Structural Magnetostrictive Alloys:

From Flexible Sensors to Energy Harvesters and Magnetically Controlled Auxetics

<u>Prof. Alison Flatau & MANY OTHERS!!!</u>

Magnetostrictive Materials Group
Department of Aerospace Engineering
University of Maryland, College Park

Primary Research Sponsors: ONR, NSF, DARPA, DOT, State of Maryland

CEMAG - Gijón Spain - 11/30/2018

IEEE Magnetics Society

- **IEEE Magnetics Society Home Page: www.ieeemagnetics.org**
  - 3000+ full members
  - 300 student members
- **The Society**
  - Conference organization (INTERMAG, MMM, TMRC, etc.
  - Student support for conferences
  - Large conference discounts for members
  - Graduate Student Summer Schools (June 3-8, 2018 Quito, Ecuador)
  - Local chapter activities
  - Distinguished lecturers
- **Journals (Free Electronic Access for Members**
  - IEEE Transactions on Magnetics
  - IEEE Magnetics Letters
- **Online Application for IEEE Membership: www.ieee.org/join**
  - 360,000+ members
  - IEEE student membership - IEEE full membership

Outline

Intro to Magnetostriction

- **Actuators: the “direct” effect**
- **Sensors: the “inverse” (or Villari) effect**

Structural Magnetostrictive Alloys

- **Magnetostrictive, magnetic & mechanical properties**
- **Thin, highly textured rolled sheet**
- **Introduction to auxetic behavior**

Applications that use Galfenol and/or Alfenol

- **Bending sensor applications**
- **Implantable wireless bone fixity sensor (Tech Univ. Dresden)**
- **Nanowire sensors (Univ. Minn. & UMD)**
- **Applications for auxeticity?**
- **Micro-motors (Kanazawa University, Japan)**
- **Energy Harvesting (Kanazawa Univ, UMD & Techno Sciences, Inc., Oscilla Power)**

Summary

What is Magnetostriction?

IEEE MAGNETICS

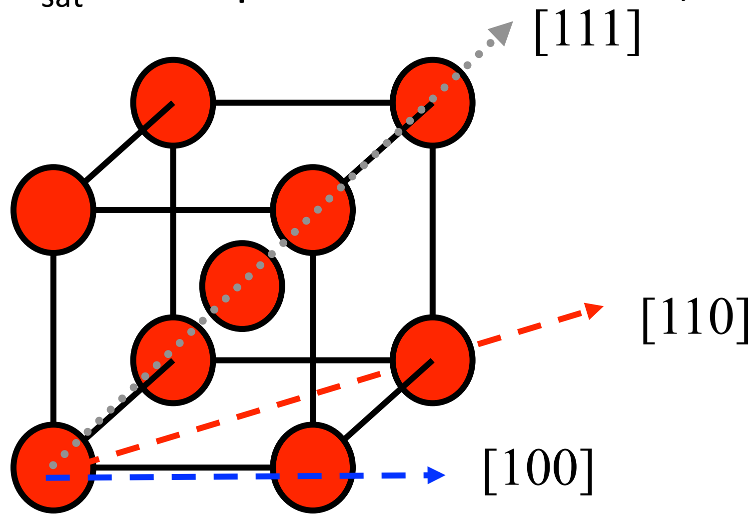
"A change in dimensions exhibited by ferromagnetic materials when subjected to a magnetic field." *(Random House Dictionary)*

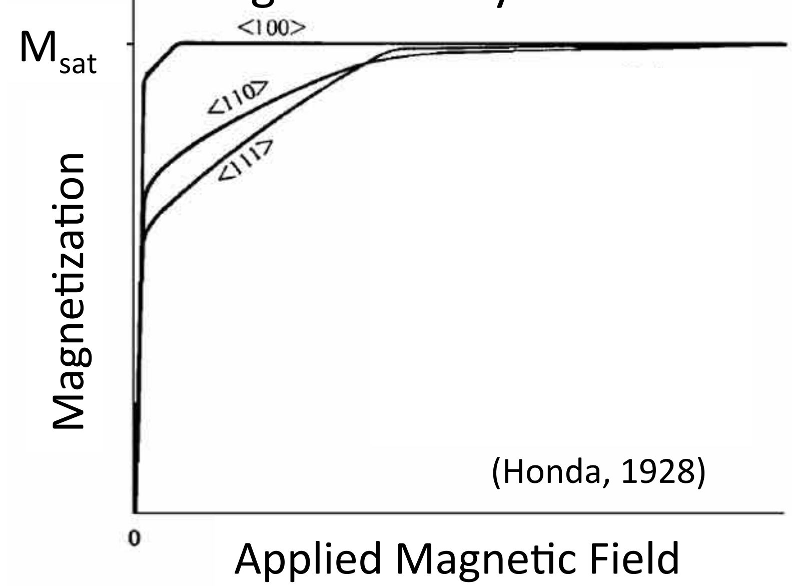
- 1st documented by James Joule in 1842. – Attribute of iron, nickel, and other ferromagnetic metals
- Effect will not "de-pole"
- Above Curie temperature (~750°C for Fe-Ga alloys) domain ordering vanishes, but order returns when cooled below Curie temperature.

What Produces Magnetostriction?

Magnetostriction arises from magnetic-field induced changes in crystal structure

- **Reorientation of electron spins to align fields with an externally applied magnetic field changes inter-atomic spacing** while maintaining conservation of volume.
- Simple body centered cubic structure of Fe has maximum magnetostriction (λ_{sat}) along the <100> directions. ($\lambda_{sat <100>} > \lambda_{sat <110>} > \lambda_{sat <111>}$)
- M_{sat} is independent of direction, but <100> are magnetic “easy” directions.

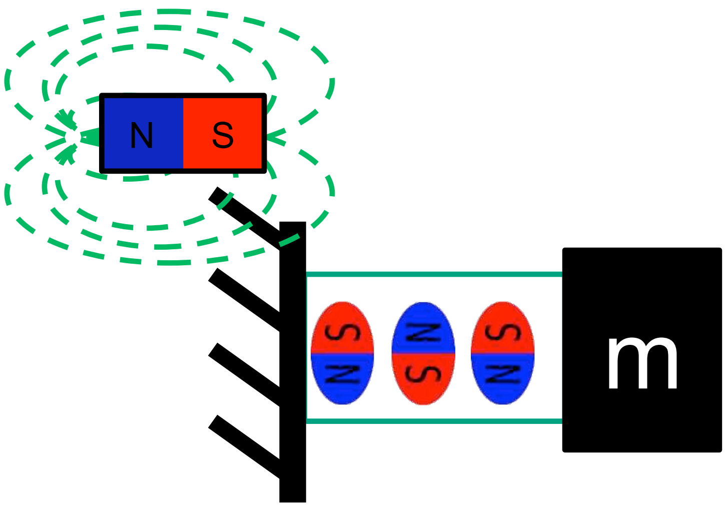




Typical uses for Magnetostriction?

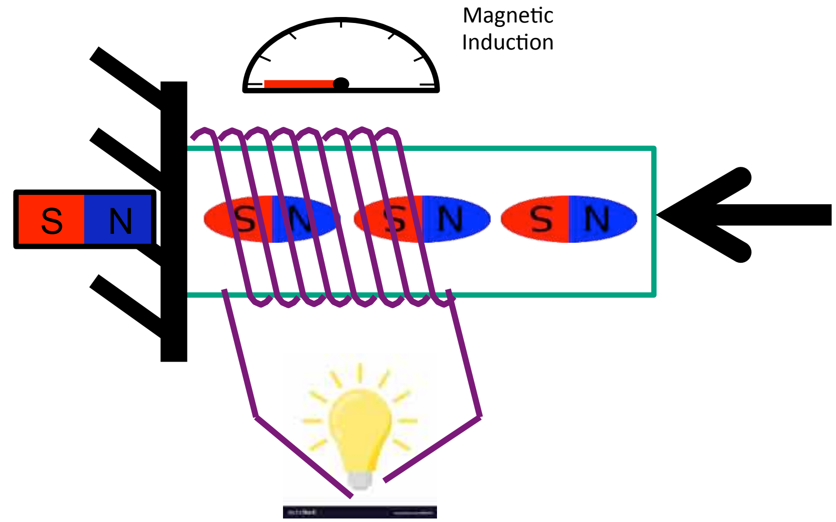
ACTUATION

- Moving a mass
- Producing a force



SENSING & ENERGY HARVESTING

- Detecting motion or strain
- Detecting a force or moment
- Voltage in a surrounding coil proportional to dB/dt



Magnetostriction often modeled using 1-D Linear constitutive equations

Actuation along [100] axis modeled by the "direct effect" (Joule magnetostriction):

$$\varepsilon = \sigma / E_y^H + d_{33} H + \alpha \Delta T$$

Sensing along [100] axis modeled by the "inverse effect" (Villari effect):

$$B = d_{33}^{*} \sigma + \mu^{\sigma} H + P \Delta T$$

where $H=nI$

Magnetostriction often modeled using 1-D Linear constitutive equations

Actuation along [100] axis modeled by the "direct effect" (Joule magnetostriction):

$$\varepsilon = \sigma / E_y^H + d_{33} H + \alpha \Delta T$$

Sensing along [100] axis modeled by the "inverse effect" (Villari effect):

$$B = d_{33}^* \sigma + \mu^\sigma H + P \Delta T$$

where $H = nI$

Magnetostriction often modeled using 1-D Linear constitutive equations

Actuation along [100] axis modeled by the "direct effect" (Joule magnetostriction):

$$\varepsilon = \sigma / E_y^H + d_{33} H + \alpha \Delta T$$

Sensing along [100] axis modeled by the "inverse effect" (Villari effect):

$$B = d_{33}^* \sigma + \mu^\sigma H + P \Delta T$$

The 33 subscript indicates the effect and response are in the same directions

Magnetostriction often modeled using 1-D Linear constitutive equations

Actuation along [100] axis modeled by the "direct effect" (Joule magnetostriction):

$$\varepsilon = \sigma / E_y^H + d_{33} H + \alpha \Delta T$$

Sensing along [100] axis modeled by the "inverse effect" (Villari effect):

$$B = d_{33}^* \sigma + \mu^\sigma H + P \Delta T$$

where $H = nI$

Magnetostriction often modeled using 1-D Linear constitutive equations

Actuation along [100] axis modeled by the "direct effect" (Joule magnetostriction):

$$\varepsilon = \sigma / E_y^H + d_{33} H + \alpha \Delta T$$

Sensing along [100] axis modeled by the "inverse effect" (Villari effect):

$$B = d_{33}^{*} \sigma + \mu^{\sigma} H + P \Delta T$$

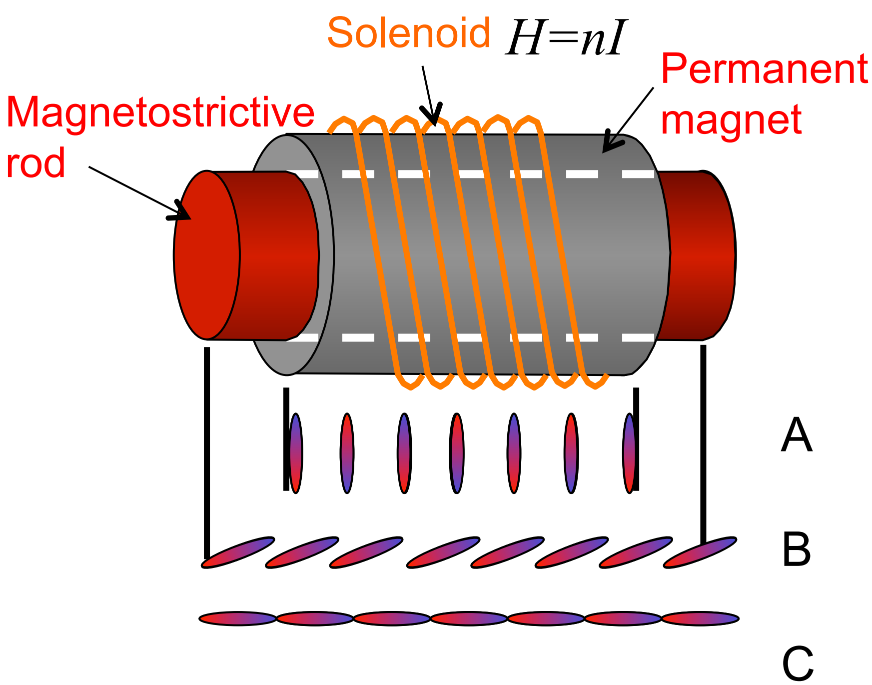
Magneto-mechanical coupling terms

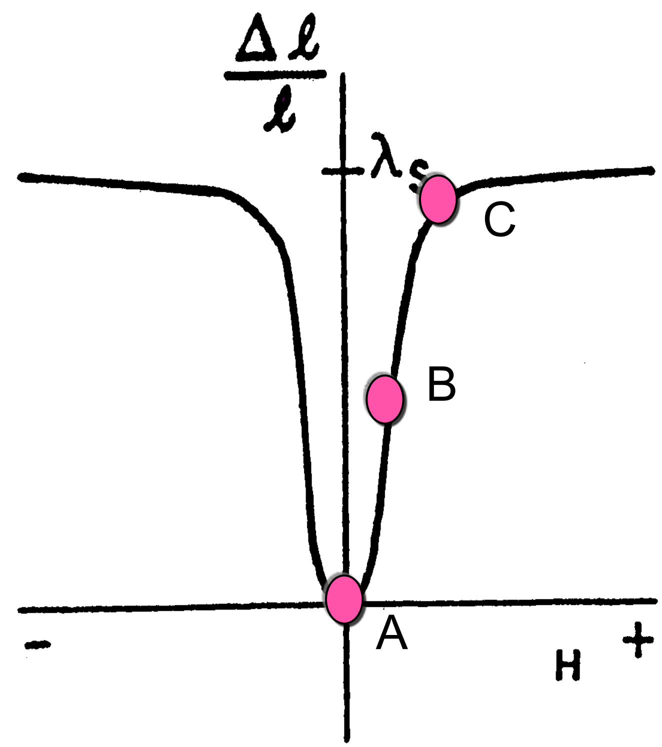
where $H = nI$

The Direct Effect (Joule magnetostriction):

The change in the dimensions of a ferromagnetic body caused by a change in its state of magnetization.

$$\Delta H \rightarrow \Delta\lambda$$

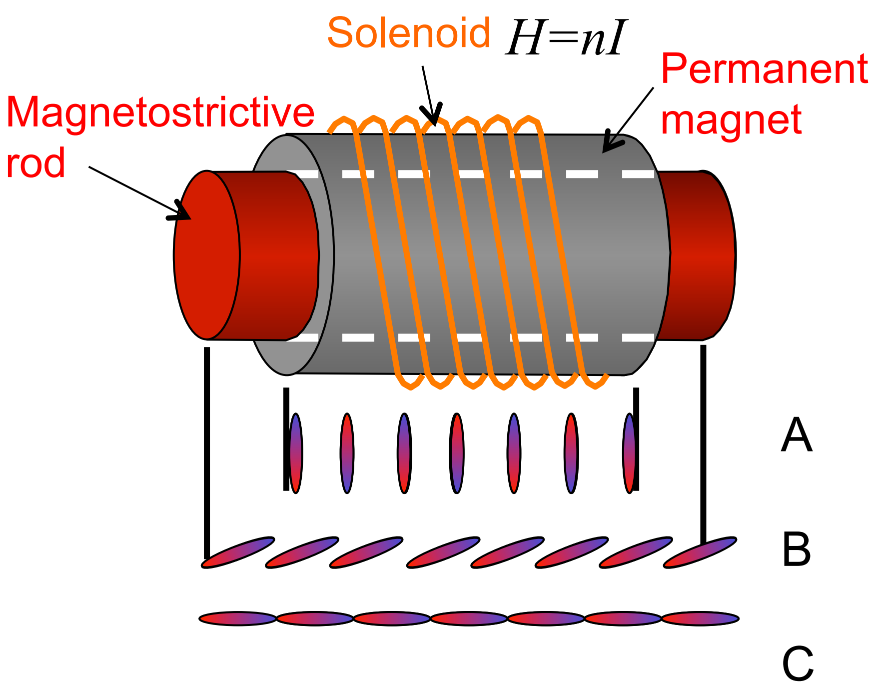


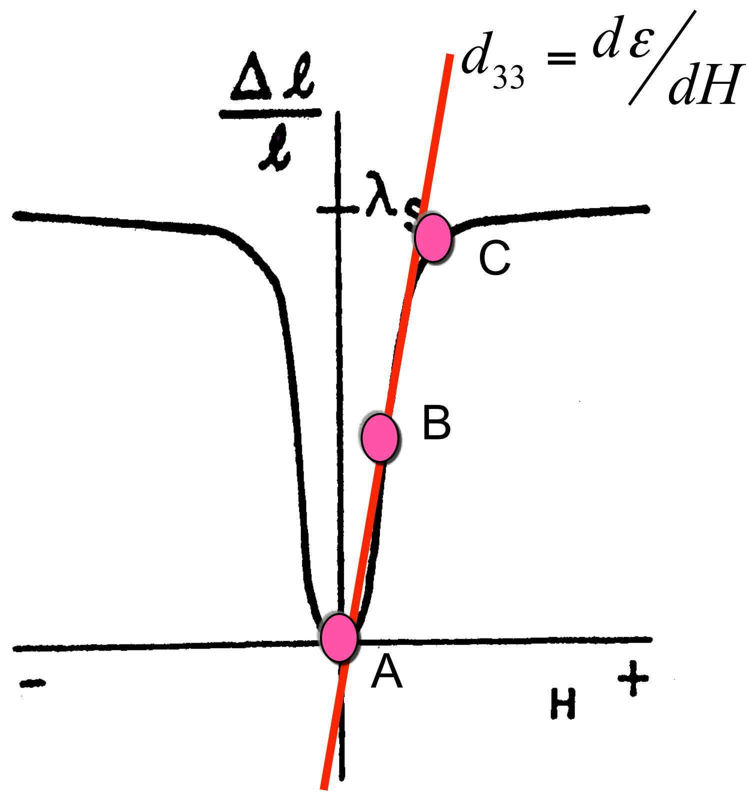


The Direct Effect (Joule magnetostriction):

The change in the dimensions of a ferromagnetic body caused by a change in its state of magnetization.

$$\Delta H \rightarrow \Delta \lambda$$

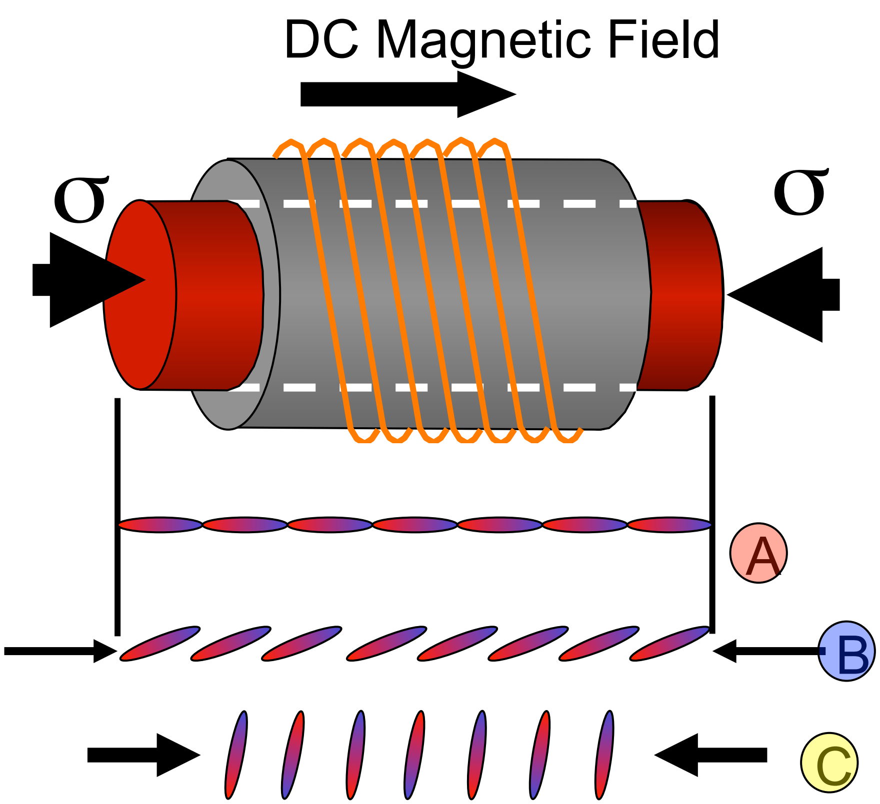


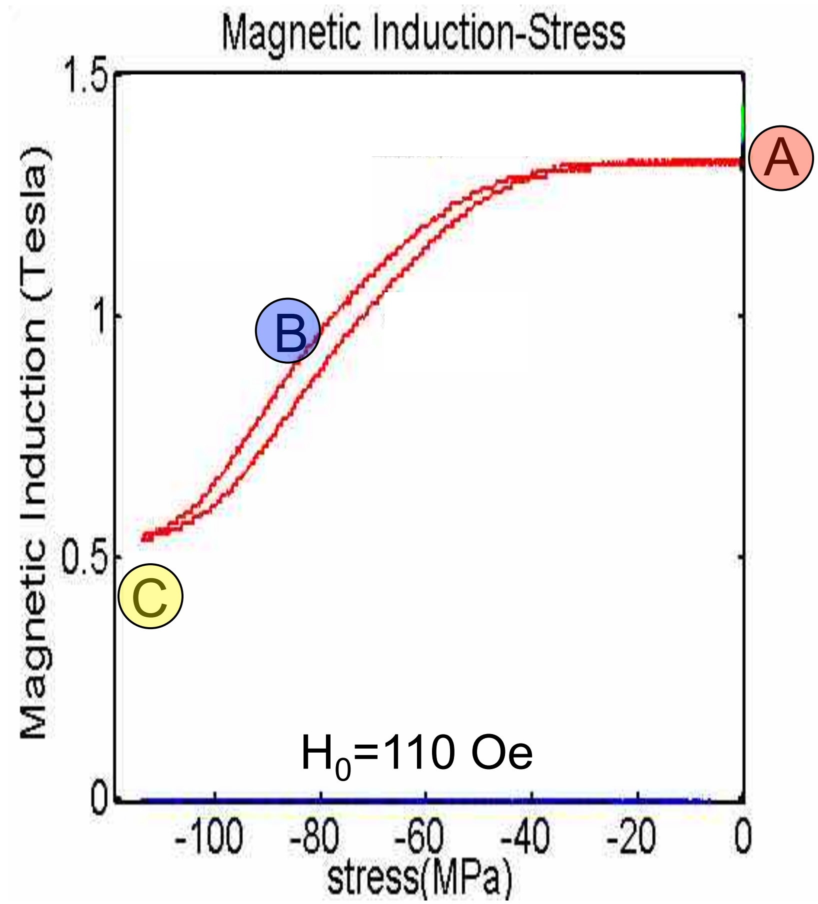


The Inverse Effect (Villari effect):

A change in magnetic state caused by a change in stress.

$$\Delta\sigma \Rightarrow \Delta B$$

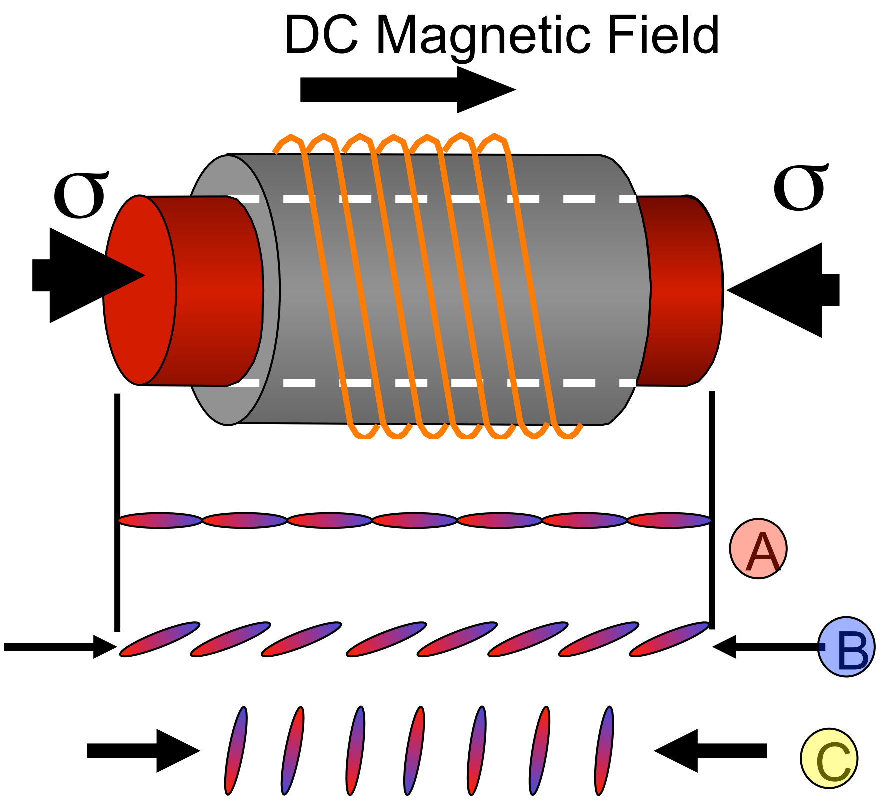


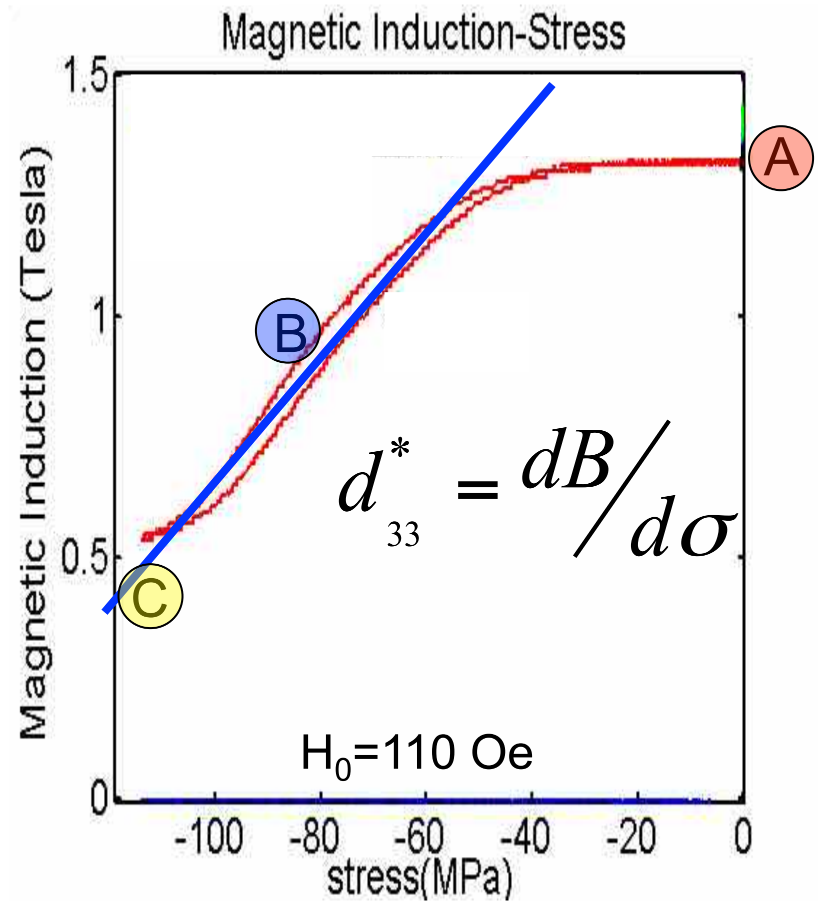


The Inverse Effect (Villari effect):

A change in magnetic state caused by a change in stress.

$$\Delta\sigma \Rightarrow \Delta B$$

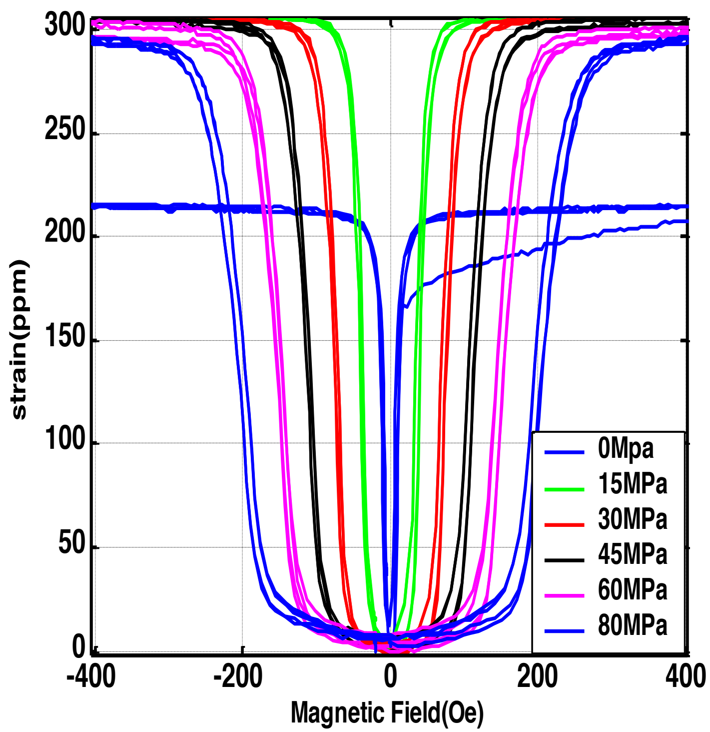




19% Ga single crystal Galfenol

The Direct Effect:

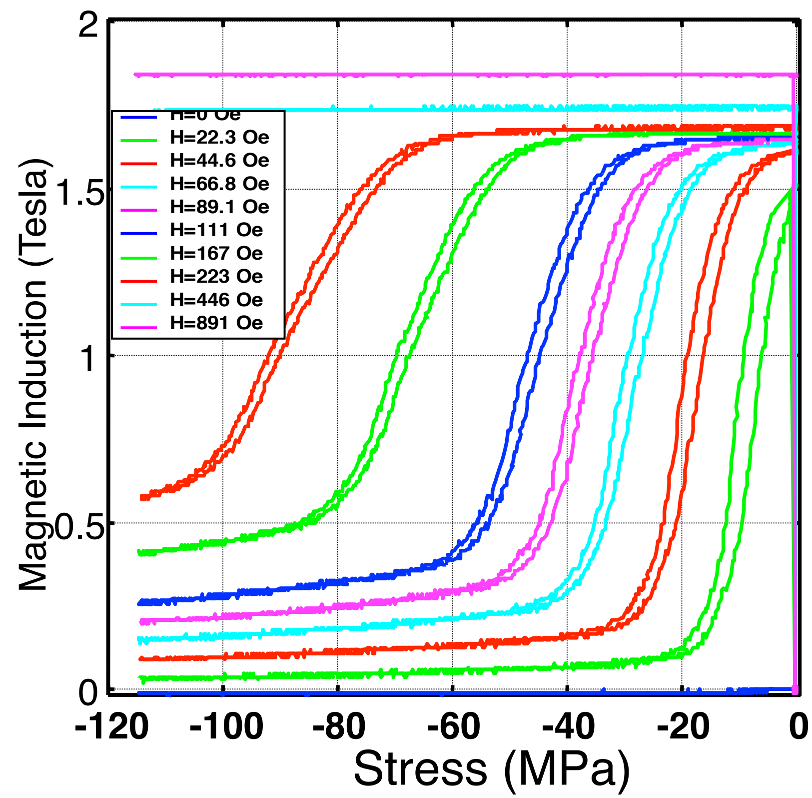
The change in the dimensions of a ferromagnetic body caused by a change in its state of magnetization.



$\Delta H \Rightarrow \Delta\lambda$

The Inverse Effect:

A change in magnetic state caused by a change in stress.



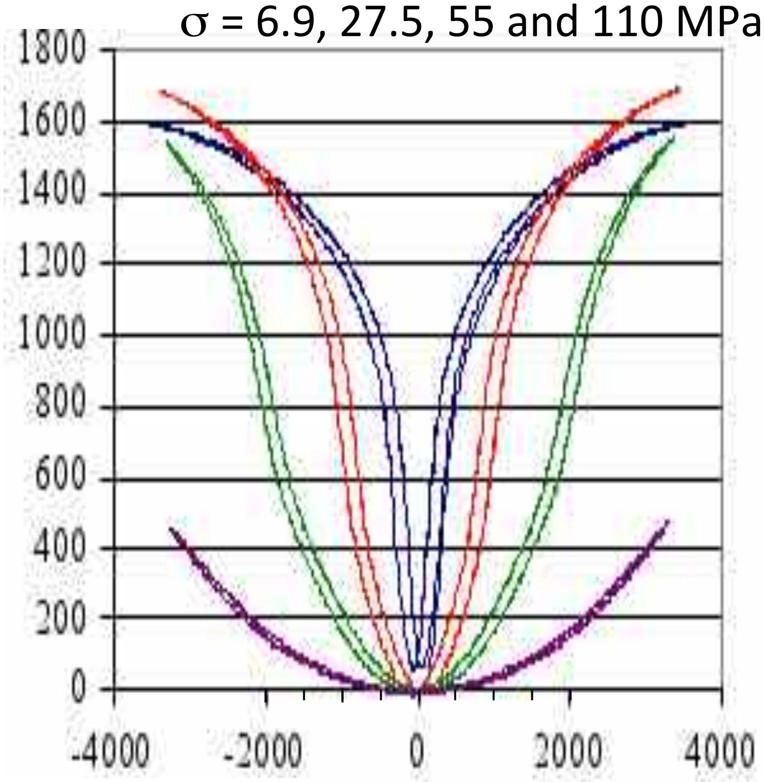
$\Delta\sigma \Rightarrow \Delta B$

Production grade Terfenol-D

The Direct Effect:

The change in the dimensions of a ferromagnetic body caused by a change in its state of magnetization.

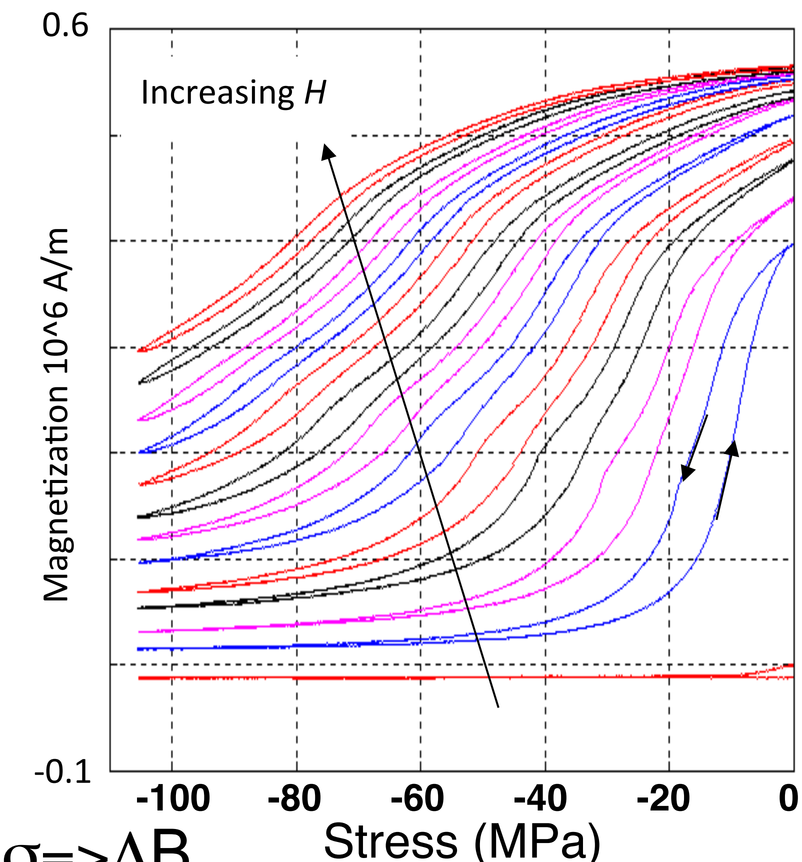
σ = 6.9, 27.5, 55 and 110 MPa



$\Delta H \Rightarrow \Delta\lambda$

The Inverse Effect:

A change in magnetic state caused by a change in stress.

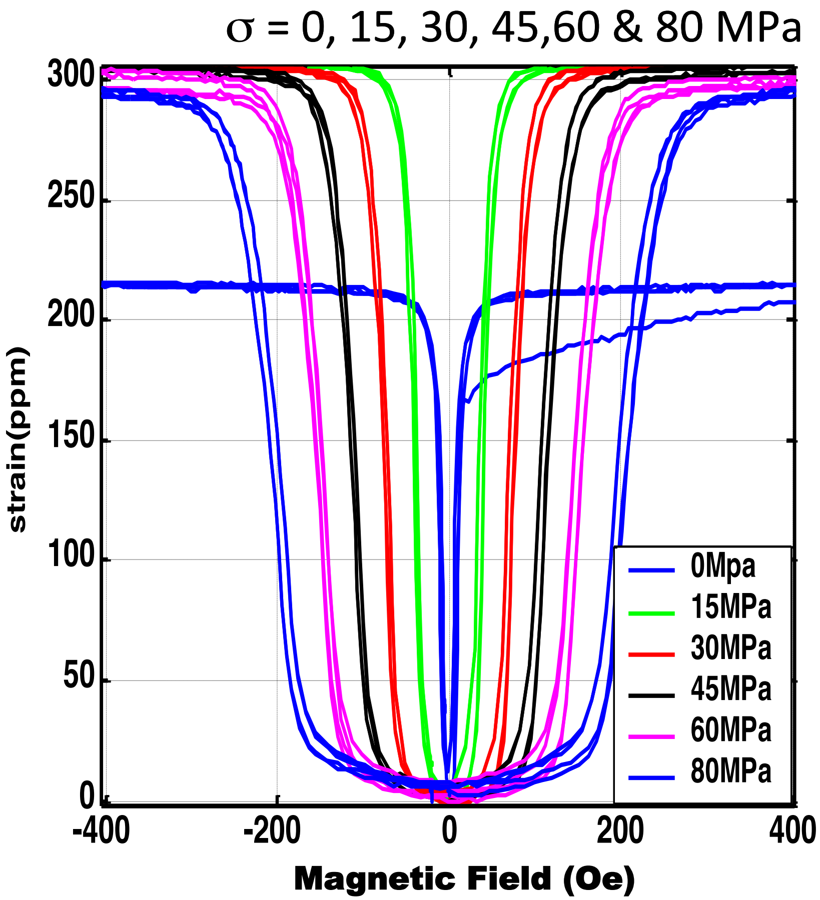


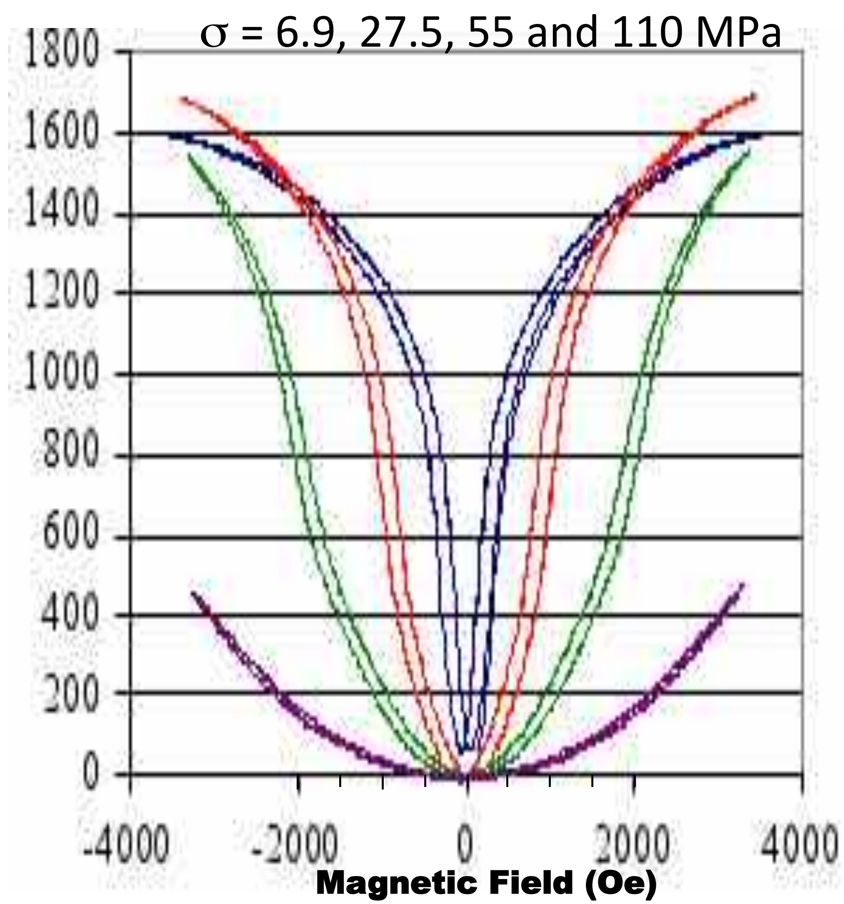
$\Delta\sigma \Rightarrow \Delta B$

Comparison of direct effect in Galfenol (left) and Terfenol-D (right)

19% Ga single crystal Galfenol

Production grade Terfenol-D

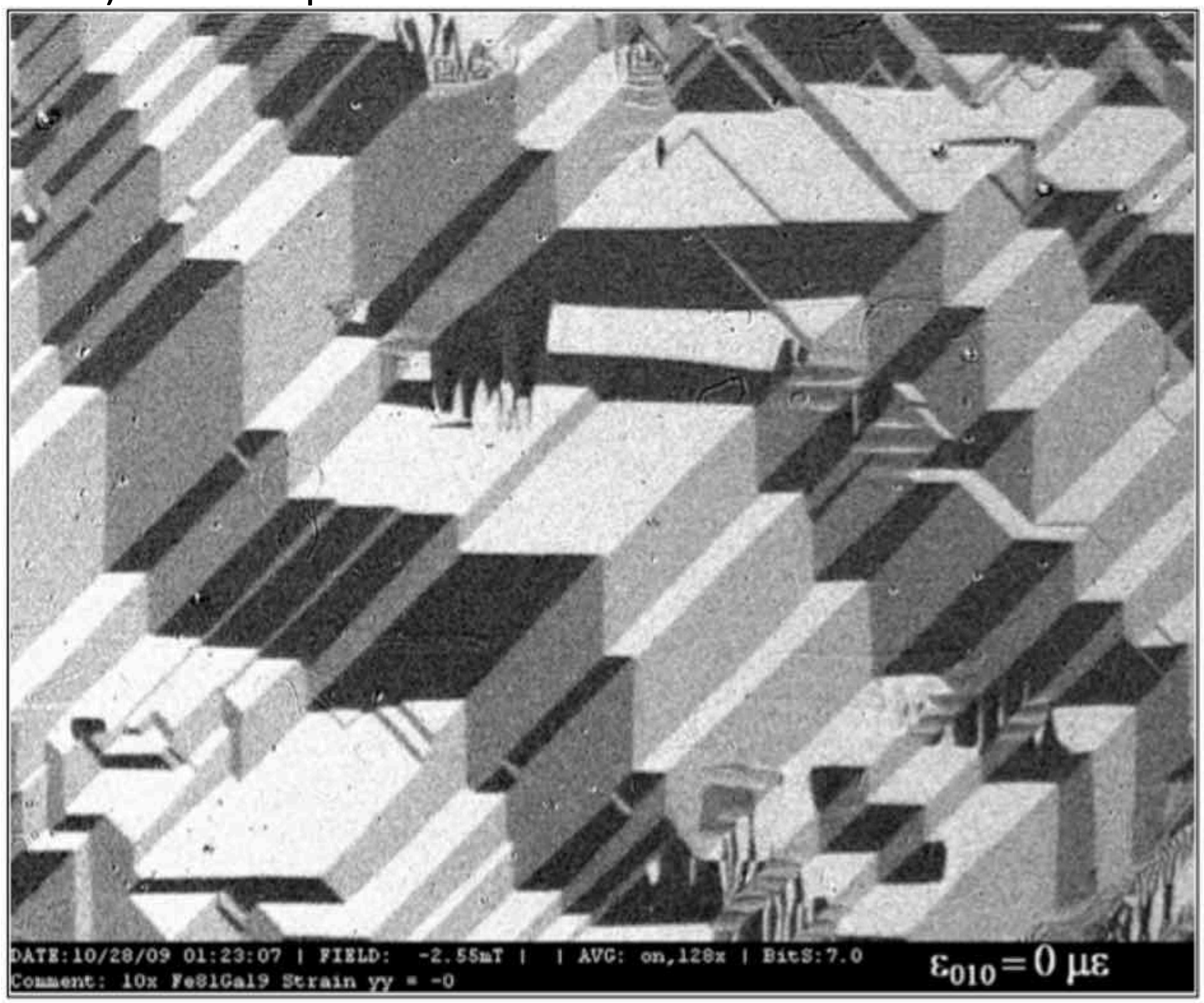


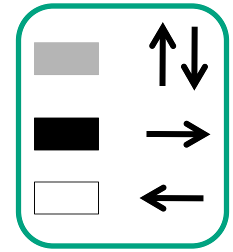


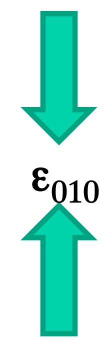
Galfenol data from Dr. J.“Atul” Atulasimha’s dissertation (2006)
Terfenol-D data from ETREMA Products, Inc. product sheet

MOKE images of quenched $Fe_{81}Ga_{19}$ under compressive stress/strain (0-1500 microstrain)

Images of Galfenol obtained using Evico Magnetics GMBH Magneto-Optic Kerr Effect (MOKE) microscope







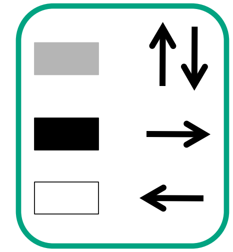
[010]

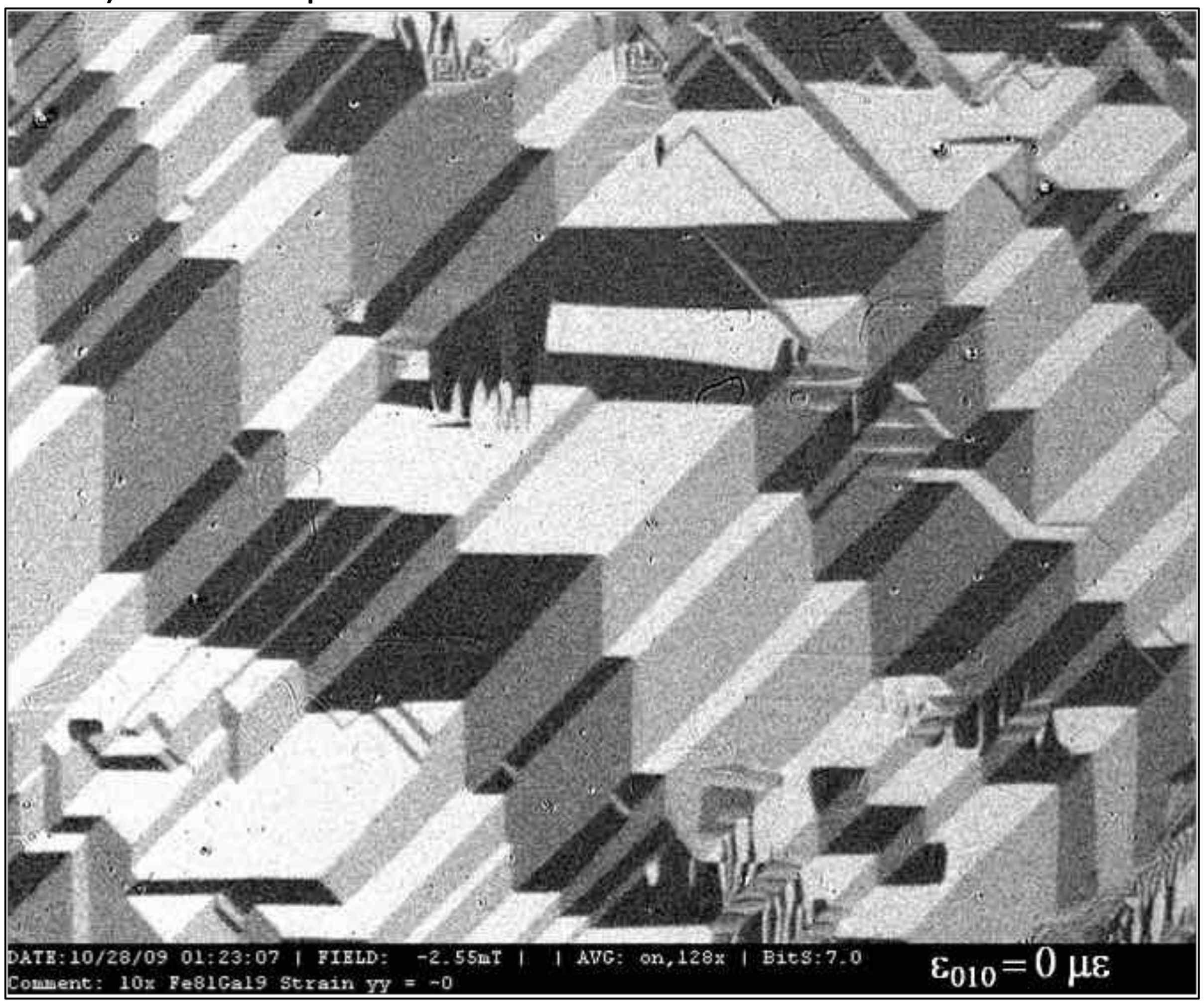
[100]

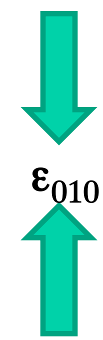
100 μm

MOKE images of quenched $Fe_{81}Ga_{19}$ under compressive stress/strain (0-1500 microstrain)

Images of Galfenol obtained using Evico Magnetics GMBH Magneto-Optic Kerr Effect (MOKE) microscope







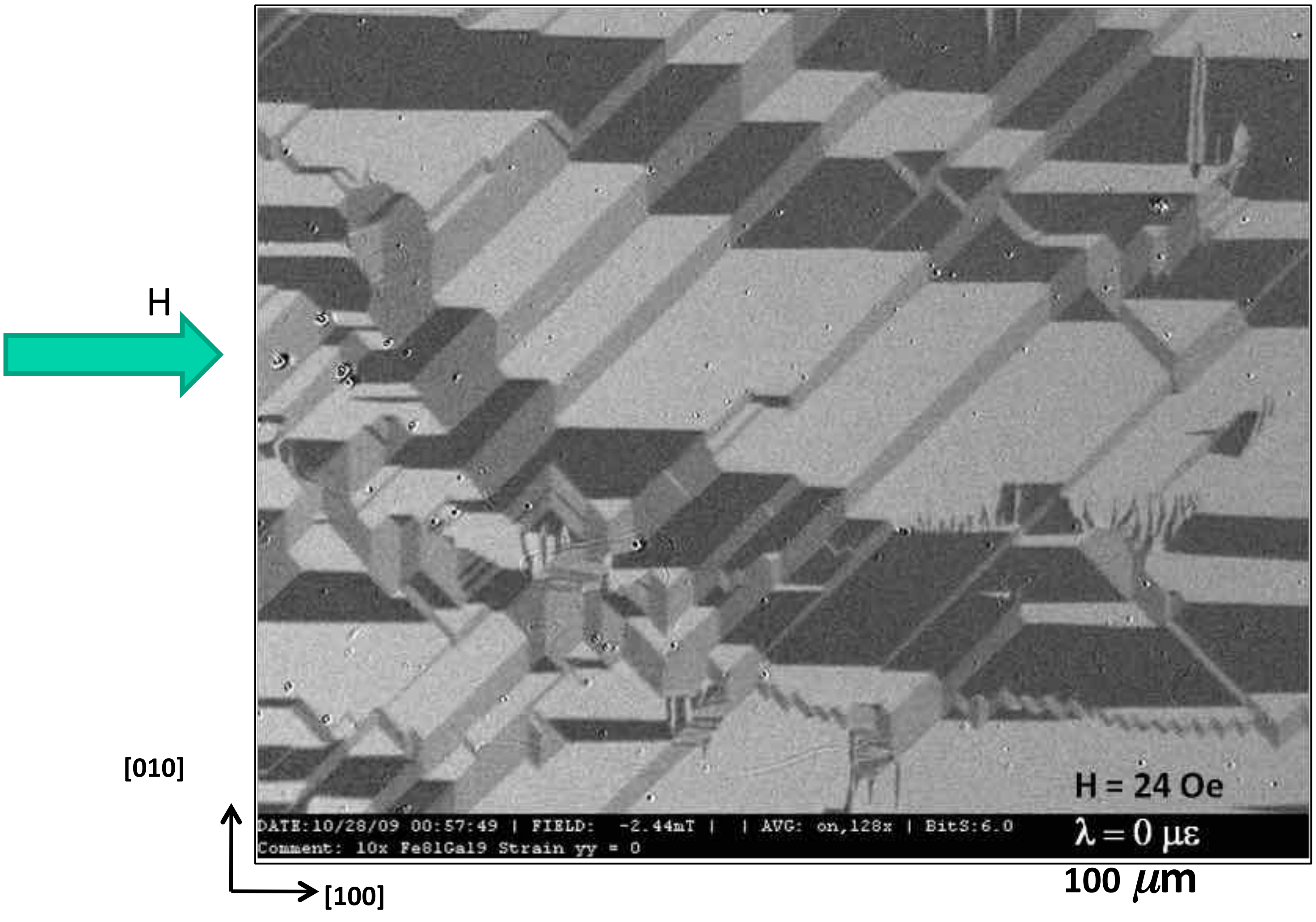
[010]

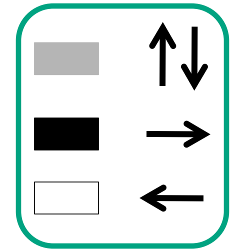
[100]

100 μm

MOKE images of quenched $Fe_{81}Ga_{19}$ under magnetic field (0-200+ Oe)

Images of Galfenol obtained using Evico Magnetics GMBH Magneto-Optic Kerr Effect (MOKE) microscope





Outline

Intro to Magnetostriction

- **Actuators: the "direct" effect**
- **Sensors: the "inverse" (or Villari) effect**

Structural Magnetostrictive Alloys

- **Magnetostrictive, magnetic & mechanical properties**
- **Thin, highly textured rolled sheet**
- **Introduction to auxetic behavior**

Applications that use Galfenol

- **Bending sensor applications**
- **Implantable wireless bone fixity sensor (Tech Univ. Dresden)**
- **Nanowire sensors (Univ. Minn. & UMD)**
- **Applications for auxeticity?**
- **Micro-motors (Kanazawa University, Japan)**
- **Energy Harvesting (Kanazawa Univ, UMD & Techno Sciences, Inc., Oscilla Power)**

Summary

Common Magnetostrictive Materials

STRUCTURAL Magnetostricitve Alloys

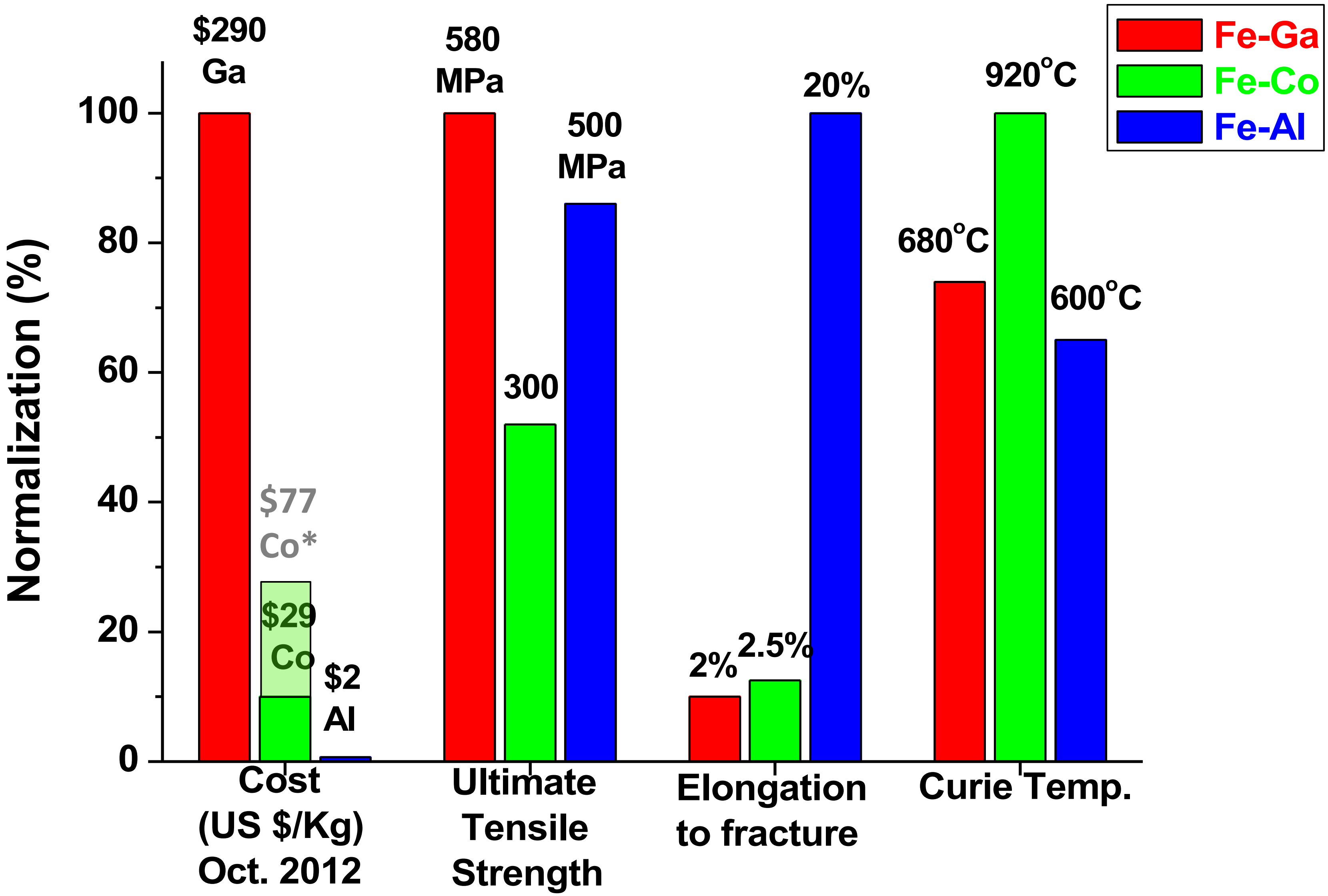
	Terfenol-D	Iron	Nickel	$Fe_{1-x}Co_x$	$Fe_{1-x}Al_x$	$Fe_{1-x}Ga_x$
3/2 λ_s (μstrain)	**1600-2400**	**-24**	**-66**	**140-220**	**185**	**~400**
Modulus (GPa)	25-35	200	207	270	65	65
Relative Permeability	2-10	5000	100-600	~3000	100	70-100
Saturation Magnetization	1.0 T	1.6-2.2 T	~0.6 T	~2T	1.4 T	1.6 T
Ultimate Tensile Strength (MPa)	28 (& very brittle)	400	500	300-870	500-800	500-600
Hysteresis in λ-H and B-H curves	Moderate	Low	Low	Very Low	Very Low	Very Low

High magnetostriction
Poor magnetic & mechanical properties

Low magnetostriction
Good mechanical properties

Good magnetostriction
Good magnetic and mechanical properties

Comparison of binary Fe-Ga (λ=400 $\mu\varepsilon$), Fe-Co (λ=150$\mu\varepsilon$) and Fe-Al (λ=175$\mu\varepsilon$)



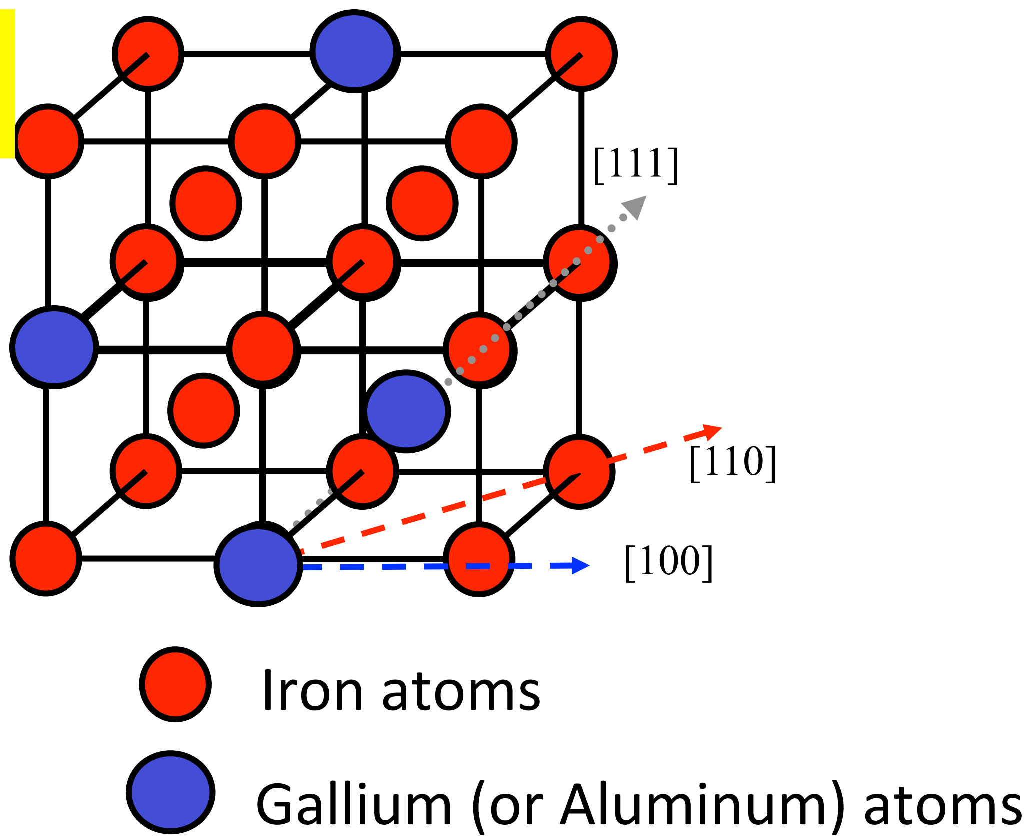
Galfenol - $Fe_{1-x}Ga_x$
(0.13 < x < 0.35)

Gallium + Iron (Fe) + Naval Ordnance Laboratory

Alfenol - $Fe_{1-x}Al_x$
(0.13 < x < 0.35)

Alumium + Iron (Fe) + Naval Ordnance Laboratory

X% Fe replaced with Ga (or Al)
Start with BCC Iron Lattice

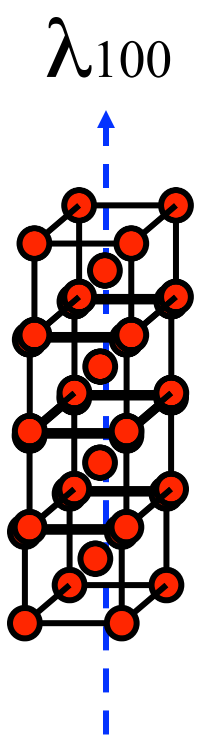


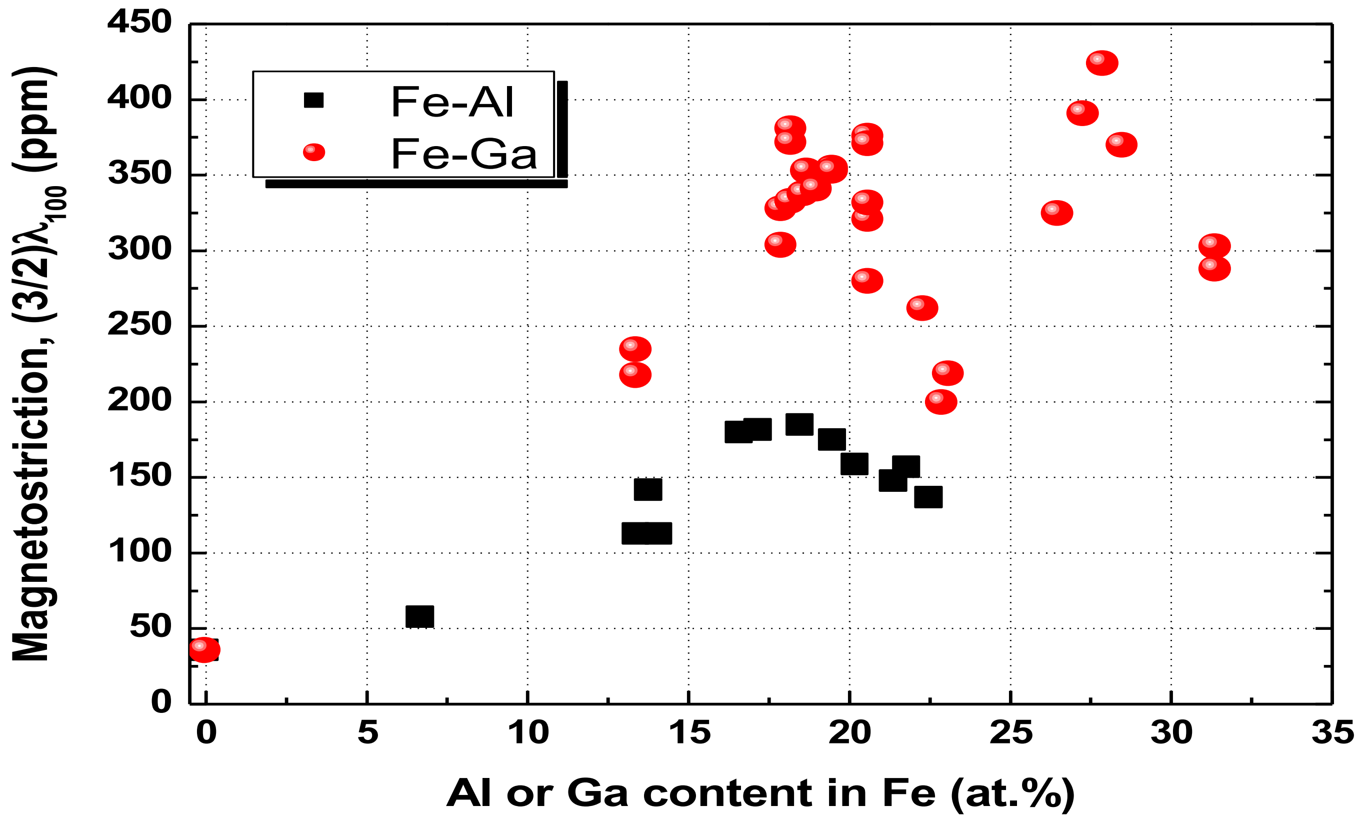
Galfenol - $Fe_{1-x}Ga_x$
($0.13 < x < 0.35$)

Gallium + Iron (Fe) + Naval Ordnance

Alfenol - $Fe_{1-x}Al_x$
($0.13 < x < 0.35$)

Alumium + Iron (Fe) + Naval Ordnance

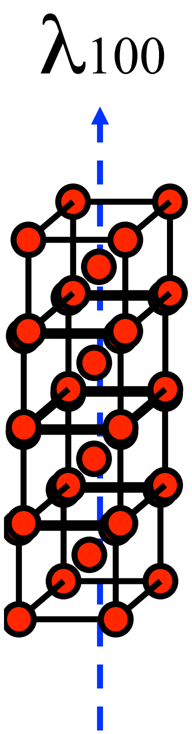


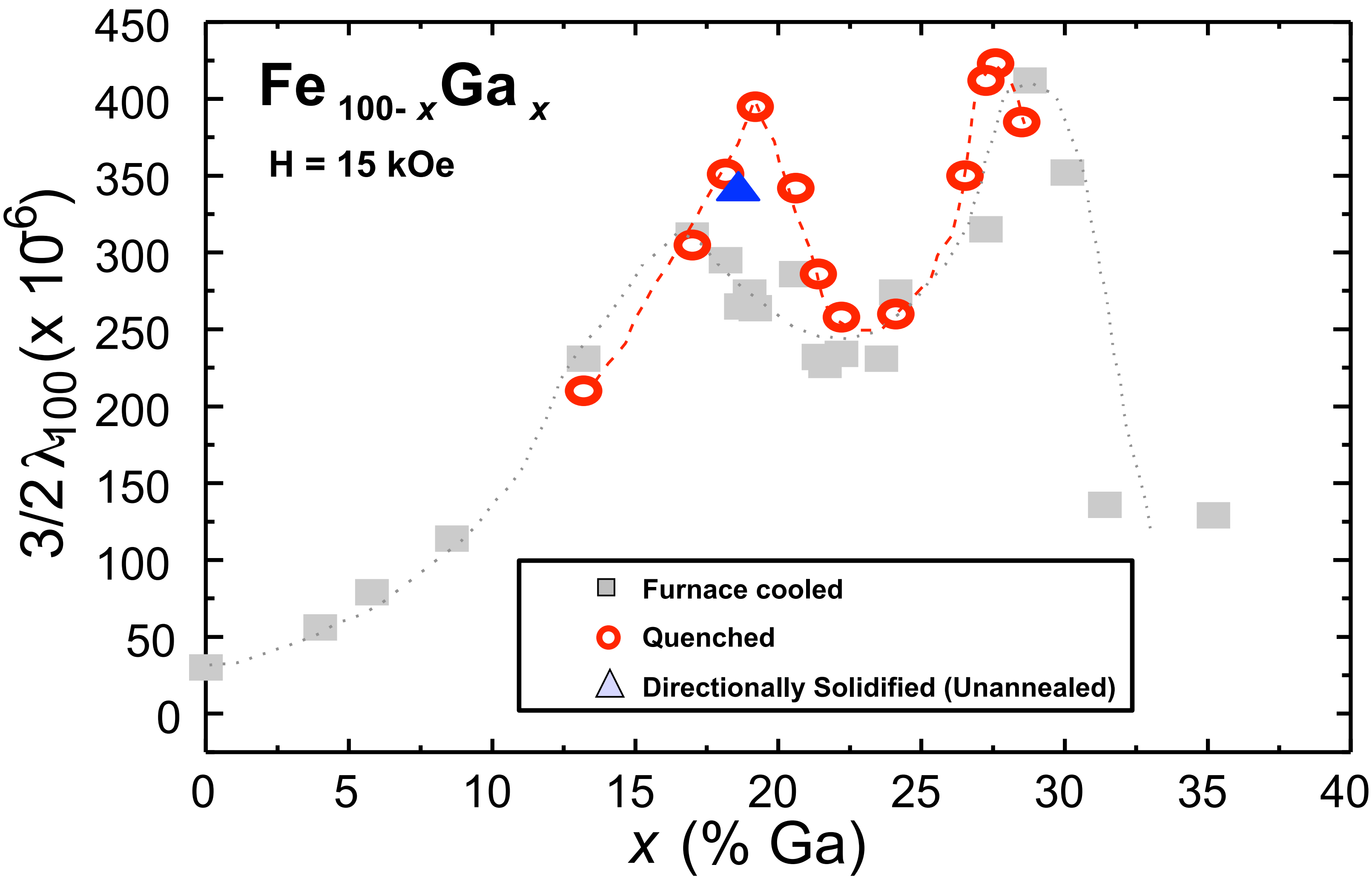


Plotting single crystal data at 15 kOe from [Restorff et al. JAP 111, 023905 (2012)]

Magnetostriction of Galfenol

•Sensitive to composition and to heat treatment [Clark et al. 2003]

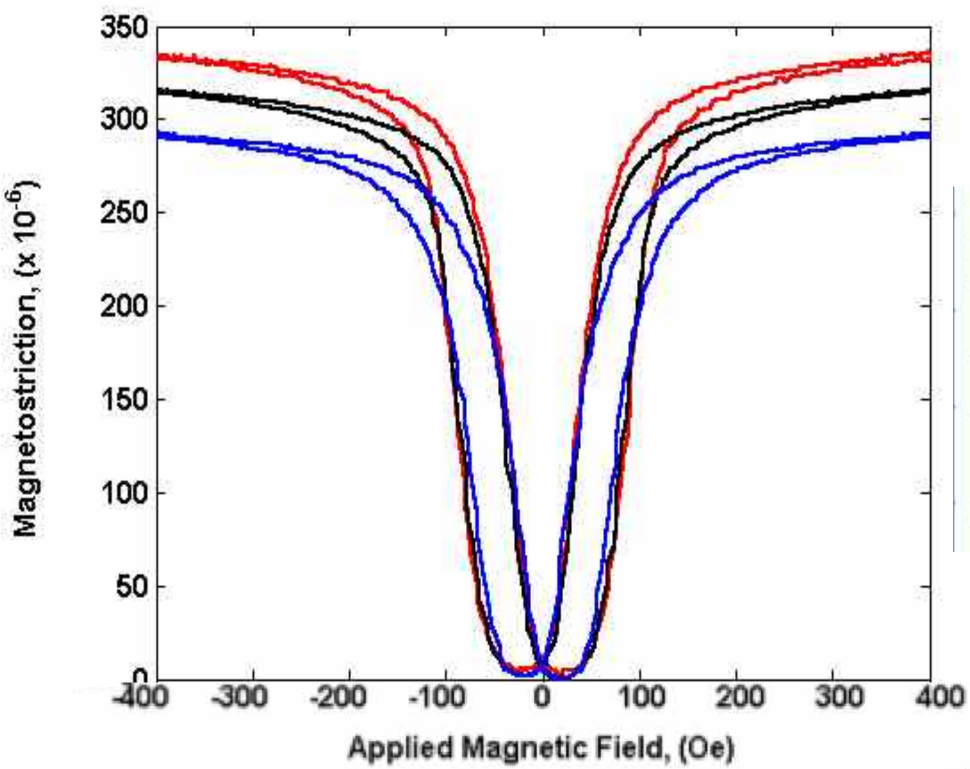


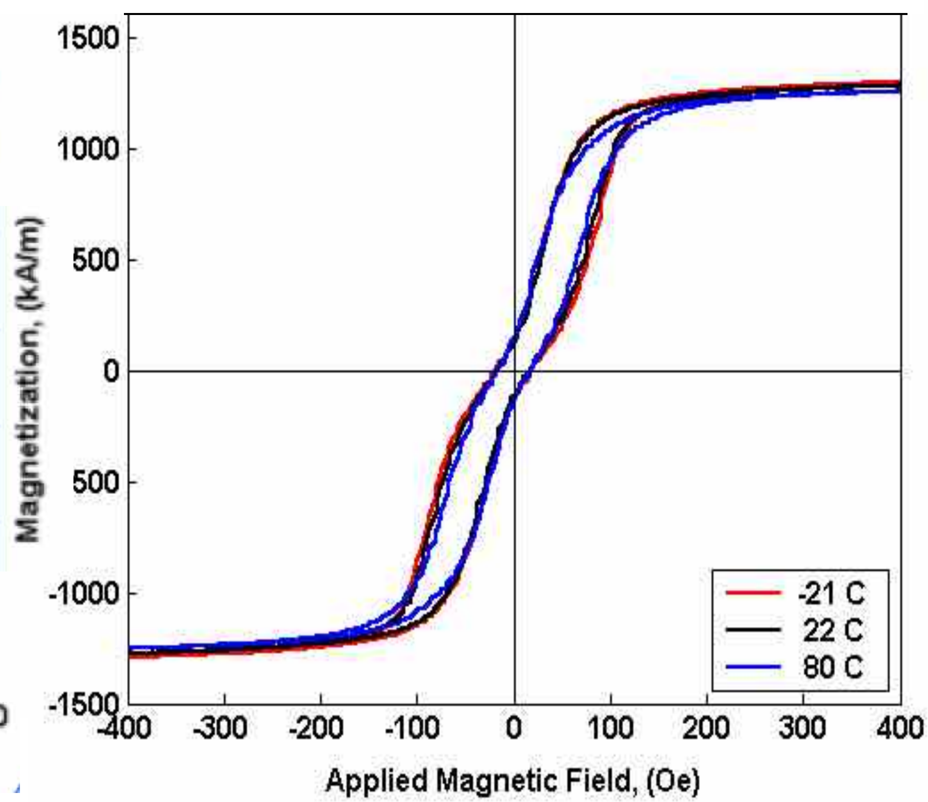


Temperature Dependencies of $\lambda(H)$ & $M(H)$ in 19% Ga Fe-Ga Single Crystal

$Fe_{81}Ga_{19}$ Single crystal @ 45.3 MPa. -22°C (red) to +80°C (blue)

Note: hysteresis is induced by transducer bushing – is not in FeGa rod

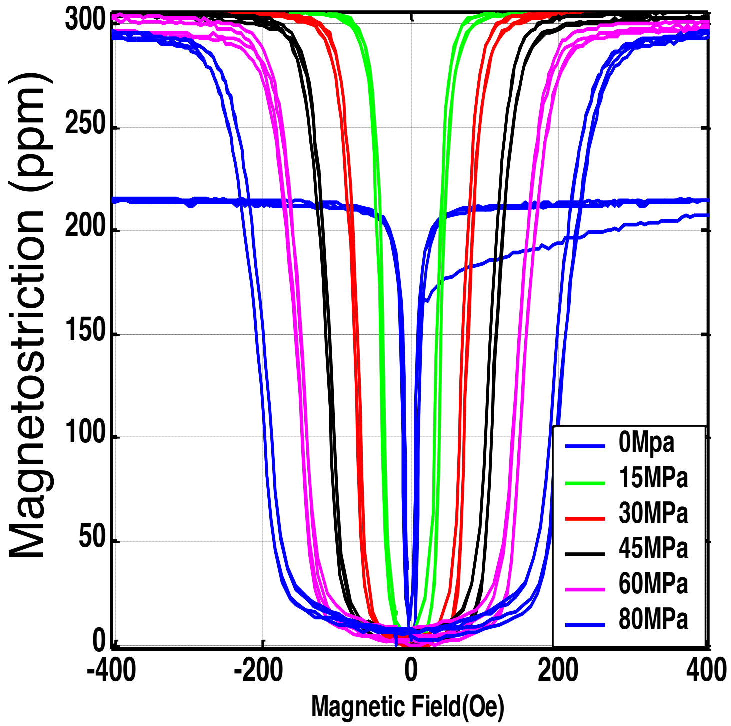




The Direct Effect: The change in the dimensions of a ferromagnetic body caused by a change in its state of magnetization.

Single Crystal FeGa

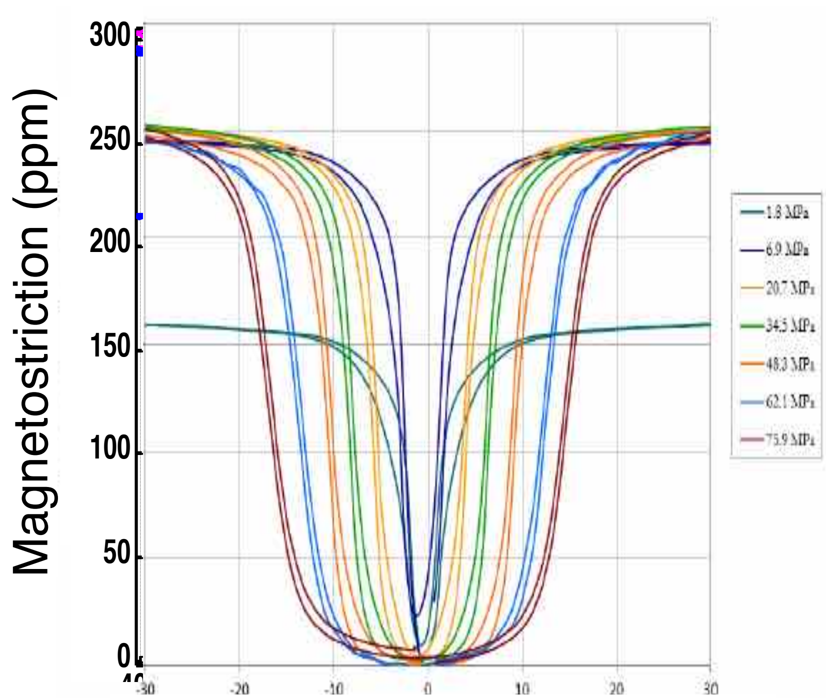
$$$$$



Magnetic Field Intensity (Oe)

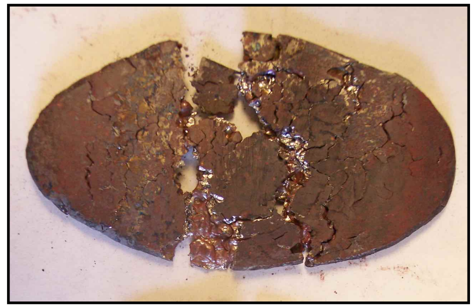
Polycrystalline FeGa

$$

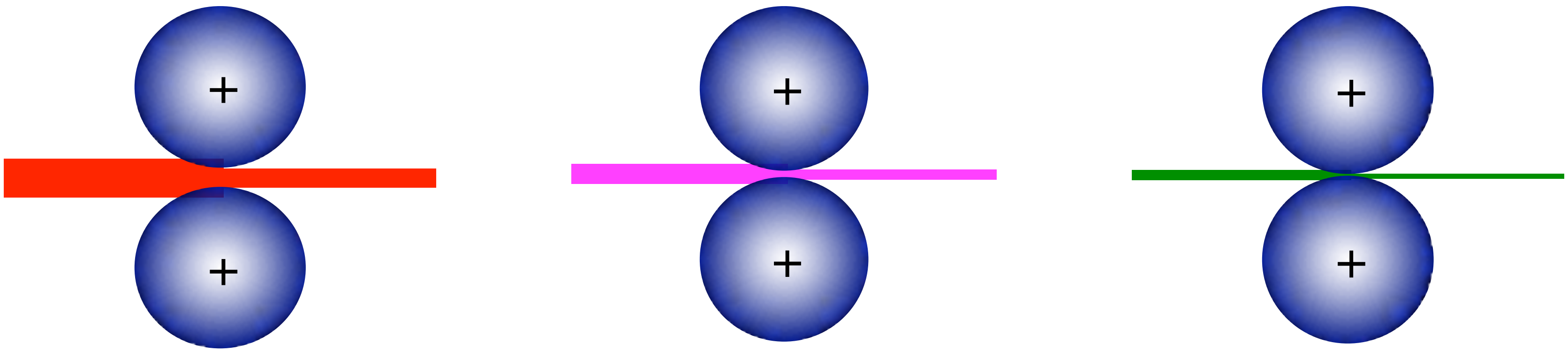


Magnetic Field Intensity (kA/m)

Rolling Steps to Lower Fabrication Costs



• Binary alloy experienced intergranular fracture



Hot Rolling

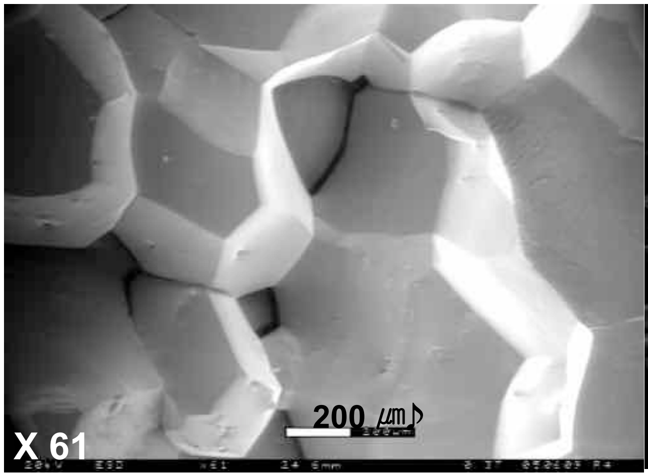
- Arc-melted buttons
- Roller set in 0.0031 inch
- 1000/800°C for 10 min. every 2 passes
- Seal in 321 Stainless

Warm Rolling

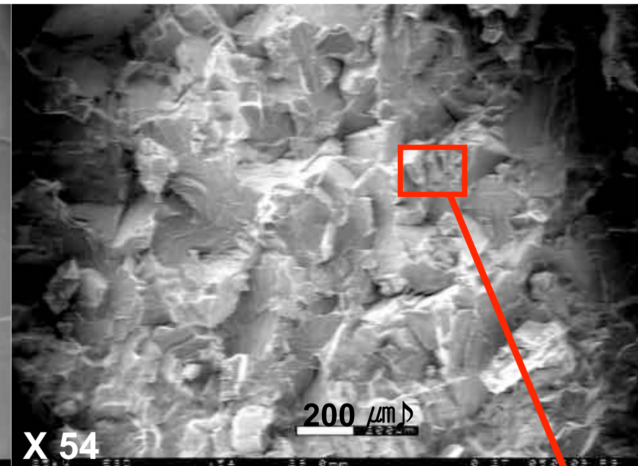
Cold Rolling

Intergranular Fracture Mode Changed to Intragranular with trace Additions of B or NbC

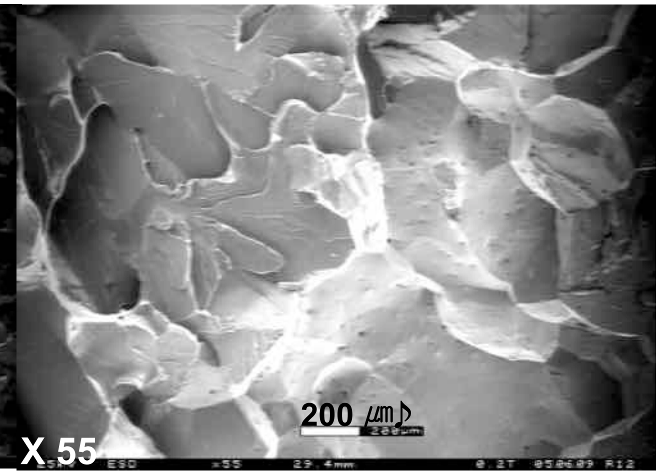
Fe-18.7% Ga



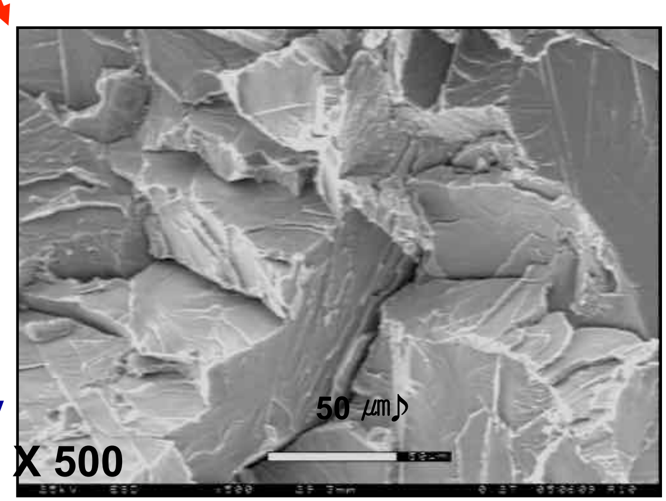
Addition of 0.5% B



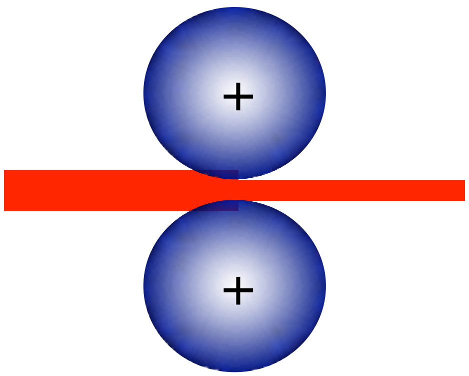
Addition of 1.0% B



- Fracture surface of the B-free Galfenol clearly appeared to a typical intergranular mode by crack propagation along grain boundaries.
- Fracture surface of the B-added Galfenol was changed to a transgranular mode by crack propagation through the grains and the grain size was also small (grain refinement).
- **Boron has a great effect on improvement of ductility due to suppressing grain boundaries fracture.**

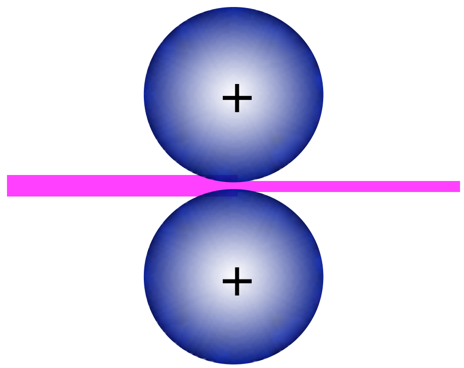


Rolling Steps



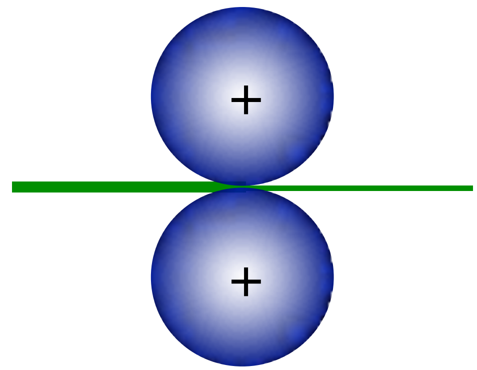
Hot Rolling

- Arc-melted buttons
- Roller set in 0.0031 inch
- 1000/800°C for 10 min. every 2 passes
- Seal in 321 Stainless



Warm Rolling

- Roller set in 0.002 inch
- 600/400°C for 10 min. every 1 pass
- Intermediate annealing @ 800°C for 2 hrs in Ar



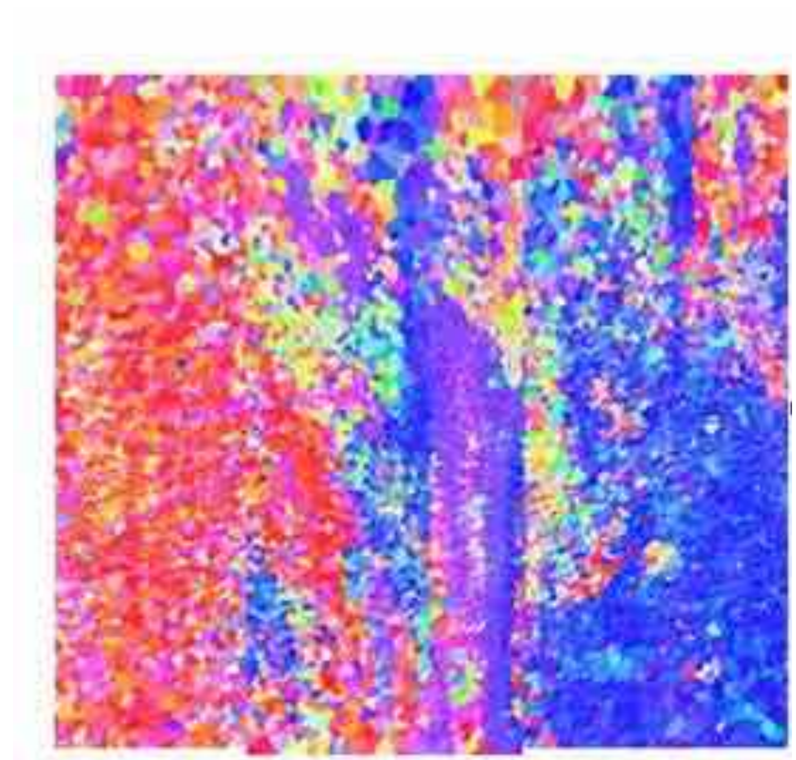
Cold Rolling

- Roller set in 0.0005 inch
- Subsequent annealing @ 1000 ~ 1200°C under flowing argon, sulfur atmoshere

As-rolled sheet: λ_{sat} ~60 ppm
Goss or Cube texture ~7X more magnetostrictive

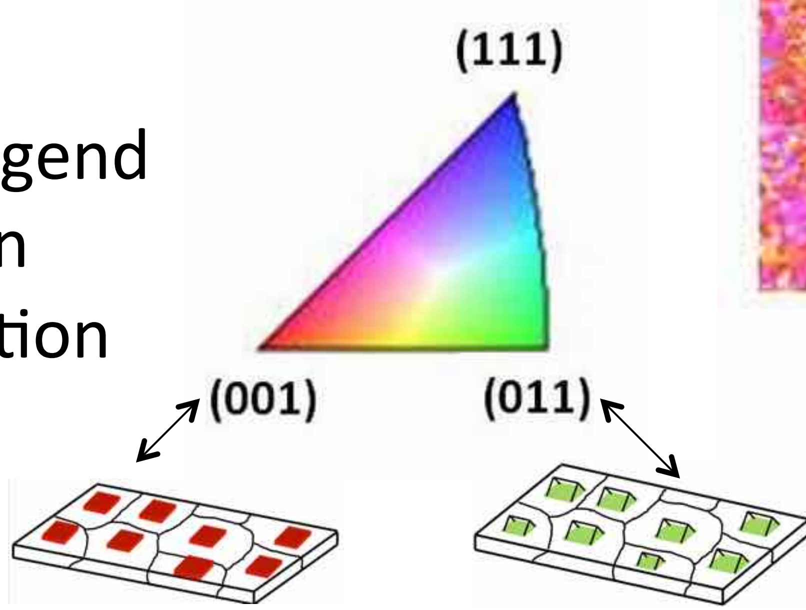
Electron BackScatter Diffraction (EBSD) images show as-rolled grains are tilted at random orientations

λ_{sat} ~60 ppm

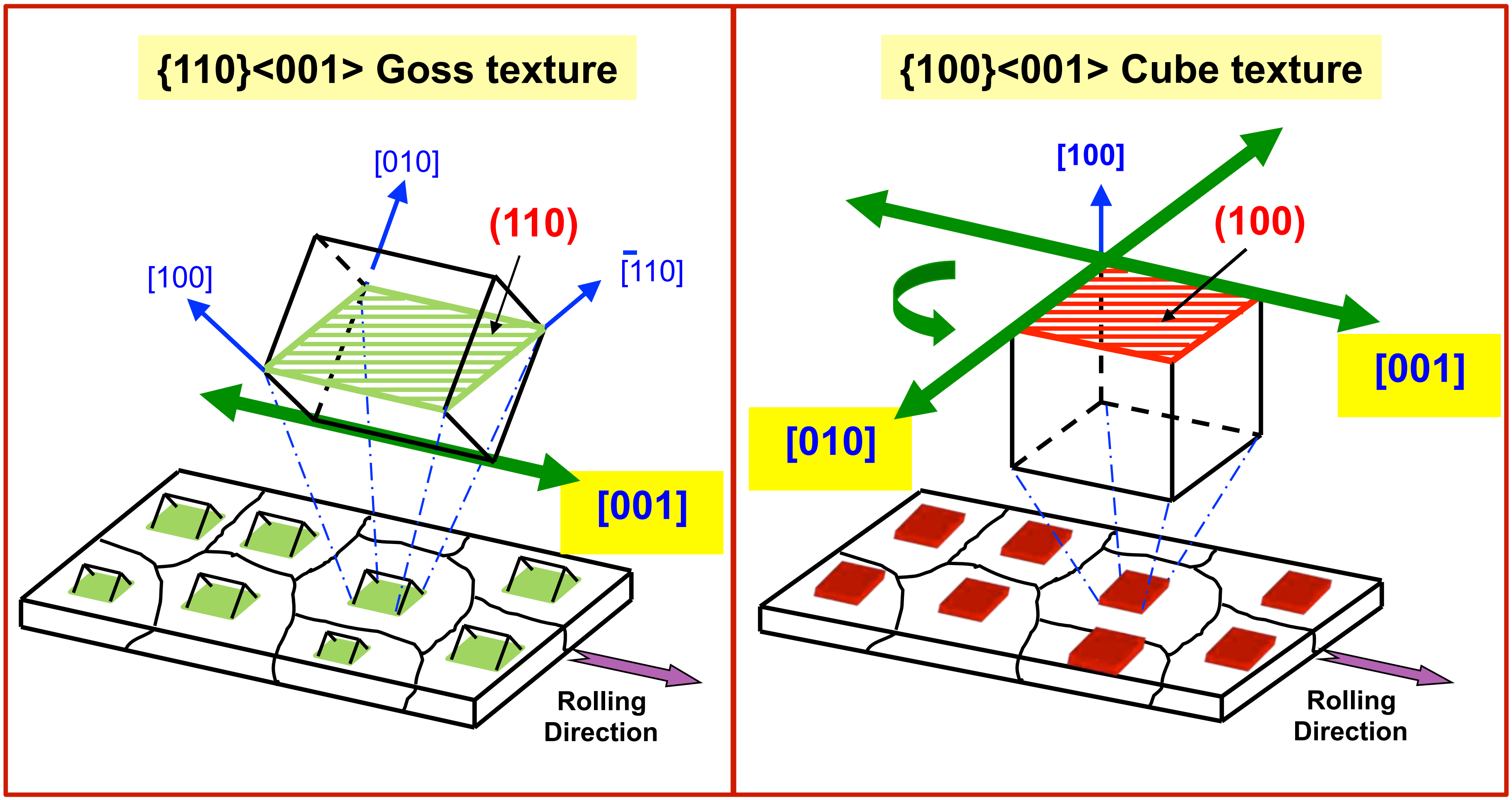


As-rolled
(γ-fiber & rotated cube textures)

EBSD legend for grain orientation



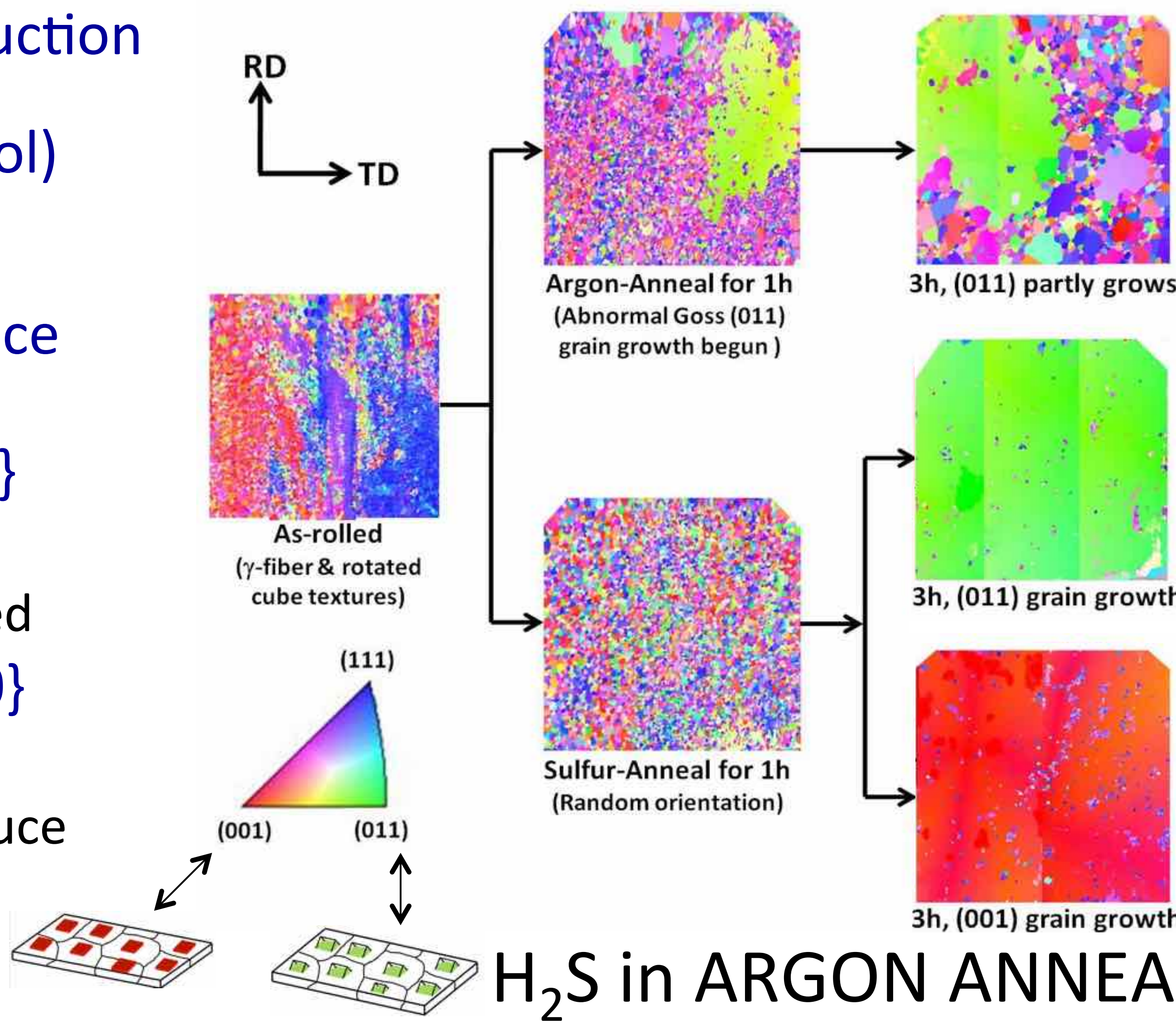
Once rolling achieved, need to develop a preferred texture in rolled sheet



Texturing of Polycrystalline Galfenol

ARGON ANNEAL

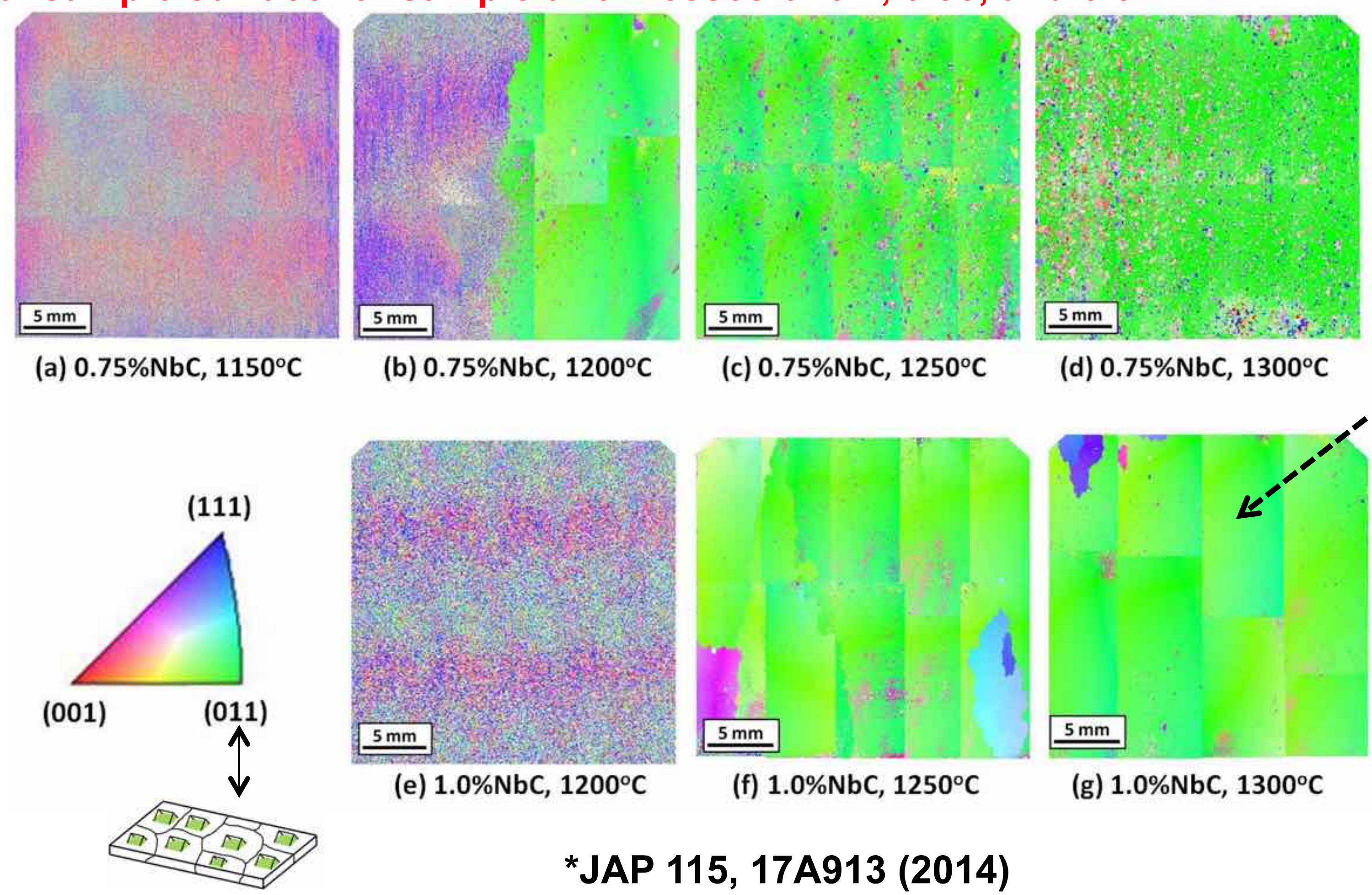
- Inexpensive production of rolled sheet Galfenol (Alfenol) relies on the abnormal grain growth of surface textures
- Goss texture {110}
  - λ_{100} ~ 200 ppm
  - Easily reproduced
- Cube texture {100}
  - λ_{100} ~ 350 ppm
  - Difficult to produce



H_2S in ARGON ANNEAL

Texturing of Rolled Sheet Alfenol

- NbC-added 20%Alfenol rolled sheets annealed under a sulfur atmosphere.
- Single (011) grain is abnormally grown, with λ = ~177 ppm.
- Large single (011) grains were fully grown in the samples, covering 80-99% of sample surface for sample thicknesses of 0.2, 0.35, and 0.5 mm.



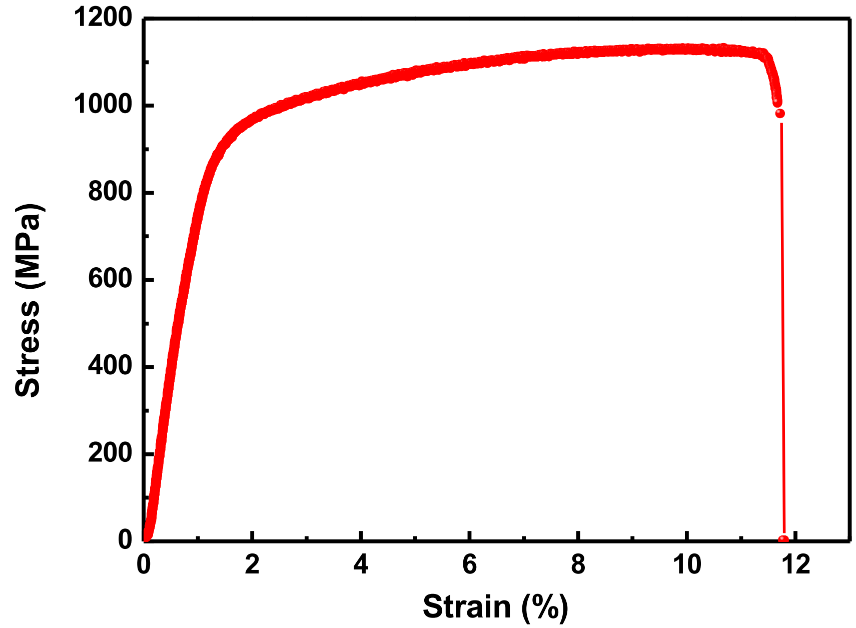
(011) Grain with <100> orientation

*JAP 115, 17A913 (2014)

Seeking additional insights lead to an unexpected result

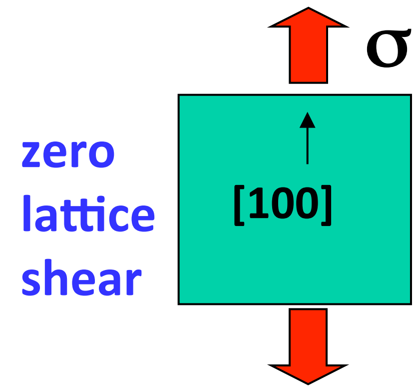
(3) Tensile Test

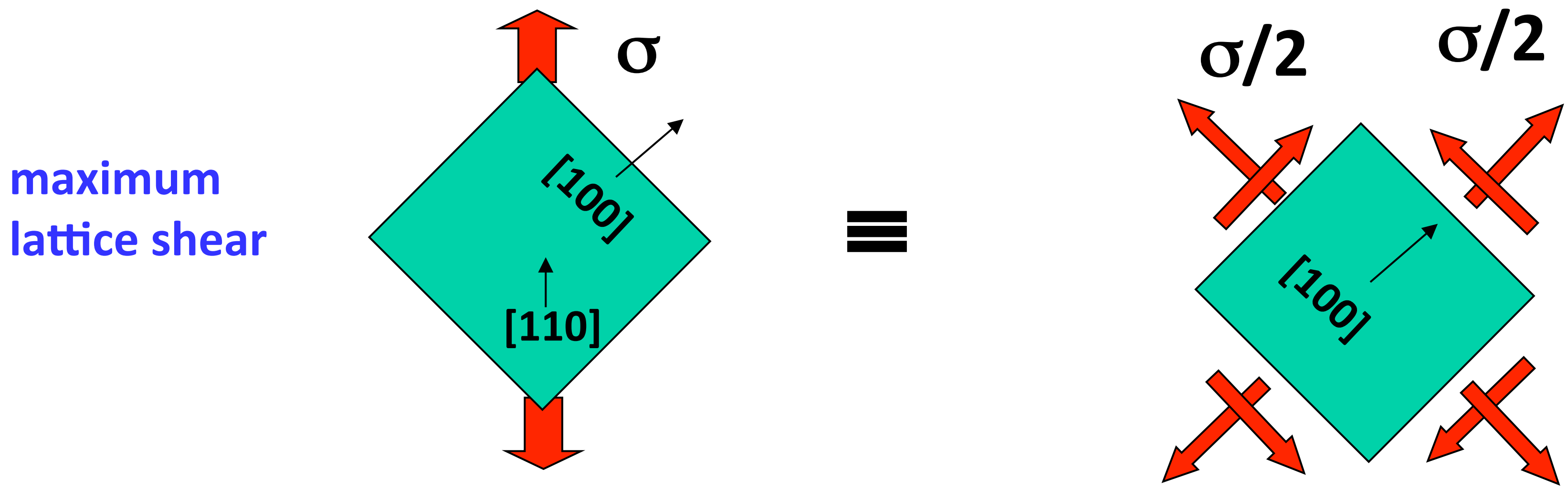
1) Test specimen thickness: 0.1, 0.2, 0.35, 0.5 mm
2) The test specimens were prepared according to ASTM A370-12a (Standard Test Methods and Definitions for Mechanical Testing).
3) Machine: MTS 858 Mini Bionix 25kN servo-hydraulic load frame at a rate of 0.0025 mm/s. The strain was monitored with a gauge length of 25 mm.



Tensile Loading to Study Slip Planes
Two Test Configurations: [100] & [110] Single Crystal Samples

- Emphasize mechanical anisotropy
- High symmetry crystal orientations
- Use axial loading (tension)





Single Crystal Galfenol Samples

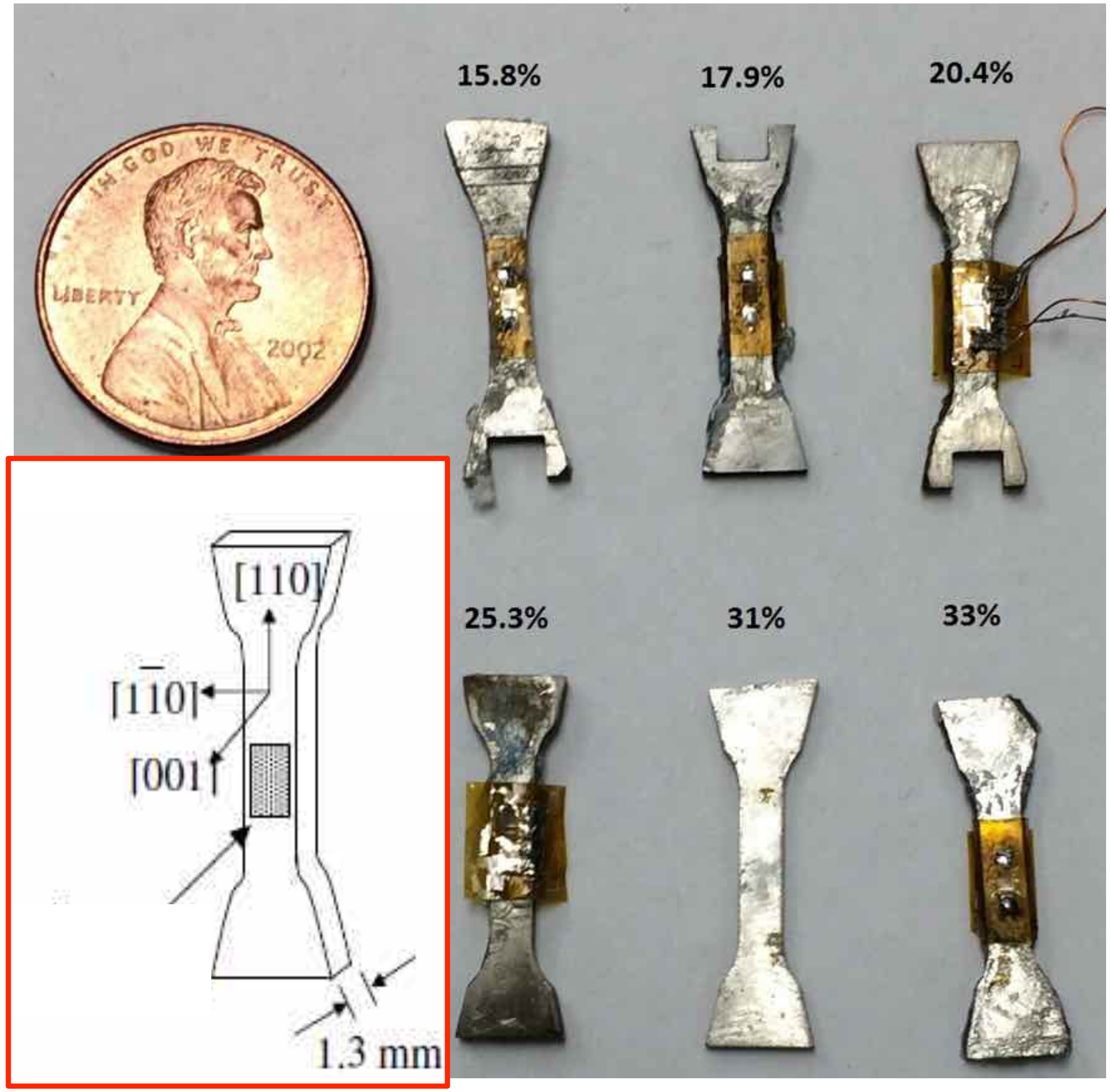
Single crystal $\mathbf{Fe_{100\text{-}x}Ga_x}$
x = 15.8, 17.9, 20.4, 25.3, 31.0 & 33.0

Composition verification:
Laue X-ray back reflection

Dogbones Cut:
EDM along (100) face in **[100]** & **[110]** directions

Strain measurement:
Bi-directional **strain gage** rosettes **[100]** &**[110]**

RUS samples (notches) cut from dogbones after testing



Monotonic Tension Tests

Setup & Procedure:

Longitudinal and transverse strain gages

Room temperature

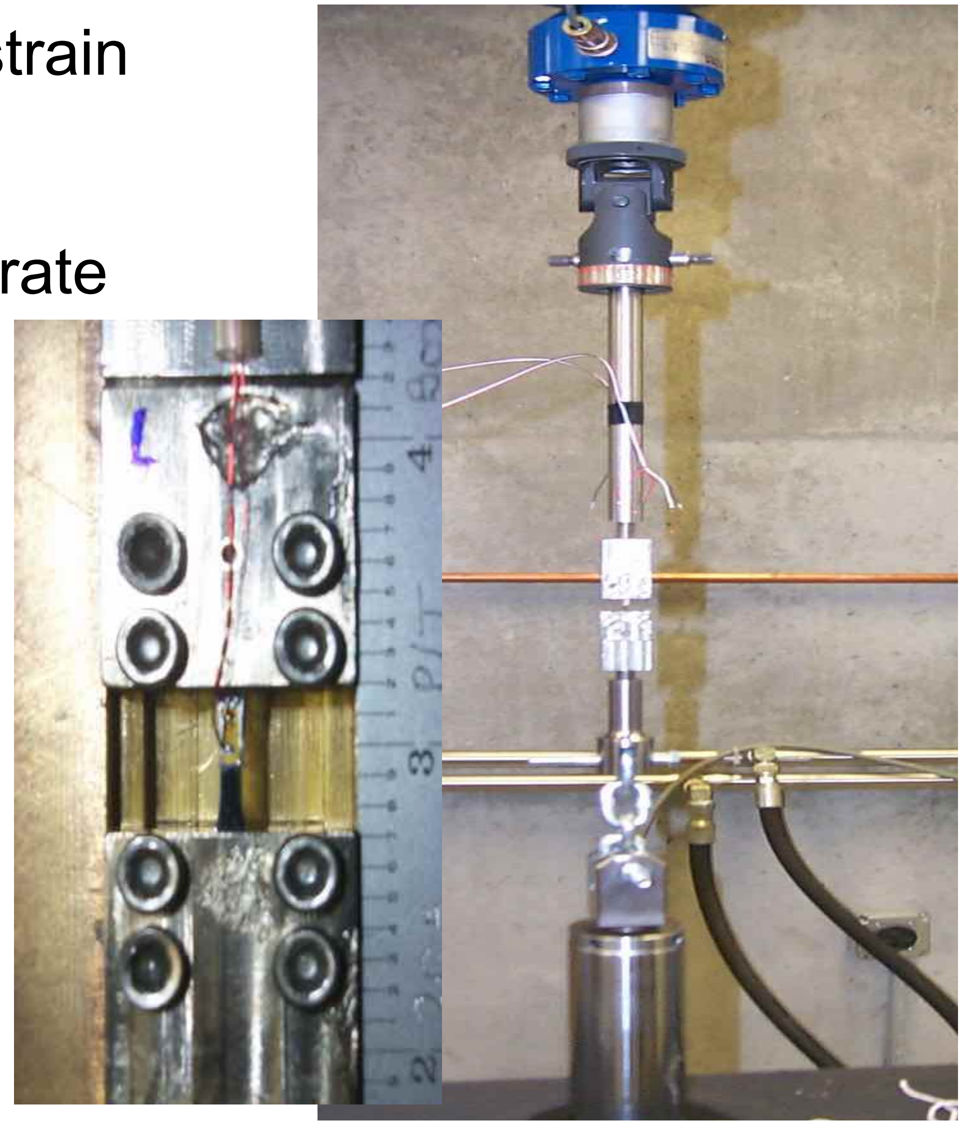
MTS machine pull - constant rate mode @ 0.5 μm/s

Elastic regime ~ 3 με/s

Plastic regime ~ 18 με/s

Pulled specimens ~ 2% strain

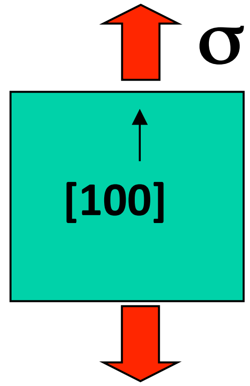
Testing under magnetic fields also conducted

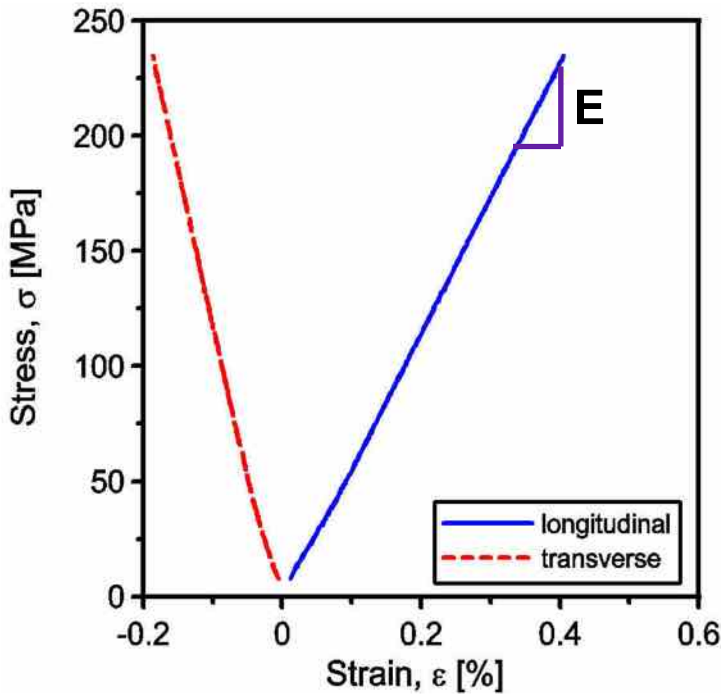


from Dr. R. Kellogg's Dissertation

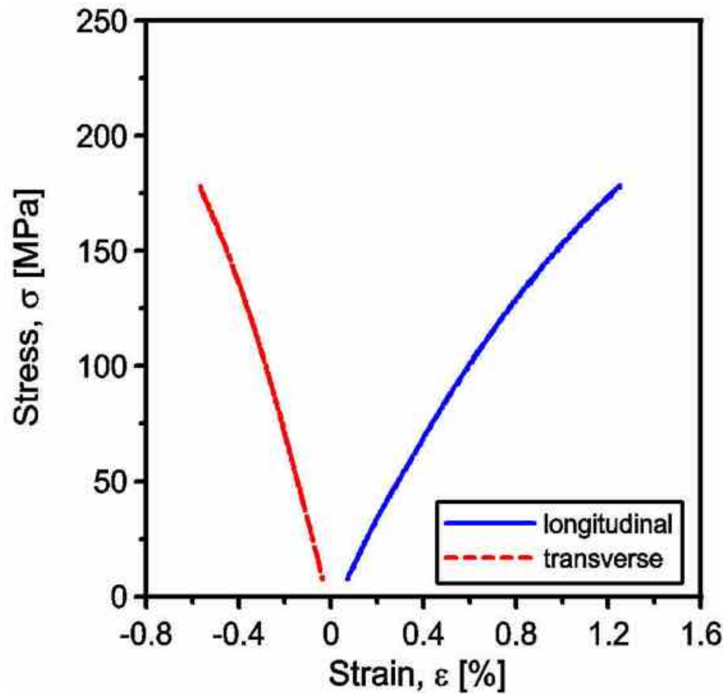
[100] Tension Test Experimental Results

- Load applied along [100] direction, measure strain responses in the longitudinal & transverse directions
- Ratio of stress & strain give **elastic modulus, E**
- Negative ratio of longitudinal and transverse strains gives the **Poison ratio, *ν*, (nu)**





• 18.6% Ga

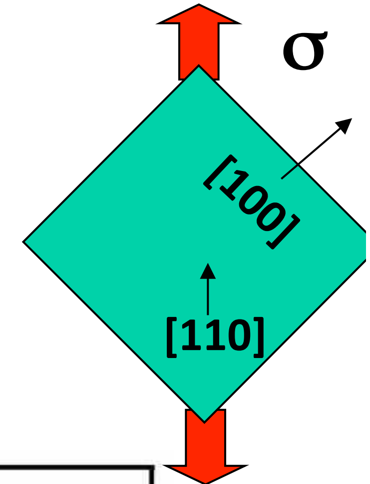


• 28.9% Ga

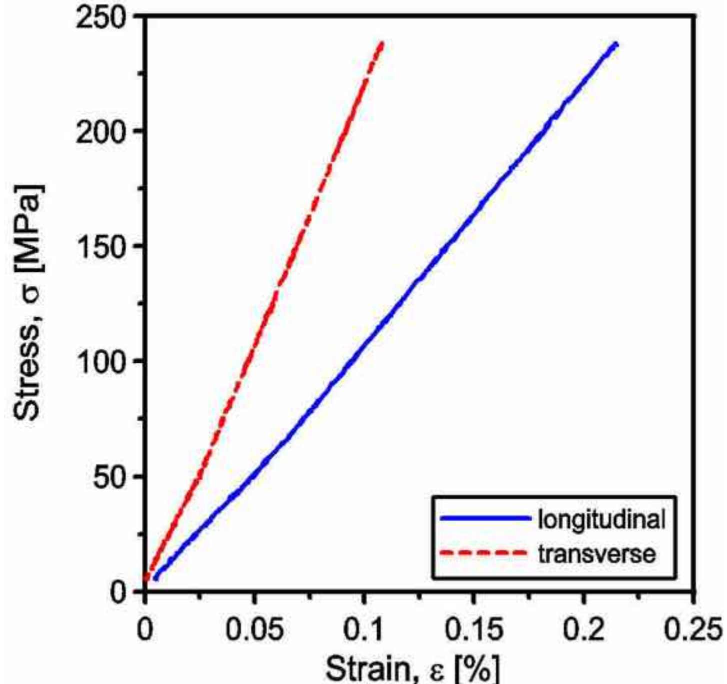
The test speed is 0.5 μm/sec in each test with constant load limits.

[110] Tension Test Experimental Results

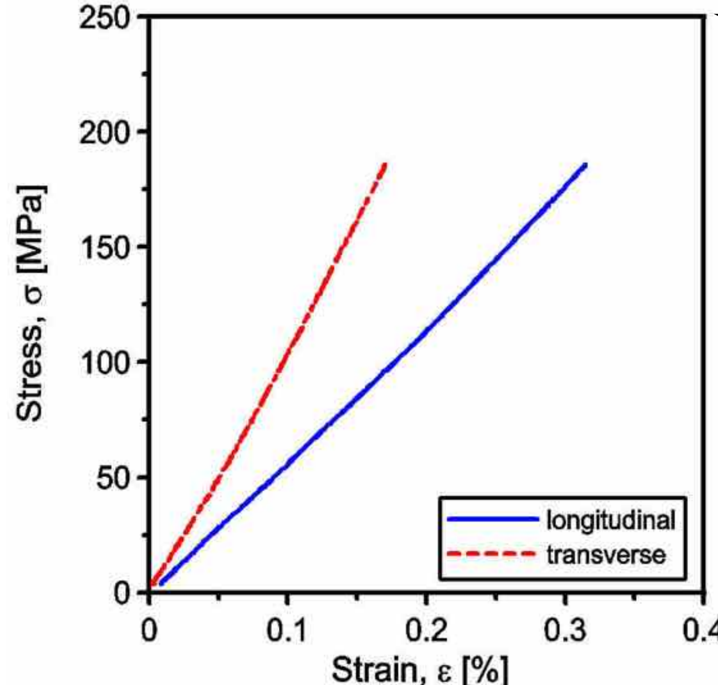
- Load applied along [110] directions
- Samples get longer and wider (and really thin!)
    - Both stress-strain curves have a positive slope!!
- The **alloys have a negative Poisson ratio**



Alloys are AUXETIC in [110] directions

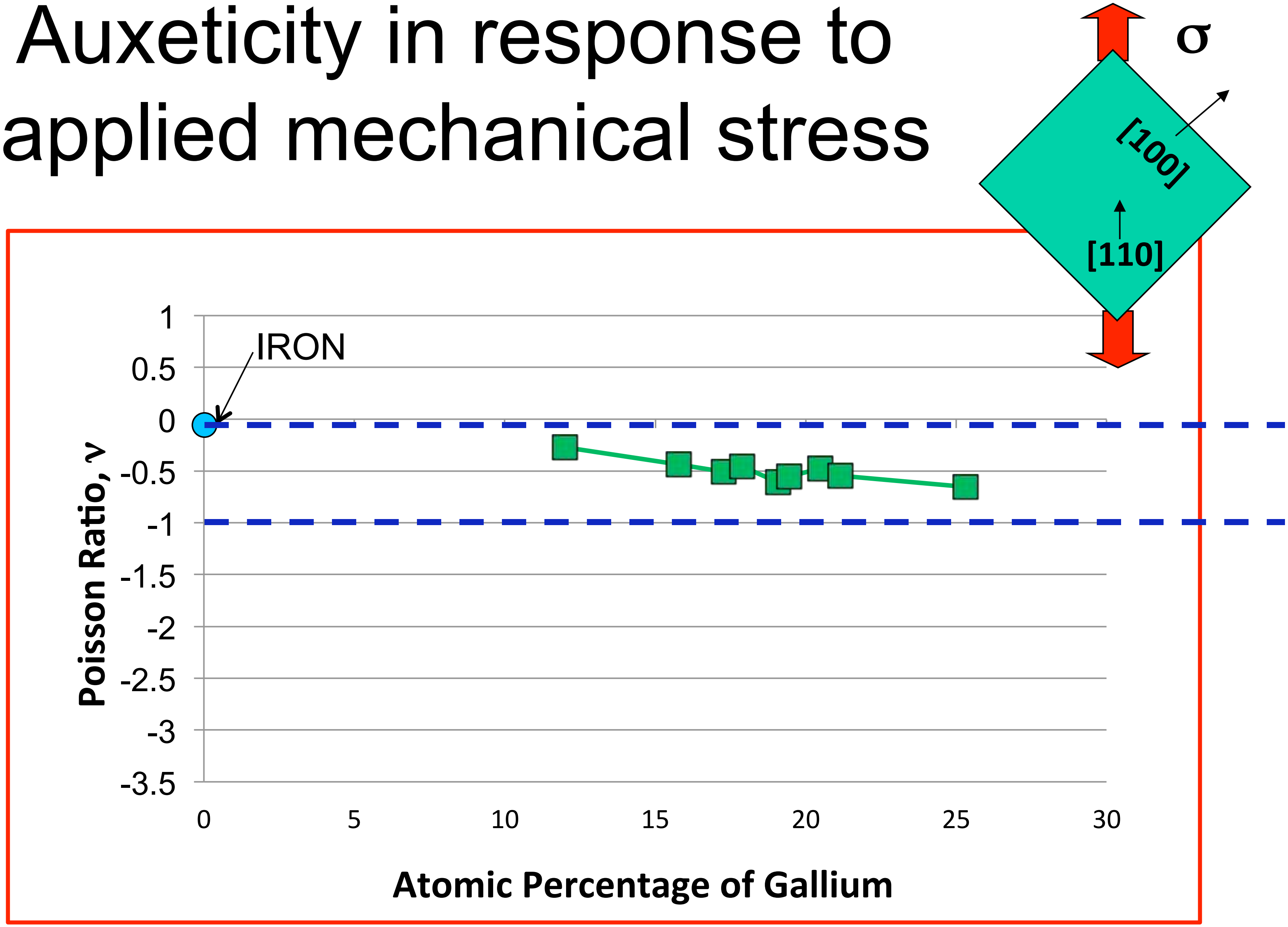


• **18.7% Ga**

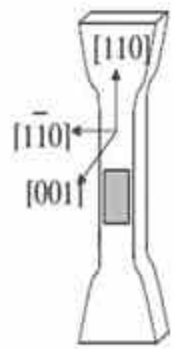


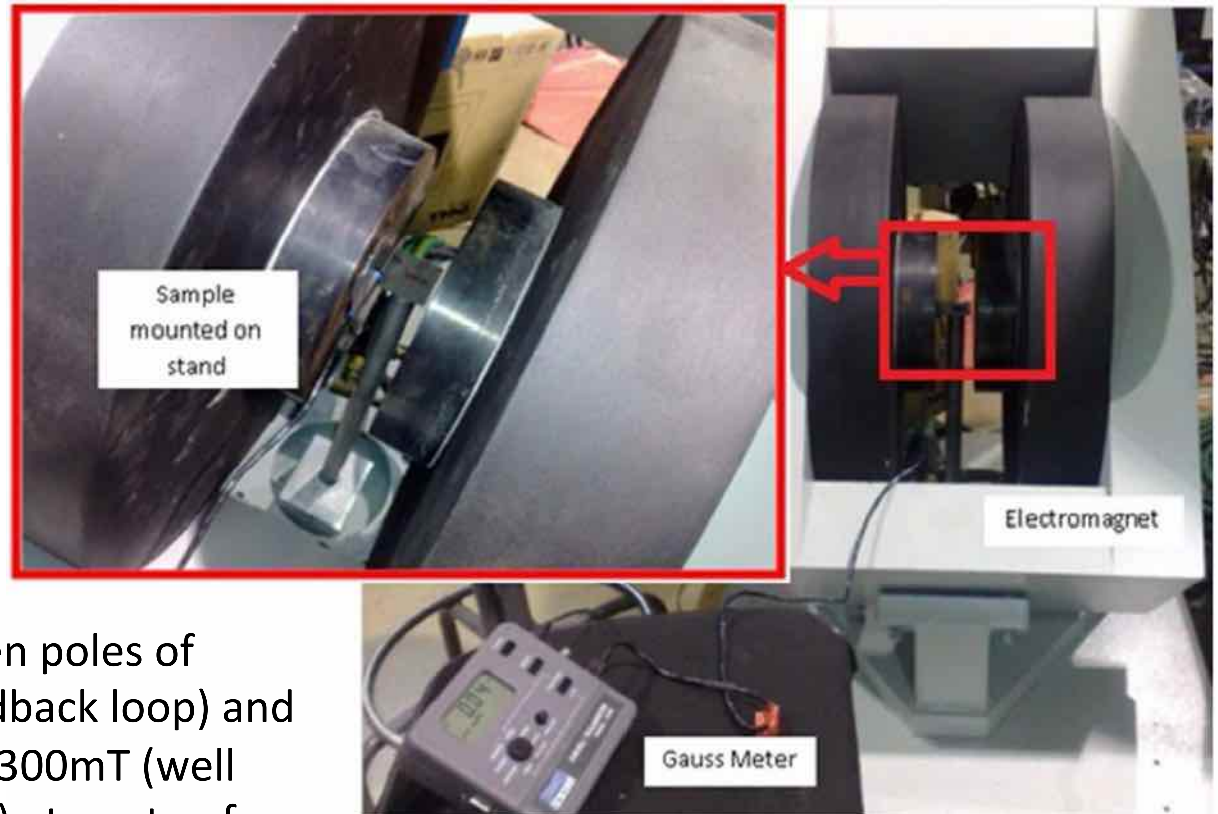
• **28.4% Ga**

Auxeticity in response to applied mechanical stress



Magnetically induced auxeticity in Galfenol?

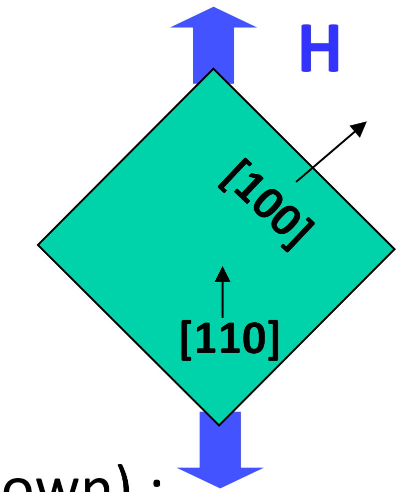




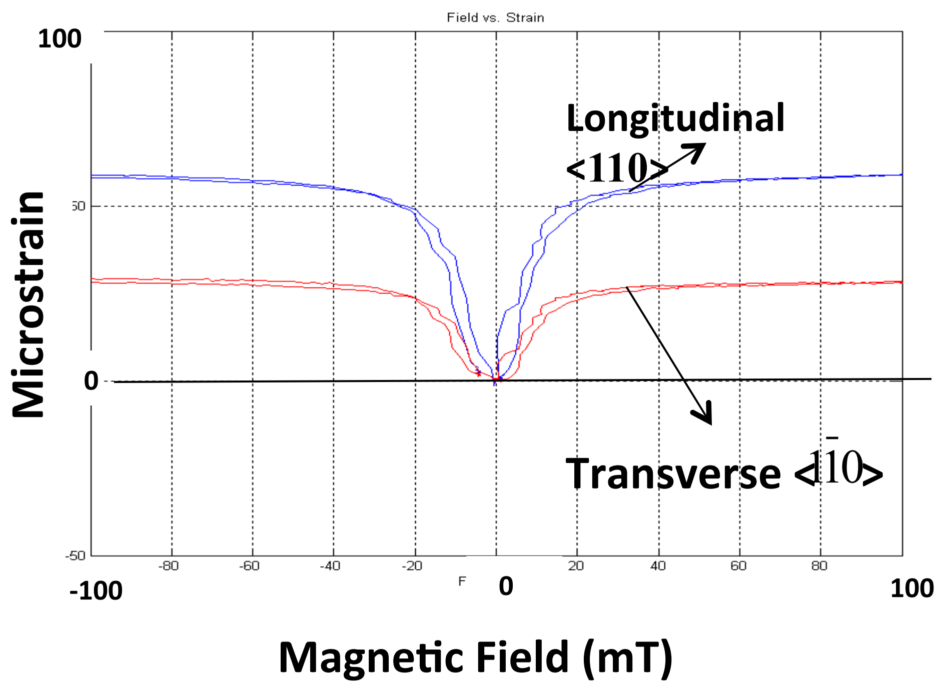
Sample mounted between poles of electromagnet (with feedback loop) and field was ramped up to ±300mT (well past magnetic saturation) at a rate of ±10mT/s

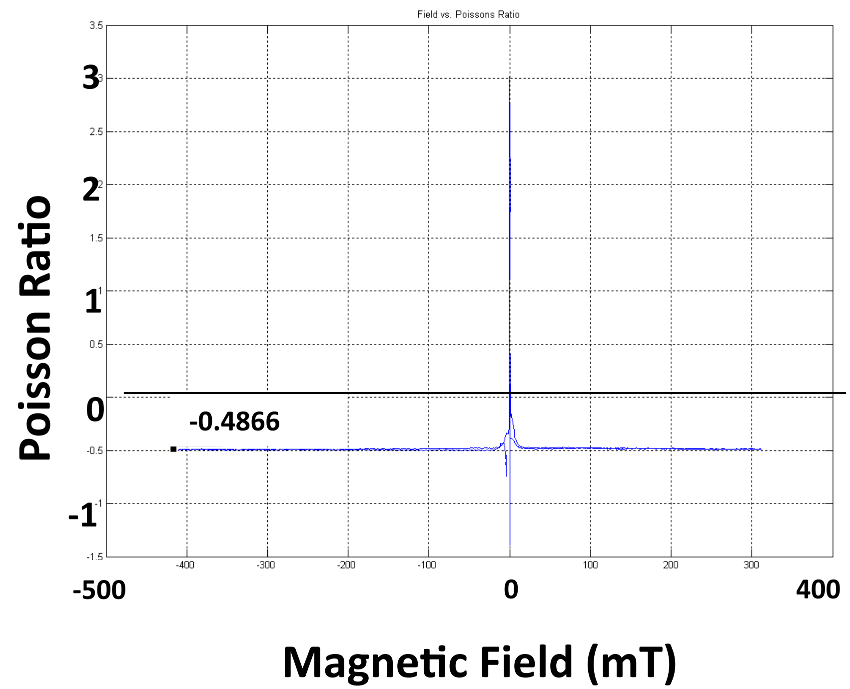
....is there a Delta Poisson Ratio Effect?

Yes! Poisson Ratio (negative ratio of longitudinal to transverse strain) changes when a DC magnetic field is applied along the sample length



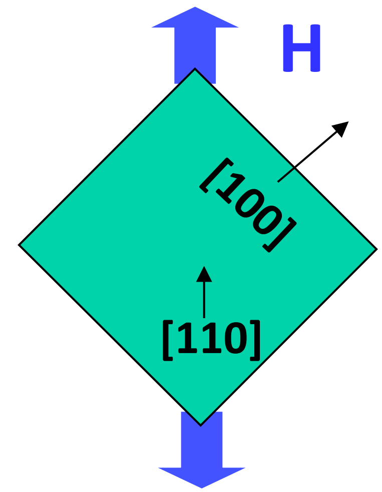
Typical results from [110] Galfenol Samples (31% Ga shown) :



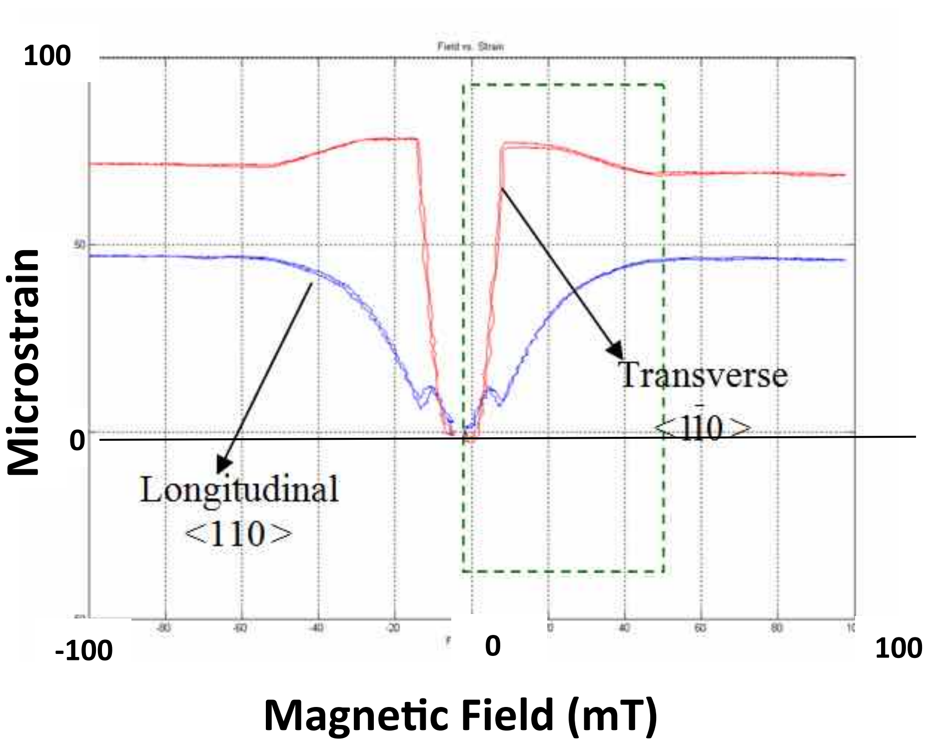


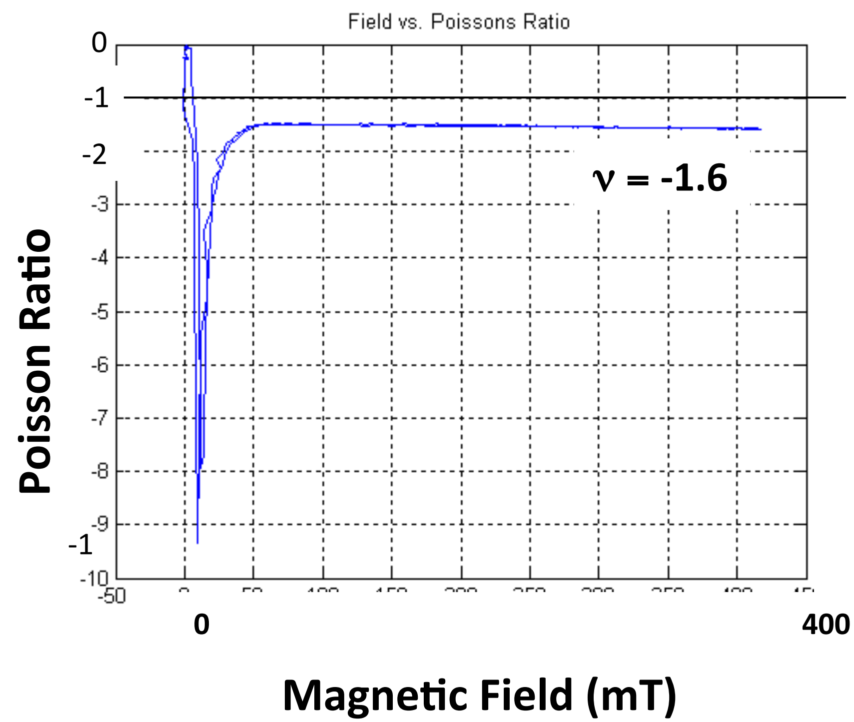
For compositions of <17% Ga, sample width increases more than the length!

Poisson ratio is less than -1.0!



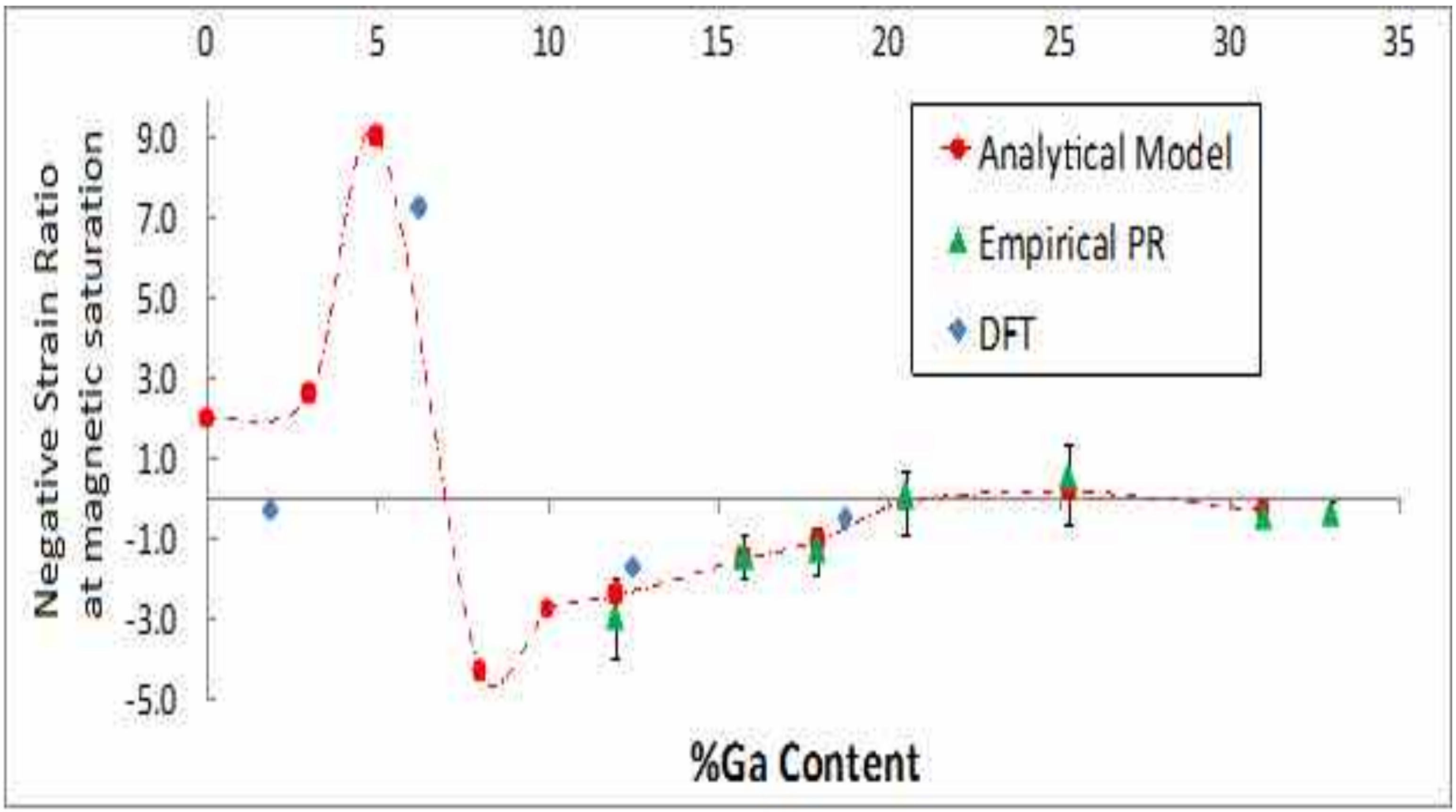
Results from the 16% Ga [110] Galfenol Sample:



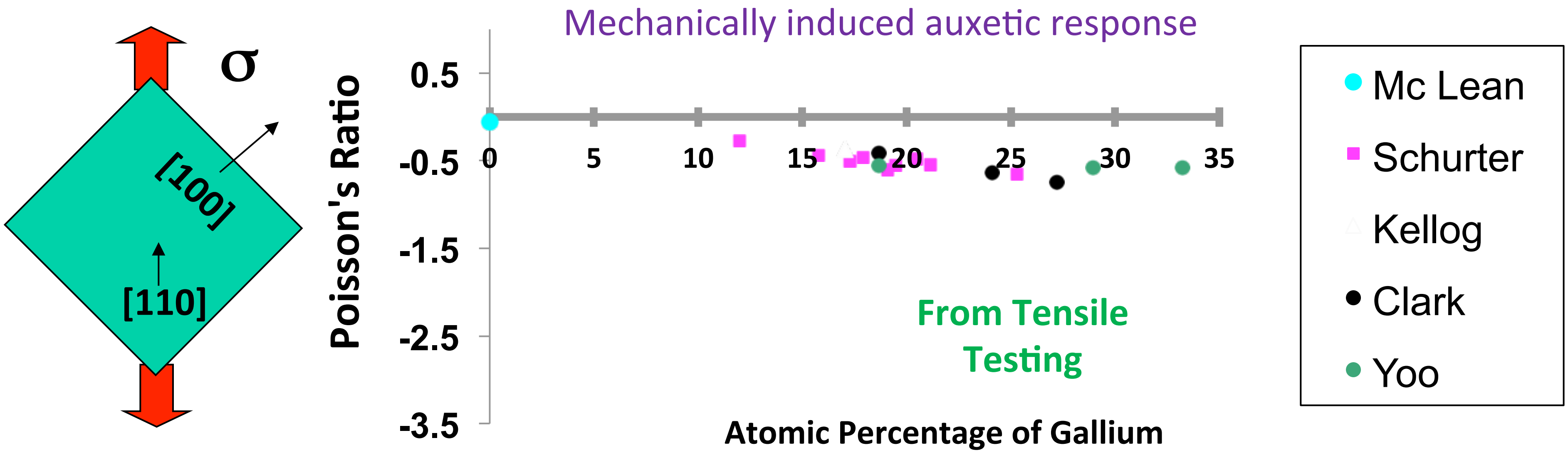


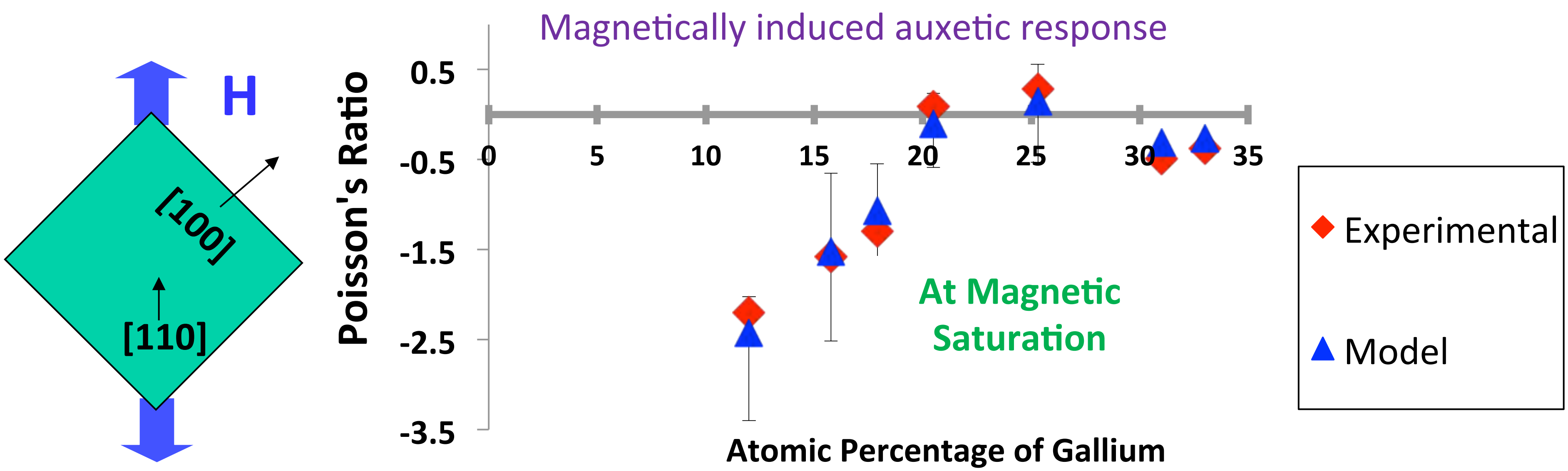
Comparison of models and experimental Poisson ratio data.

Poison ratio values under a saturating magnetic field (400 mT) for different compositions of FeGa from an energy-based analytical model, density functional theory simulations, and ratios of measured strain values

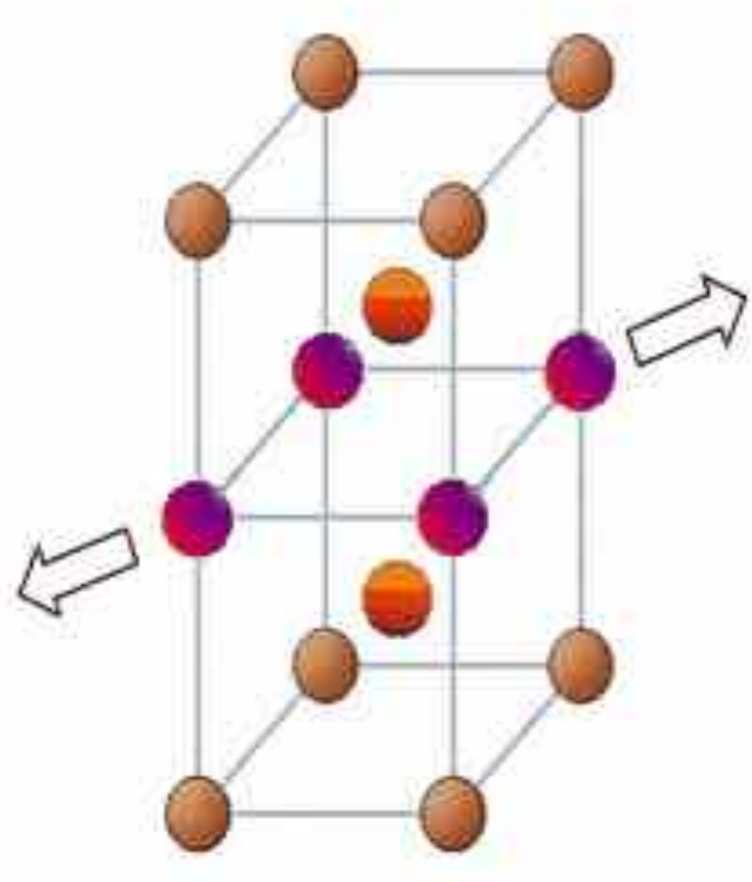


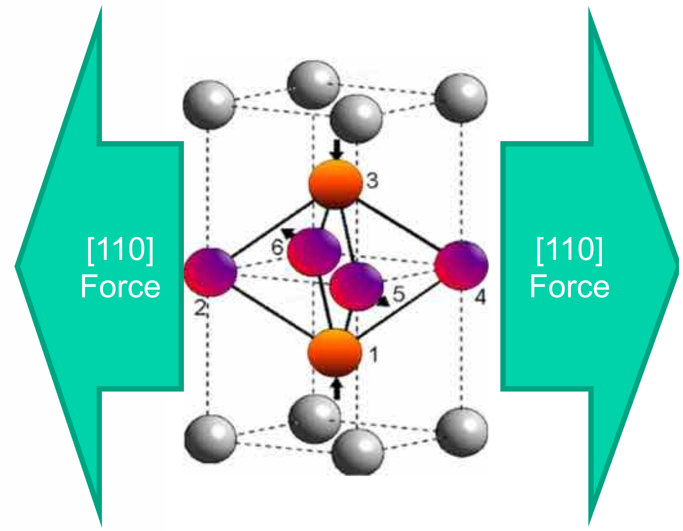
Poisson ratio data for Galfenol of different compositions





GAS MODEL FOR AUXETIC EFFECT IN BCC CRYSTALS





Atoms that move away from one another

Atoms that approach one another

Baughman 1998

Outline

Intro to Magnetostriction

- **Actuators: the “direct” effect**
- **Sensors: the “inverse” (or Villari) effect**

Structural Magnetostrictive Alloys

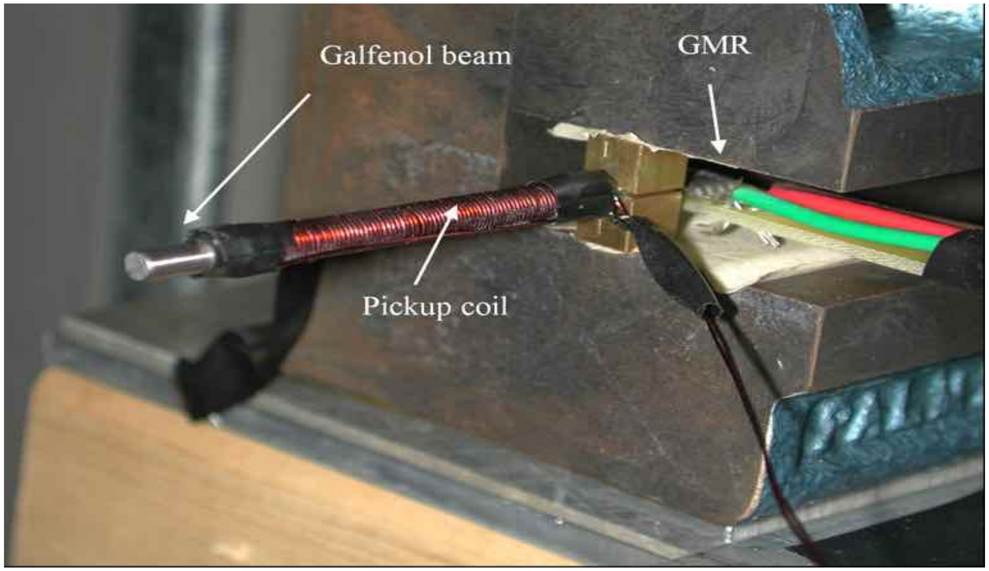
- **Magnetostrictive, magnetic & mechanical properties**
- **Thin, highly textured rolled sheet**
- **Introduction to auxetic behavior**

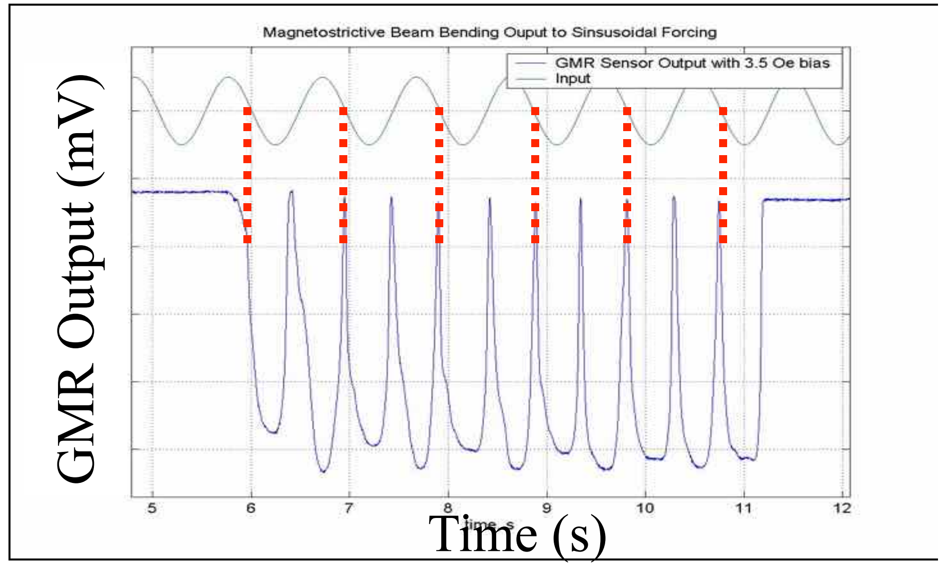
Applications that use Galfenol

- **Bending sensor applications**
- **Implantable wireless bone fixity sensor (Tech Univ. Dresden)**
- **Nanowire sensors (Univ. Minn. & UMD)**
- **Applications for auxeticity?**
- **Micro-motors (Kanazawa University, Japan)**
- **Energy Harvesting (Kanazawa Univ, UMD & Techno Sciences, Inc., Oscilla Power)**

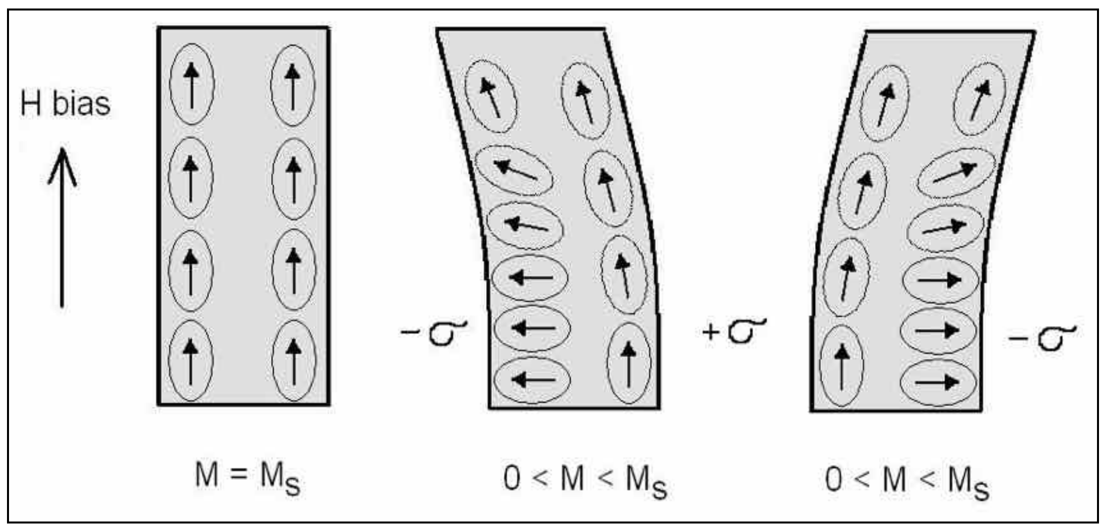
Summary

Early Bending Tests



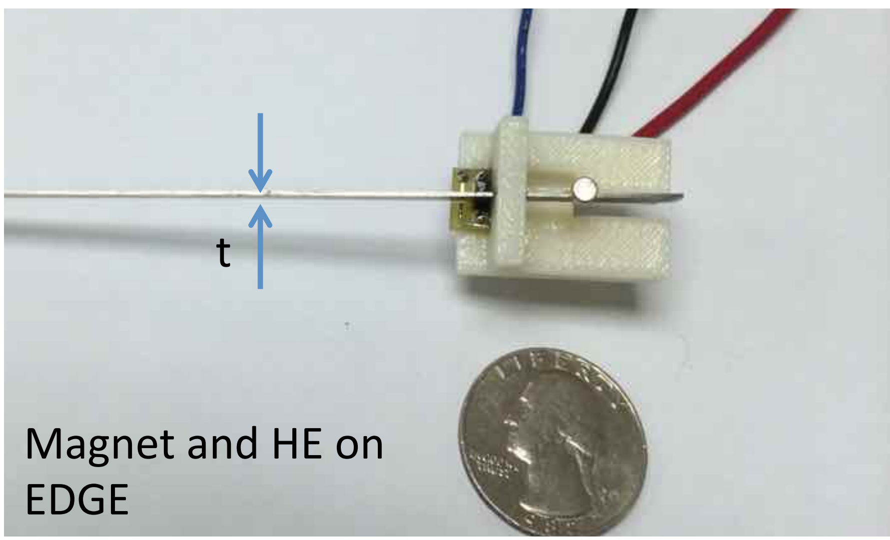


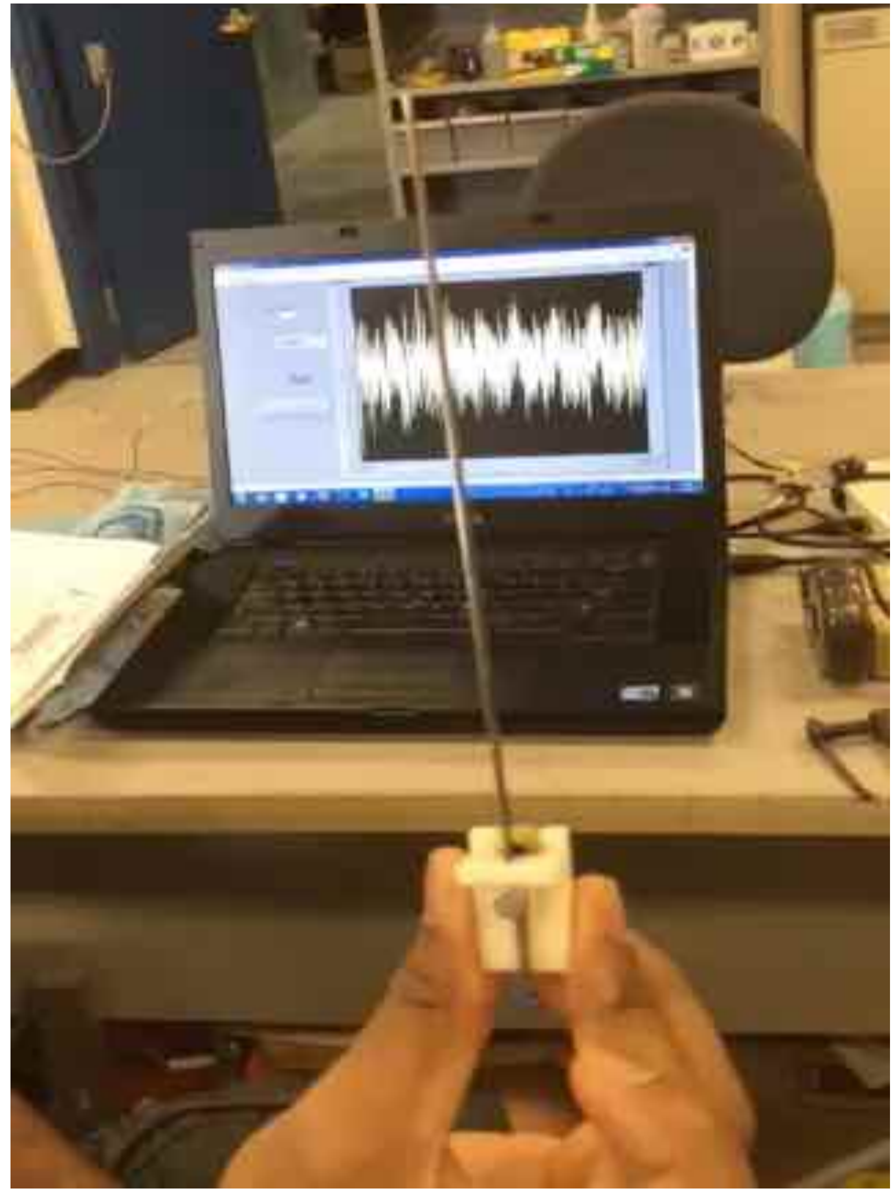
- Tensile stresses act trivially in same direction as bias field
- Compressive side of beam controls response
- Bias shifts where max coupling occurs
- GMR measures volume-averaged change in induction



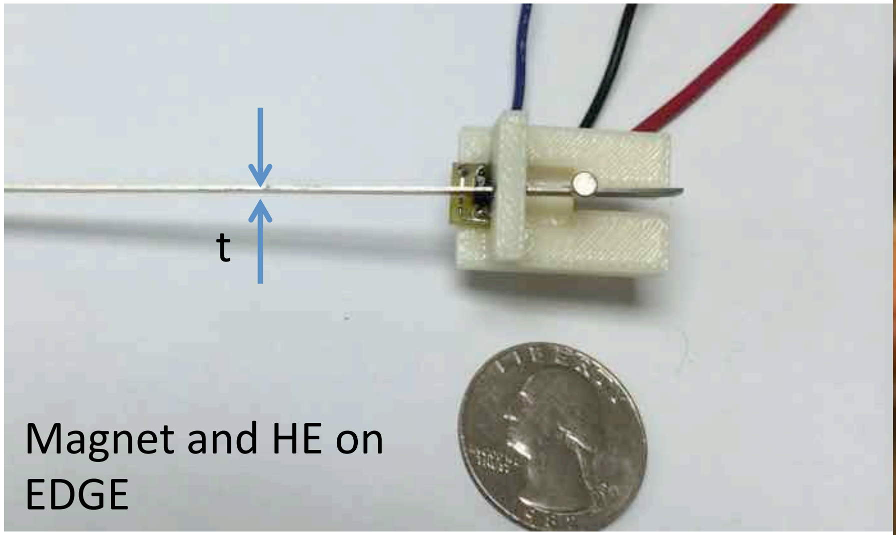
(NOTE: will show later these assumptions were only partly correct!)

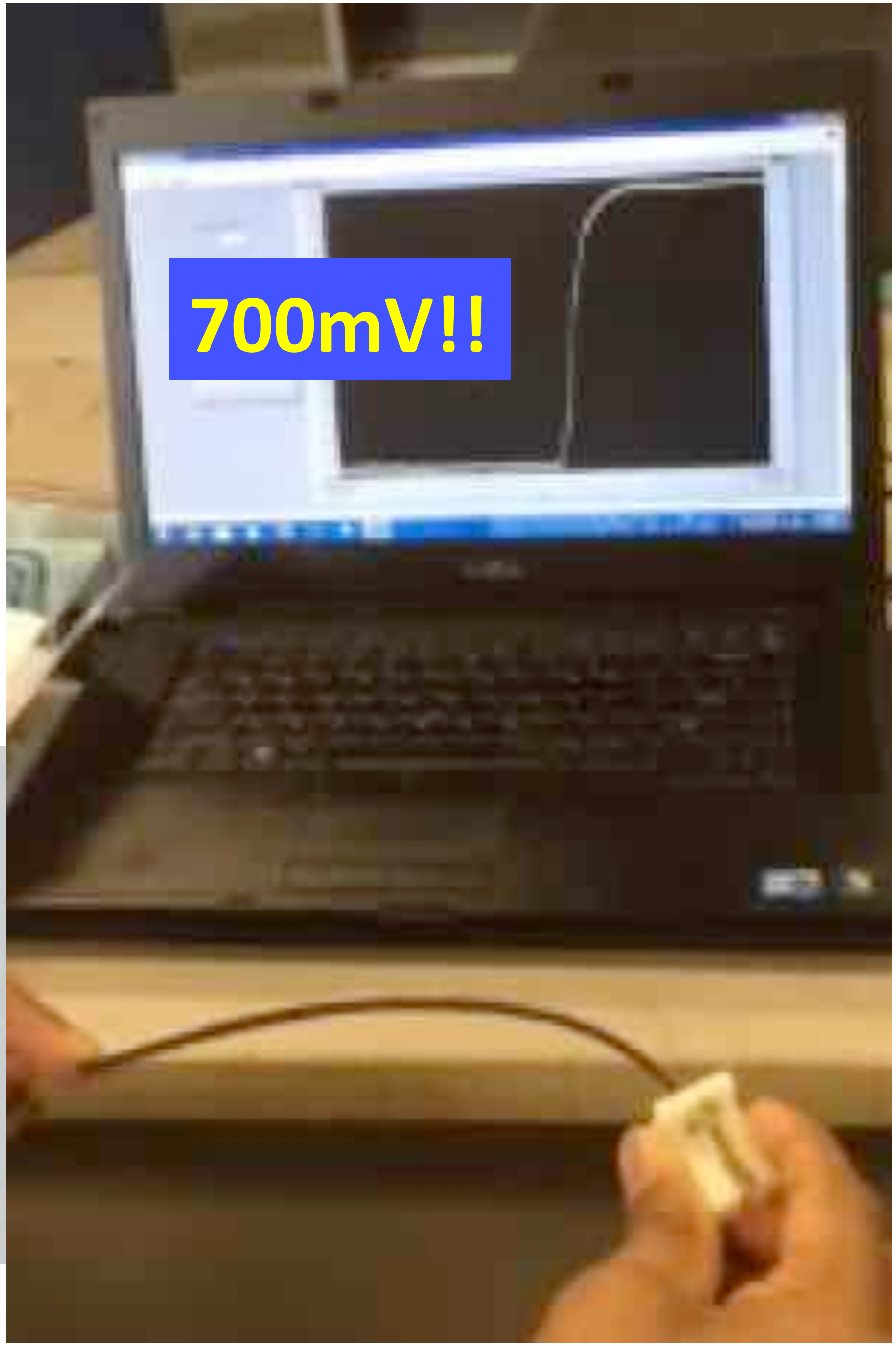
Bio-inspired thin "whisker-like" bending sensors





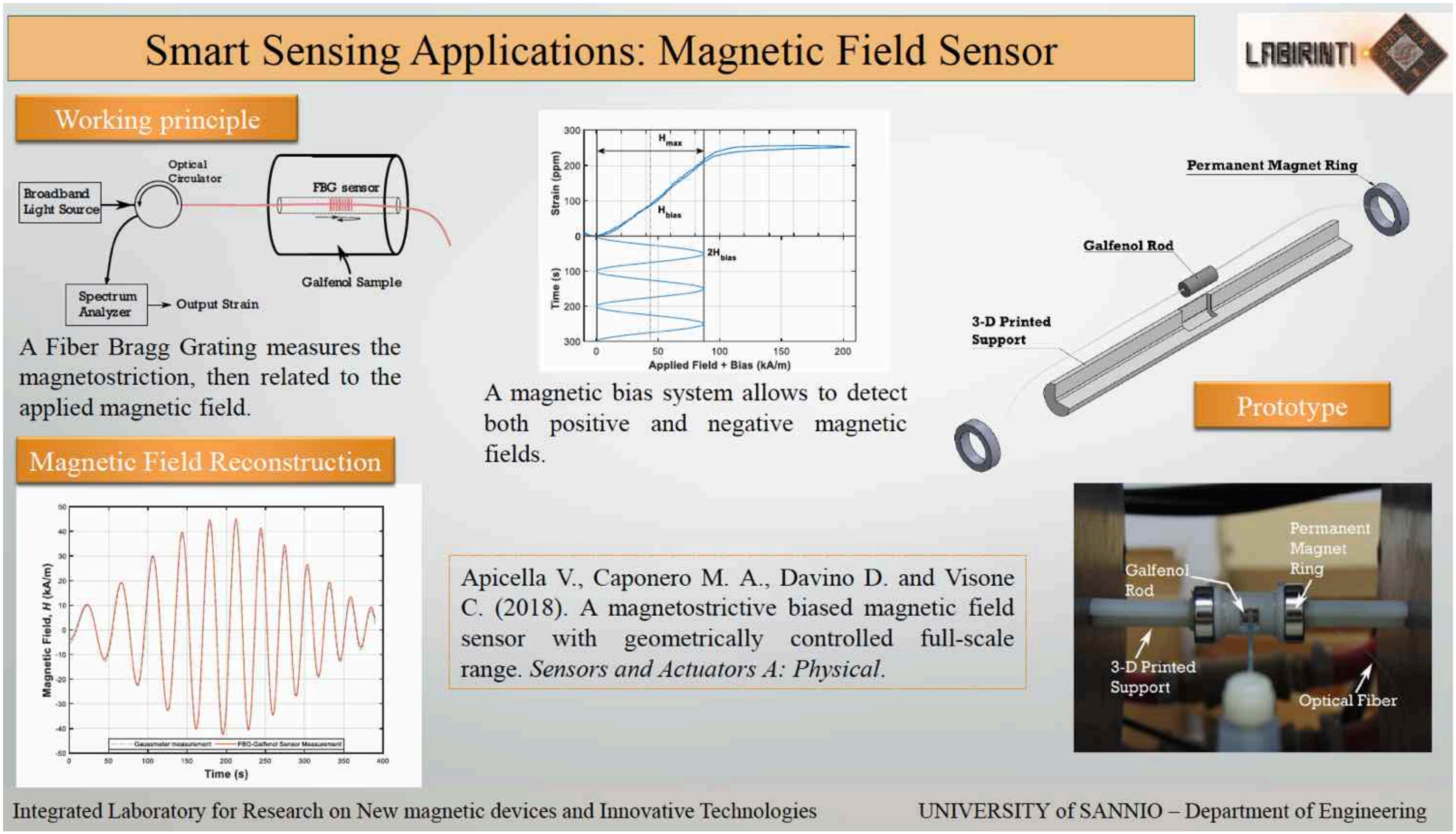
Bio-inspired thin “whisker-like” bending sensors





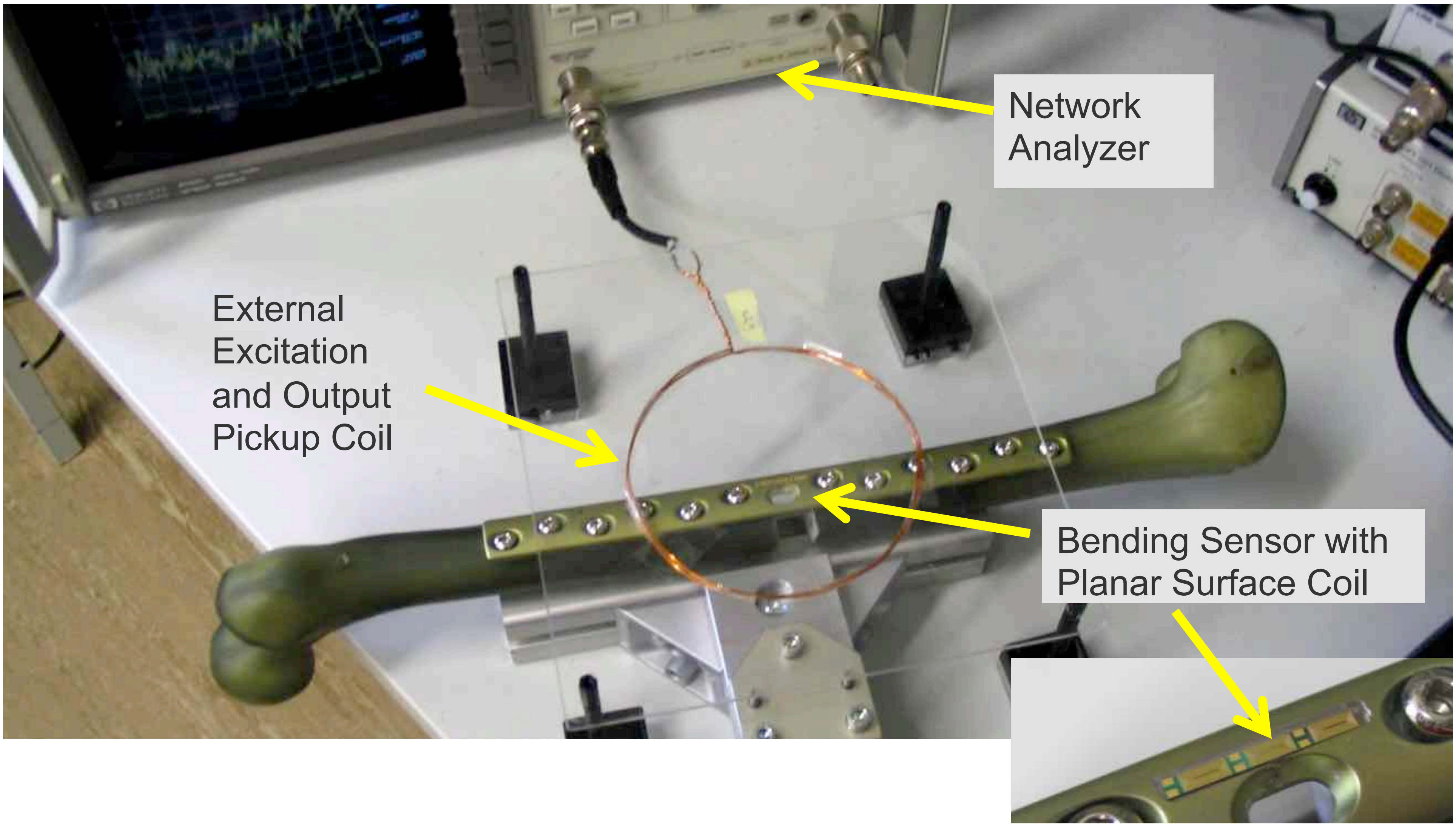
Magnetostrictive biased magnetic field sensor

Apicella, Caponero, D. Davino & C. Visone (2018); Univ. Sannio-Benevento, ITALY

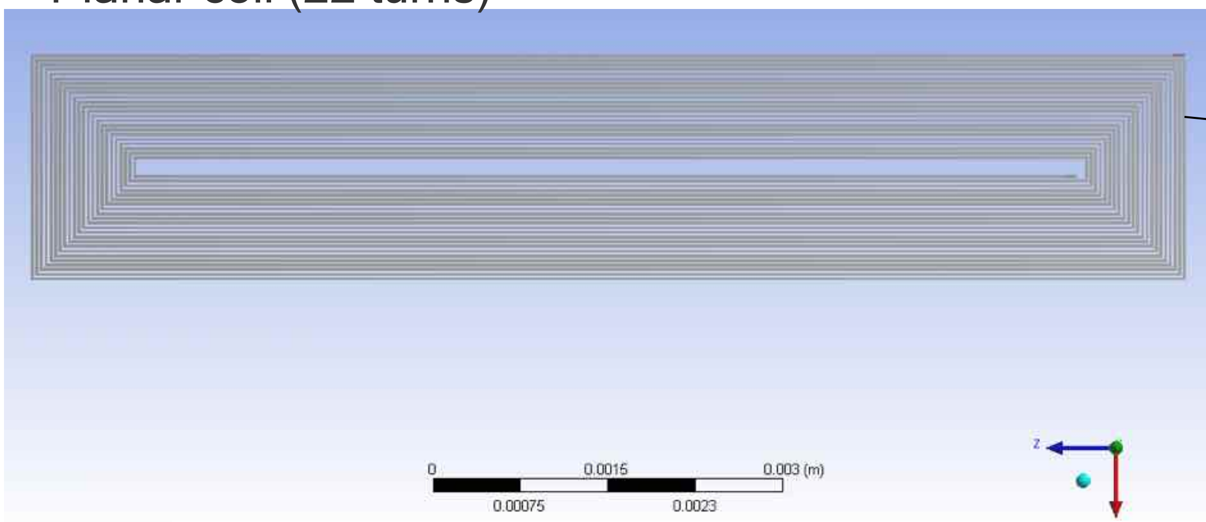


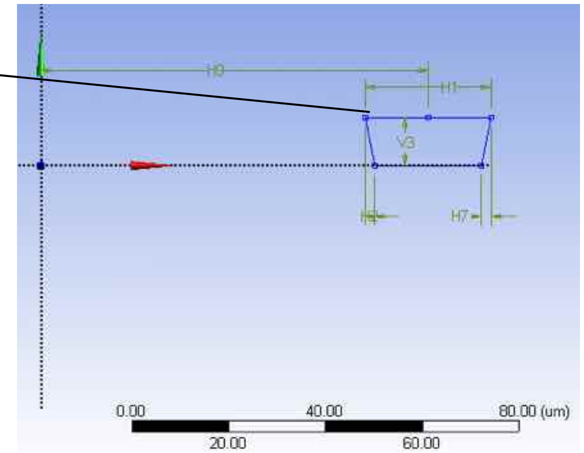
Galfenol Resonant Sensor for Indirect Wireless Osteosynthesis Plate Bending Measurements

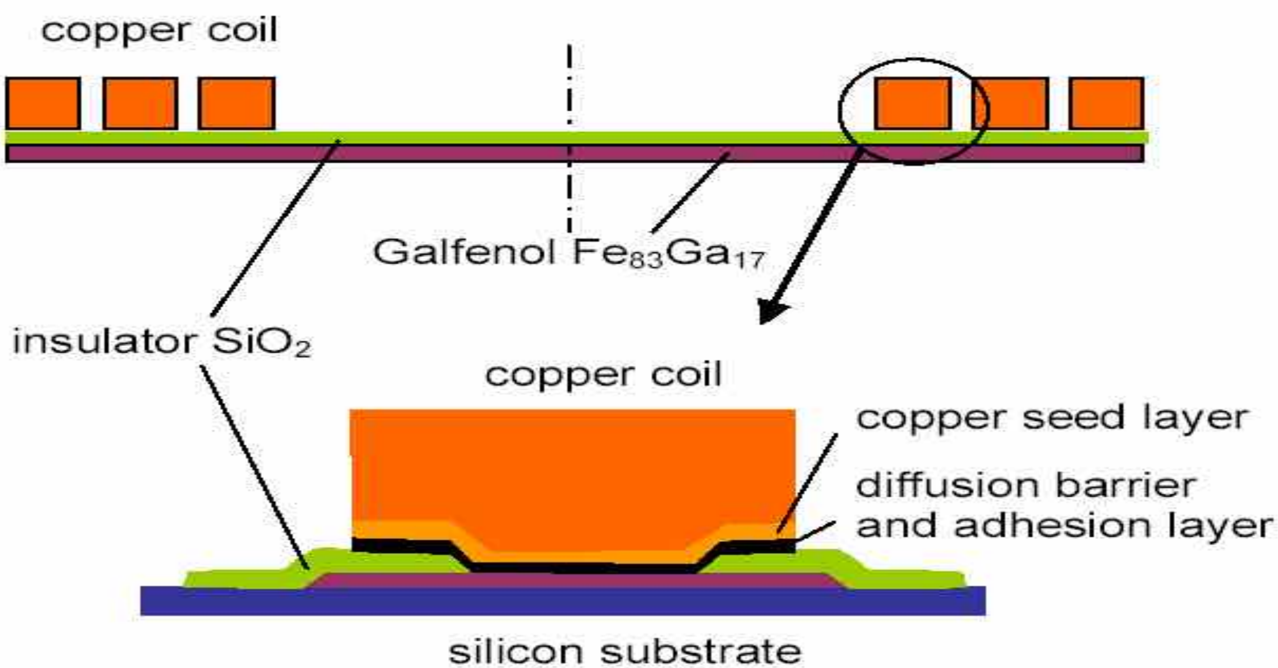
Fischer et al. (2009); Wentzel et al. (2009); Tech. Univ. Dresden



Planar coil (22 turns)







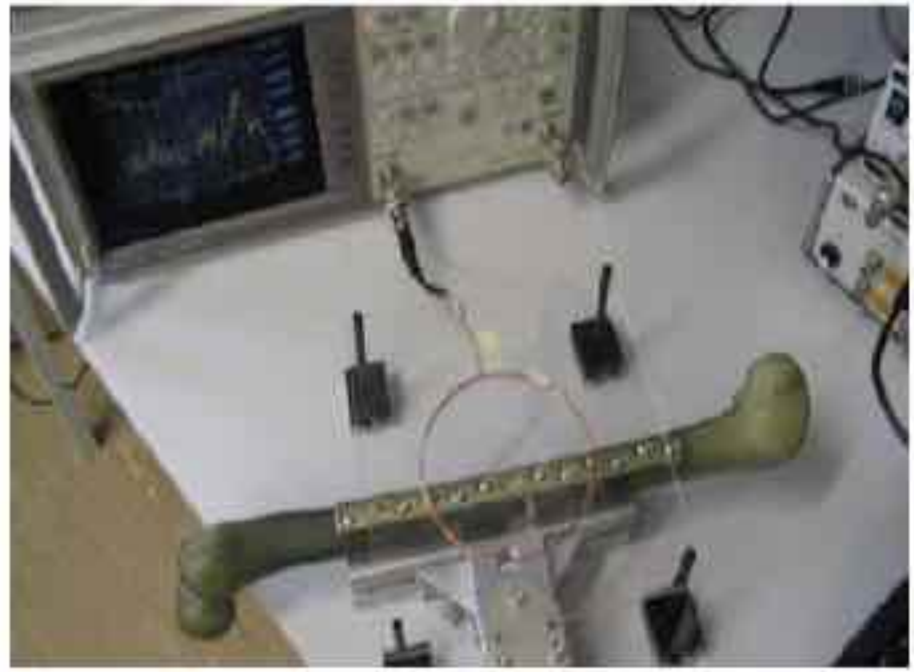
Fischer et al. (2009); Wentzel et al. (2009); Tech. Univ. Dresden

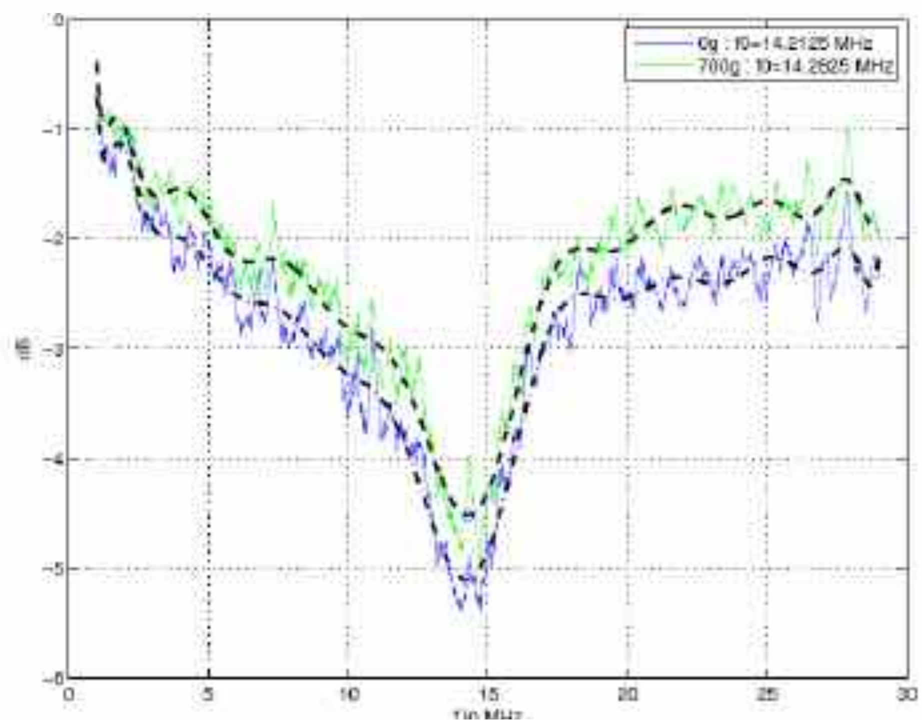
Stress induces a change in permeability. Changes resonance of planar coil

Excitation/pickup coil 1 cm above bone plate and 6 cm radially from center of 10 x 2 x 100 mm^3 sample

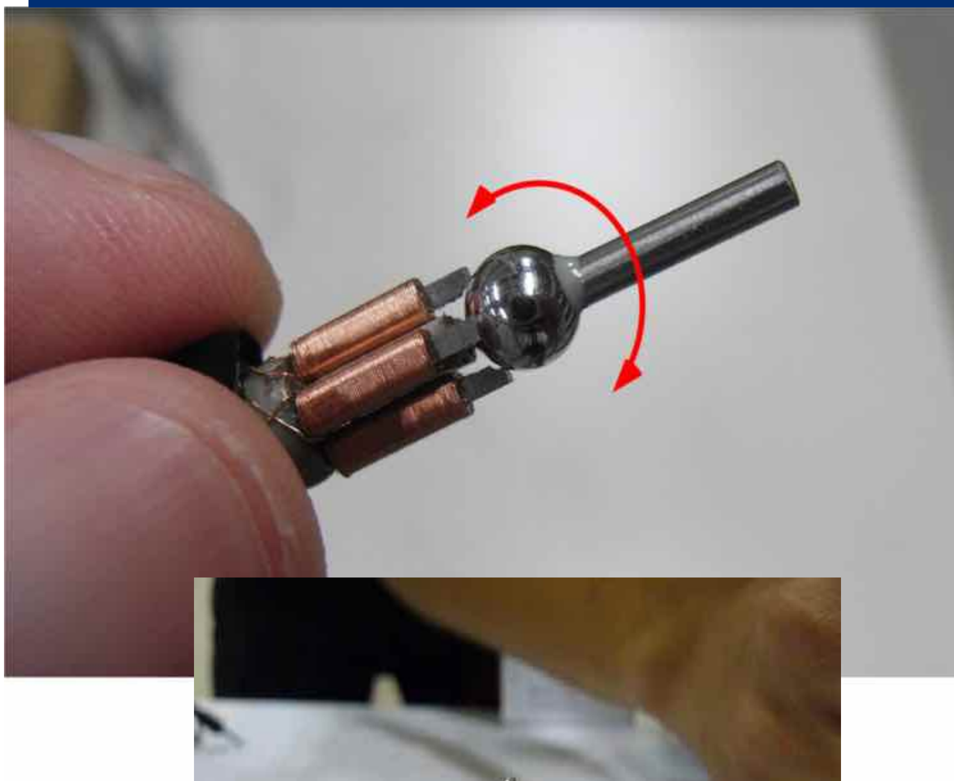
Loading of 700 grams produces a 70kHz shift in resonance

Fischer et al. (2009); Wentzel et al. (2009); Tech. Univ. Dresden





Micro spherical motor Prof Toshiyuki Ueno
Kanazawa Univeristy, Japan



Galfenol → drive element and magnetic core

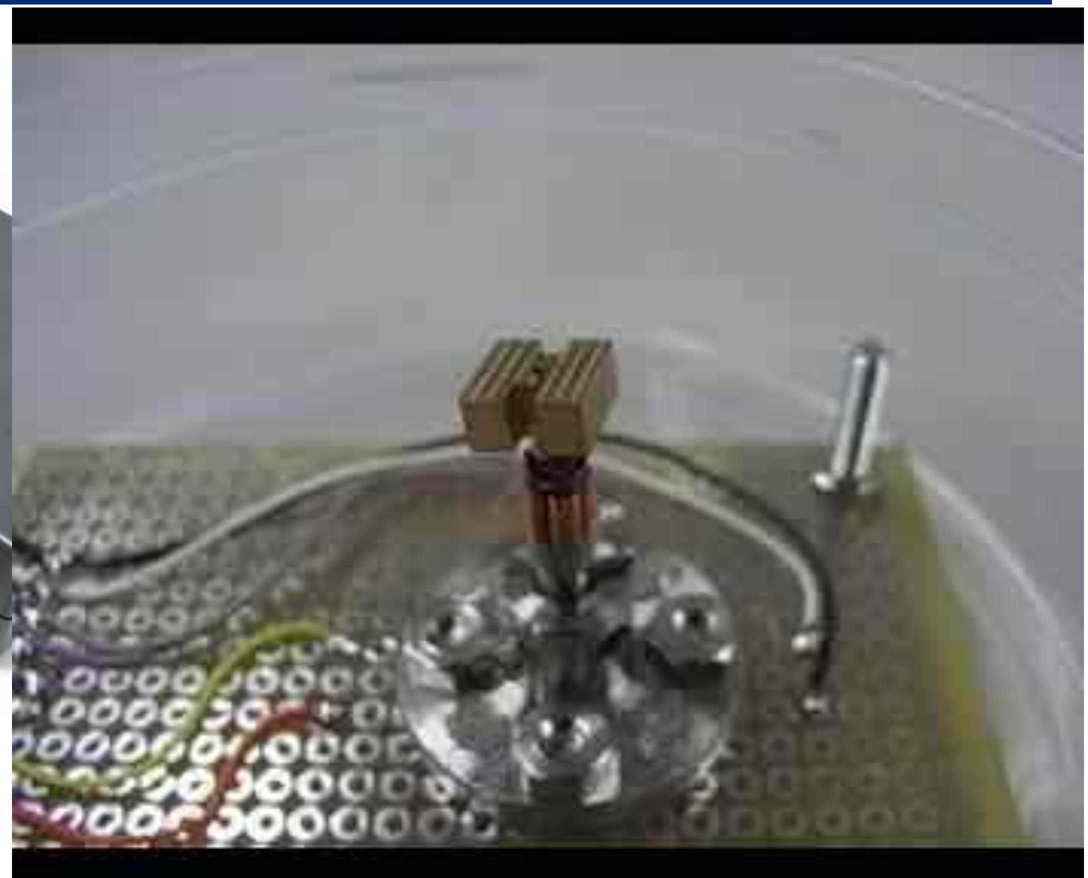
Advantage

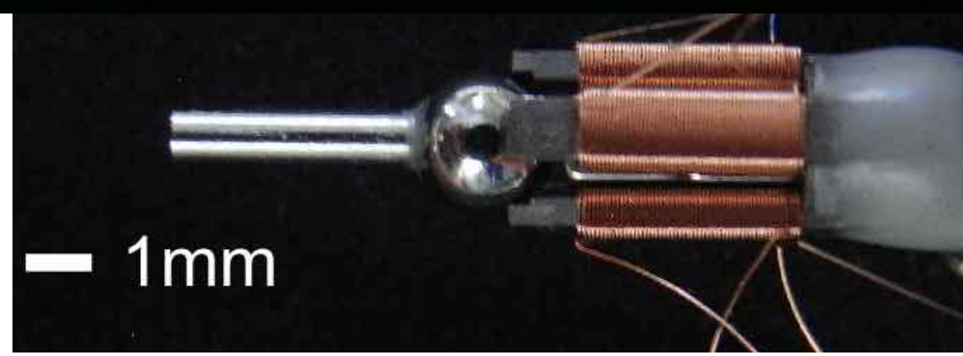
- ○ **Simple and small**
- ○ **Holding mechanism**
- ○ **Low voltage driving by simple circuit**

used at endoscope for e.g. minimally invasive surgery

Joint of micro robot (amusement)

Movie of movement



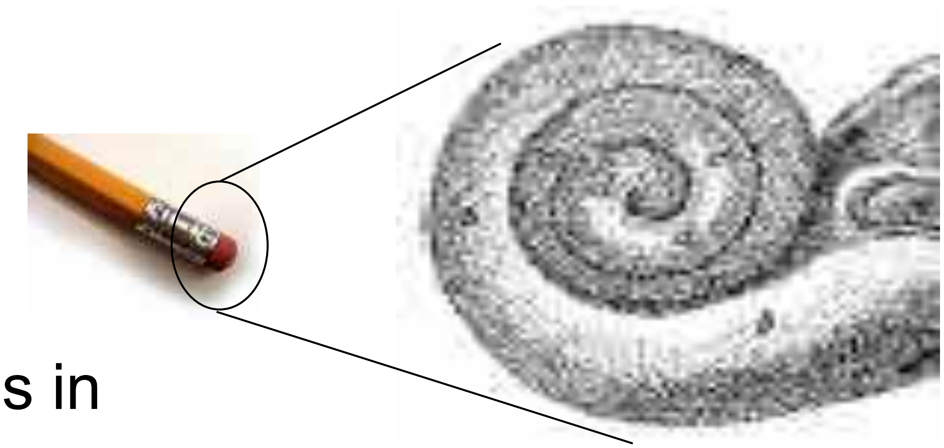


Driving condition: saw tooth current ±0.2A 2 kHz

DOF	2
Angle range	360°
Angle velocity	50°/sec
Driving voltage	5V (USB)

Cilia: Nano-scale transducers

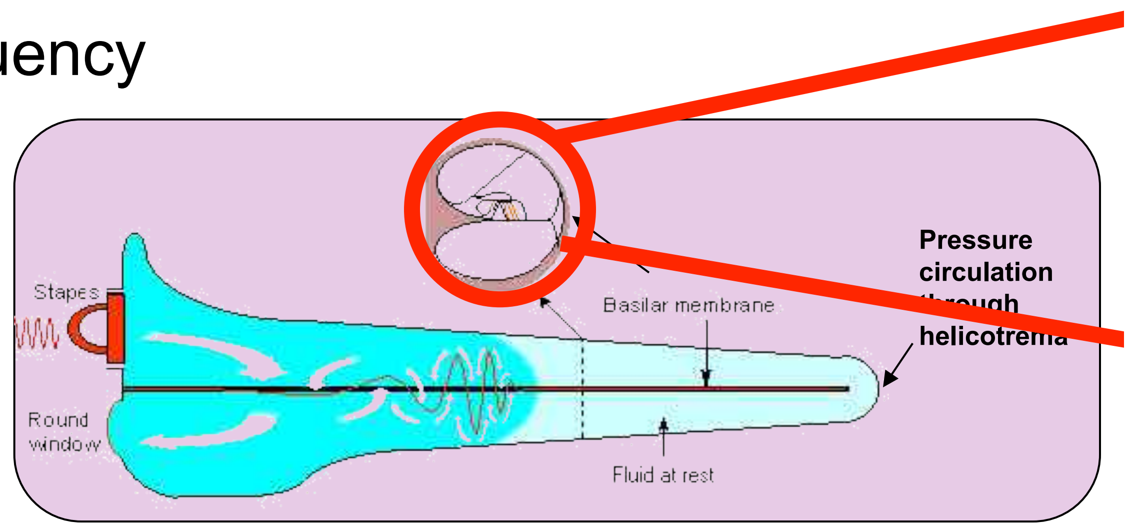
- Human cochlea: ~98mm^3
  - ~ 35 mm long with varied width & thickness.



- Basilar membrane increases in width and thickness with distance

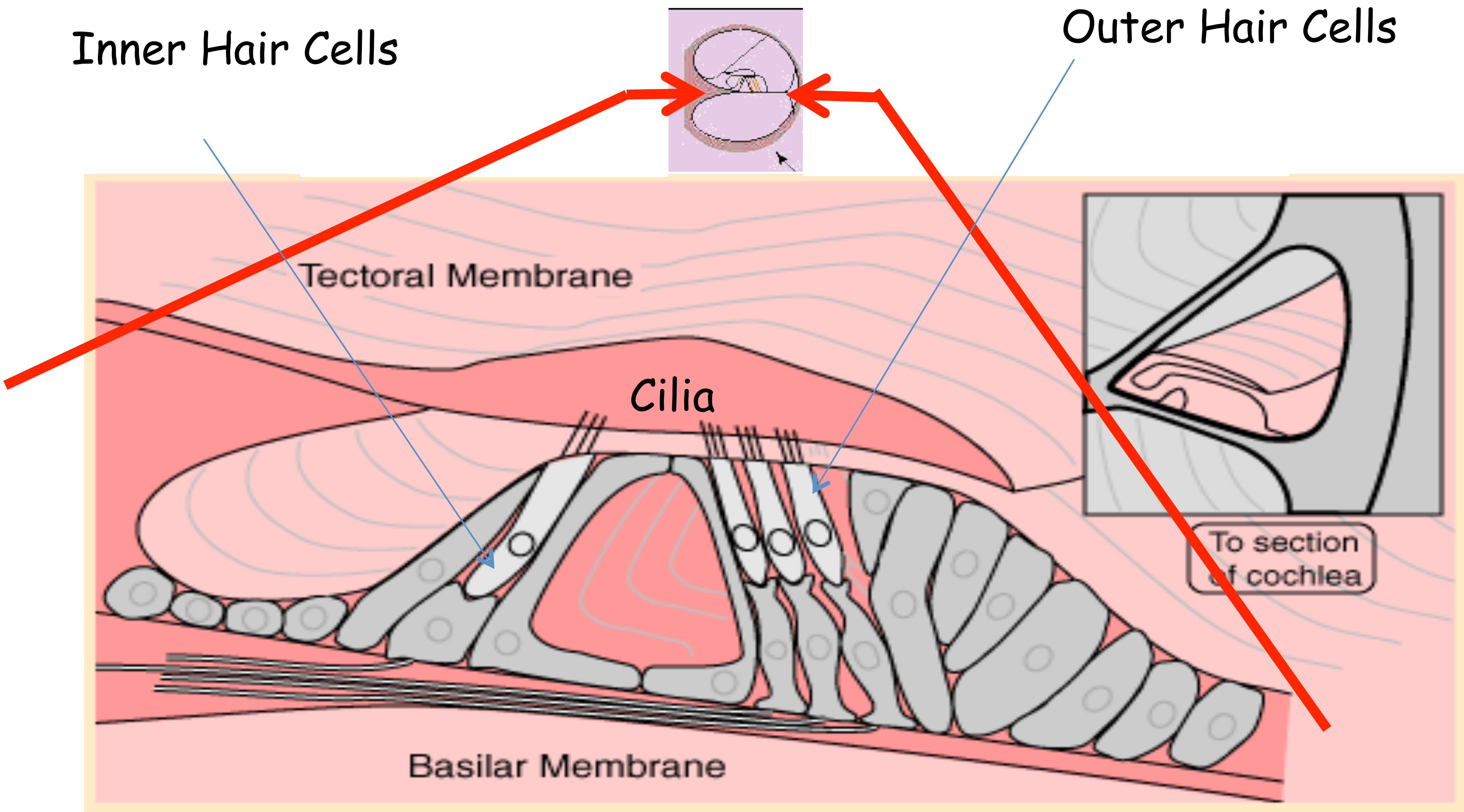
- Cochlea acts as a low pass spatial filter, with high frequency response near stapes/oval window

- Location of maximum motion correlates to the detected frequency



/www.vimm.it/cochlea/cochleapages/theory/hydro/hydro.htm

Schematic of the cross-section of the human-ear cochlea



Ref: http://hyperphysics.phy-astr.gsu.edu/hbase/sound/corti.html

Cochlea/Cilia-based Sensors

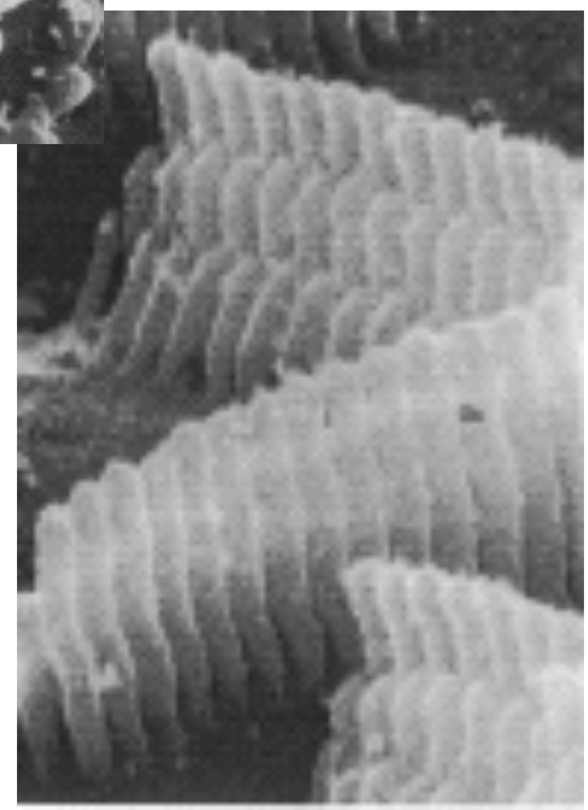
Cilia from inner hair cell

- ~3500 inner hair cells with
  ~50 cilia/cell

- ~12,000 outer hair cells with
  ~150 cilia/cell

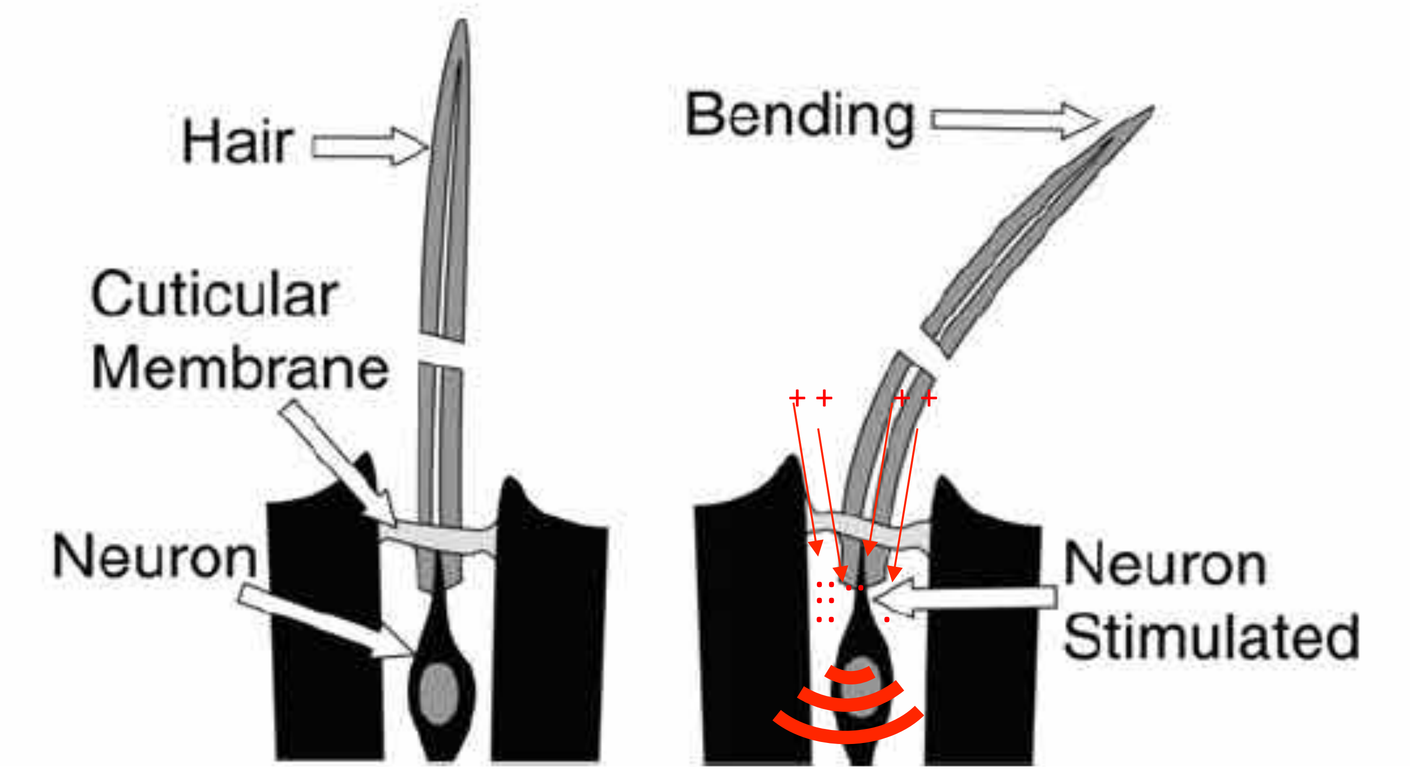
- Cilia dimensions:
  - ~2-6 μm long
  - ~100 nm at their base
  - ~250 nm at their tip (ohc)

- Cilia tips are tethered to neighboring cilia

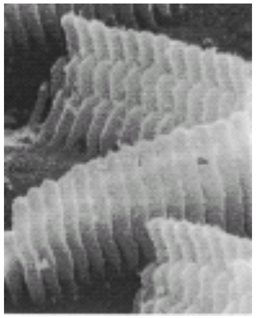


Cilia from outer hair cell

Cilia & Whiskers as sensors

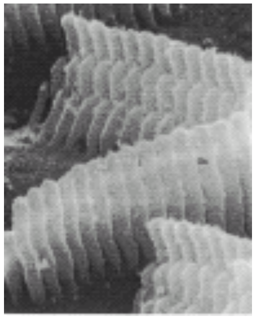


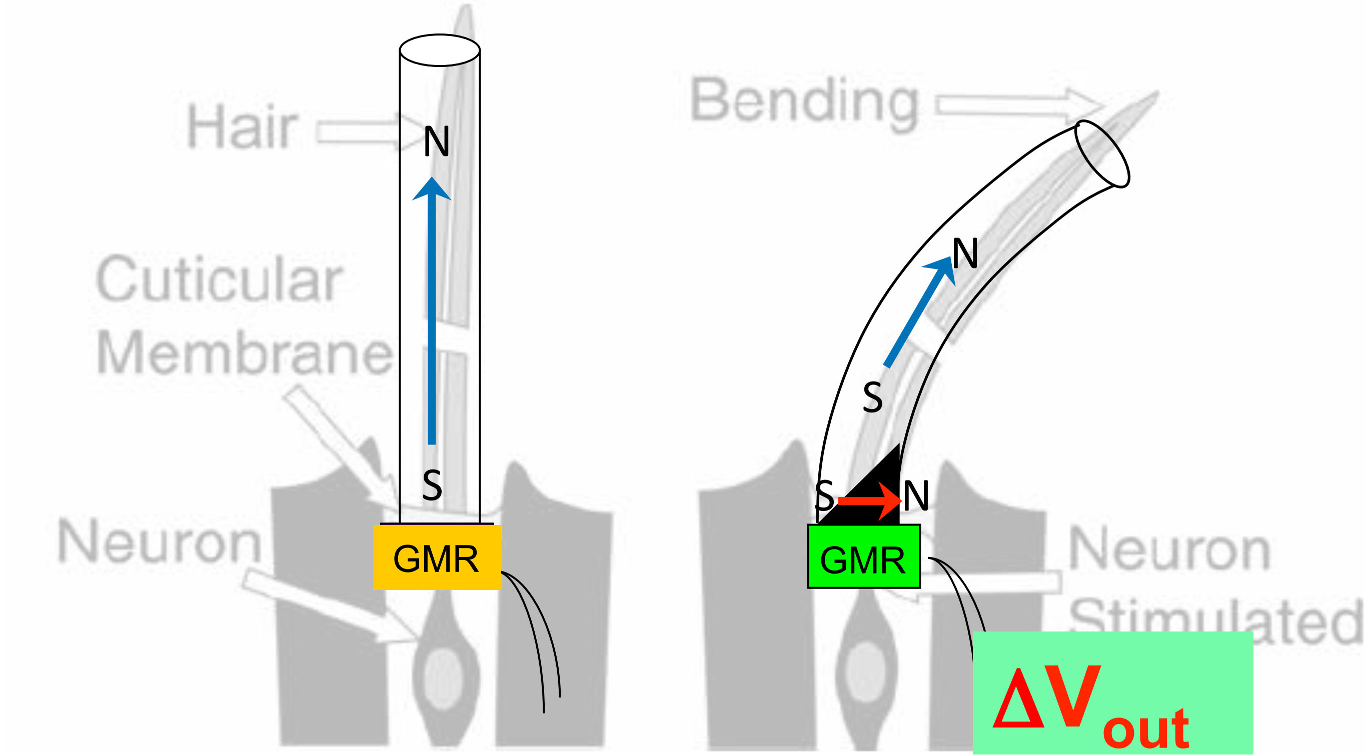
Chen et al The 12th Solid State Sensors, Actuator, and Microsystems Workshop, June 2006. Hilton Head, SC, USA



Whisker deflection creates chemical potential change that fires neuron

Magnetostrictive whisker sensors at the SAME nanoscale



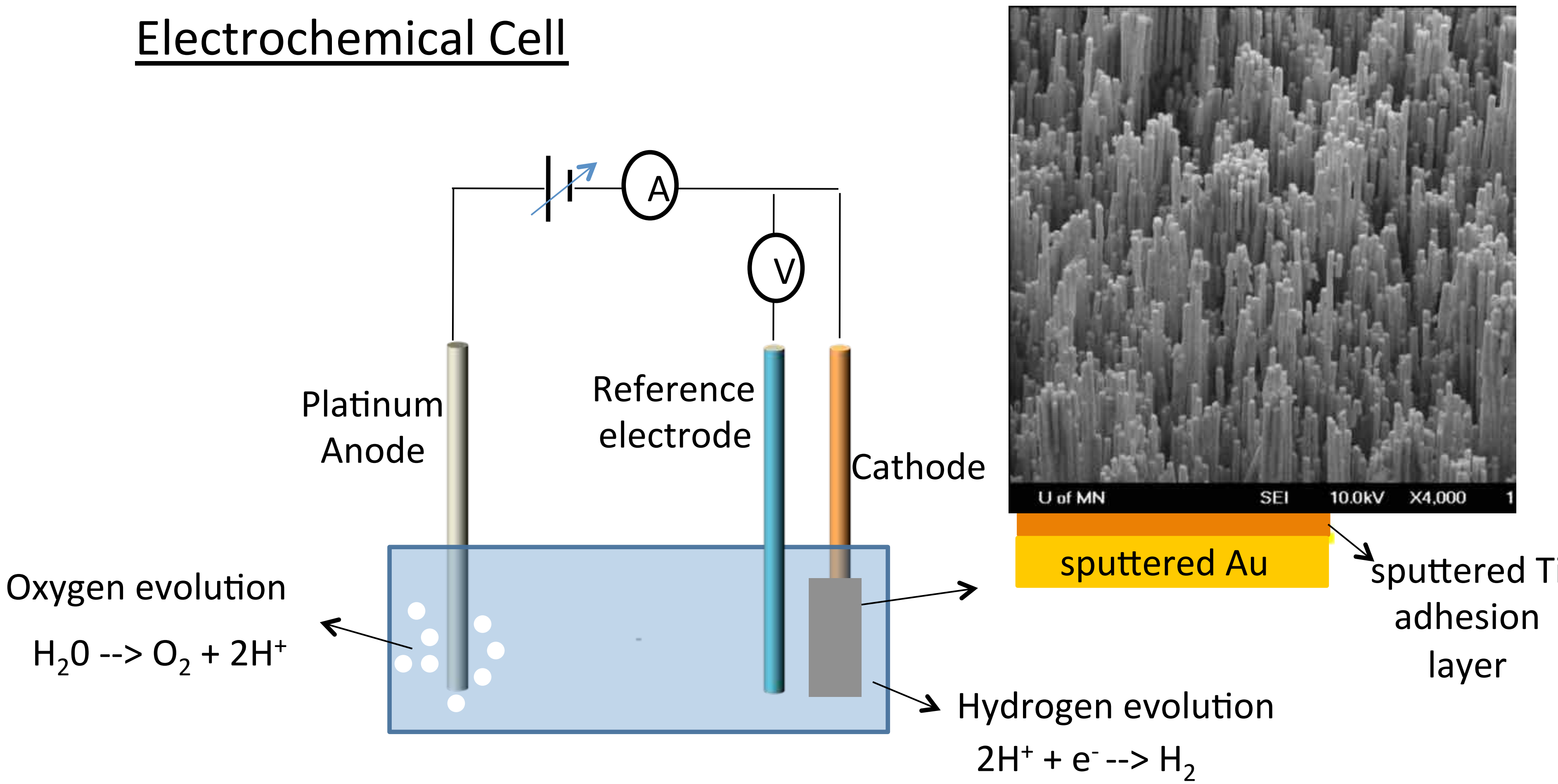


Whisker deflection creates chemical potential change that fires neuron

Wire deflection creates magnetization change that changes GMR resistance

Fe-Ga NW: DC Electrodeposition

<u>Electrochemical Cell</u>

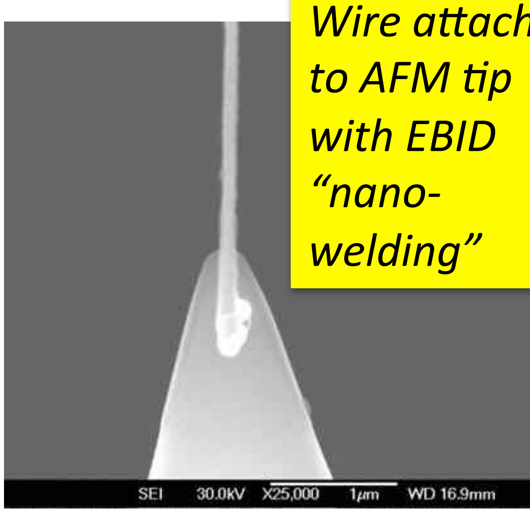


- ❑ FeGa nanowires are grown using a single bath containing Fe^{+2} and Ga^{+3} ions with Sodium Citrate as complexing agent.

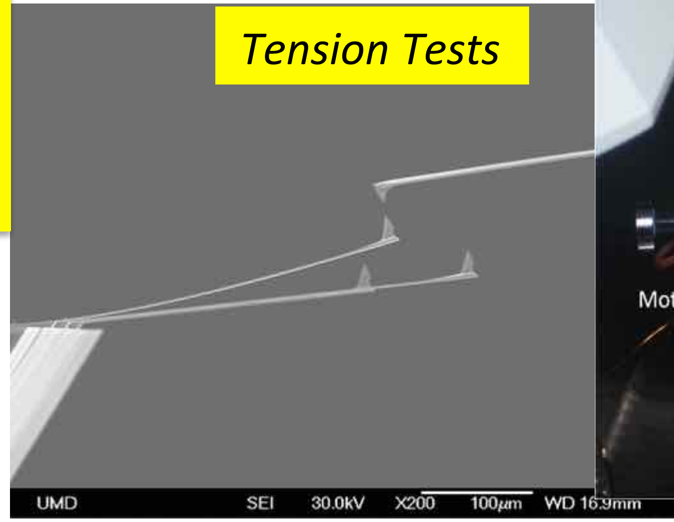
Mechanical properties of Fe-Ga NWs

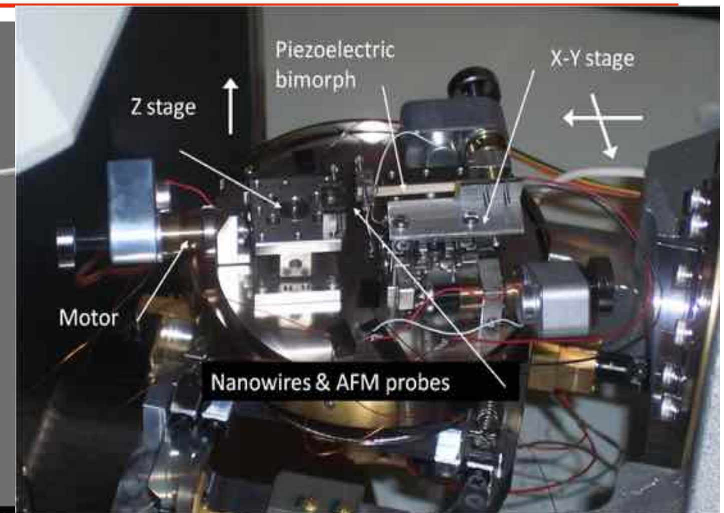
UNIVERSITY OF MINNESOTA

Wire attached to AFM tip with EBID "nano-welding"



Tension Tests



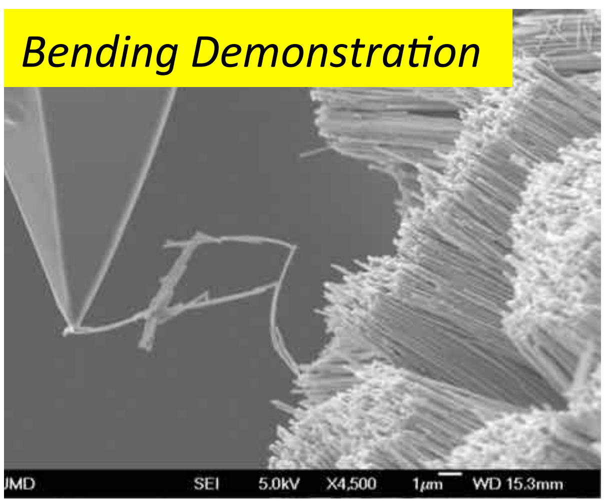


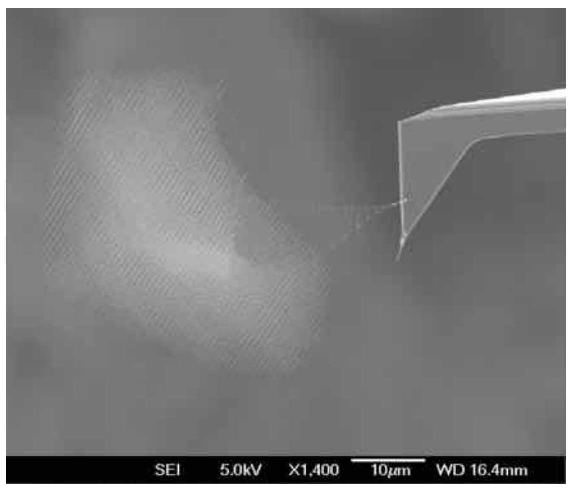
McGary et al. J. Appl. Phys 99 (2006)
Downey et al. J. Appl. Phys 103 (2008)

During testing the soft AFM cantilever deflects upward

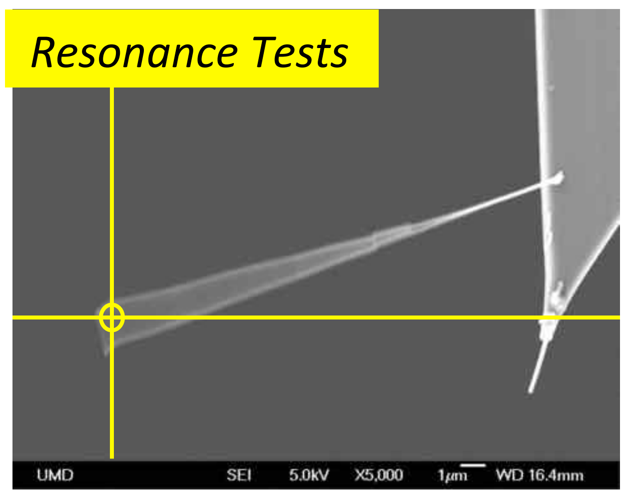
Nano-manipulator

Bending Demonstration

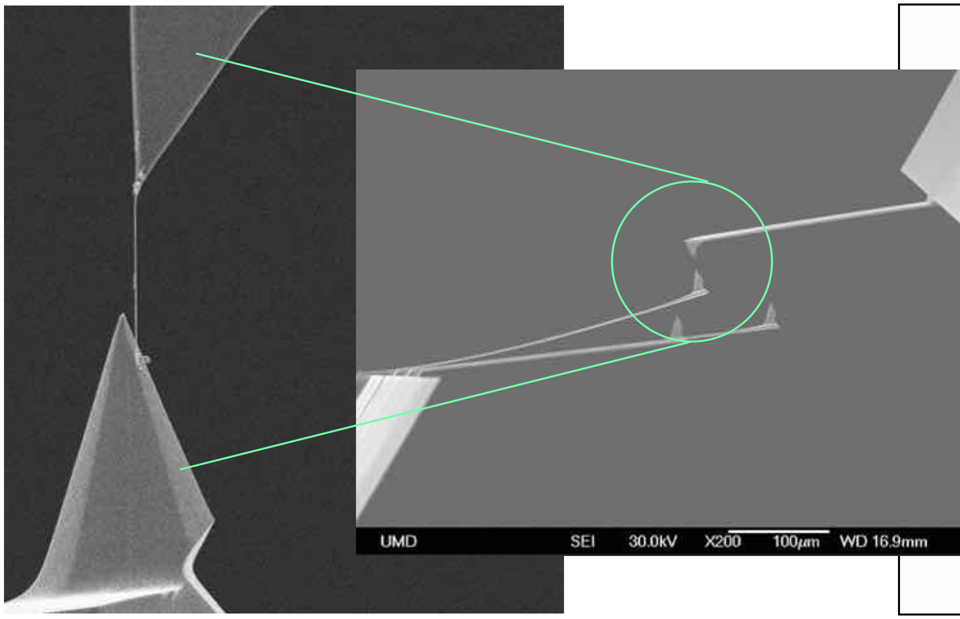


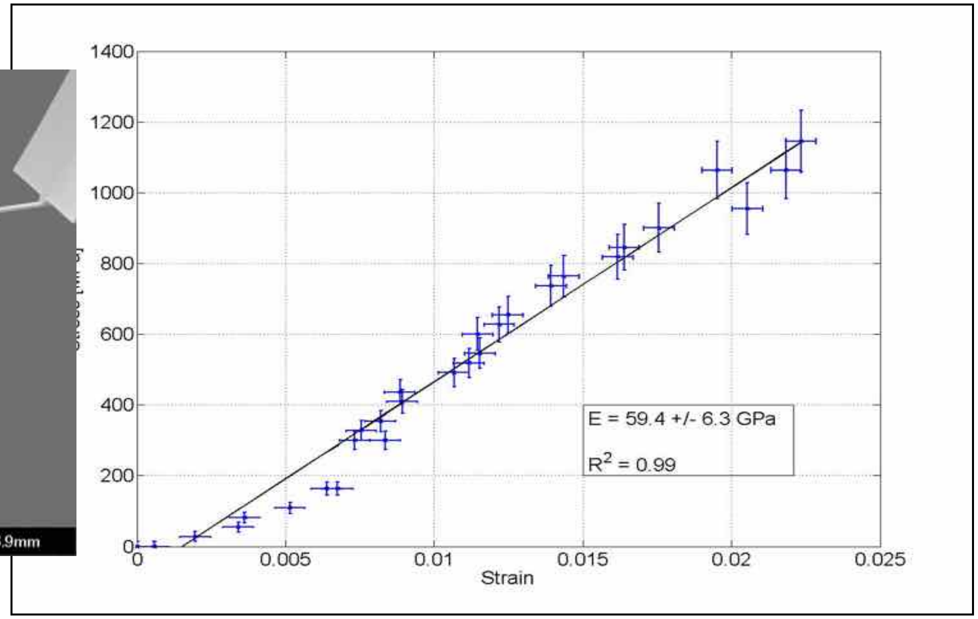


Resonance Tests



Tensile Tests





Wire #	Diameter (nm)	Length (μm)	Ultimate Strength (MPa)	Young's Modulus (GPa)
1	105 +/- 5	9.80 +/- 0.01	1232 +/- 147	58.3 +/- 6.0
2	135 +/- 5	13.8 +/- 0.01	1202 +/- 119	59.4 +/- 6.3
3	225 +/- 5	36.8 +/- 0.01	1084 +/- 60	54.9 +/- 7.1
4	130 +/- 5	7.55 +/- 0.01	1050 +/- 91	58.9 +/- 8.6

Bulk $Fe_{83}Ga_{17}$ [100] (Kellogg et. al, *Acta Mater.* 52, 2004)	500	65

Resonance Method Results

Wire attachment assumed fixed

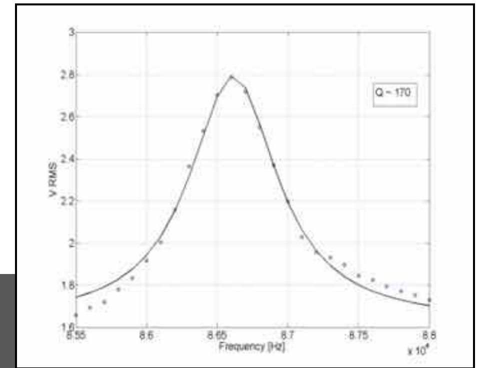
Frequencies swept with piezo

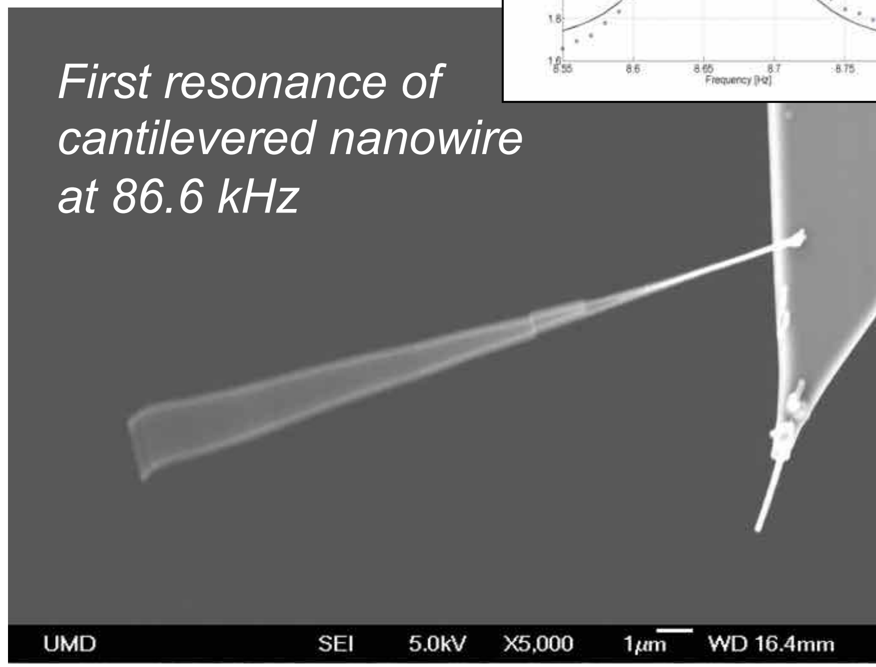
Modulus related to resonance:

$$f_0 = \beta_0^{\ 2} / 2\pi \sqrt{\left(EI / mL^4\right)}$$

Results are lower bounds

Two distinct values suggest a compositional variation

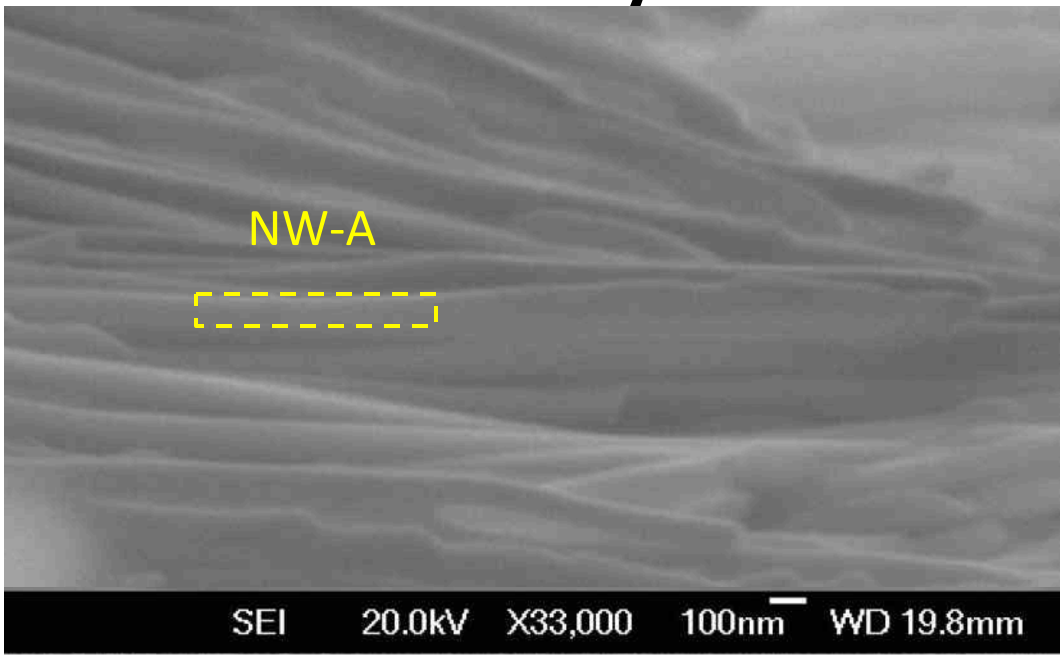




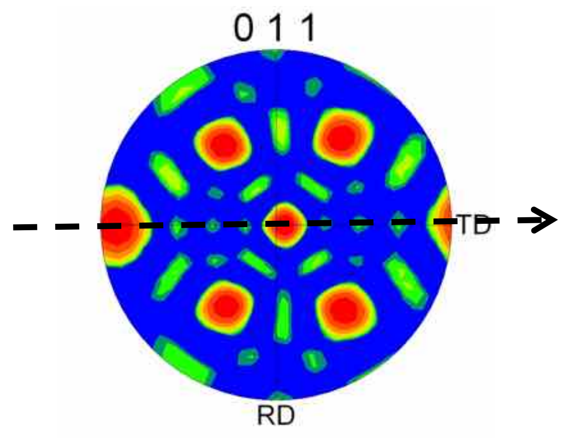
First resonance of cantilevered nanowire at 86.6 kHz

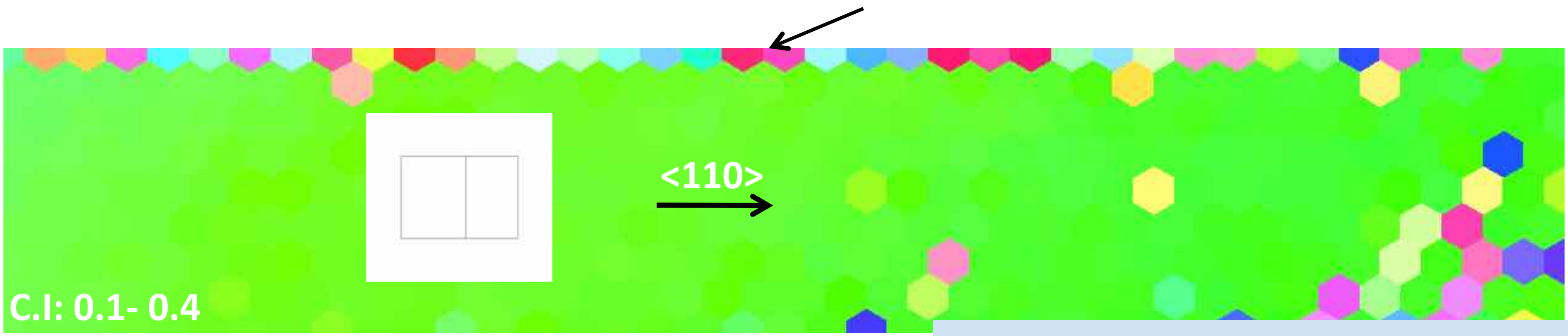
Wire #	Diameter (nm)	Length (µm)	Resonance Frequency (kHz)	Young's Modulus (GPa)
5	100 +/- 5	19.4 +/- 0.01	86.6 +/- 0.05	44.2 +/- 8.2
6	120 +/- 5	11.6 +/- 0.01	304.3 +/- 0.05	45.1 +/- 7.9
7	225 +/- 5	7.88 +/- 0.01	1781.1 +/- 0.05	93.1 +/- 8.3
8	125 +/- 5	4.43 +/- 0.01	3143.0 +/- 0.05	93.8 +/- 15

EBSD study on uniform FeGa NW



- **Uniform FeGa NW (ø ~ 150 nm)**

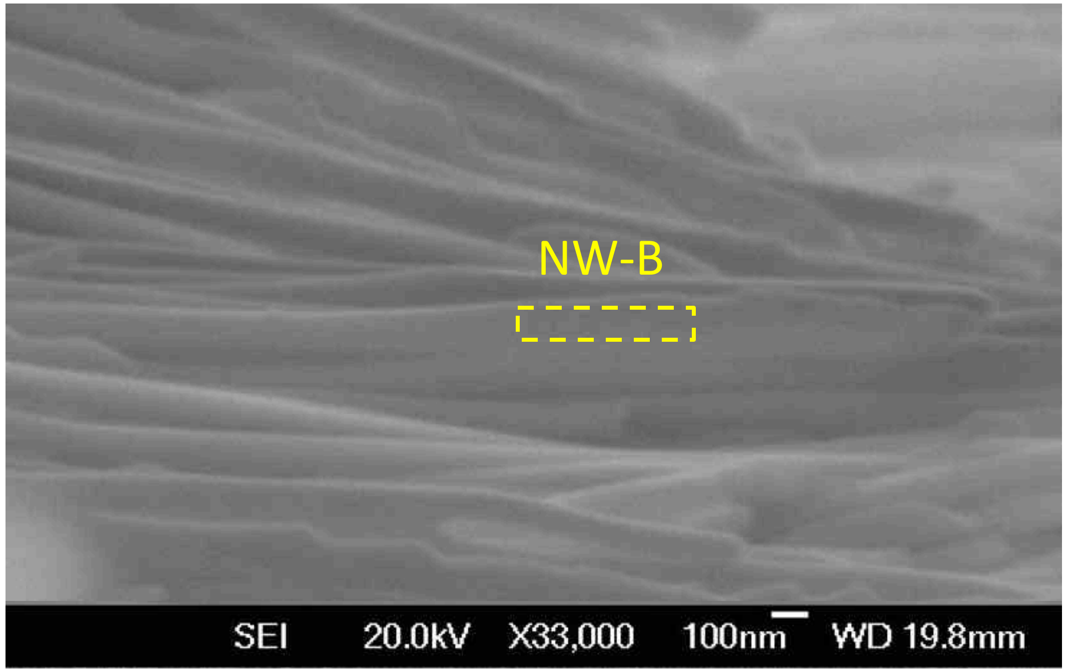


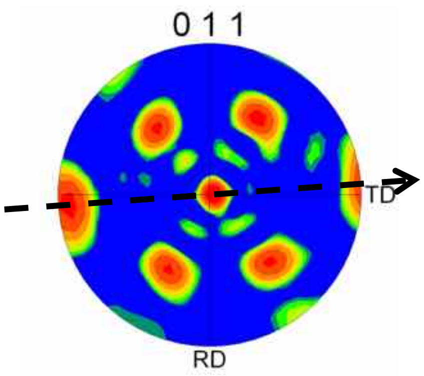


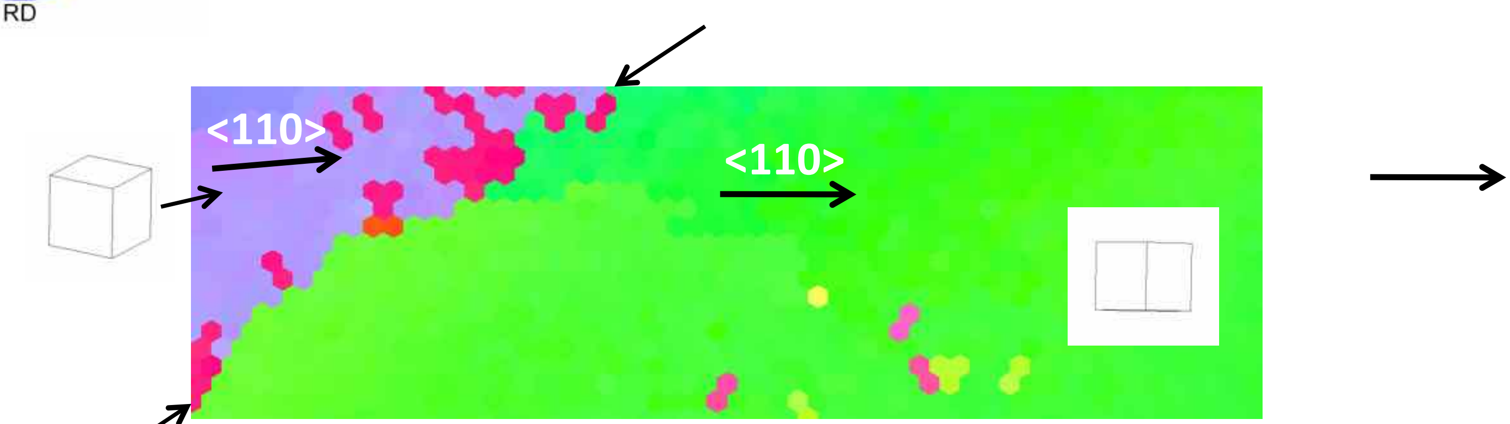
<110> orientation along NW length

EBSD study on FeGa nanowire

- **Uniform FeGa NW**
- **<110> orientation along NW length**

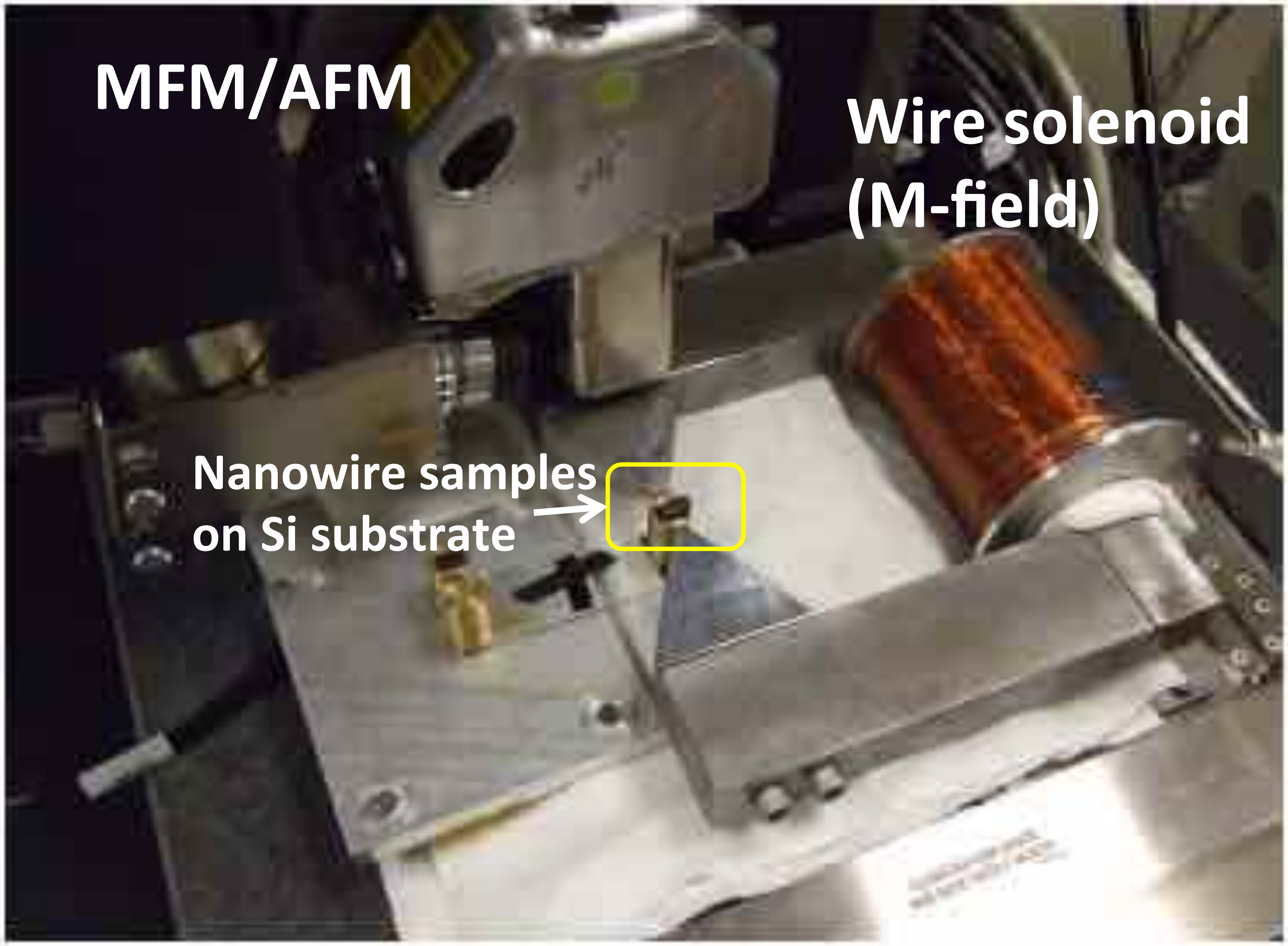






Kink line

Magnetic studies of Fe-Ga NW

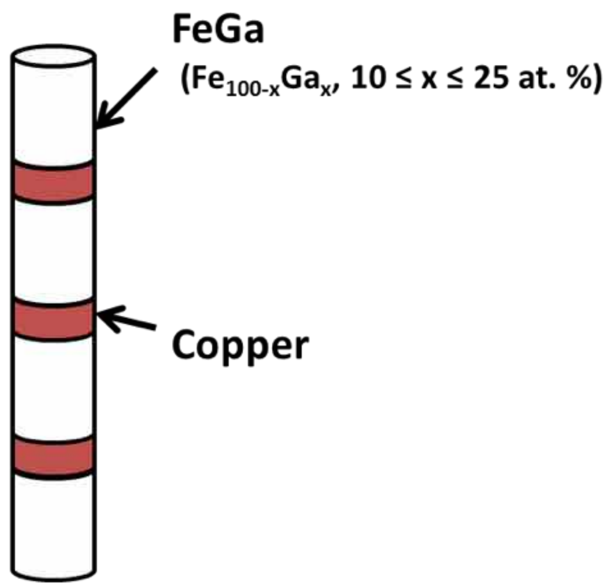


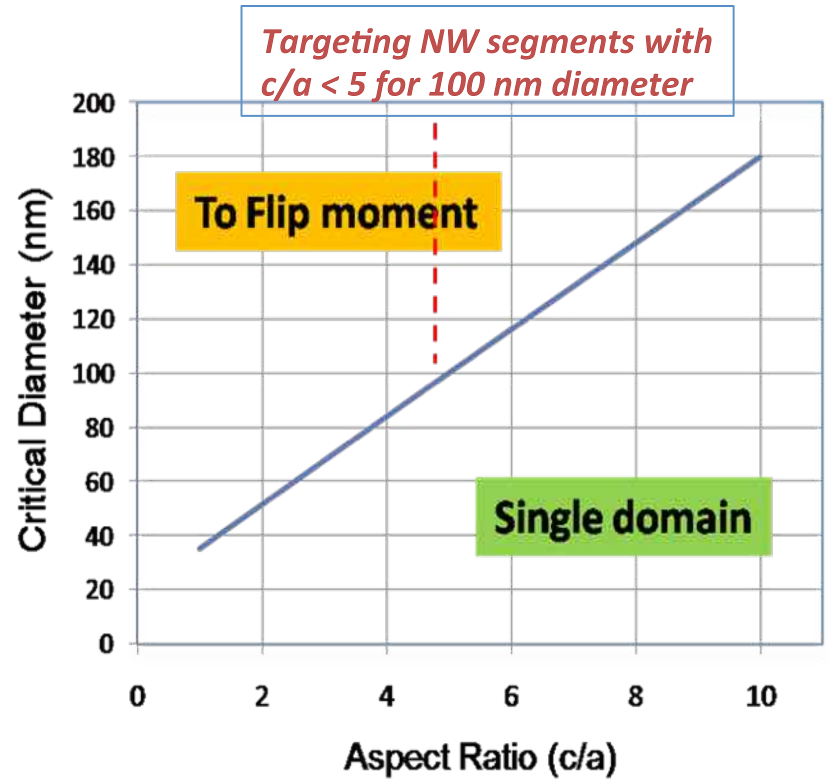
Magnetic studies of Fe-Ga NW

Scale bar: 0.5 μm

Energy term	Maximum cost [erg/cm^3]
Exchange coupling	3×10^4
Magnetocrystalline anisotropy	3×10^5
Magnetoelastic	2.5×10^3 / MPa
Shape anisotropy	7×10^6

Magnetic studies of Multilayer Fe-Ga/Cu NW



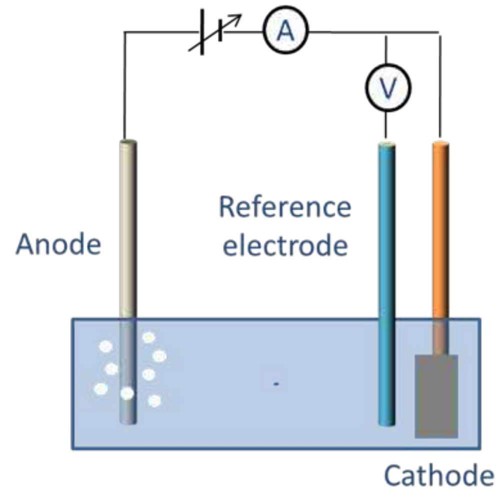


Scale bar: 0.5 µm

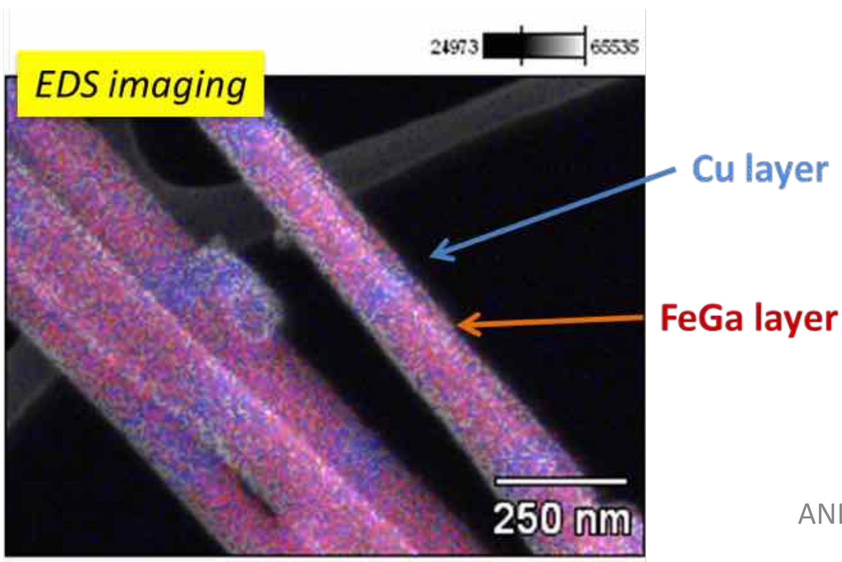
Fabrication of Multilayer Fe-Ga/Cu NW

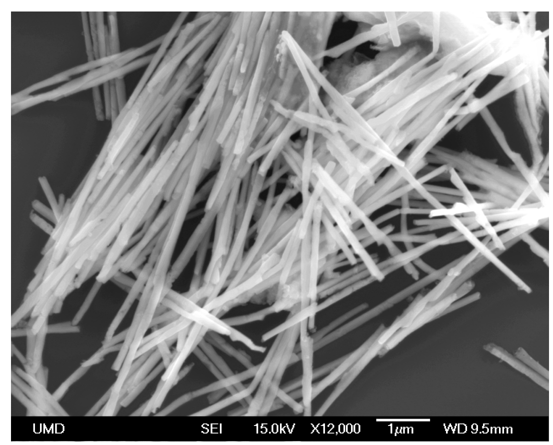
Electrodeposition

- Fe/Ga/Cu plating bath
- Deposition potential of -1.12V and -0.8V
- Grown in Anodized Aluminum Oxide (AAO) templates
- 150nm diameter, 200nm spacing



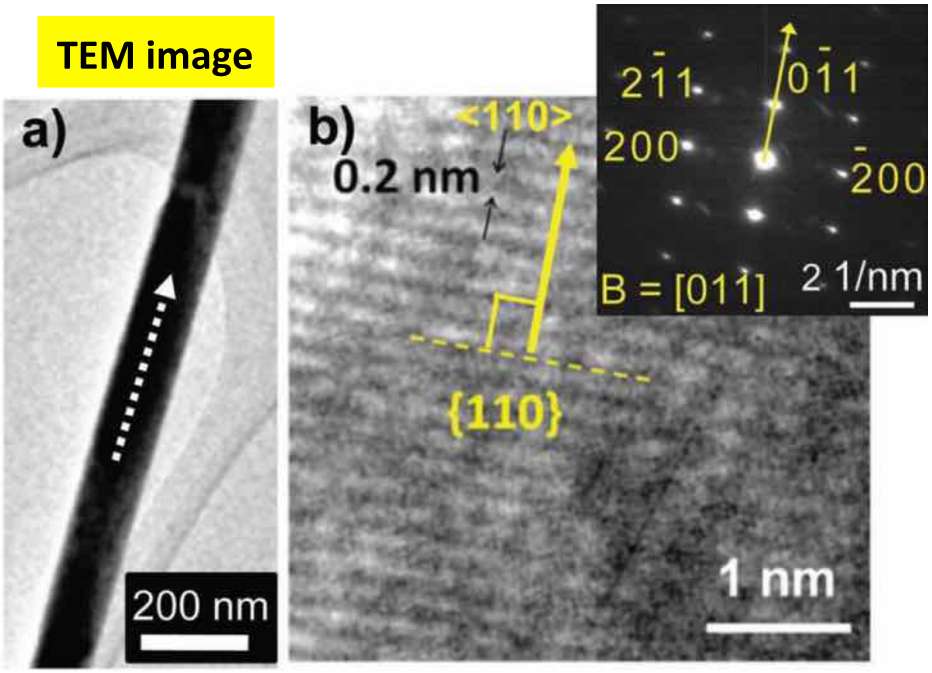
Nanowires separated and Isolated



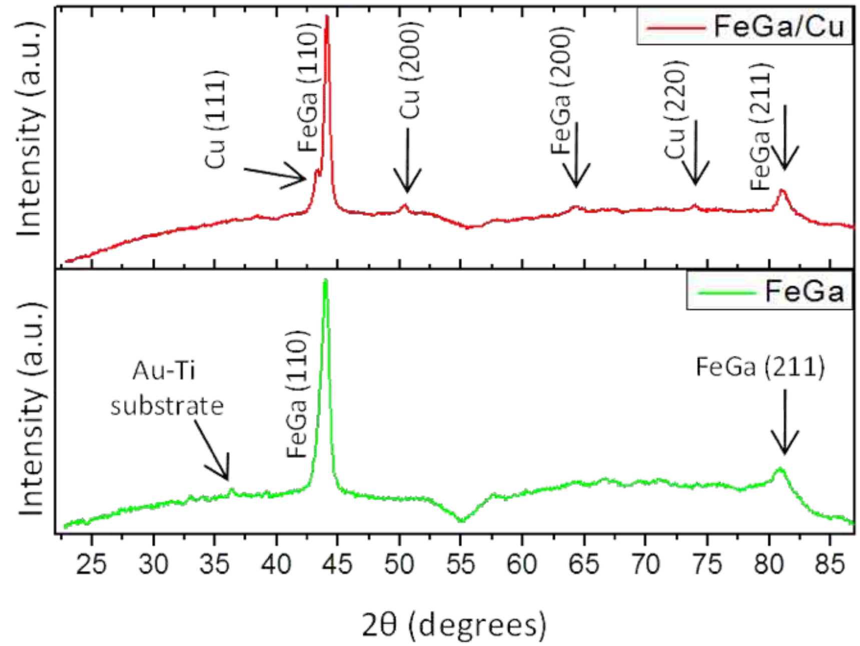


FeGa/Cu NW:
Structural characterization

TEM image

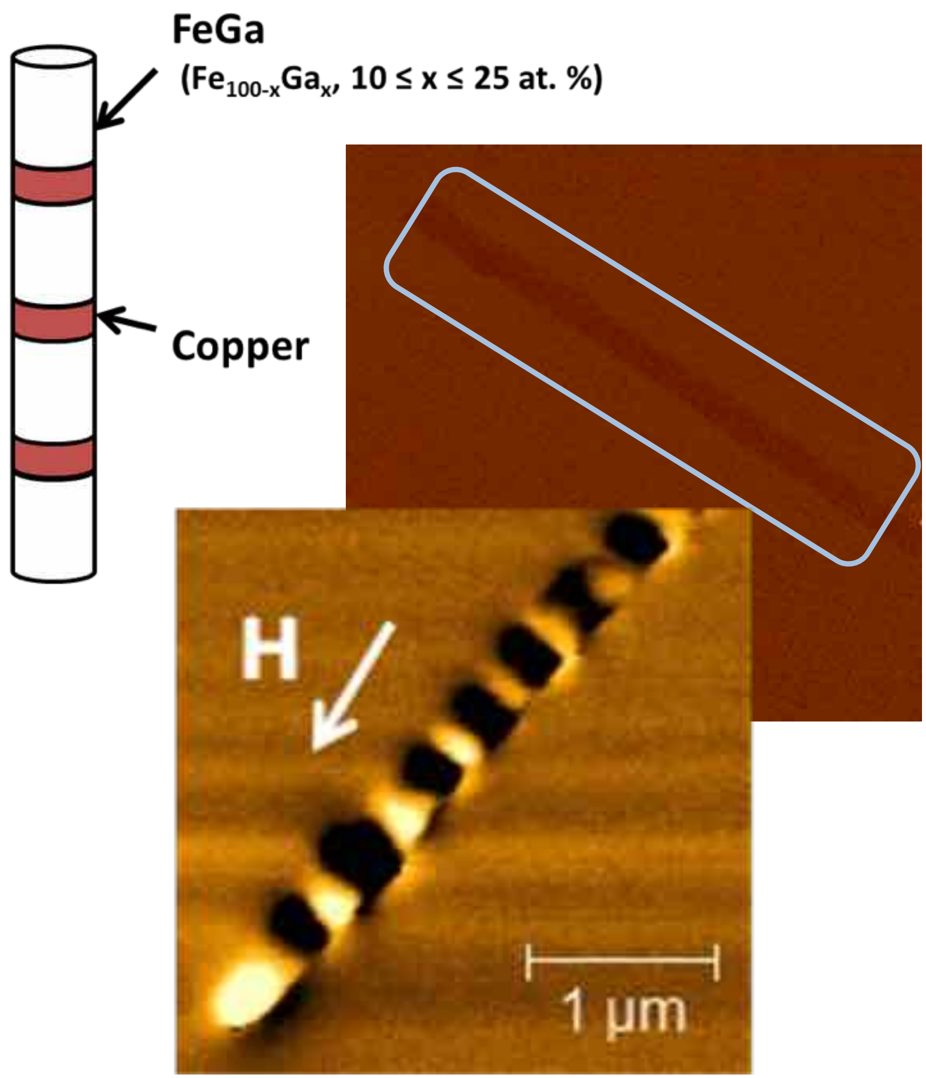


XRD analysis

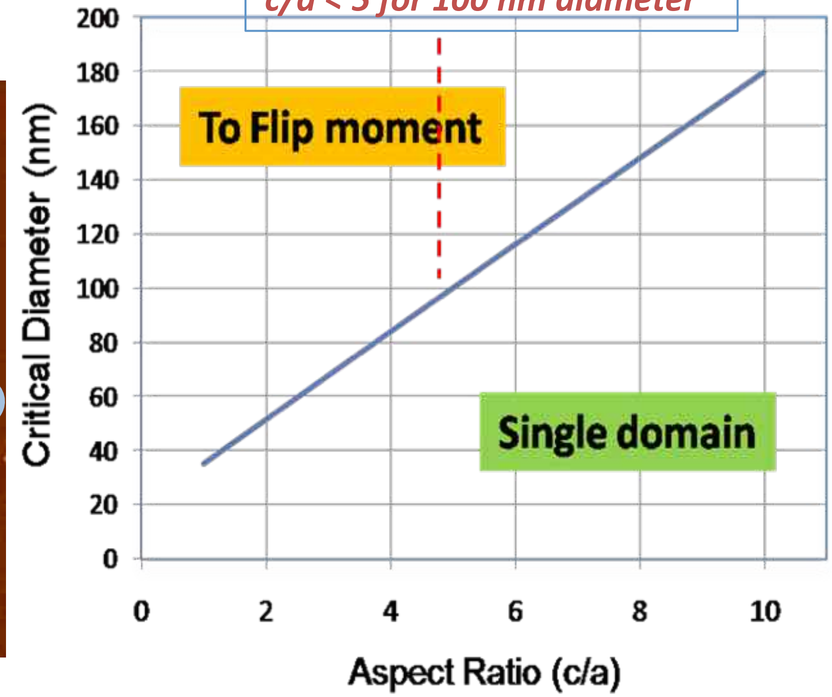


- ✓ *Use of citrate baths for electrodeposition; <u>highly textured growth</u> even for FeGa-Cu multilayered nanowires. => high magnetostriction*
- ✓ *Extensive structural characterization by XRD and TEM reveals a strong <u>< 110 > textured $Fe_{1-x}Ga_x$</u>*

Magnetic studies of Multilayer Fe-Ga/Cu NW



Targeting NW segments with c/a < 5 for 100 nm diameter



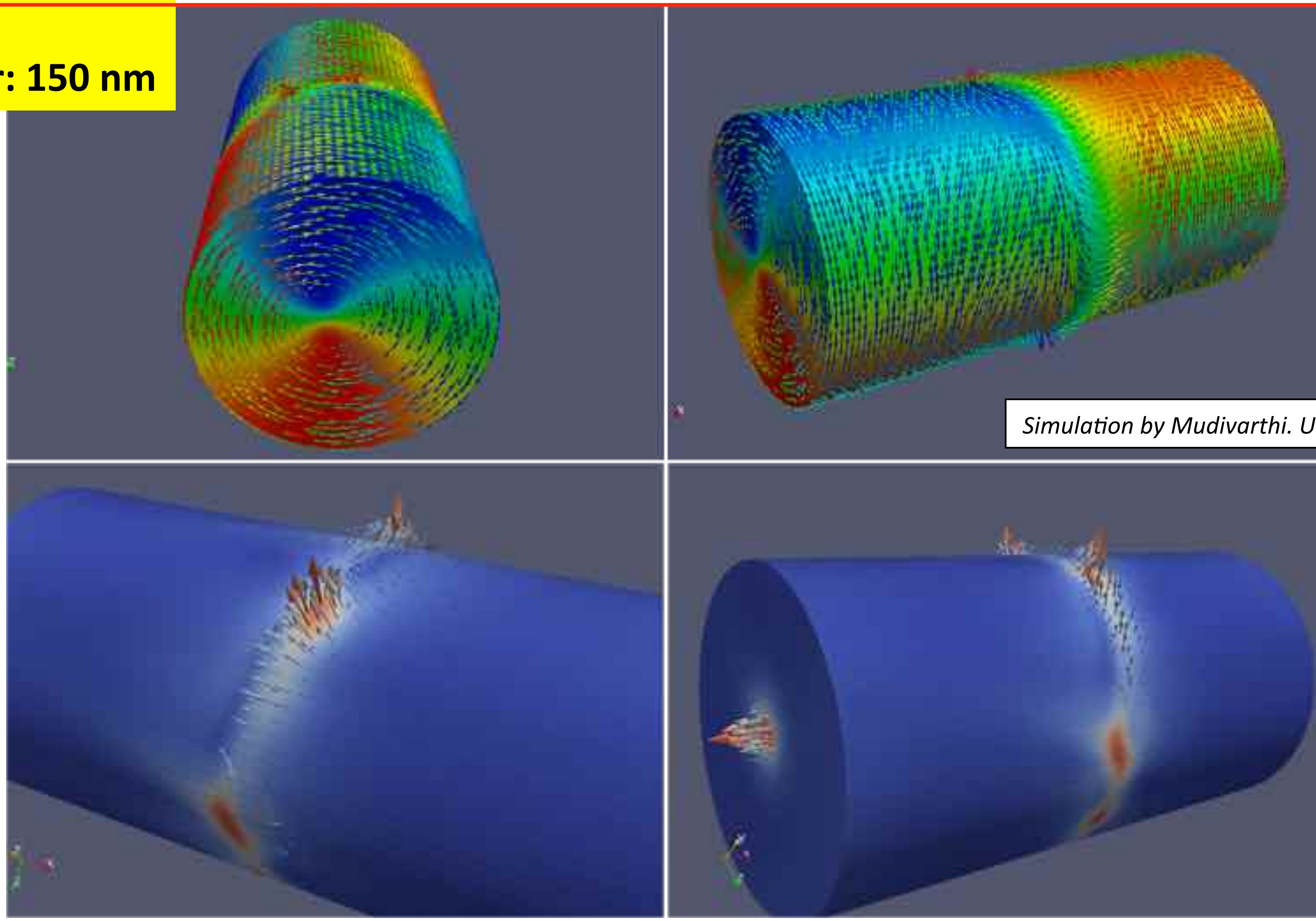
Scale bar: 0.5 µm

FEM (Magpar) of Fe-Ga segment

UNIVERSITY OF MINNESOTA

UNIVERSITY OF MARYLAND 1856

c/a = 2
Diameter: 150 nm



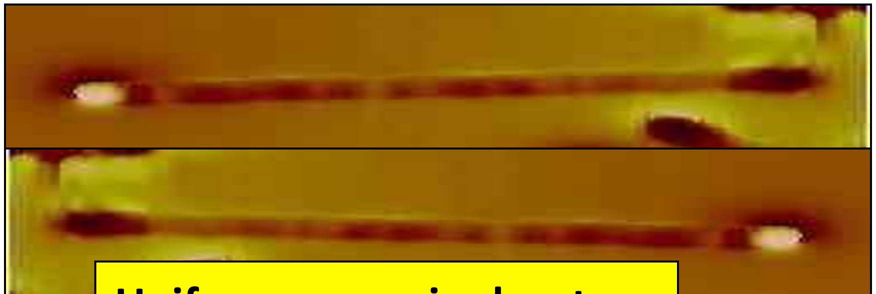
Simulation by Mudivarthi. Univ. of Maryland

FEM predicts that at remanence, a nanowire with aspect ratio of two actually forms two opposite vortex domains at each end separated by a domain wall near the center.

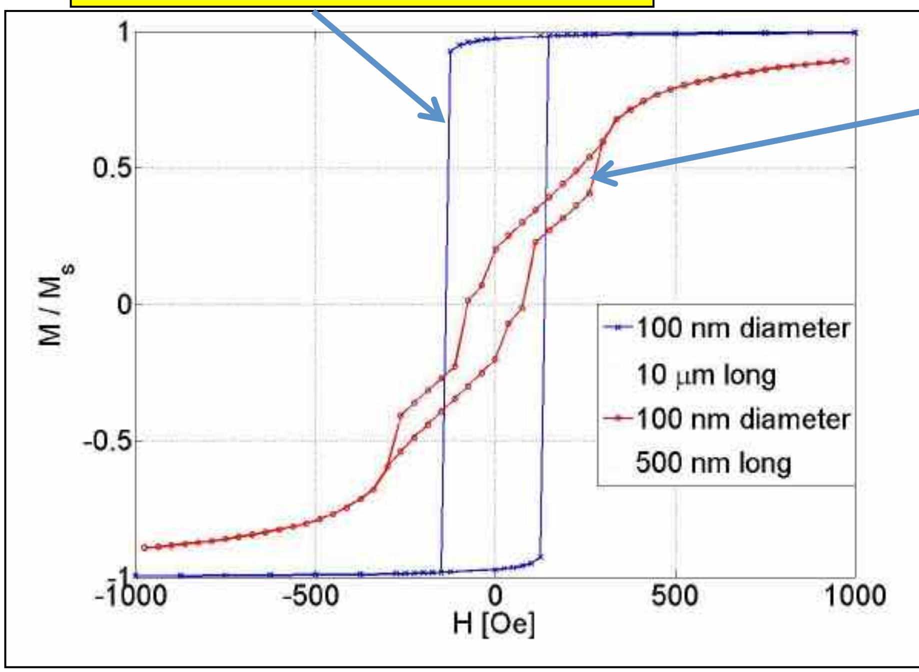
Moment rotation in Fe-Ga NW and in Fe-Ga/Cu NW

UNIVERSITY OF MINNESOTA

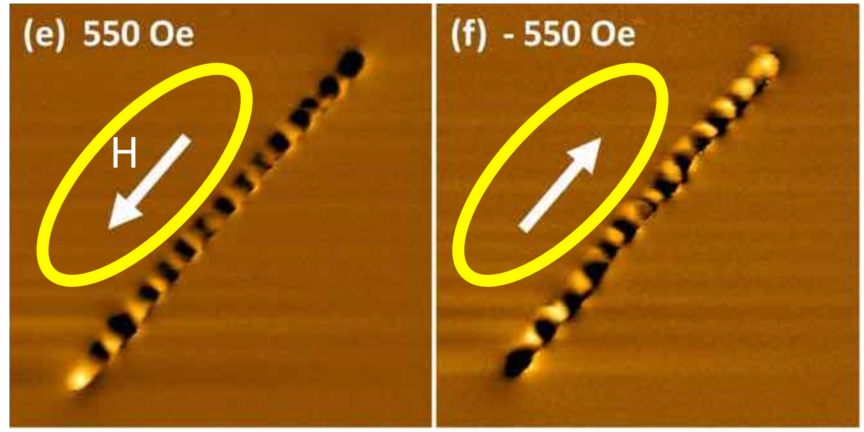
Magnetic force microscopy (MFM)



Uniform nanowire has two axial magnetization states

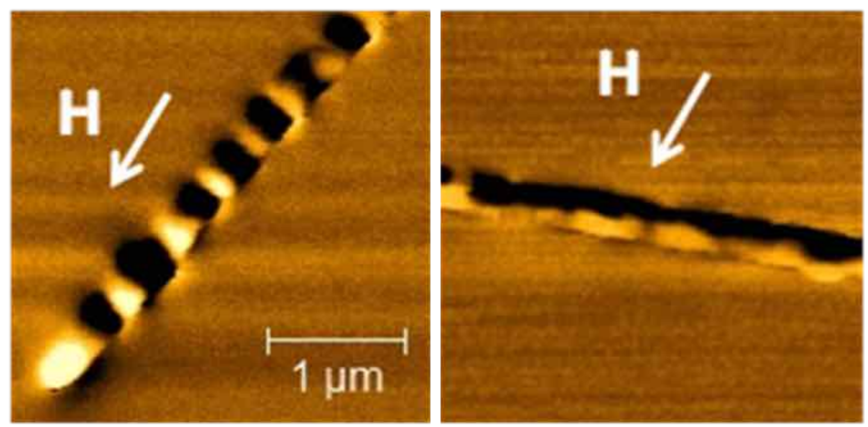


Multilayered, low aspect ratio nanowires



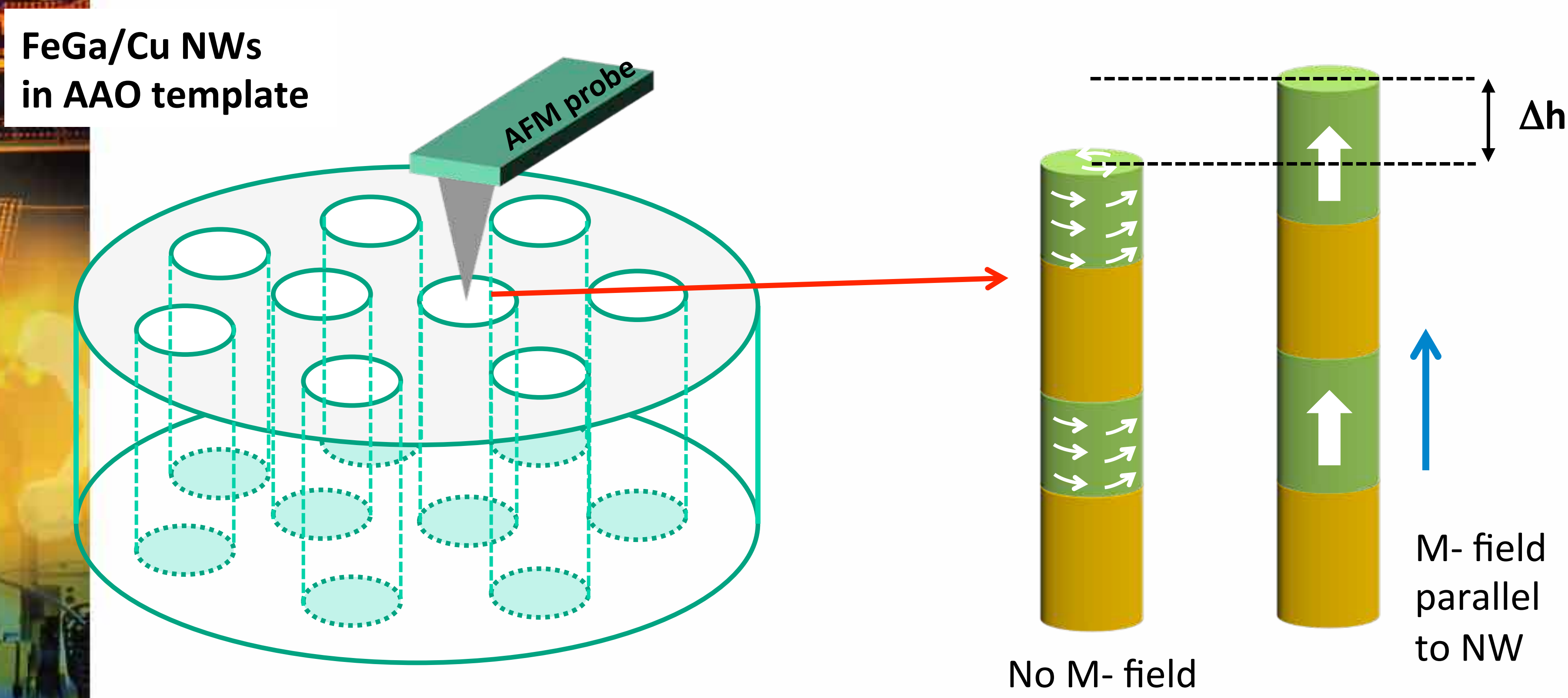
Multilayered, low aspect ratio nanowire has multiple domain structures / magnetization states

(H ~ 550 Oe) ~ 5 ° ~ 105 °



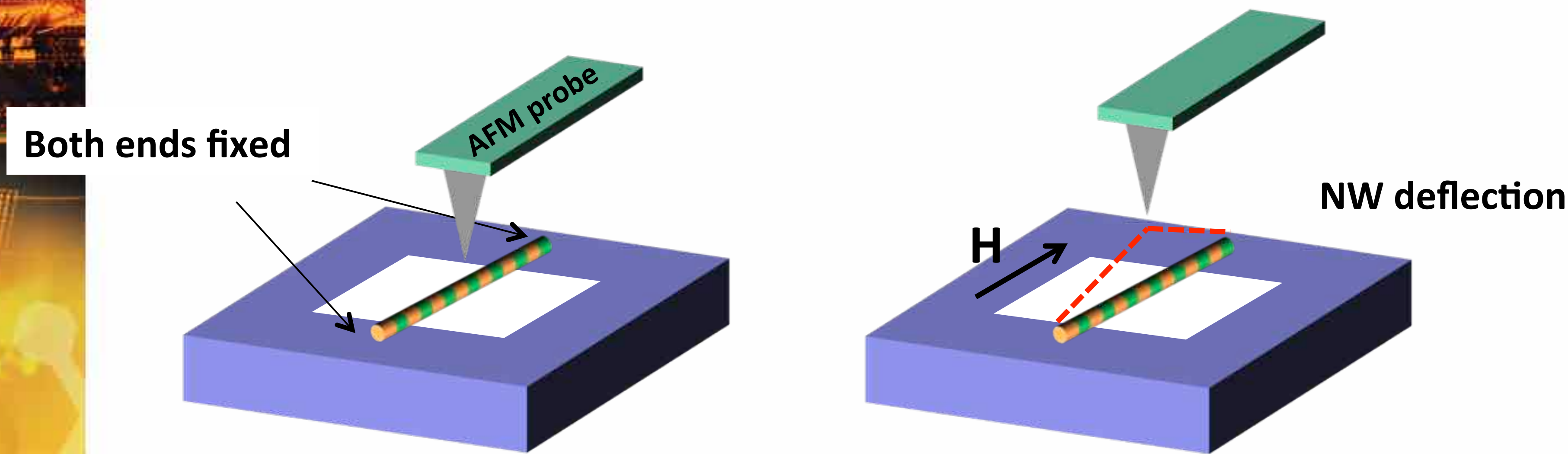
Park et al. J. applied physics (2010)

Magnetostriction of Fe-Ga/Cu NW

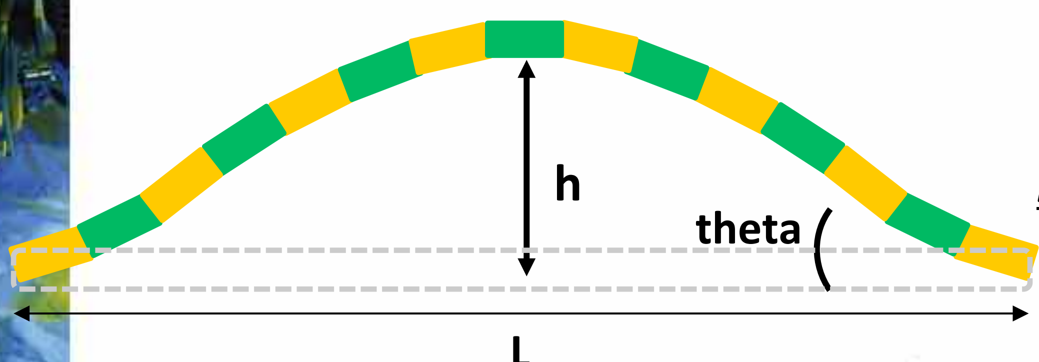


The expected length changes of 10 μm long multilayered (50:50) Fe-Ga:Cu NW with a magnetostriction of <~50 ppm along <110> are estimated to be in **range between 0.1 nm and 0.25 nm** = below the vertical resolution of our AFM system.

Magnetostriction of Fe-Ga/Cu NW



Magnetostriction generates a compressive buckling stress in the NW → Deflection of NW

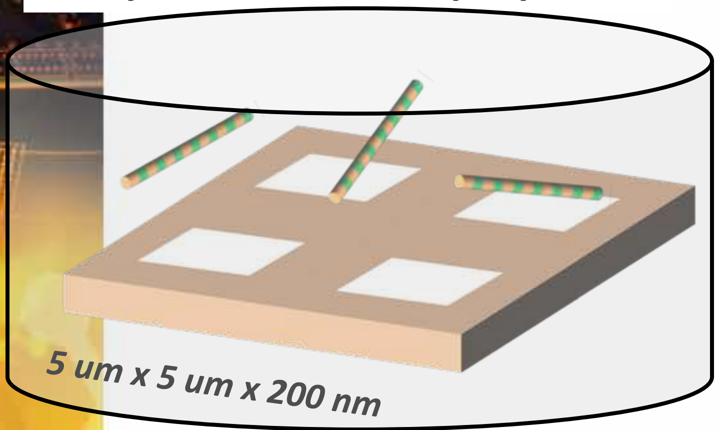


ppm	Delta L	h = sin (theta) * L/2
20	0.1(nm)	~22 (nm)
100	0.5	~50
200	1	~70
300	1.5	~86

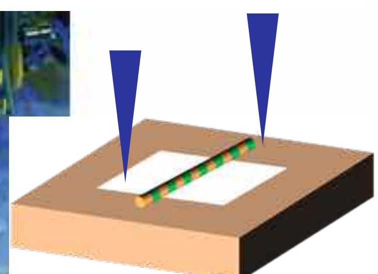
Large enough to be measured by AFM

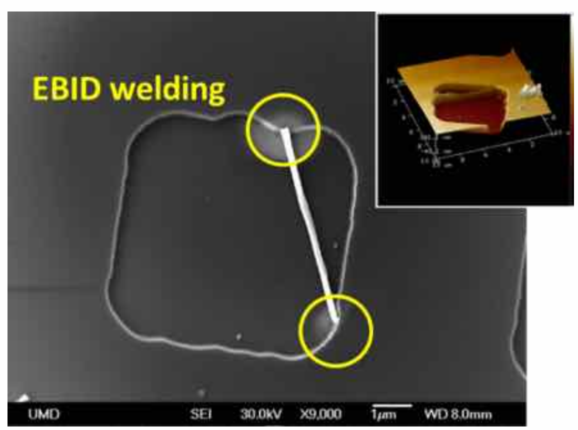
Sample preparation and AFM measurement

NW placement in isopropanol

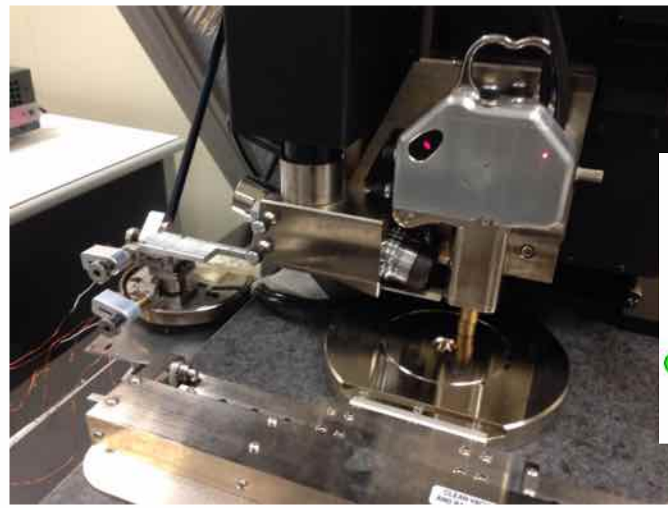


NW welding (EBID)





AFM with external magnetic field



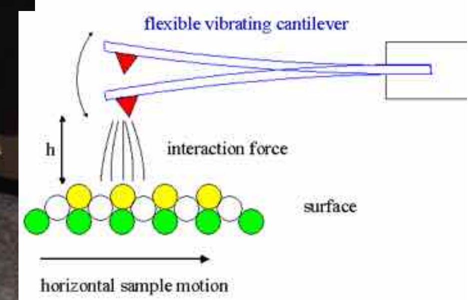
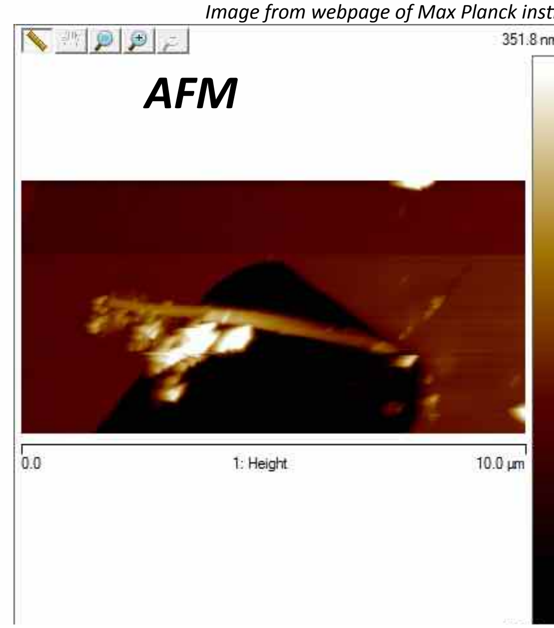
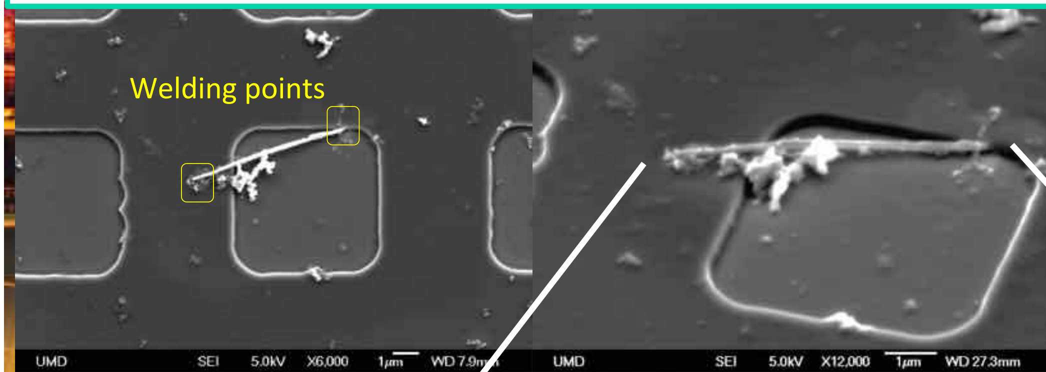
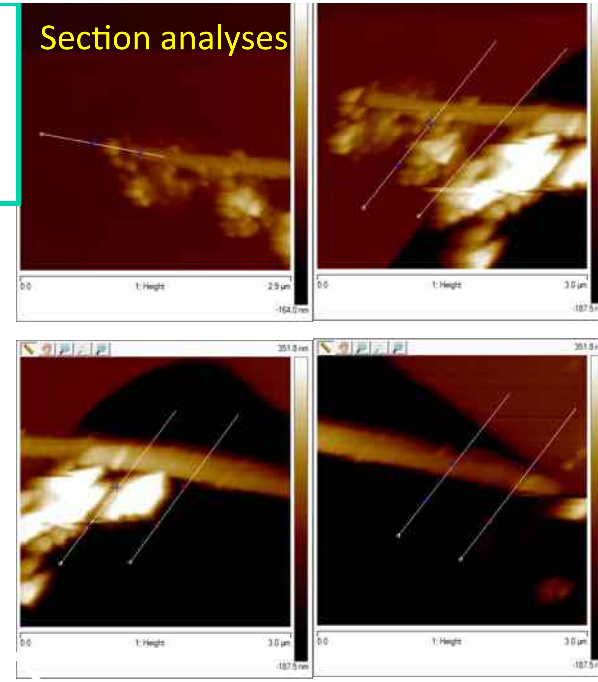


Image from webpage of Max Planck institute

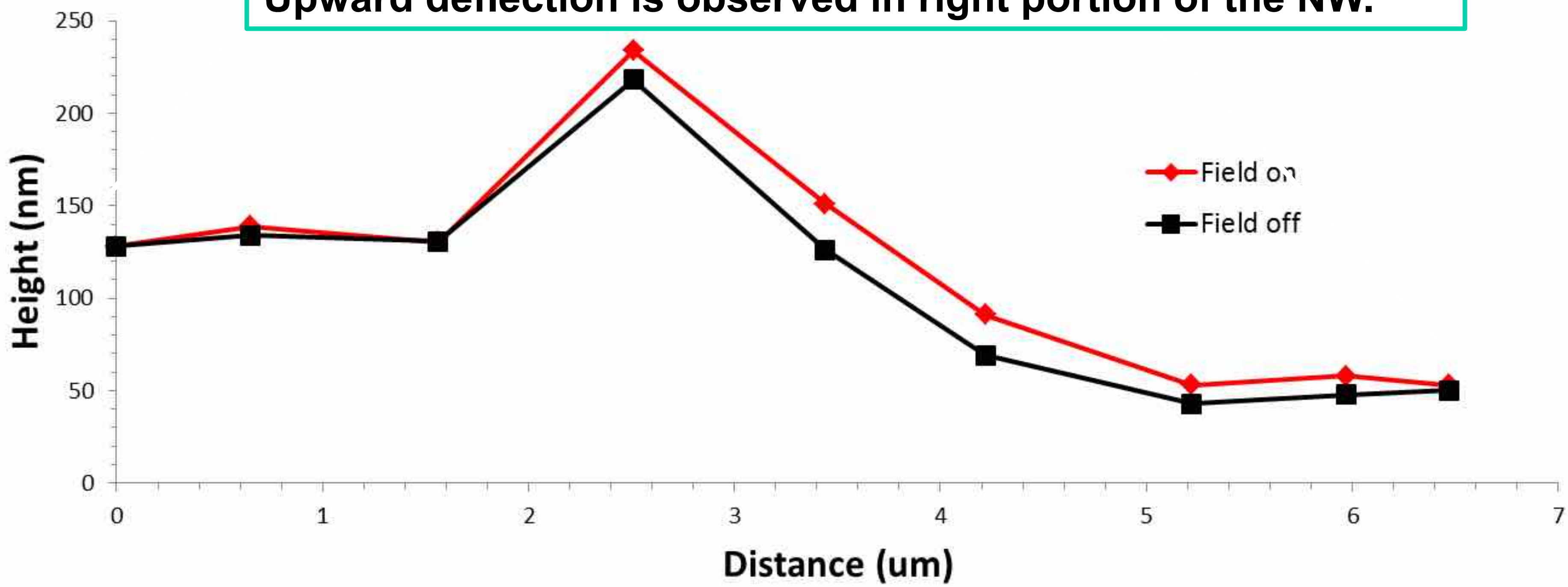


Height profile measurement along NW

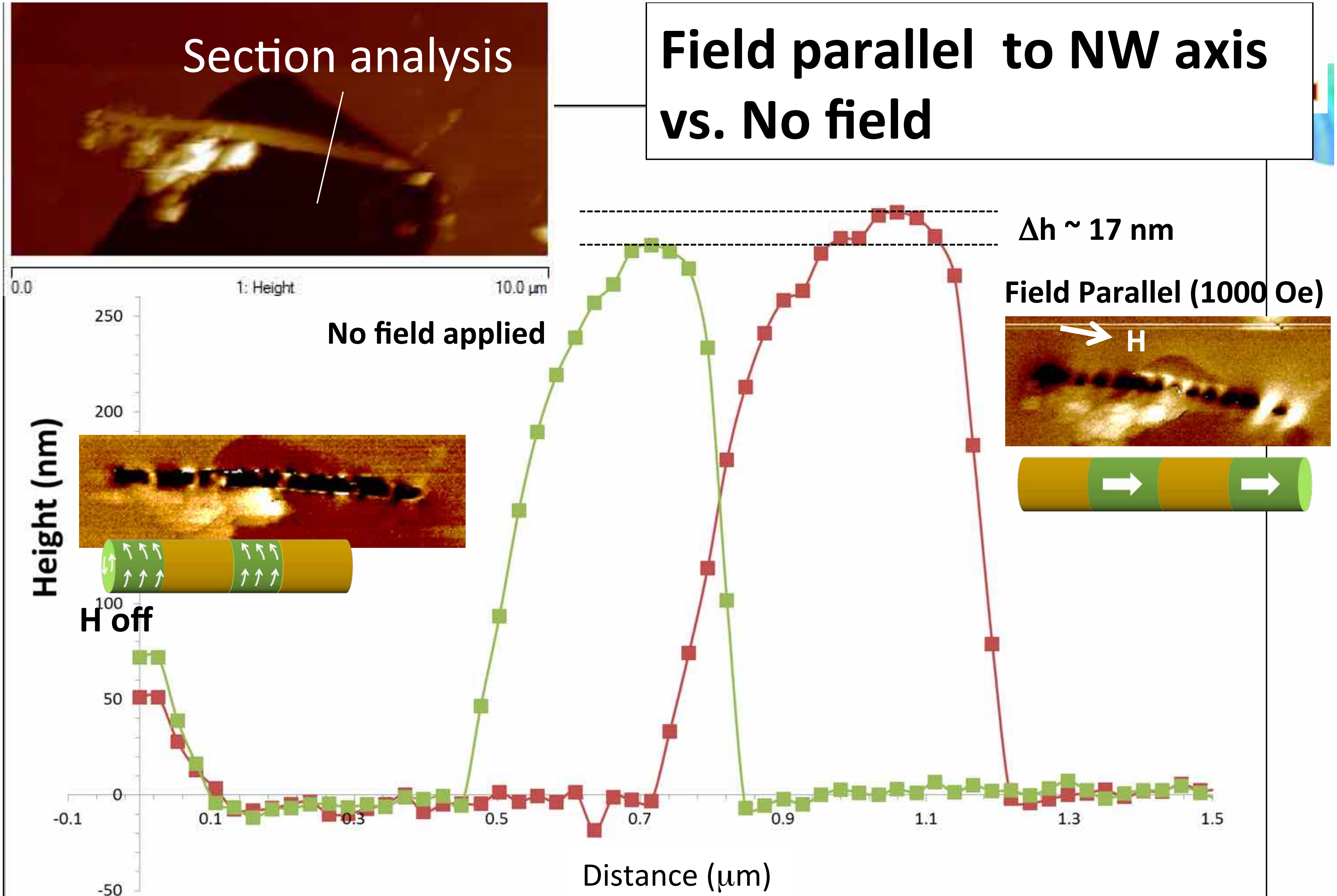




Upward deflection is observed in right portion of the NW.



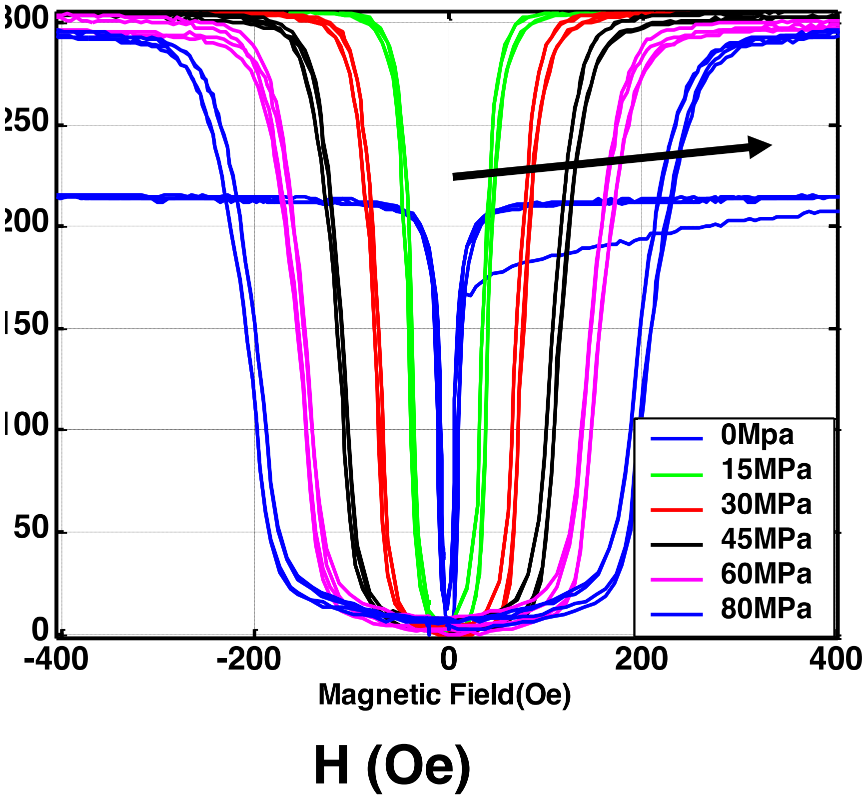
Field parallel to NW axis vs. No field



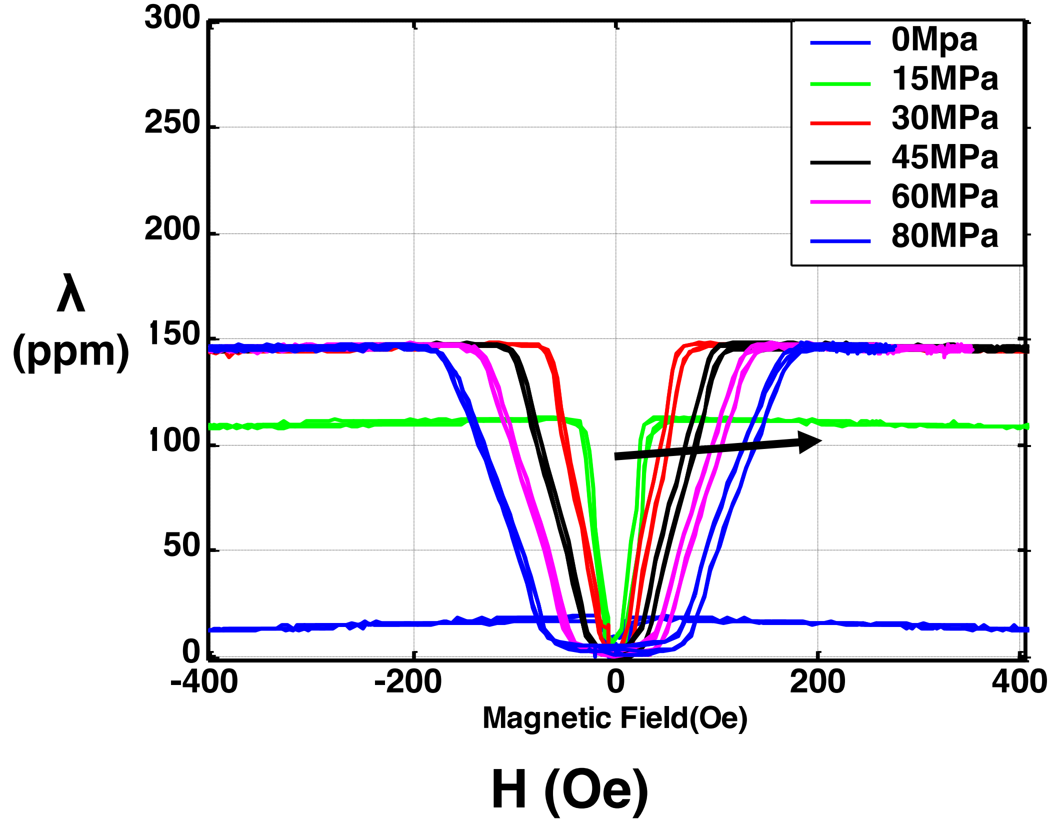
Parallel field elongated NW indicates magnetostriction of ~20 ppm compares well with reportd values of λ_{sat} = ~20 to 50 ppm in bulk alloy

Direct Effect λ-H along <100> and <110>

<100>, 19 at. % Ga



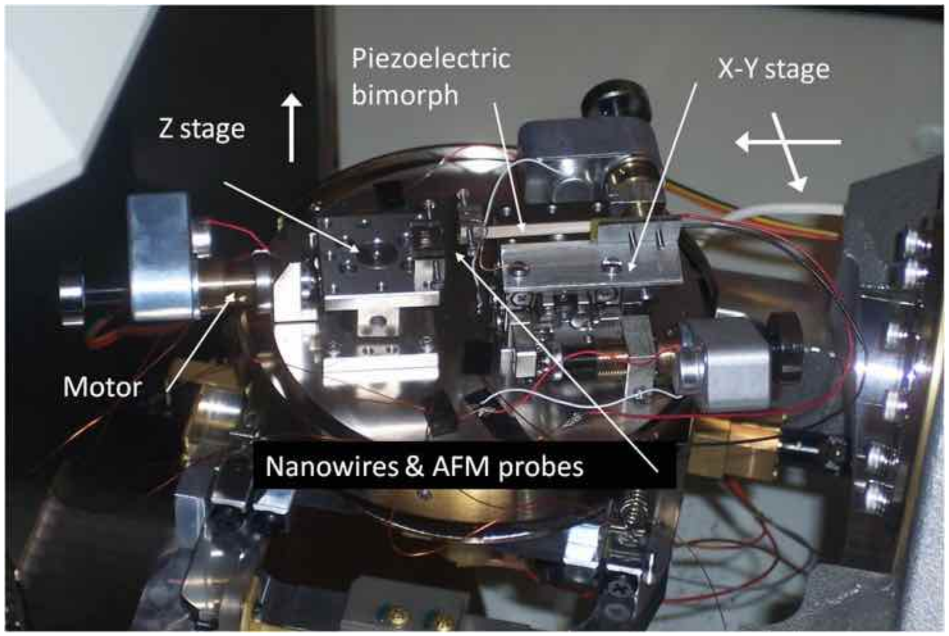
<110>, 18 at. % Ga



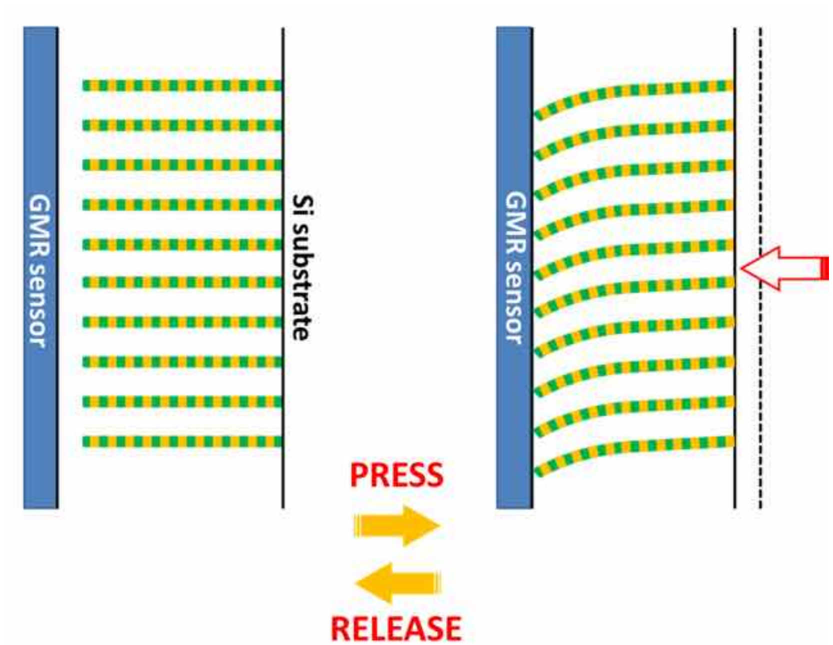
18-19 at. % Ga, single crystal

Pressure sensing: GMR sensing of magnetostrictive NW array

UNIVERSITY OF MINNESOTA



Schematic GMR sensing process



Partially etched AAO allows free standing NW array which is attached on a top substrate.
We would like to observe contact between NWs to GMR surface in SEM, using a nano-manipulator.

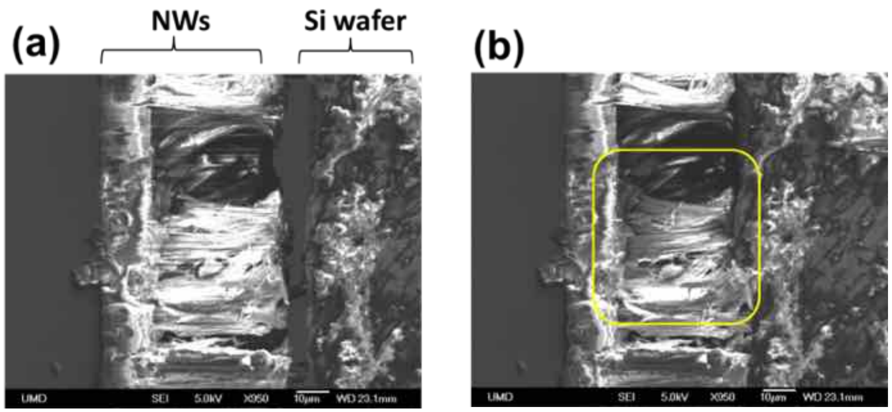
- ***Minimize stress on GMR sensor***
- ***Appropriate NWs contact on GMR surface***
- ***NW deformation***

=>Controlled experiment

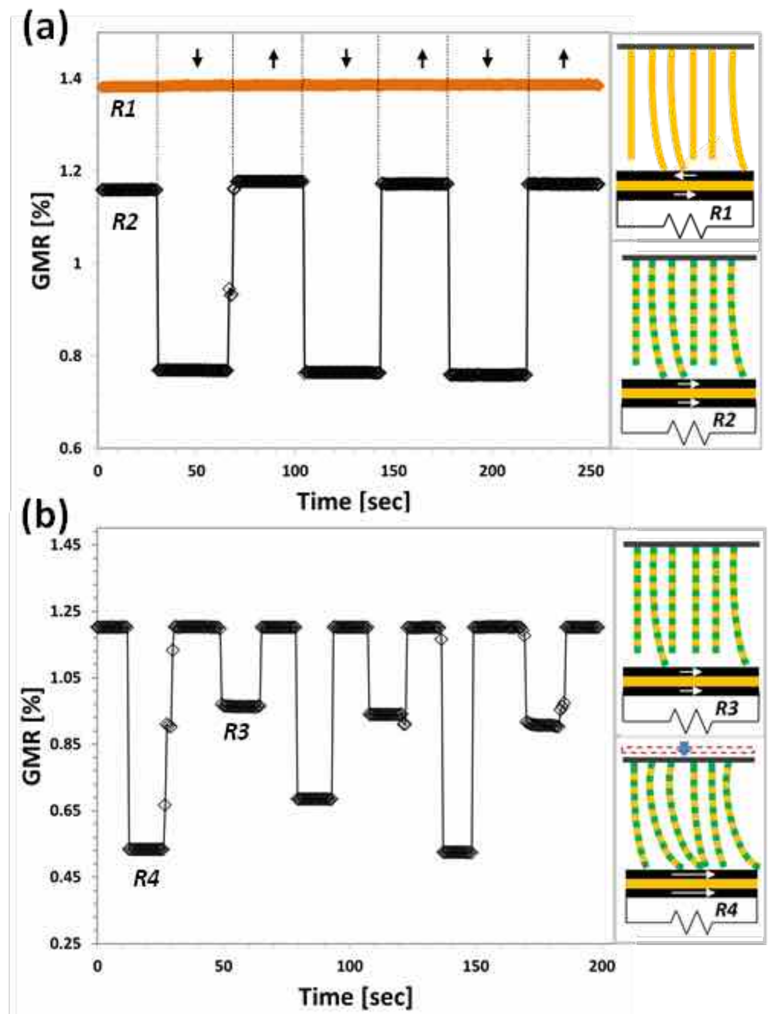
Magnetostrictive Fe-Ga/Cu Nanowires for Sensing Applied Pressure

UNIVERSITY OF MINNESOTA

SEM: nanowire array compression



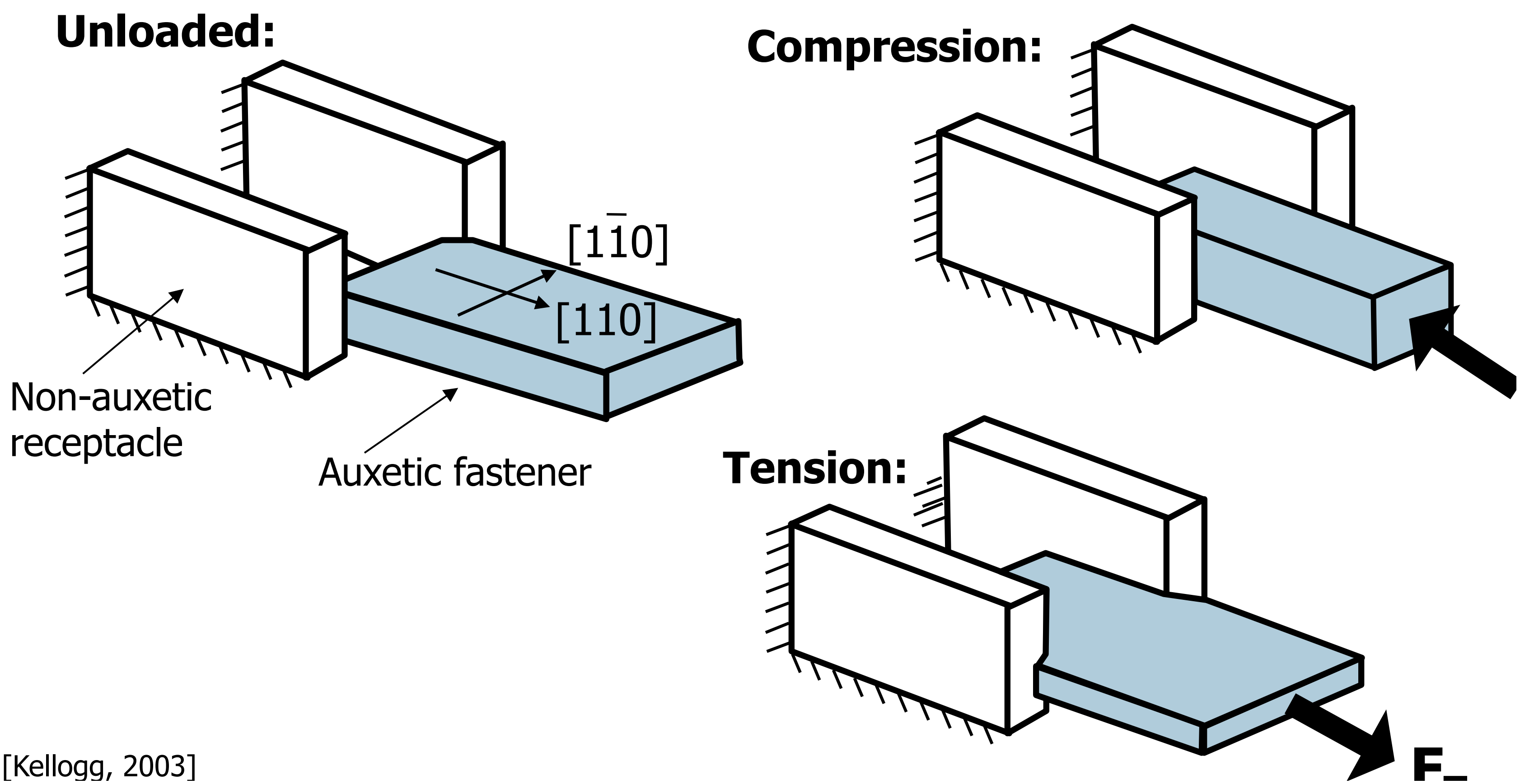
- No resistance change was observed by Cu NW array sample.
- The coarse step (~ 1 μm) causes 2 times larger GMR % value change (0.5 – 0.65%) than the value change (0.2 – 0.3%) caused by the fine step (~ 100 nm).
- Estimated values of sensor sensitivity are 1 ~ 4 mΩ/kPa.



$[GMR\% = ((R(H) – R(H_{max})))/R(H_{max})\%]$

Applications for Auxeticity include:

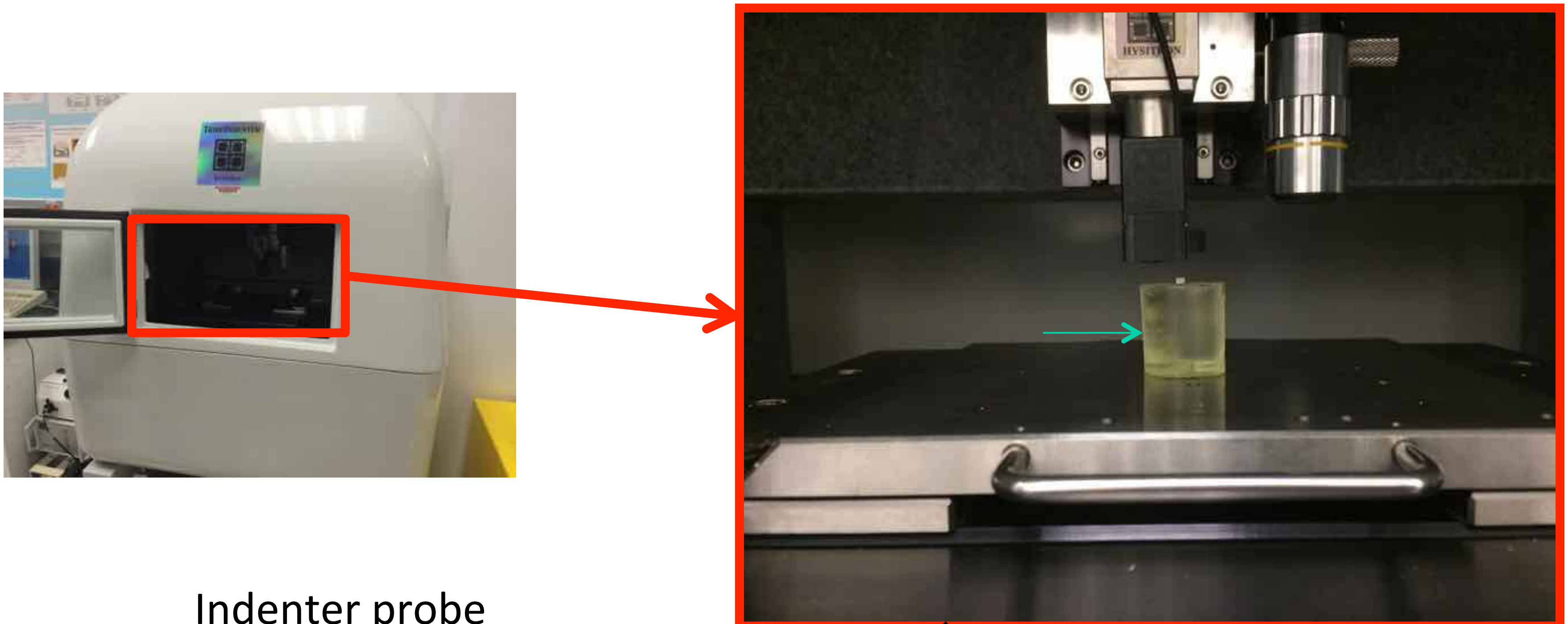
- Impede crack propagation
- Increased indentation resistance
- Reduced fiber pull-out
- Press fit fastening devices – control actively with Galfenol?

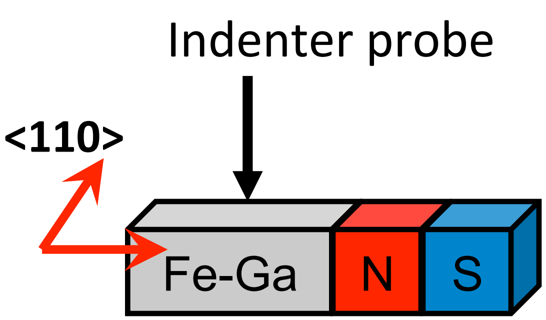


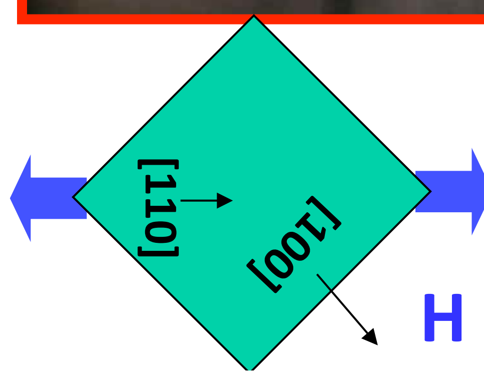
[Kellogg, 2003]

Nano indenter experiment to visualize effect of “magnetically tunable”auxeticity

Hardness is proportional to $1/(1-\nu^2)$







NANO INDENTATION DATA: HARDNESS AT 18% Ga Galfenol

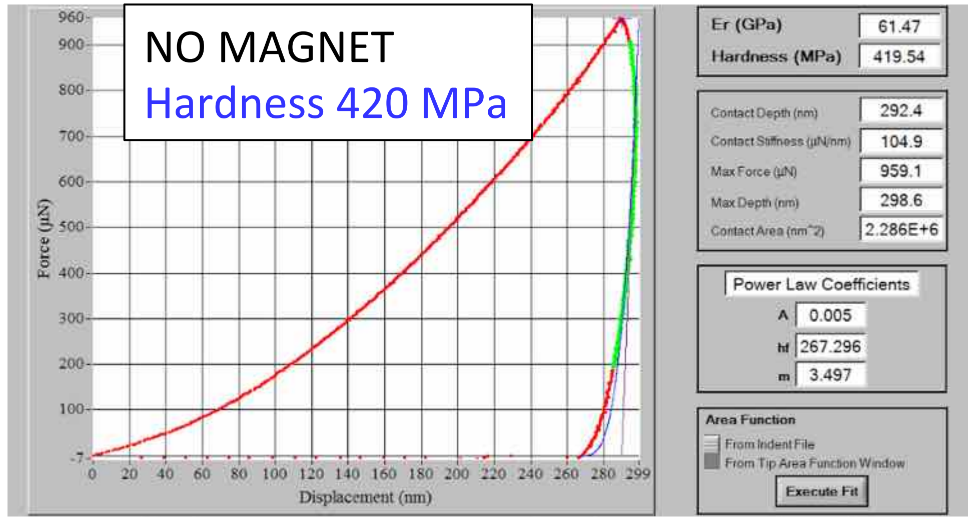
Vicker's Hardness ~600MPa in Iron

Without magnetic field:

Hardness ~ 400-700 MPa

Average Hardness ~550 MPa

Applied force of 0-980 microNewton
Displacement scale is 0-300 nm

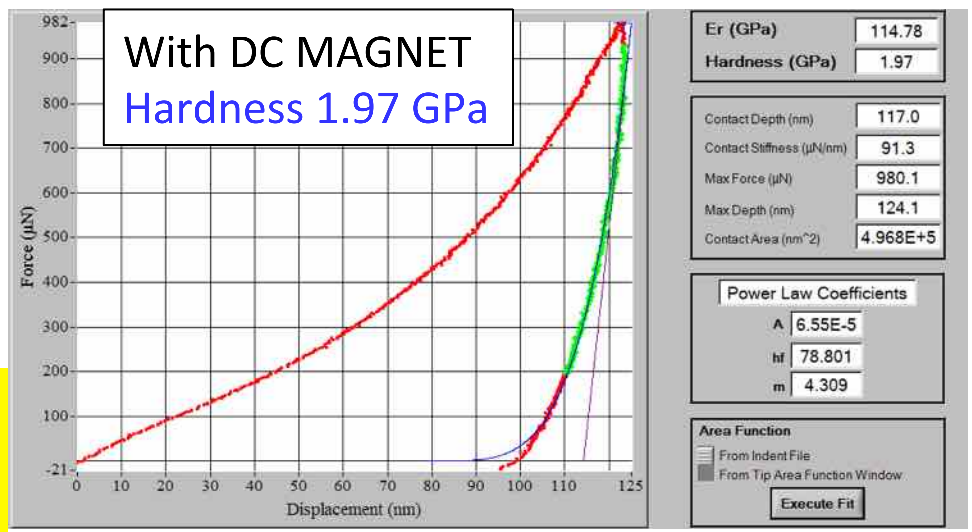


With a DC magnetic field ~150mT ($>H_{sat}$):

Hardness ~ 0.95- 2GPa

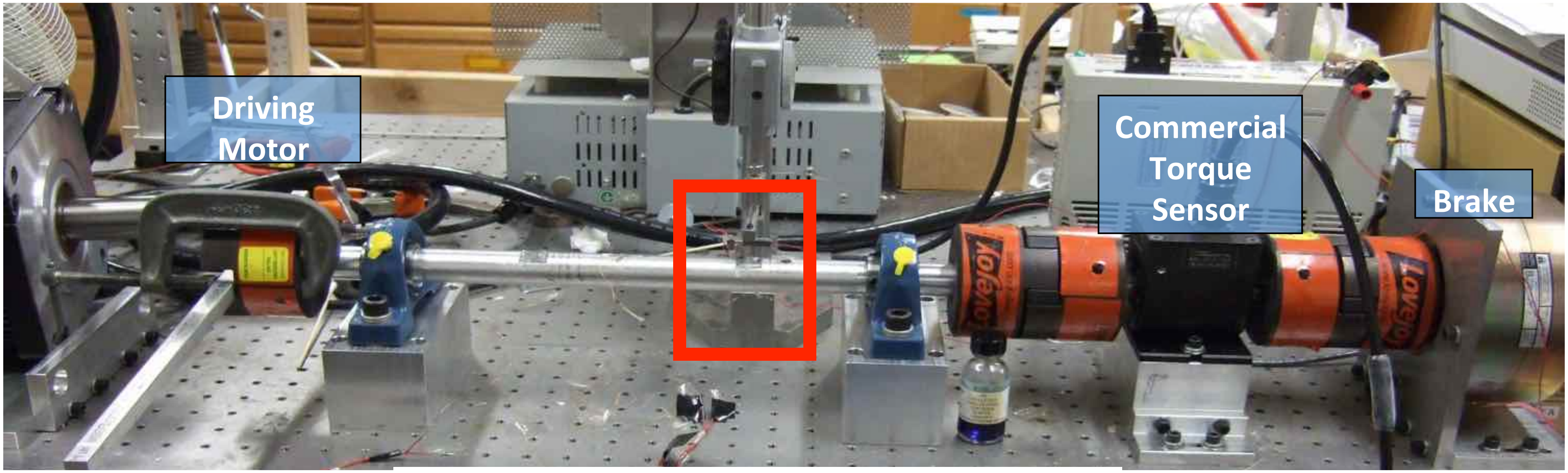
Average Hardness ~ 1.5GPa

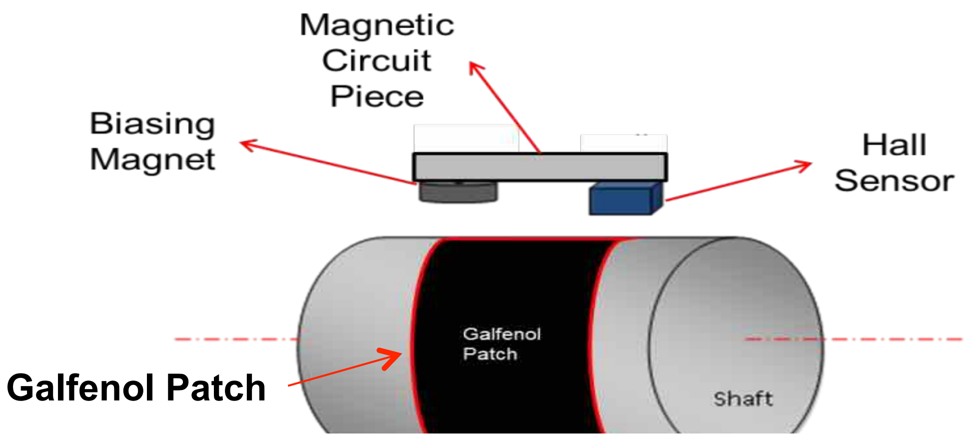
Applied force of 0-980 microNewton
Displacement scale is 0-125 nm



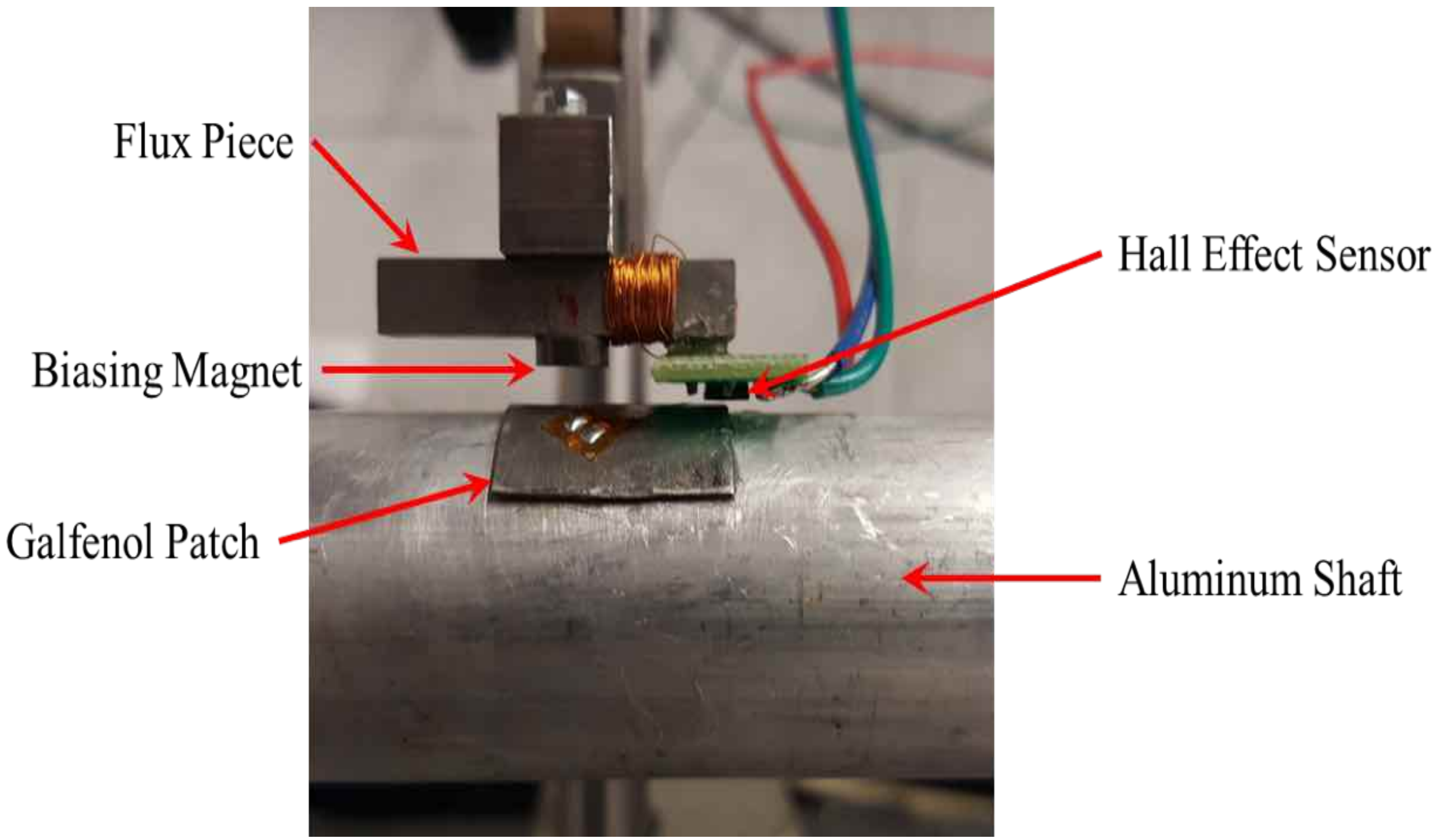
Measured Hardness Ratio 2.72
Predicted Estimate of 2.51!!

Benchtop Wireless Torque Sensor Setup

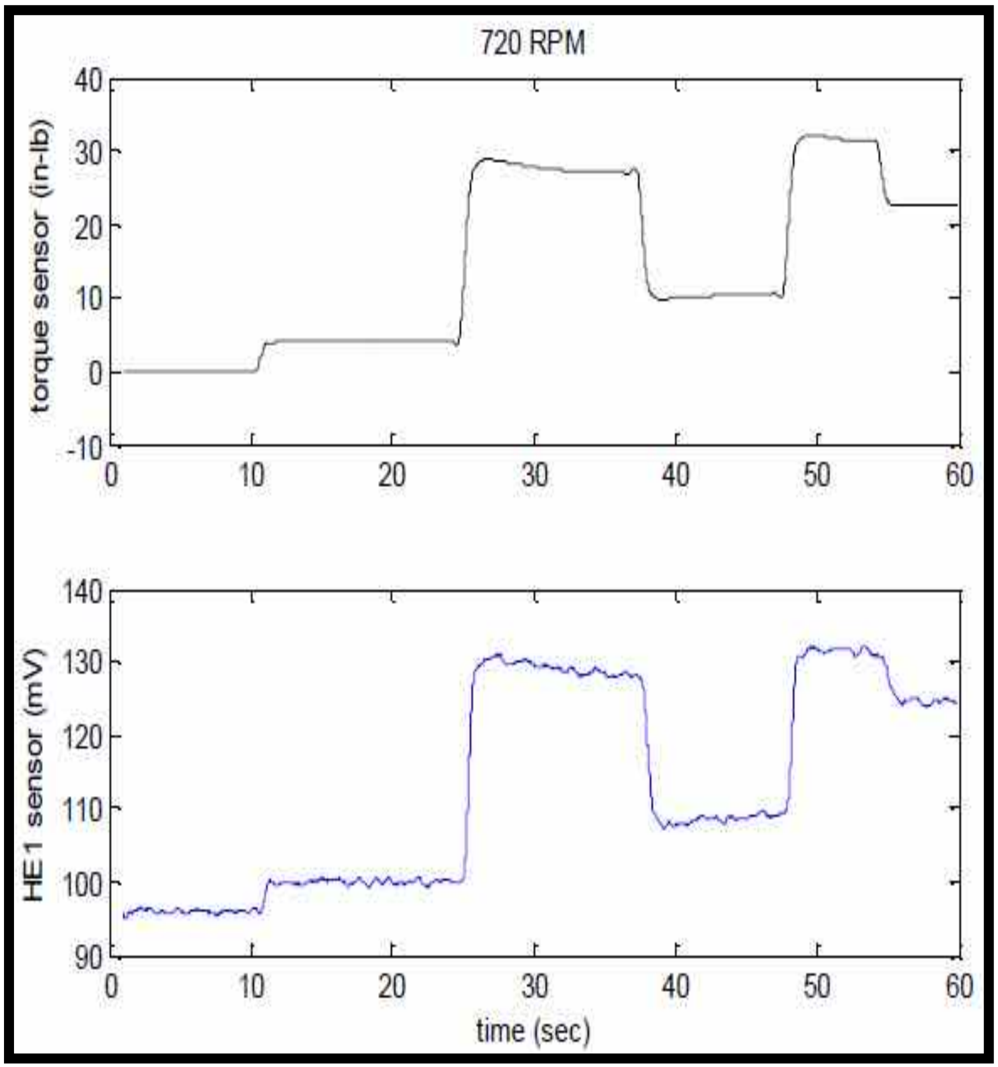


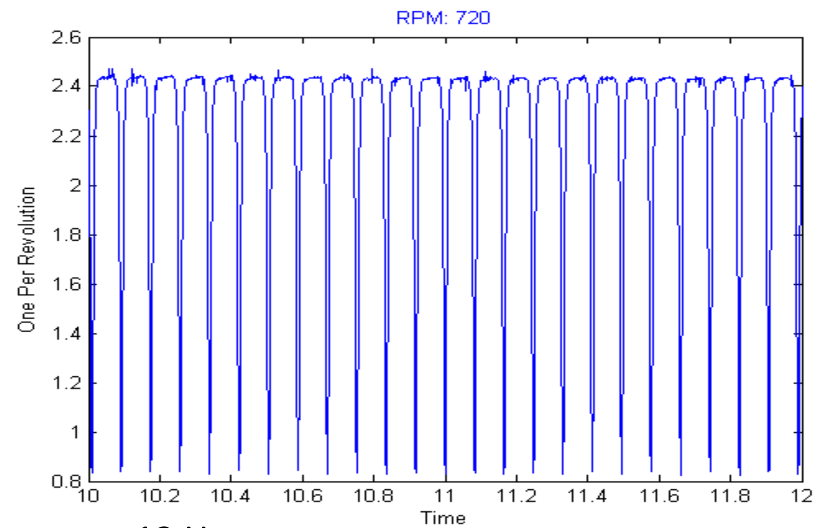


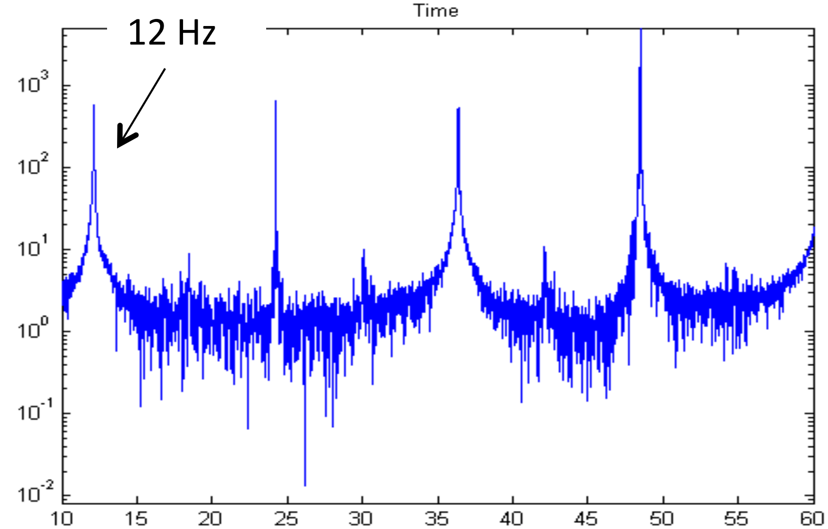
Close up of Galfenol patch on Aluminum shaft and flux piece with attached permanent magnet, coil and Hall effect sensor



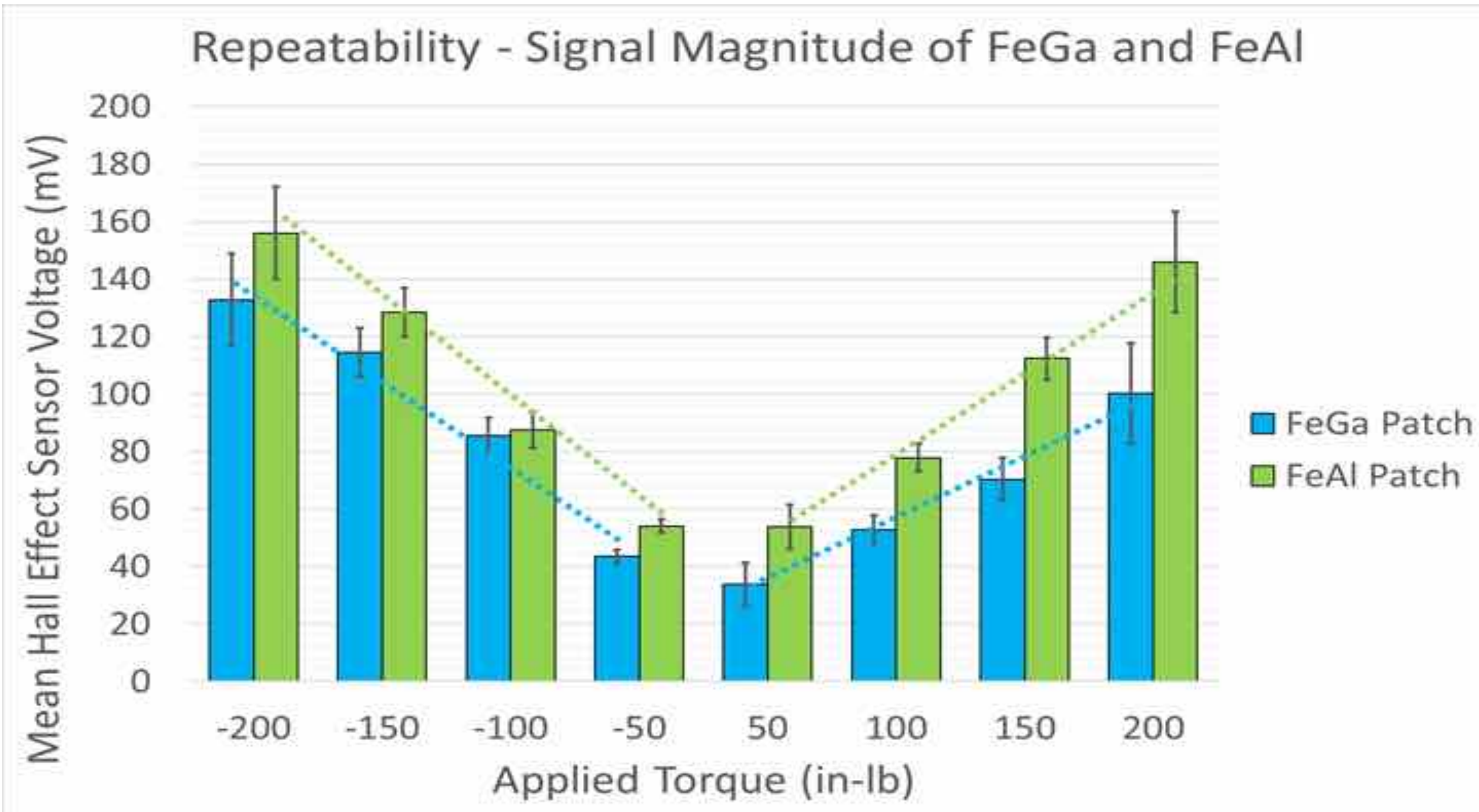
Black: COTS torque sensor
Blue: averaged Hall effect sensor







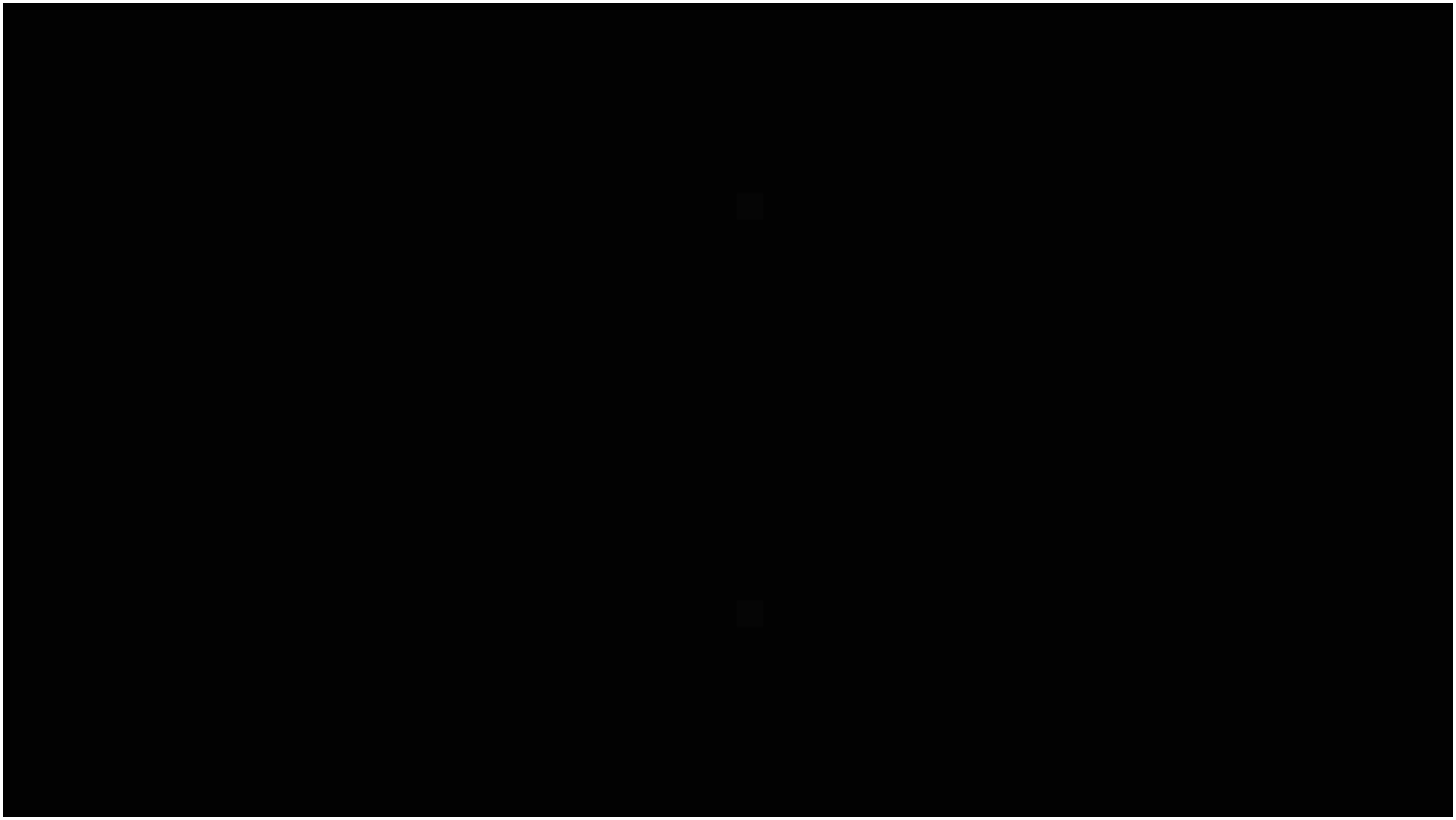
Galfenol and Alfenol patch output for clockwise and counterclockwise torque loading



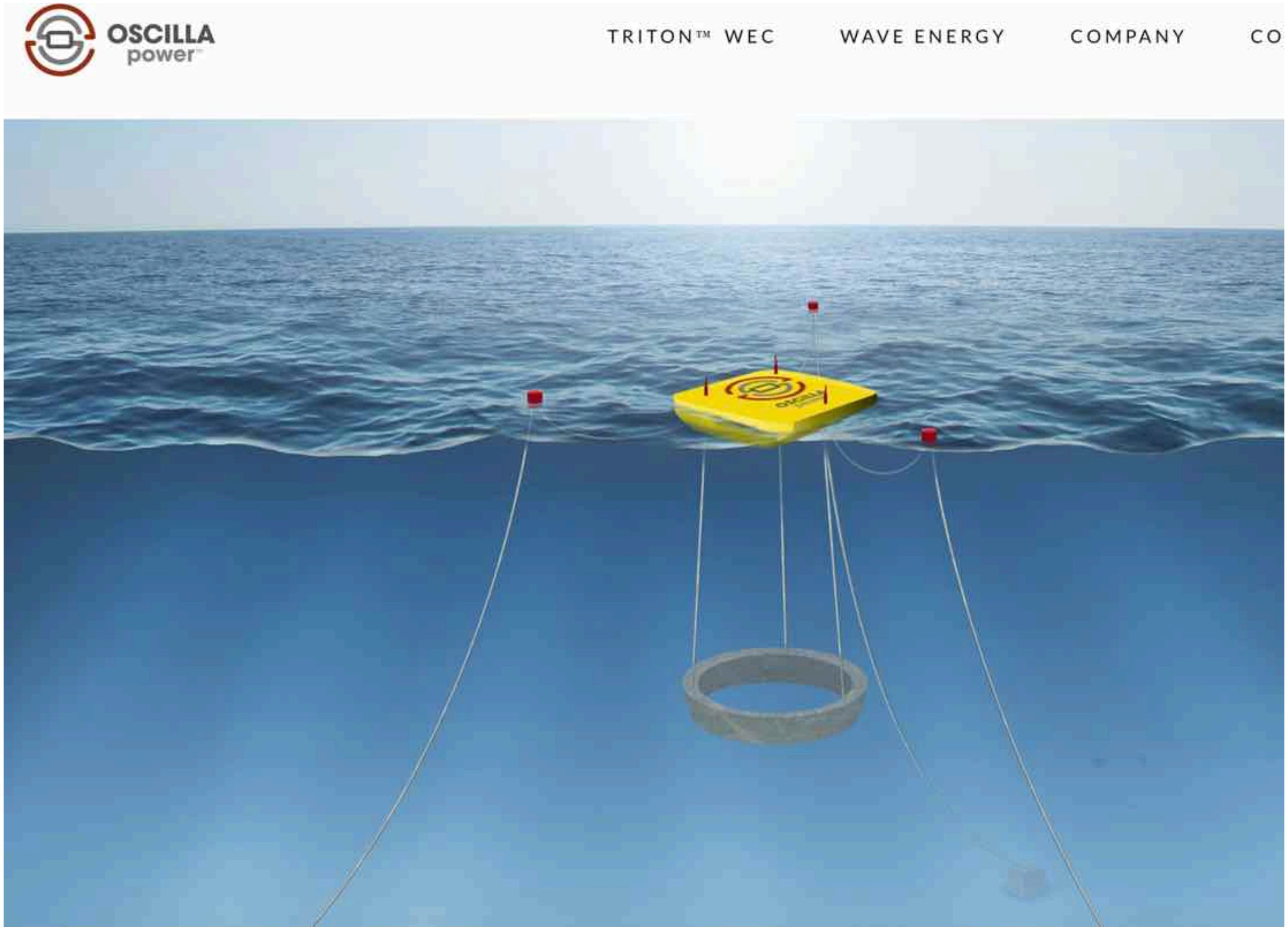
Spinning shaft at 360 and 1800 rpm

Upper: COTS Torque sensor

Lower: Hall effect sensor output (mean of 4)



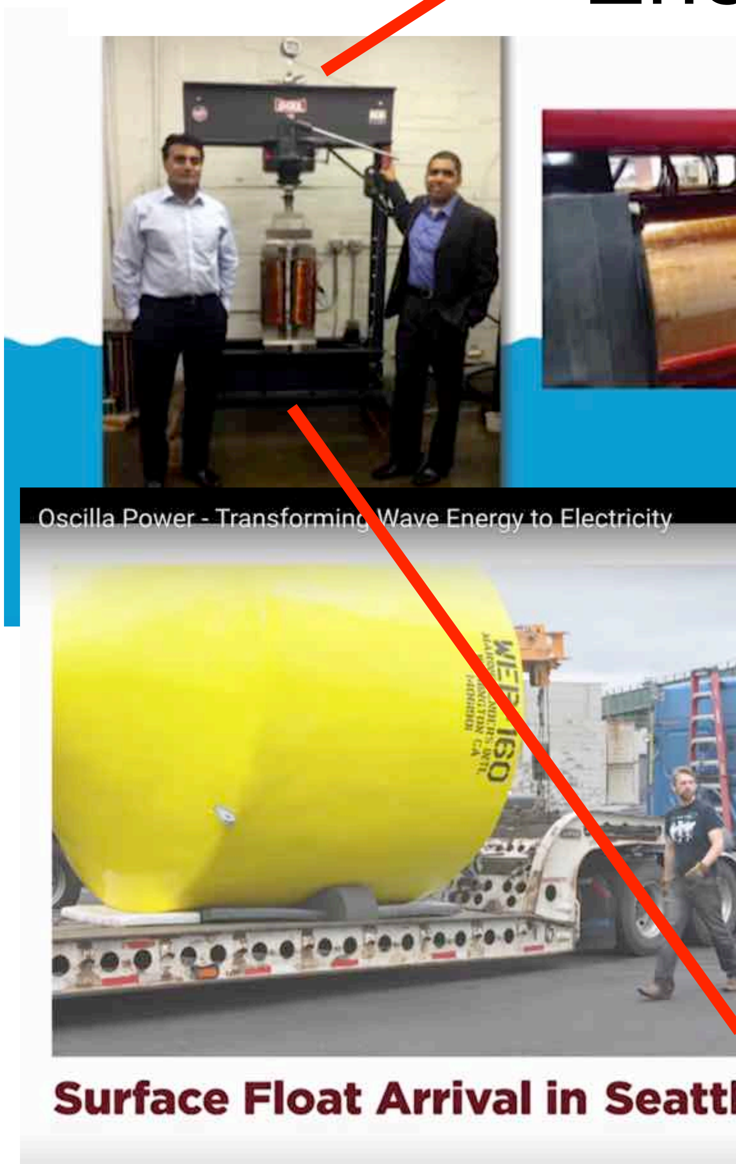
Oscilla Power is developing cost-effective magnetostrictive devices to harvest wave energy

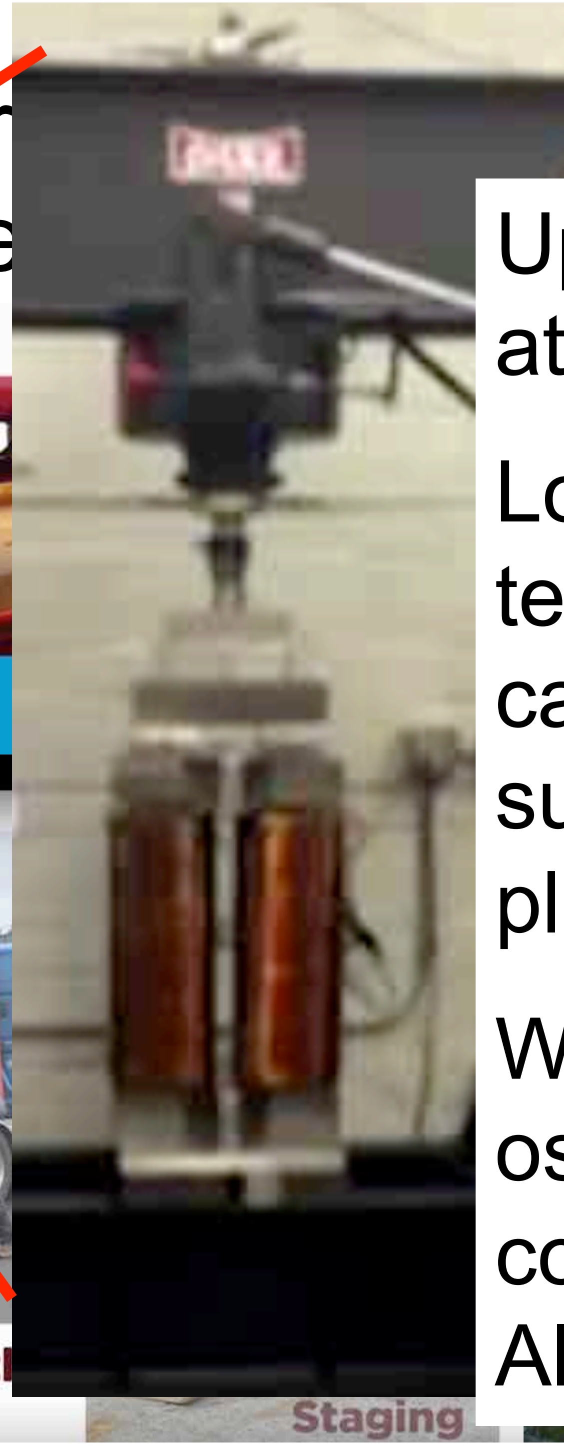


https://vimeo.com/154632694?swipeboxvideo=1

Oscilla Power's Magnetostrictive Wave Energy Harvesters

Oscilla Power rictive Wave Ene

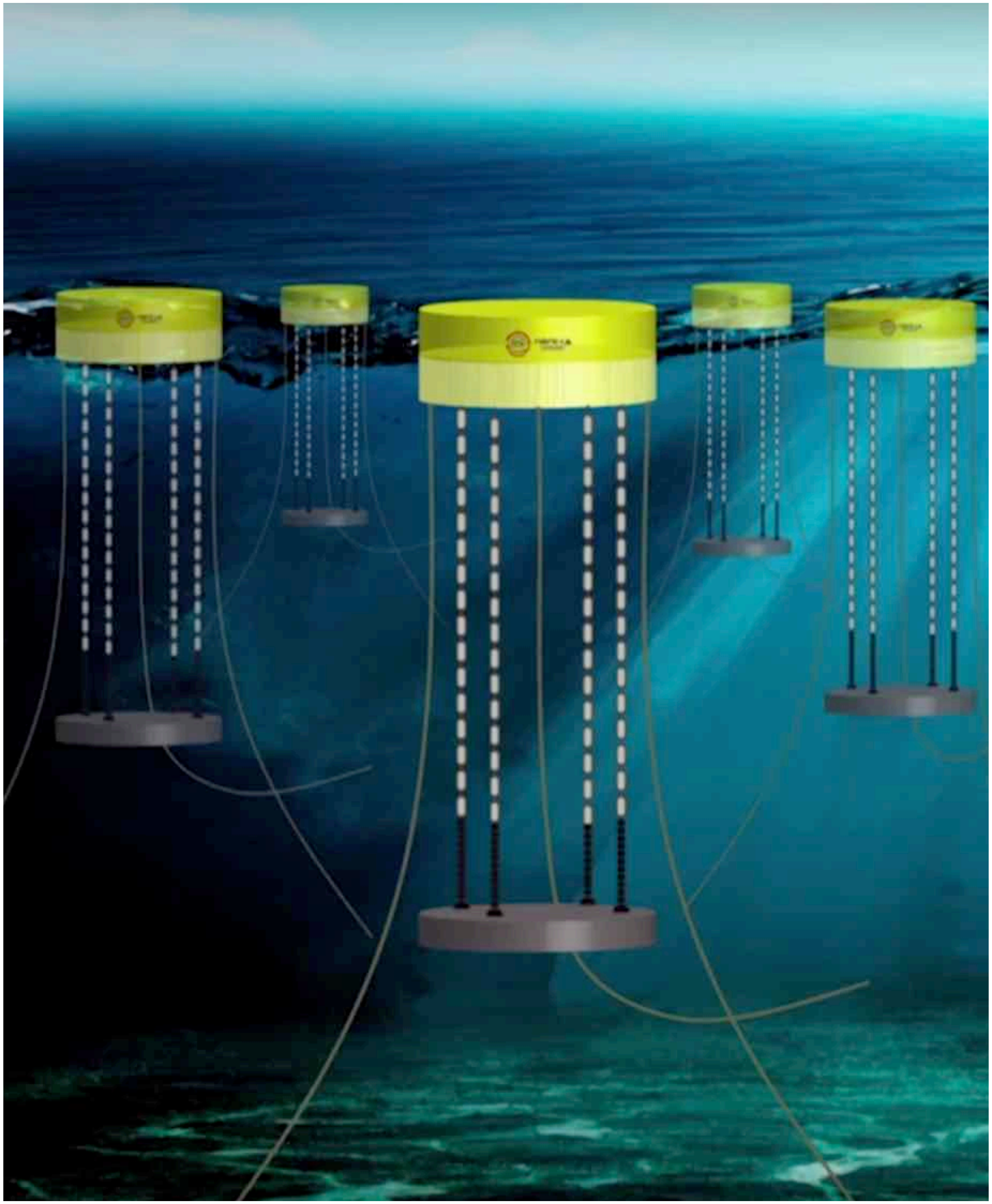




Upper end rigidly attached to float.

Lower end is tethered by cables to a subsurface heave plate.

Waves cause oscillatory axial compression in Alfenol rods



IEEE MAGNETICS

Thank you

With acknowledgement of the efforts of many colleagues and students.

And in particular the support of the NSF/ Sensors and Sensor Technologies Program, Program manager: Dr. Shih Chi Liu and ONR MURI, Program Manager Mr. Jan Lindberg and the IEEE Magnetics Society

Thank you

With acknowledgement of the efforts of many colleagues and students, past and present who have made significant contributions to the work in this presentation. This includes, among many others:

Drs. Rick Kellogg, Pat Downey, Atul Atulasimha, Supratik Datta, Chaitanya Mudivarthi, Ganesh Raghunath Jung Jin Park, Suok Min Na, Jin H. Yoo, and to Michael Marana and Michael Van Order.

At the Univ. Minn: Prof. Bethanie Stadler, Madhukar Reddy

ONR MURI team members: Drs. Tom Lograsso, Rob McQueeney, Marcelo Dapino, Steve Thompson, Dwight Viehland, Manfred Wuttig, Ichiro Takeuchi, Dick James, Uwe Marschner

ETREMA Products, Inc., Eric Summers, Jon Snodgrass

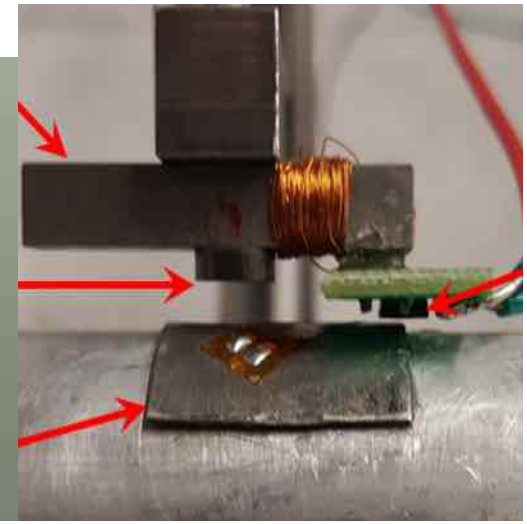
NSWC/CD, Marilyn Wun-Fogel, James Restroff, Art Clark

Kanazawa University in Japan, Prof. Toshiyuki Ueno

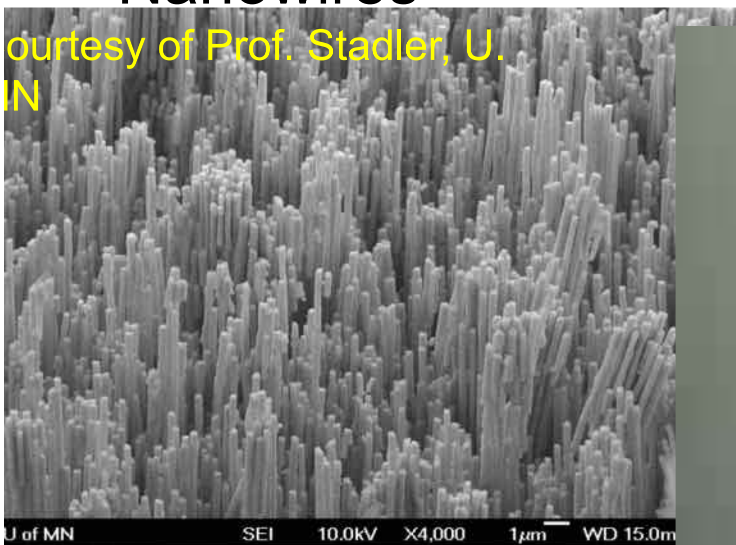
Oscilla Power: Dr. Balky Nair and Rahul Shendur

Examples of ***Structural*** Magnetostrictive Alloys

Torque Sensor

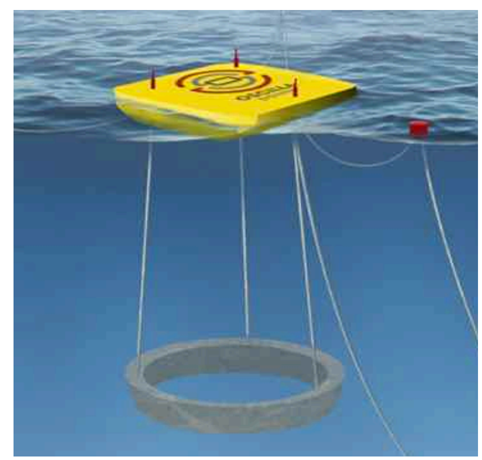


Nanowires

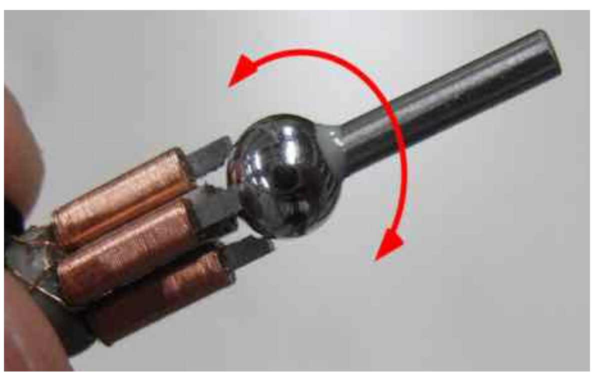


Rolled Sheet

Large-scale Wave Energy Harvesting



Micro-scale motion



Courtesy Prof. Ueno, U. Kanazaga

Implanted Bone-Plate Sensor

Courtesy of Profs. Fischer & Marschner TUDresden