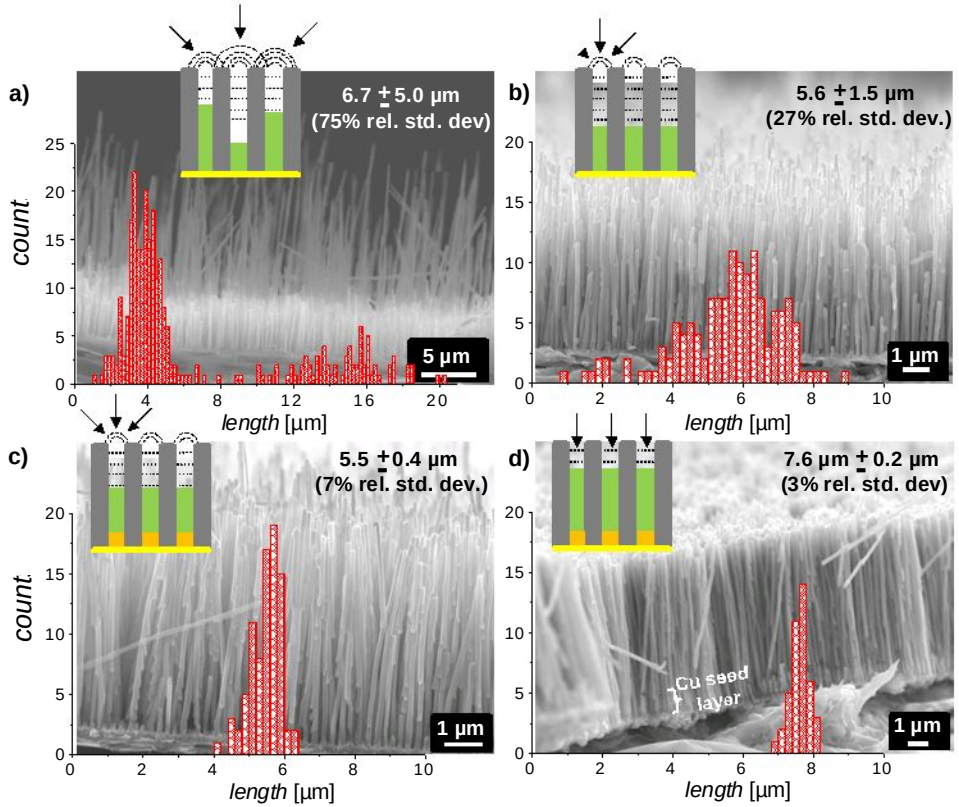
Rotating Electrode contols length distribution



High and low rotation gives low standard dev, but low rotation also has slow mass transfer

Repeatability of Nanowire Dimensions

No optimization

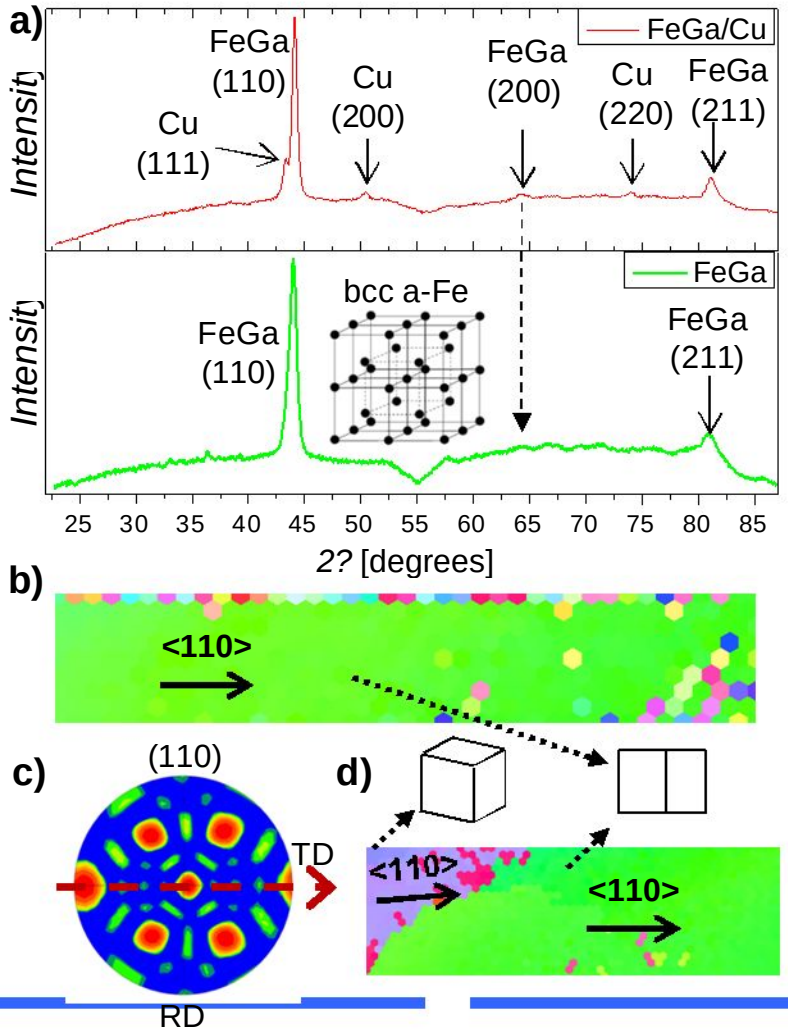


rotation

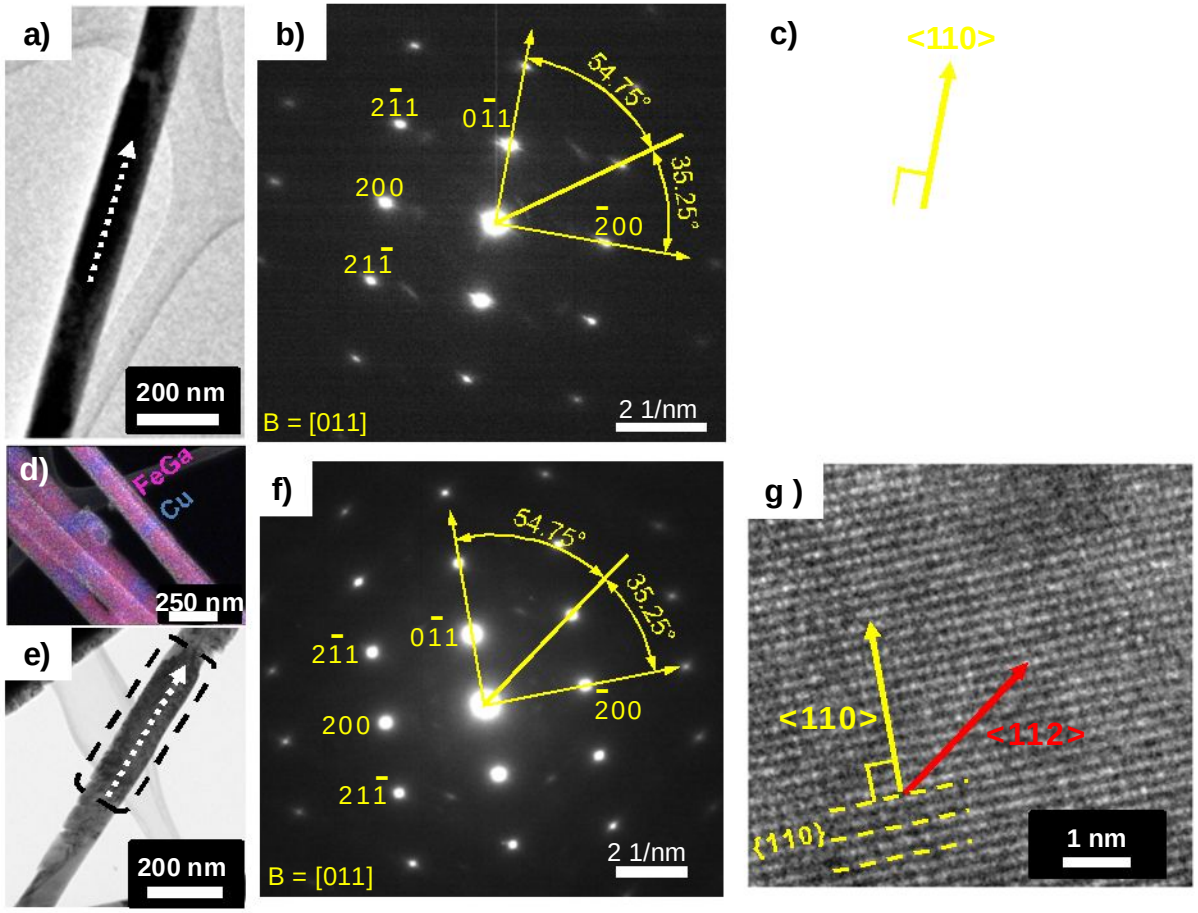
Cu seed layer

pulsed

High Quality FeGa (Galfenol) structure

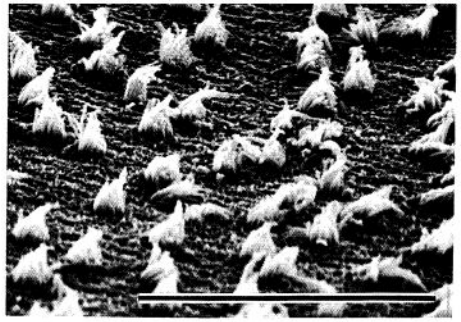


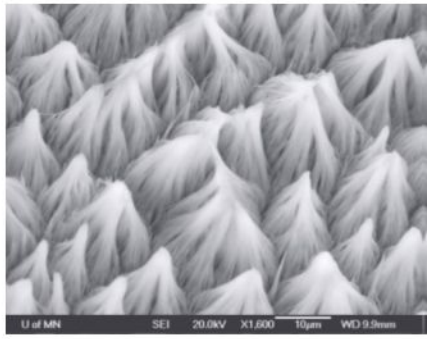
TEM confirms XRD



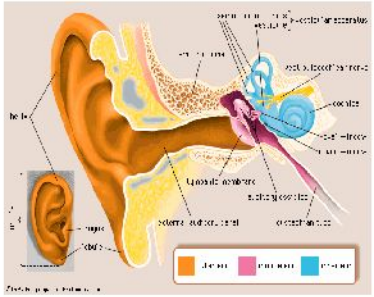
UMD

Outine

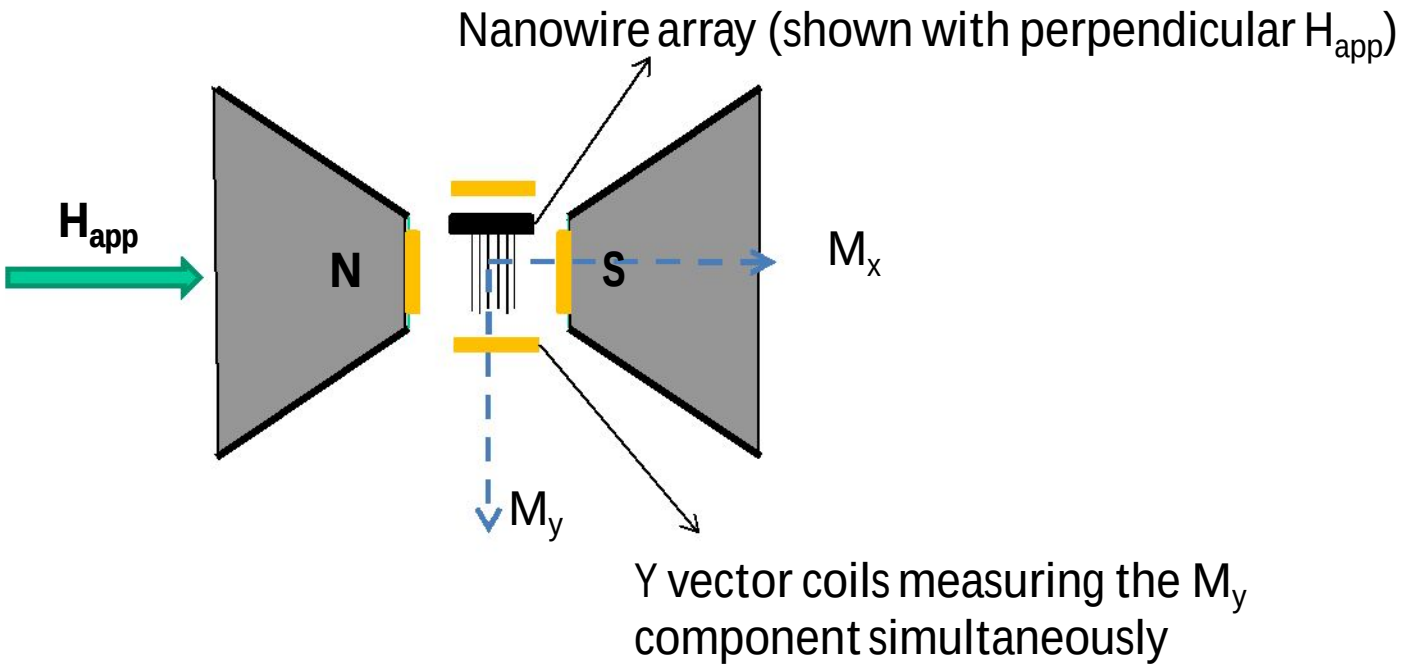




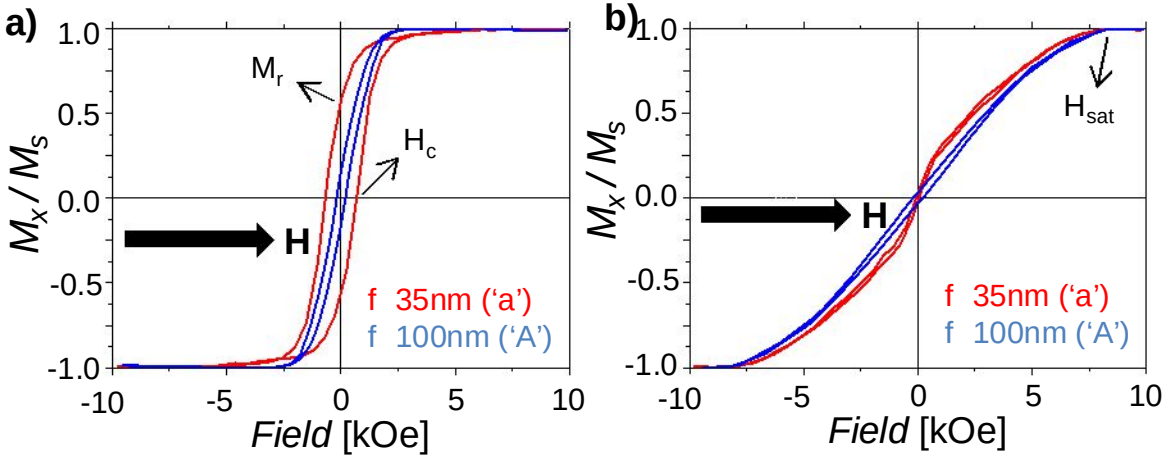
- Motivation: Artifical Cilia
- Magnetostrictive Galfenol
- Measuring Magnetic Multilayers
- Applications: flow and vibration sensing



Magnetic Characterization



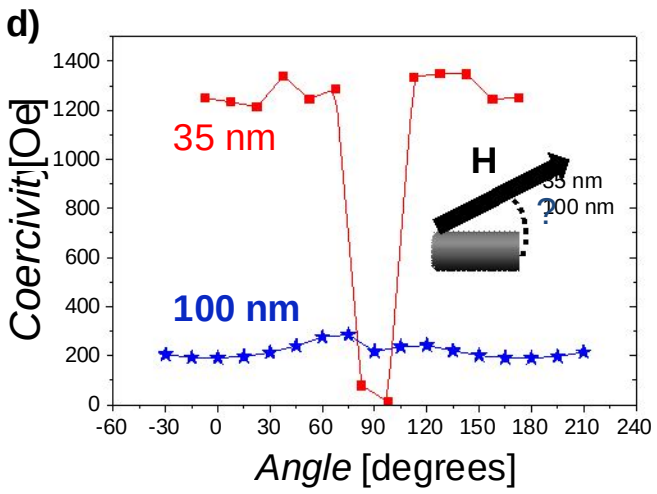
Barcode wires have easy axes along wire axes



c)

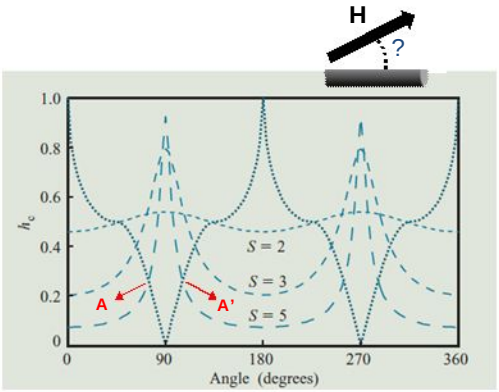
CR T C V

Cross-section of vortex domain wall

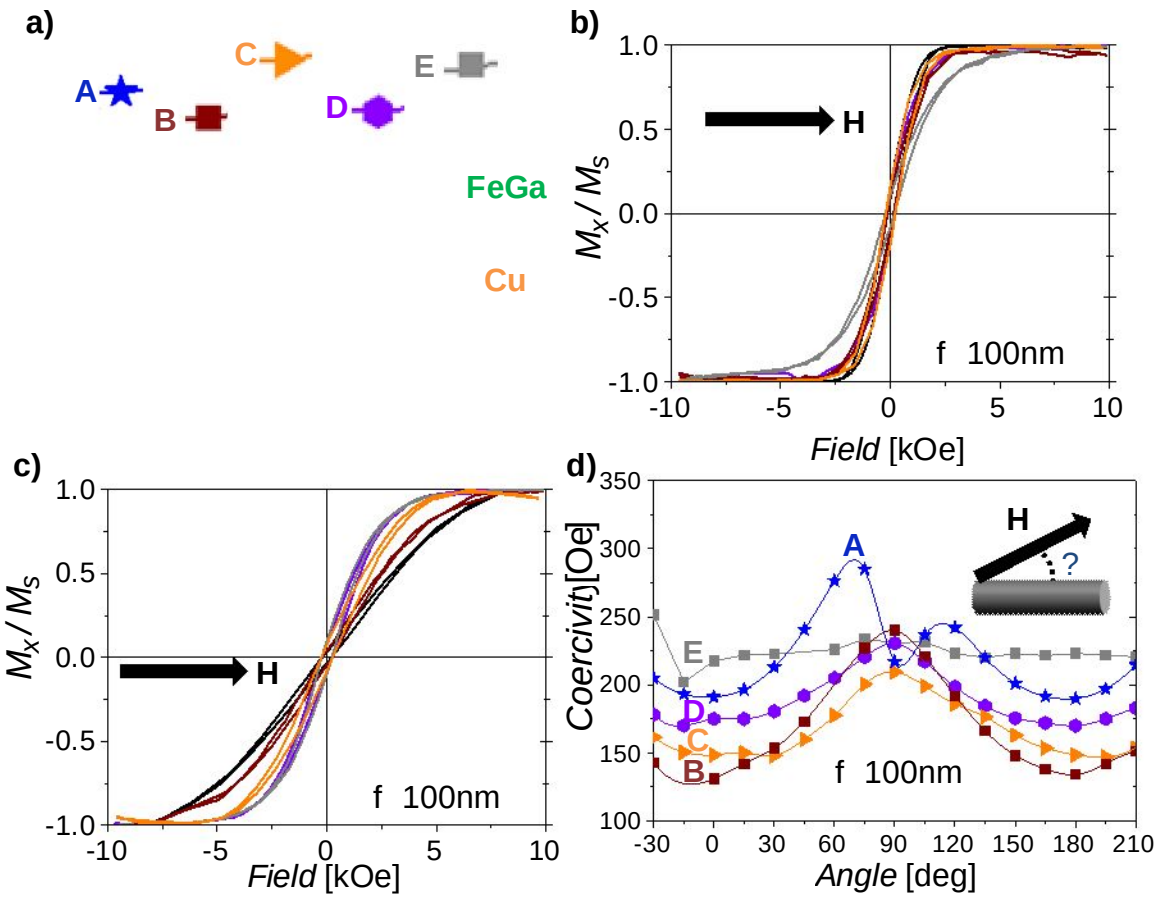


It has been theoretically predicted that at low applied field angles, small diameter nanowires undergo reversal by T mode, whereas larger diameter nanowires undergo reversal by V mode.

However, at applied field angles approaching 90°, CR mode is preferred.



Vary segment lengths for best magnetic control



A: [> 25 AR^{FeGa}]

B: [4.0 AR^{FeGa} / 0.5 AR^{Cu}]$_{29}$

C: [3.0 AR^{FeGa} / 3.0 ARCu]$_{8}$

D: [1.0 AR^{FeGa} / 1.0 ARCu]$_{15}$

E: [0.5 AR^{FeGa} / 5.0 ARCu]$_{50}$

AR = aspect ratio = length/diameter
subscripts denote number bilayers

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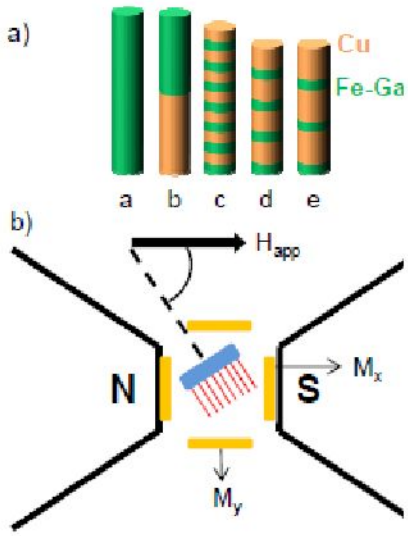
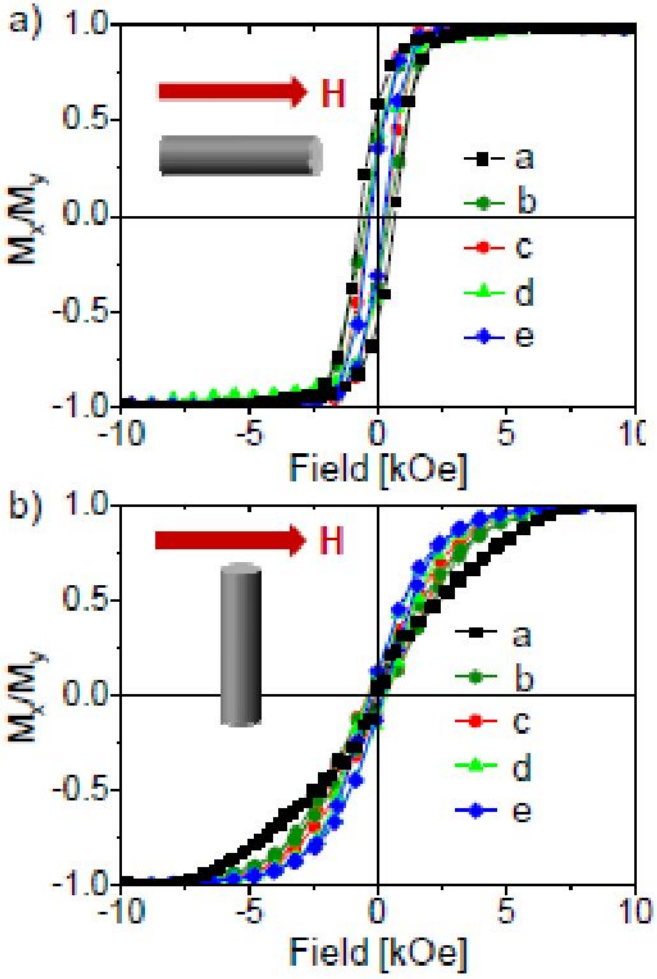
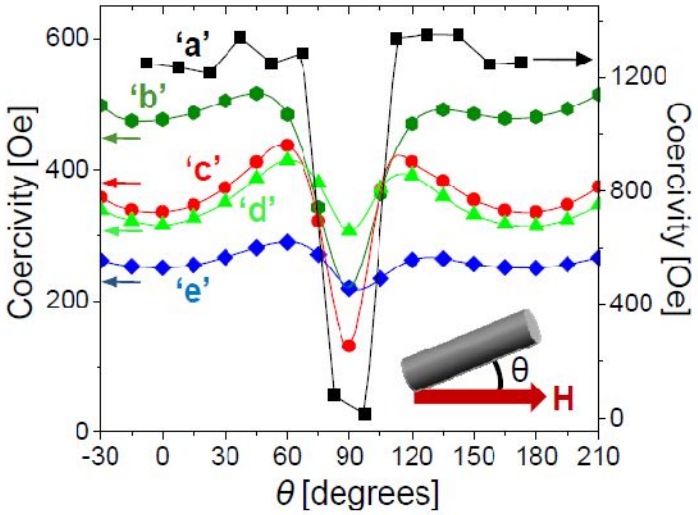
The ratio of the lengths of FeGa and Cu segments determined the curvature of the bell curves: the smaller the ratio, the flatter the curve

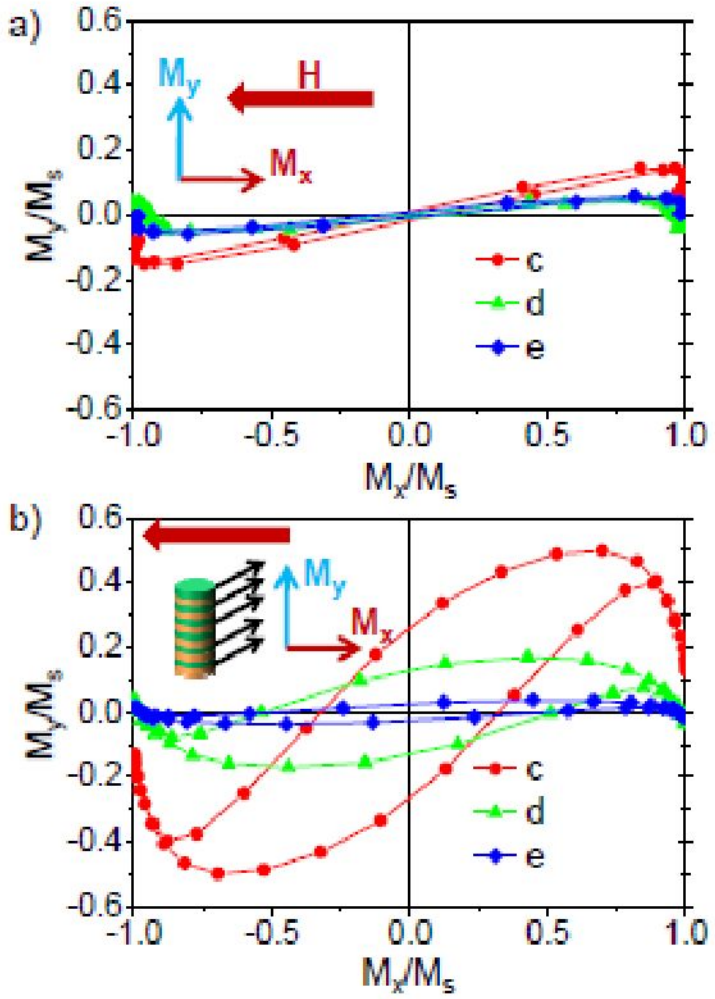

a)
Cu
Fe-Ga
a b c d e
b)
H_{app}
N
S
M_x
M_y


a)
H
a
b
c
d
e
M_x/M_y
Field [kOe]
b)
H
a
b
c
d
e
M_x/M_y
Field [kOe]


'a'
'b'
'c'
'd'
'e'
θ
H
Coercivity [Oe]
Coercivity [Oe]
θ [degrees]

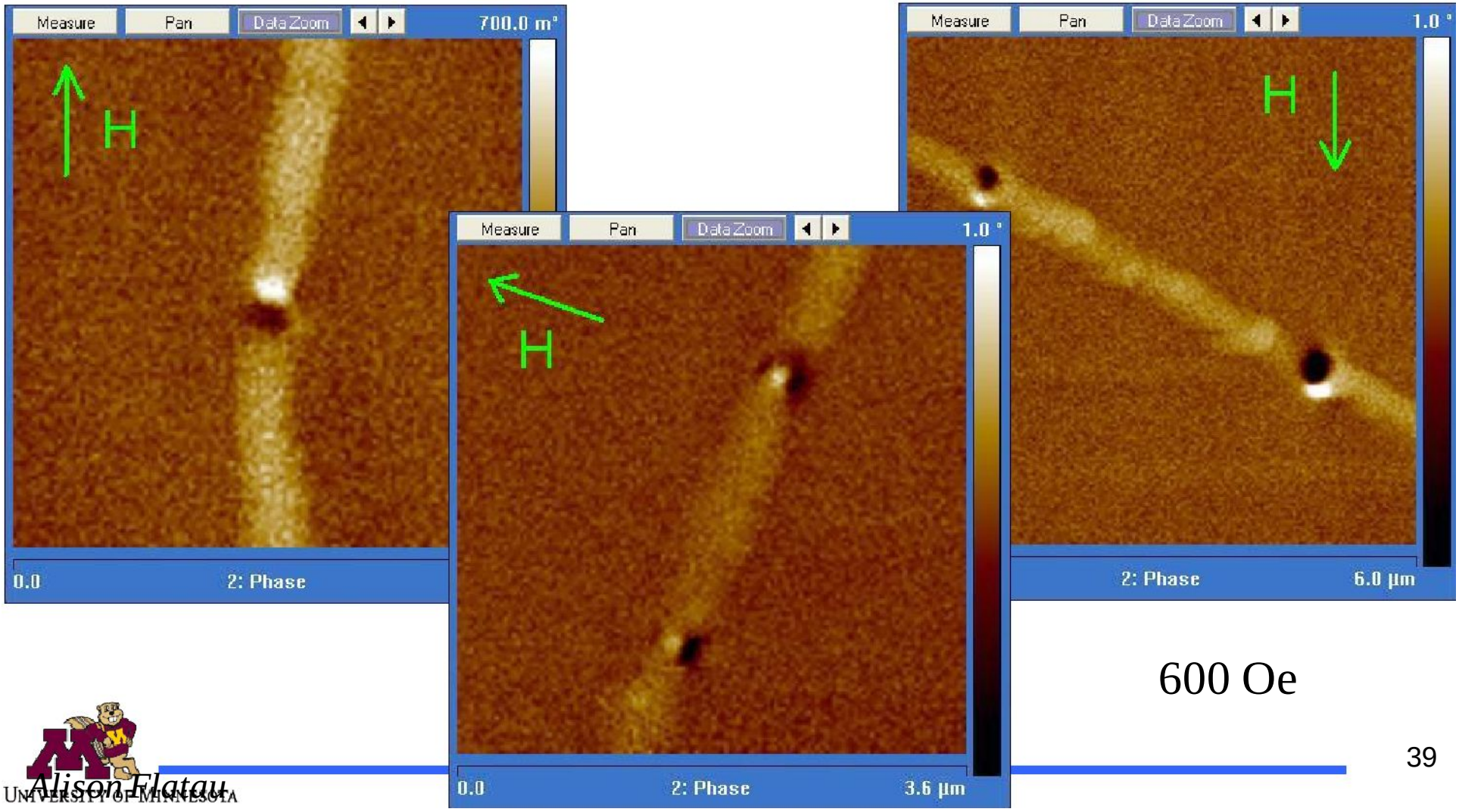
Vector VSM

M_y - M_x plots for
(a) Parallel
(b) perpendicular applied fields:
shows the cooperative rotation of moments in adjacent Fe-Ga segments.



MFM Results Show Moment Rotation- UMD

150nm x 150 nm FeGa separated by 4-6um Cu



600 Oe

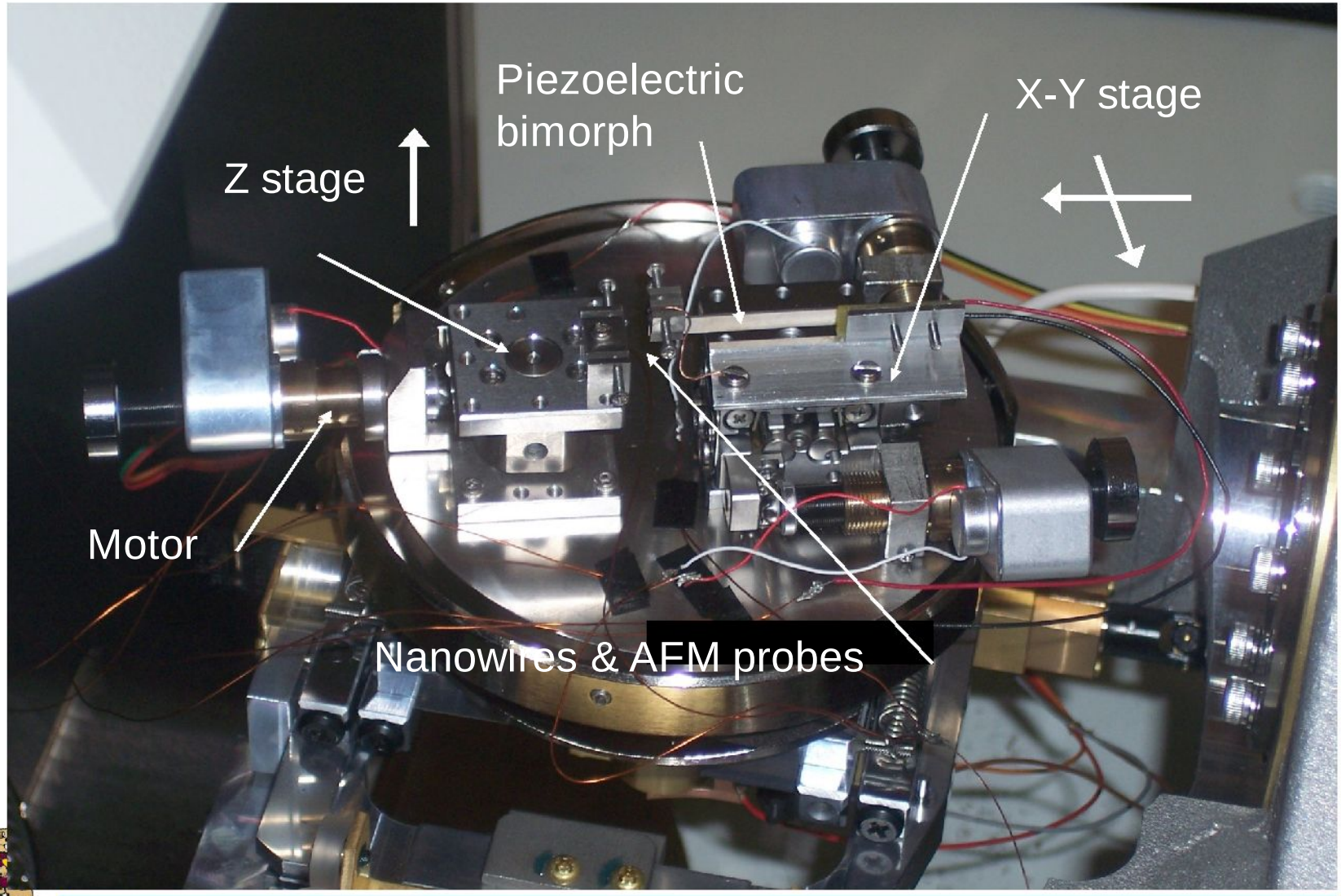
Magnetizaton Rotation- UMD

Vary Field

Vary Angle

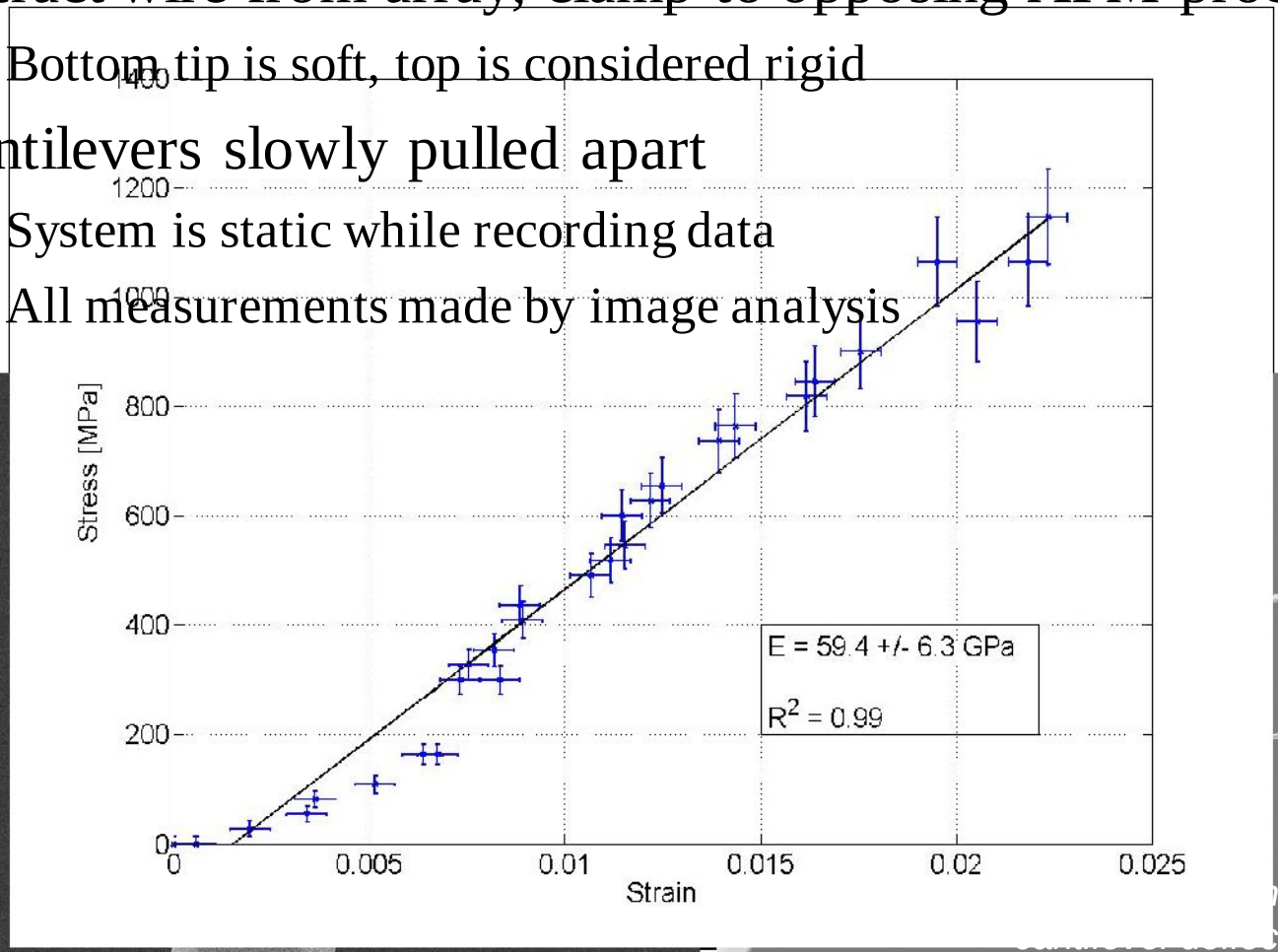
550 Oe

Manipulator Stage for Mechanical Testing- UMD



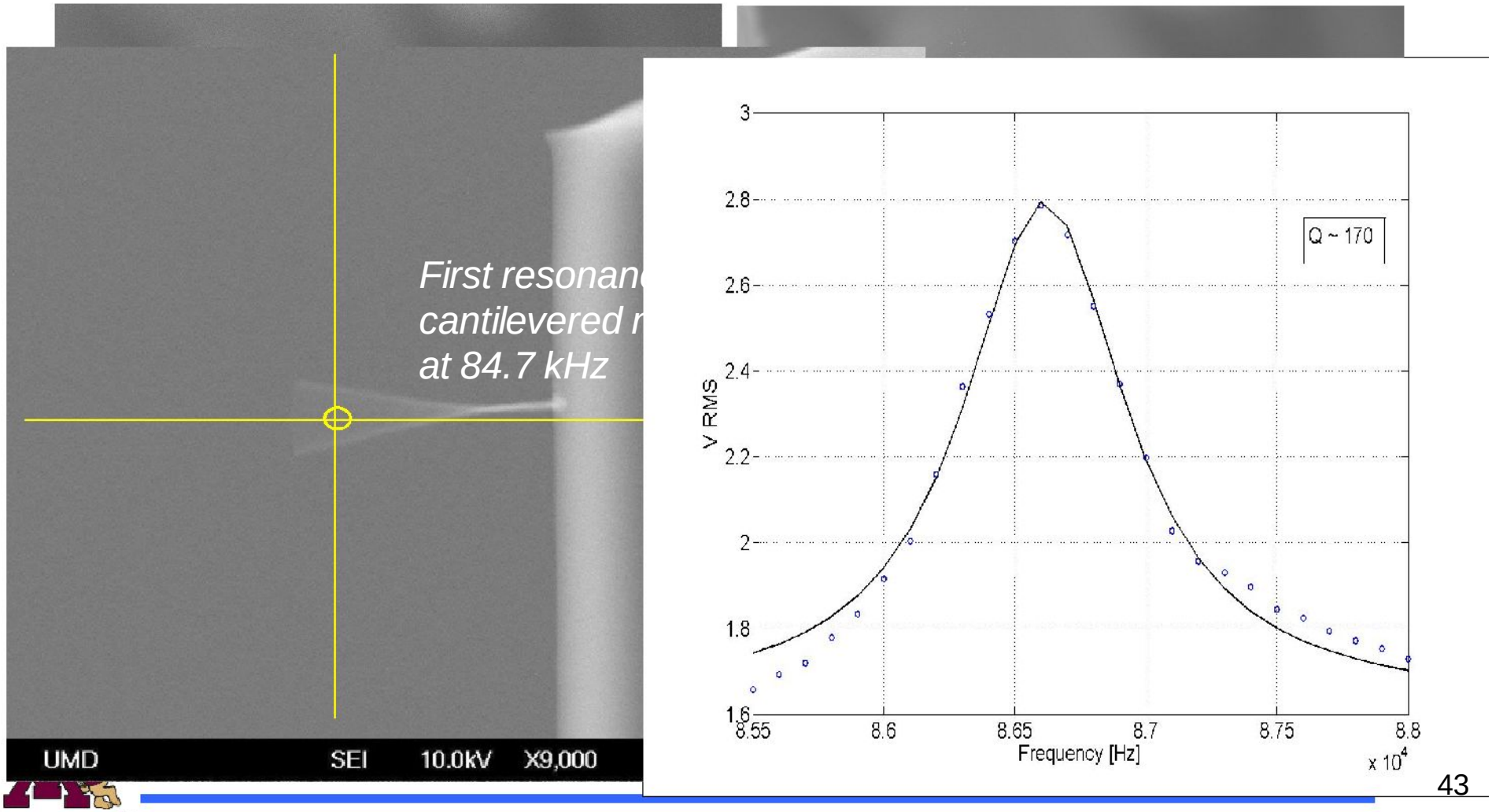
Tensile Procedure

- Extract wire from array, clamp to opposing AFM probes
  - Bottom tip is soft, top is considered rigid
- Cantilevers slowly pulled apart
  - System is static while recording data
  - All measurements made by image analysis



…e soft AFM …cts upward

Measuring Resonance



Bimodal Distributions are not always undesirable!

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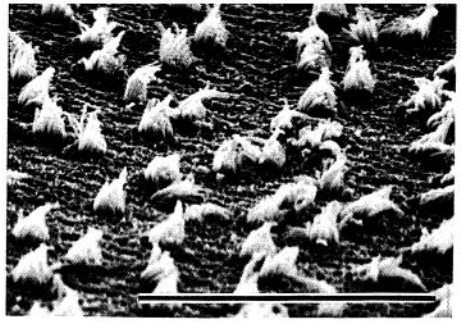
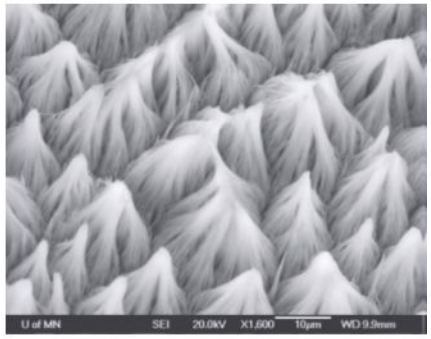
Outine





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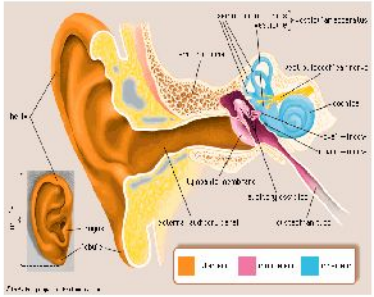

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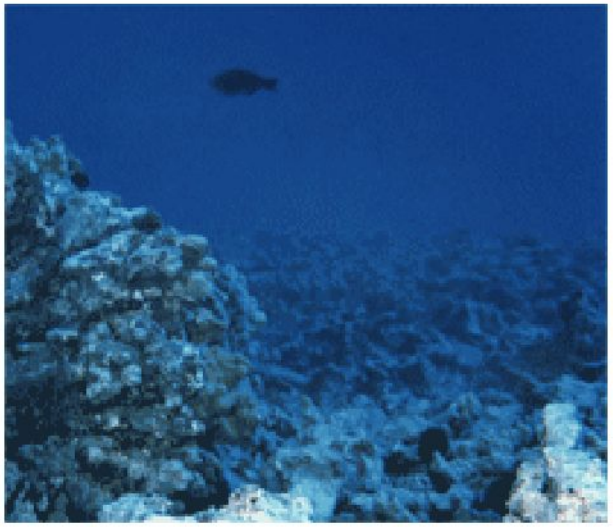
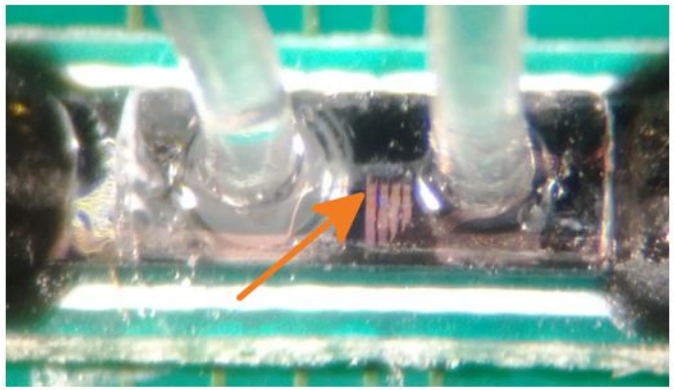
Underwater cilia

- How fish “hear”
- How we hear fish
  - Piezoelectric membrane arrays

MassaProduct



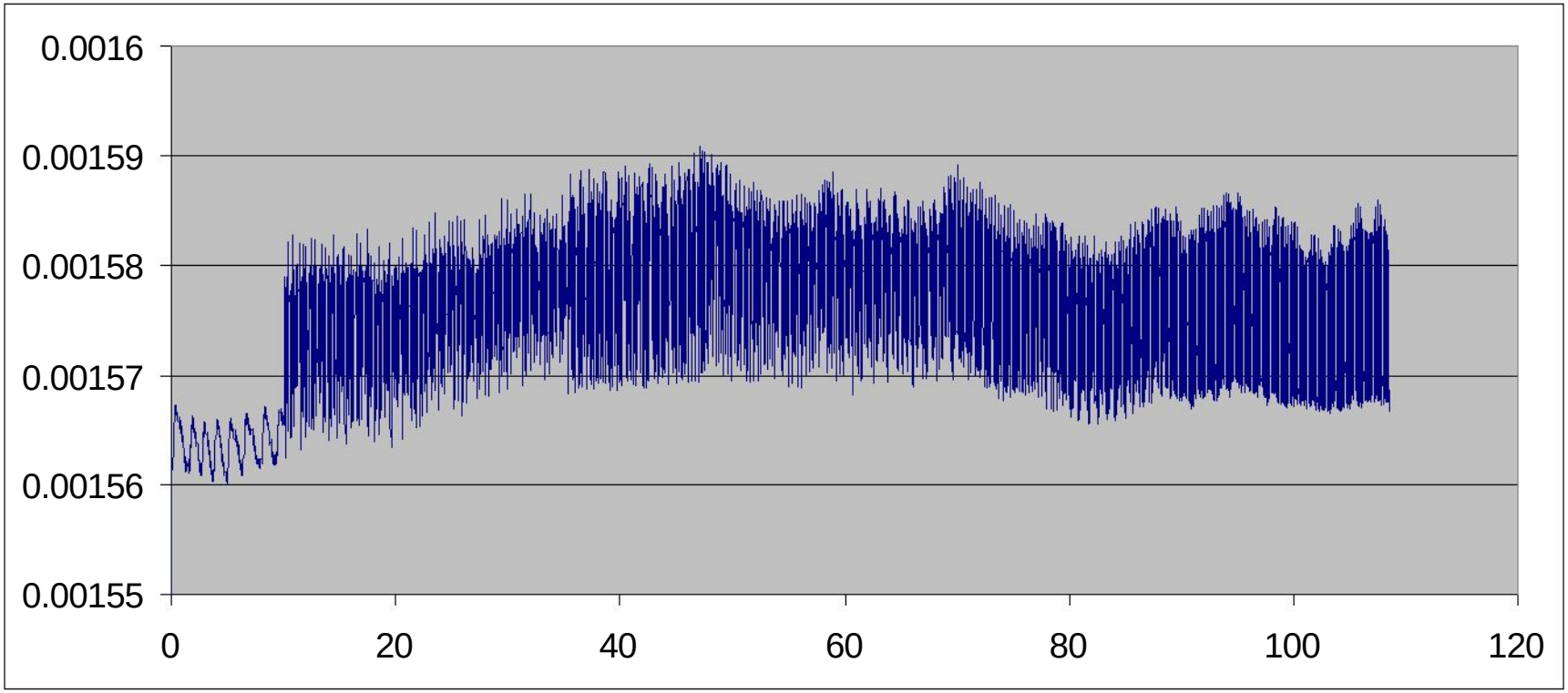
Initial Flow and Vibration Sensors



Microfluidic channels from Diagnostic Biosensors

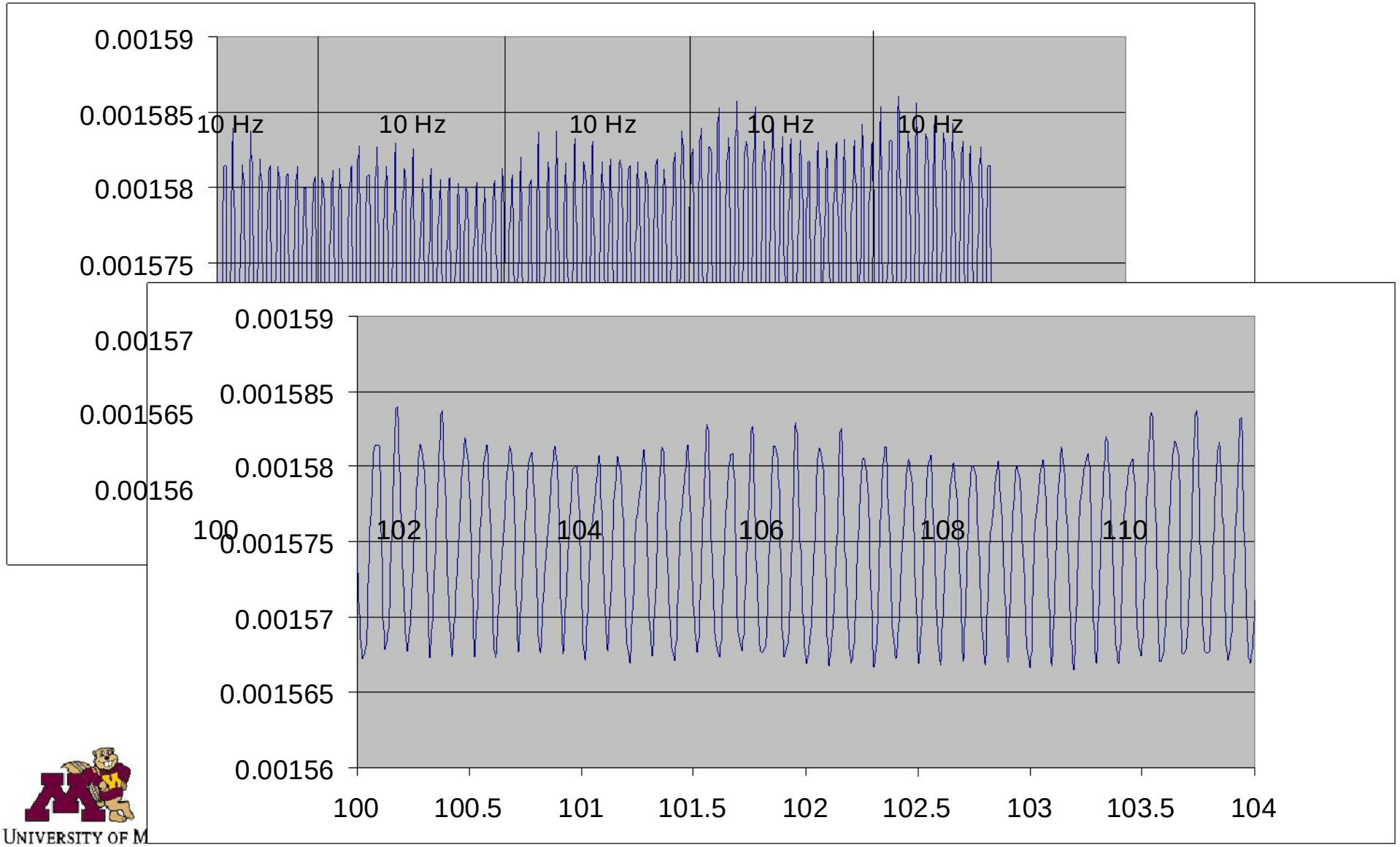
Vibration: Shake Table

GMR signal



Time (sec) Vibrations from 1Hz to 5Hz

5Hz Excitation



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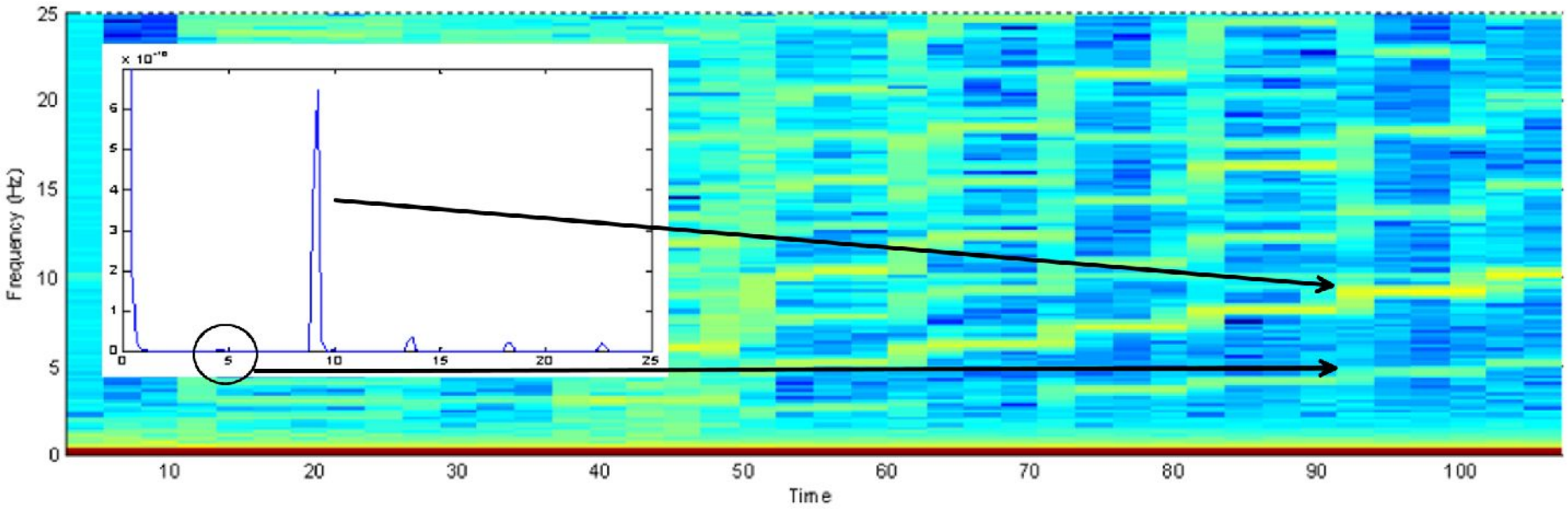
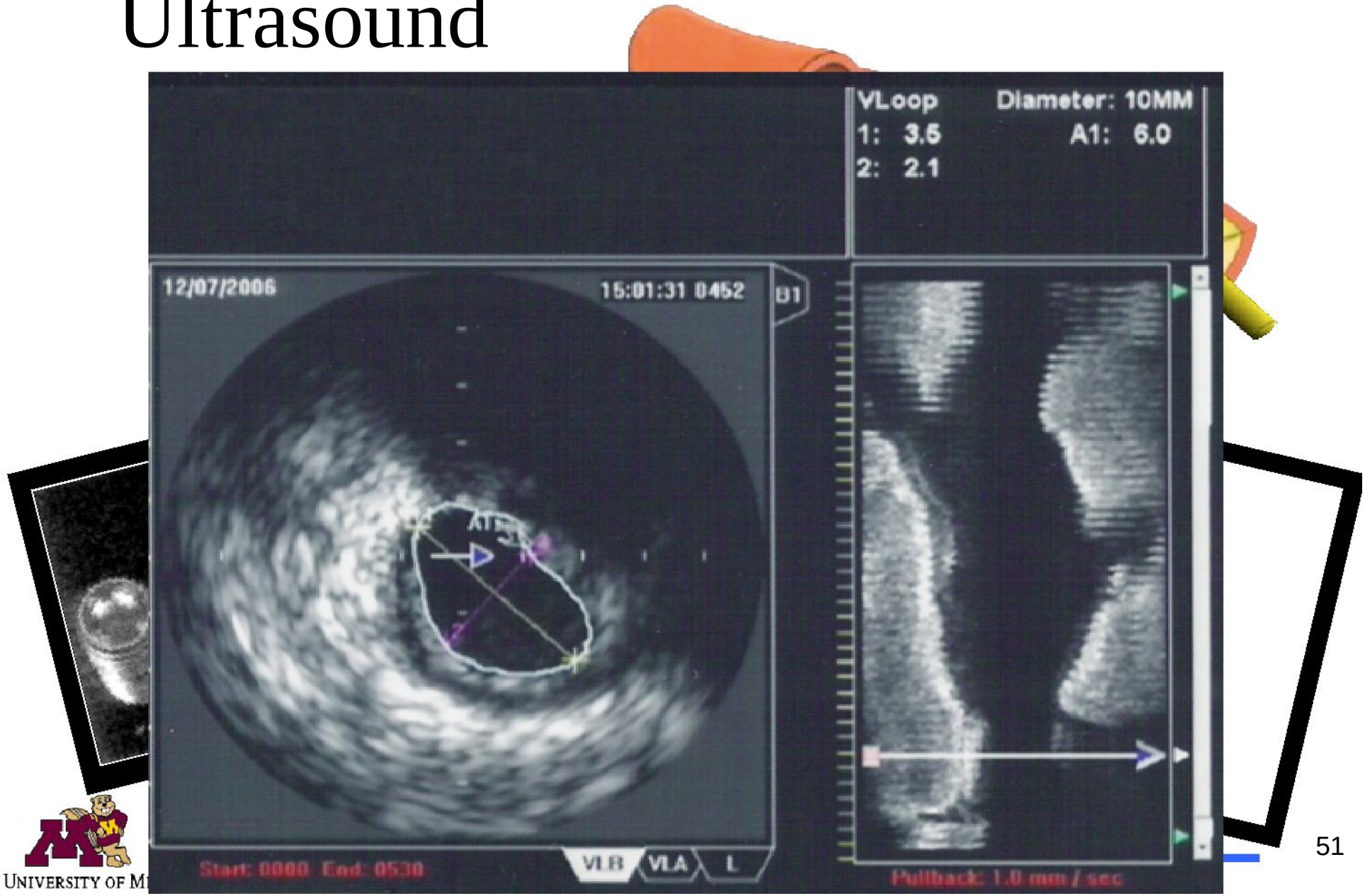
Characteristic Double Frequency

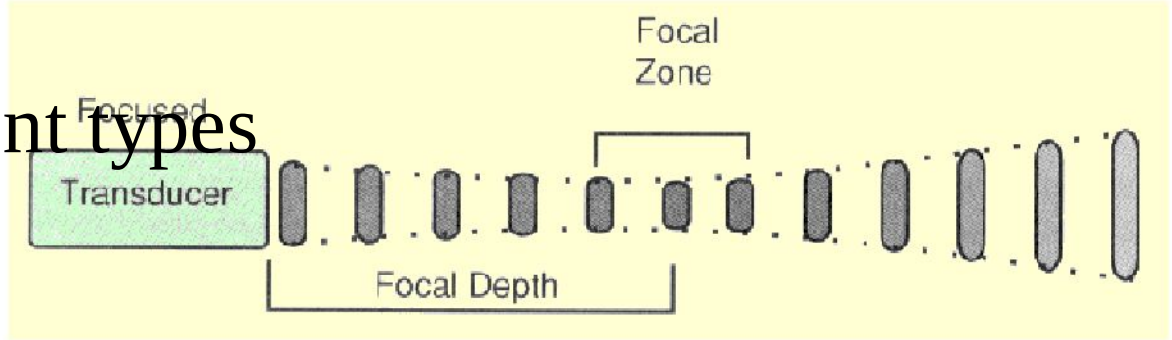


Only seen with nanowires under the GMR sensor, not in controls

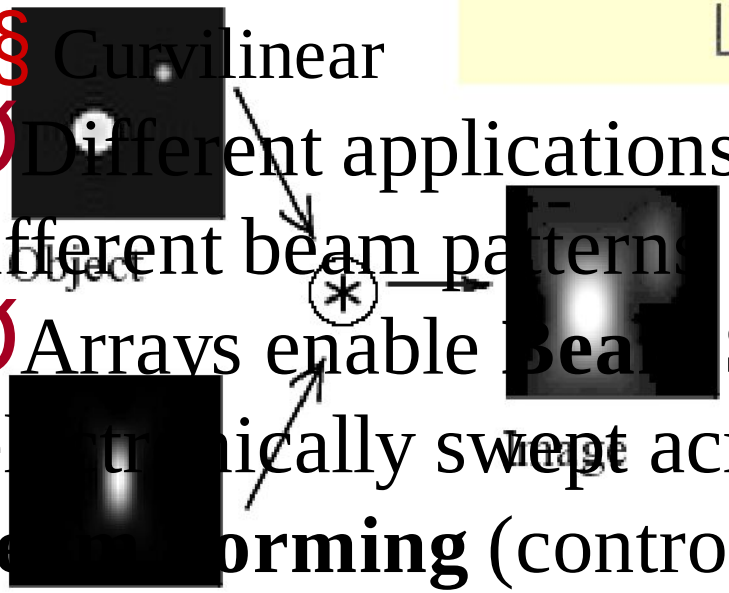
Ultrasound


VLoop
Diameter: 10MM
1: 3.5
A1: 6.0
2: 2.1
12/07/2006
15:01:31 0452
B1
Start: 0000 End: 0530
VLB
VLA
L
Pullback: 1.0 mm / sec

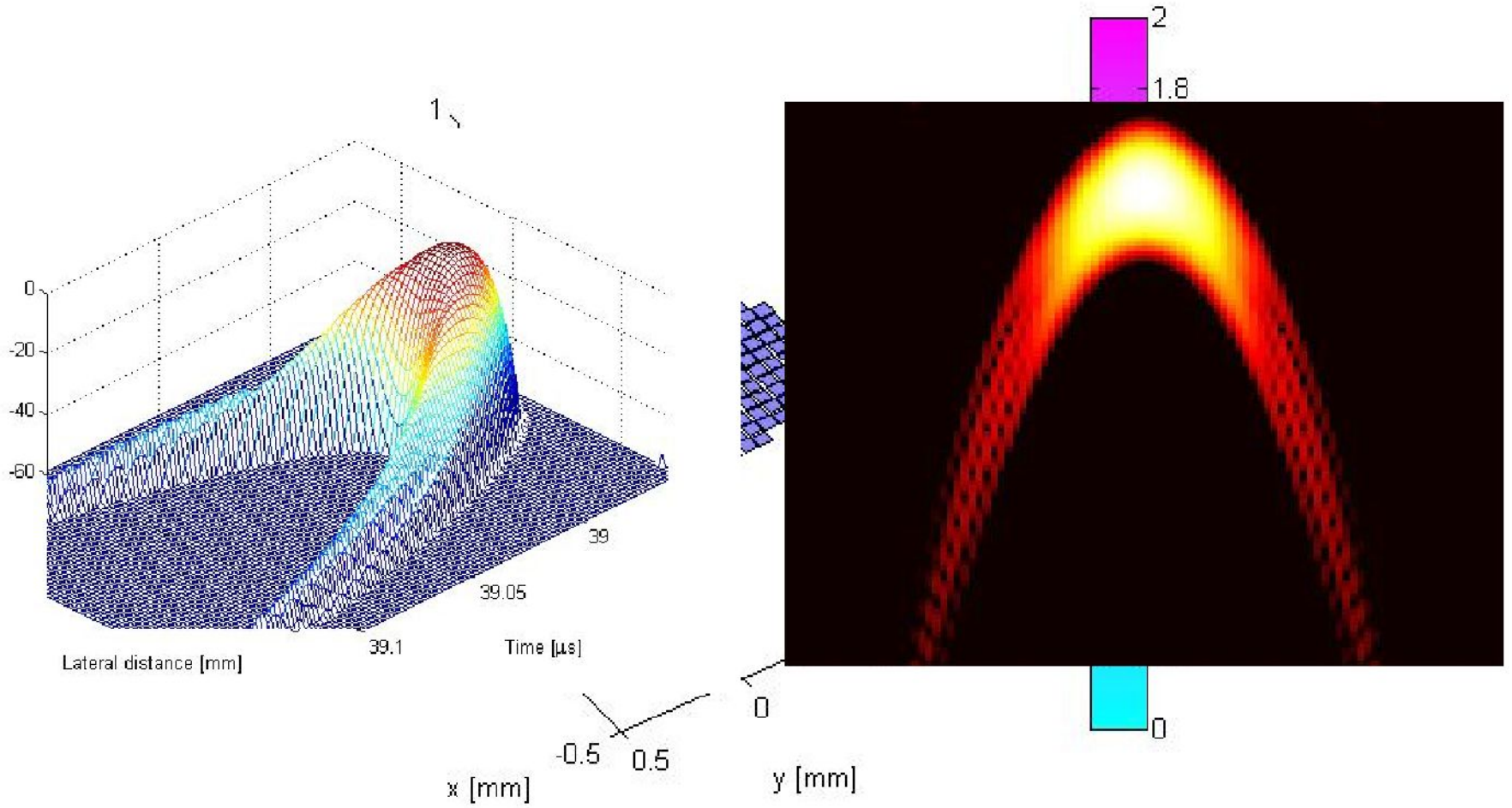
Ultrasound Transducer Arrays



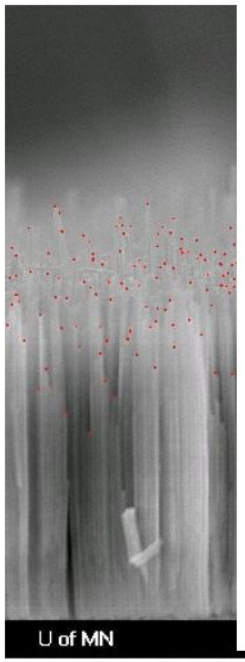
- Many different types
  - Linear
  - Curvilinear
- Different applications, different beam patterns
- Arrays enable **Beam Steering** (electronically swept across imaged field) and **Beamforming** (control of focal distance and beam width)

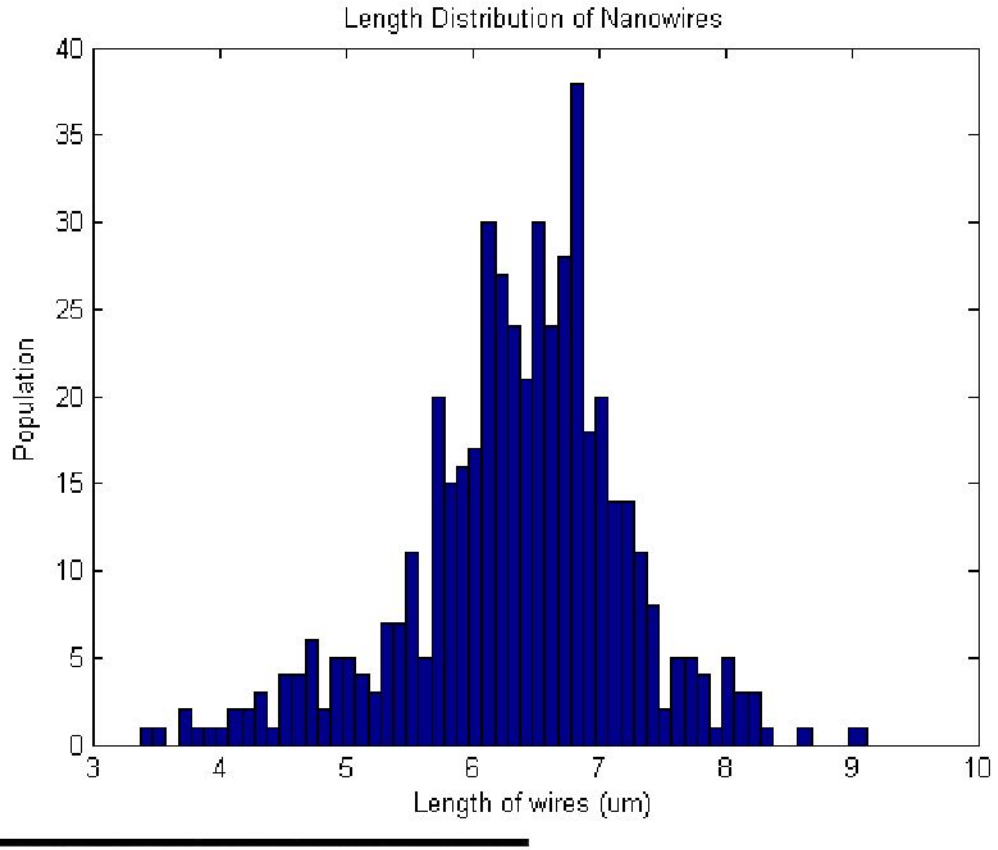


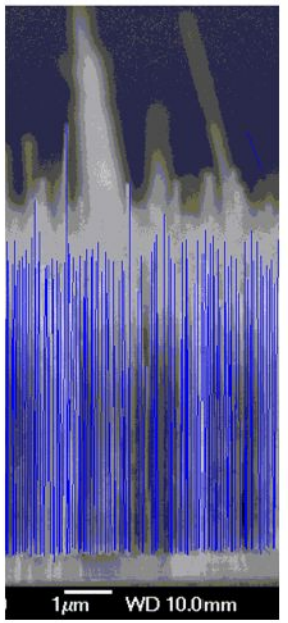
Linear vs Areal Arrays



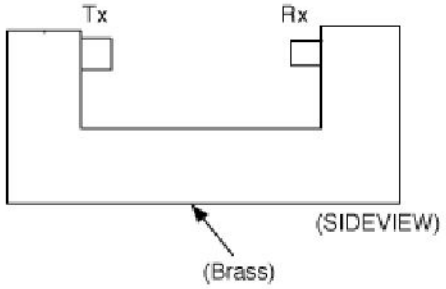
Nanowire Arrays with Broadband Response

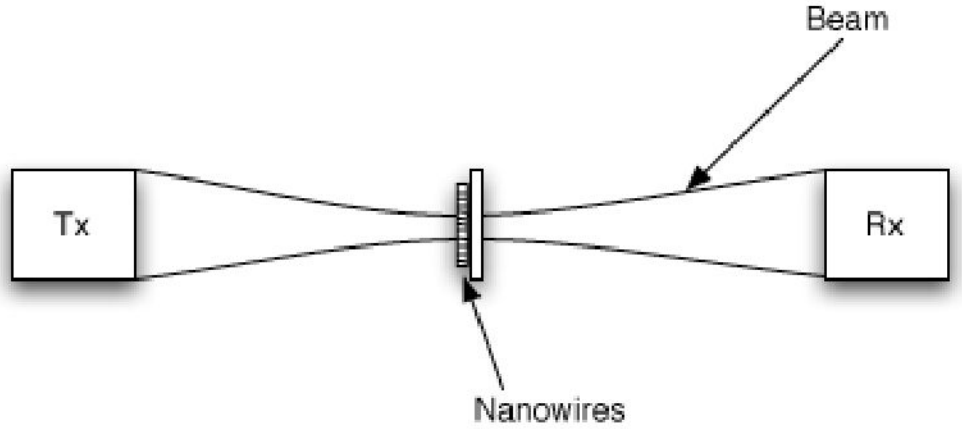


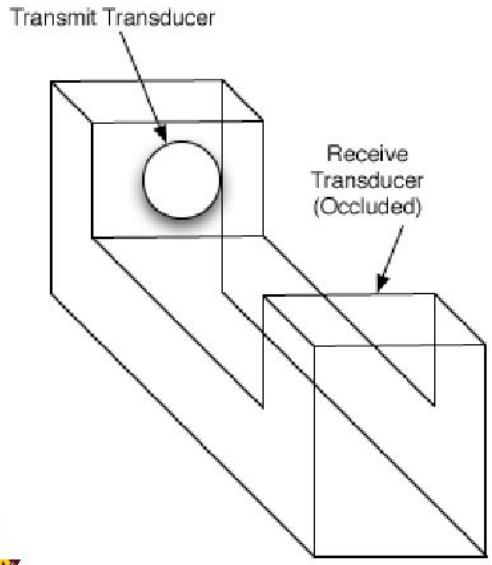


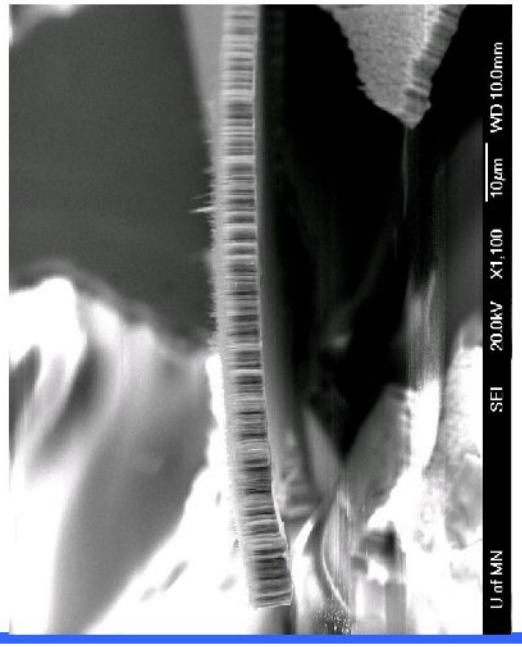


Ultrasound Response Measurement Apparatus

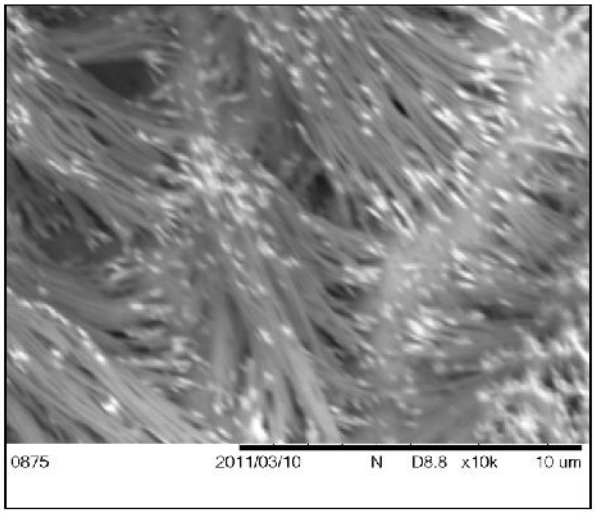


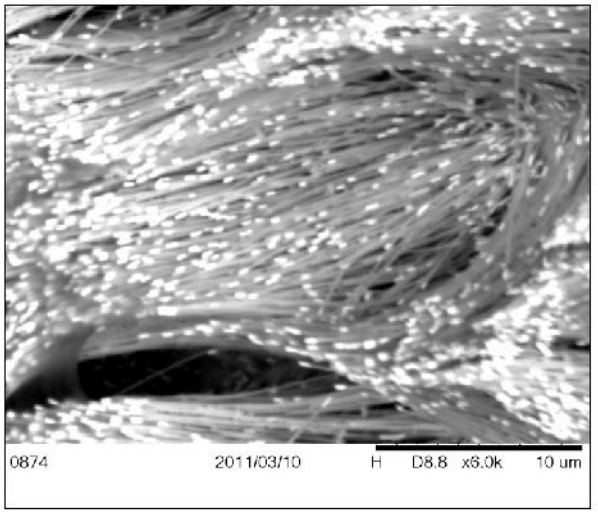


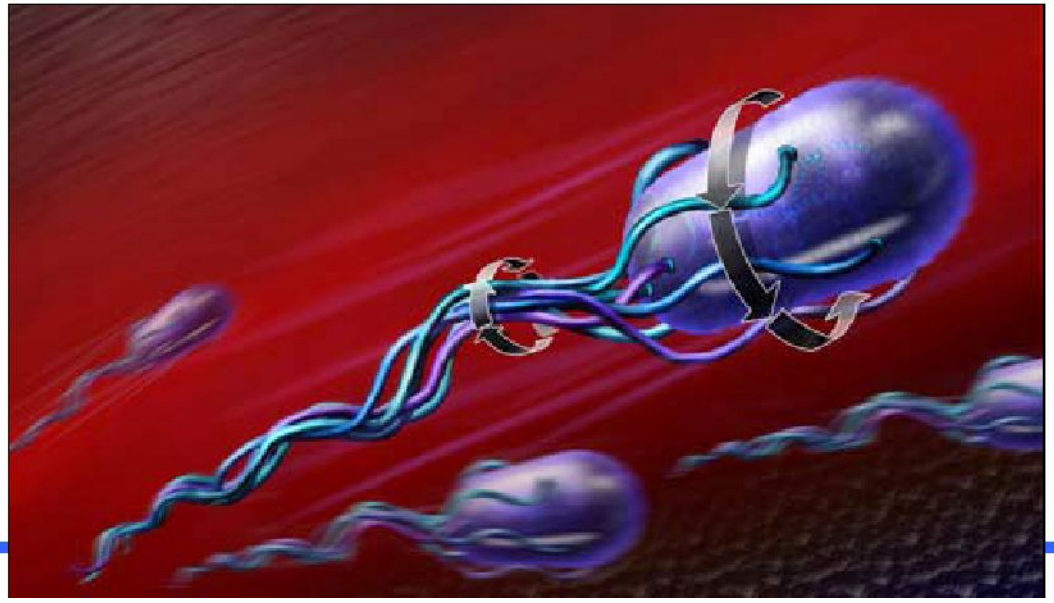




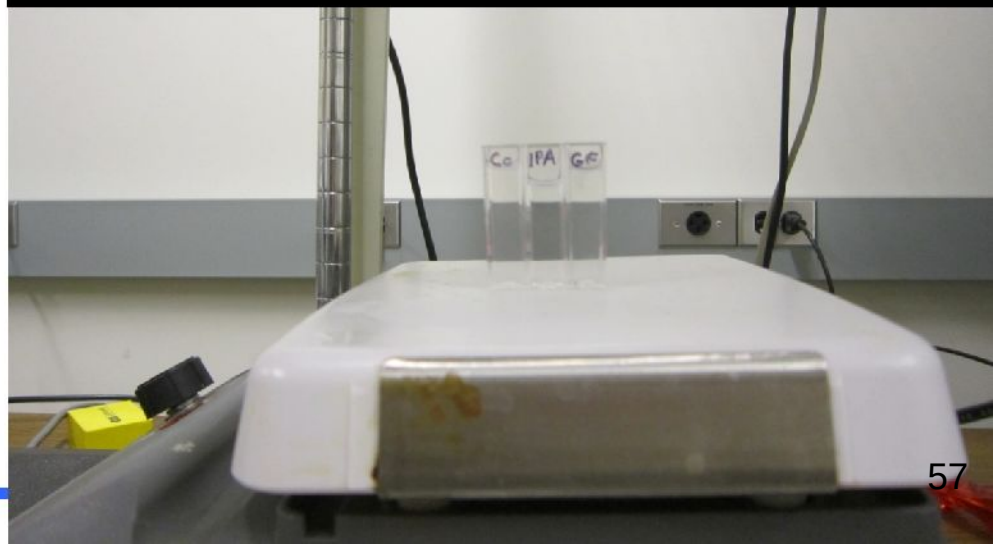
Biomagnetics







Manipulation of Nanowires



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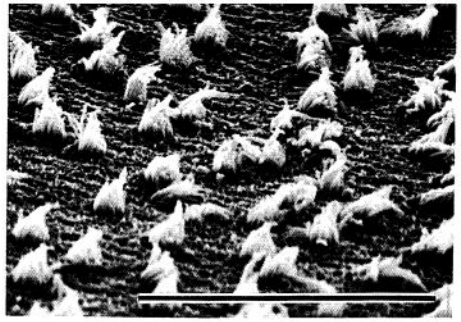
Summary

- Templates with controlled parameters
  - directional anisotropy
  - long range order, large area, small pores
- A Galfenol electroplating
- Promising nanowires for:
  - Magnetic sensors
  - Vibrations sensors
  - Energy harvesting
  - Flow detection
  - Much more

Review



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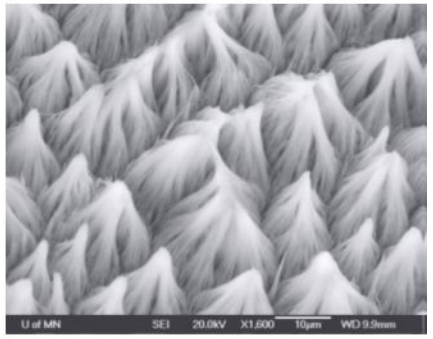
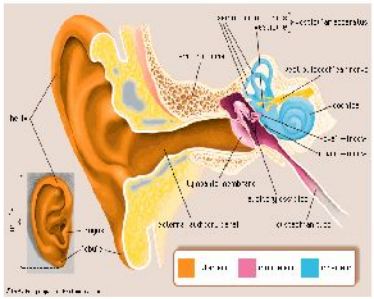
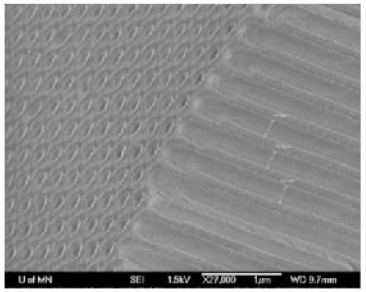
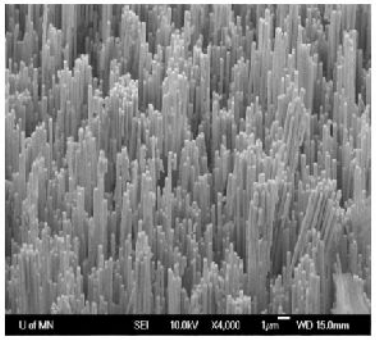


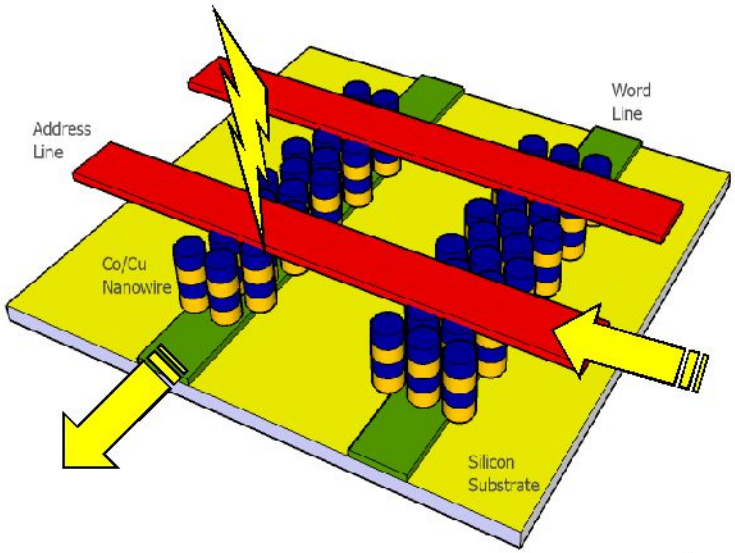


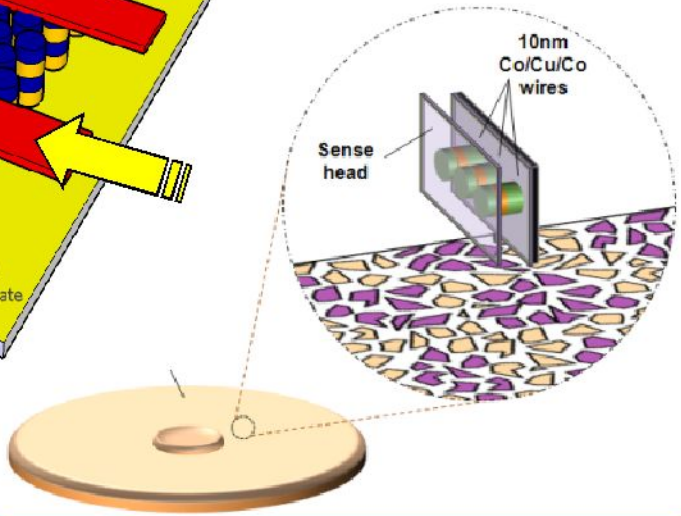
Applications

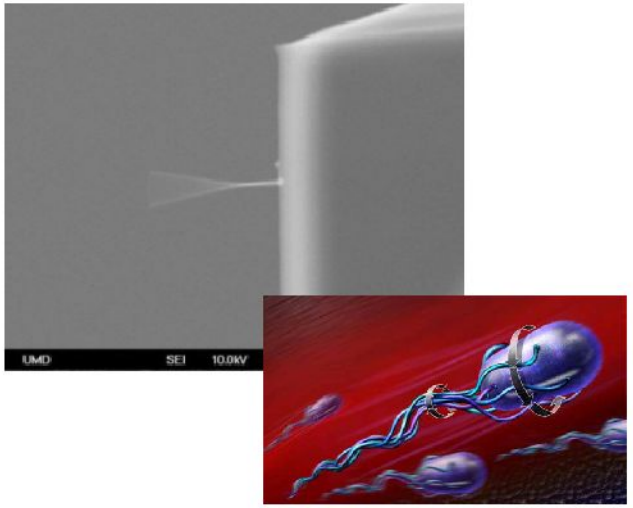
- Recording
  - Read Sensors
  - Bit patterned media (BPM)
- Random Access Memory (RAM)
- Cilia (NEMS)
- Biomagnetics











Acknowledgements

- Marilyn Wun-Fogle, Jim Restorff, Norris Lindsey

  NSWC Carderock Division

- Jan Lindberg, Office of Naval Research #N000140310953 and #N000140410583 and MURI

- National Science Foundation for grant #CMS0329975.

- University of Minnesota's
  - MRSEC #DMR0212302
  - NNIN

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