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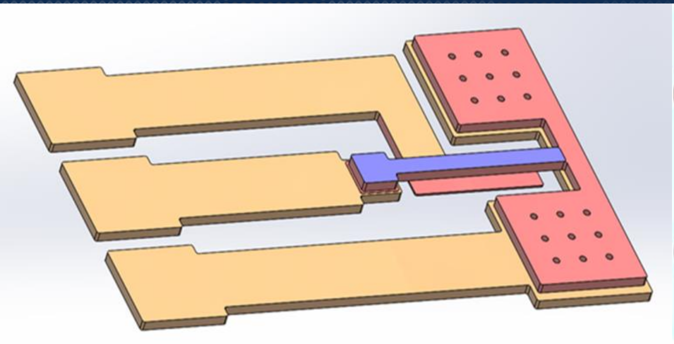

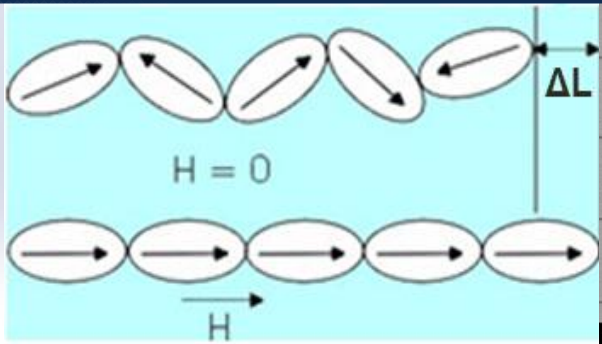

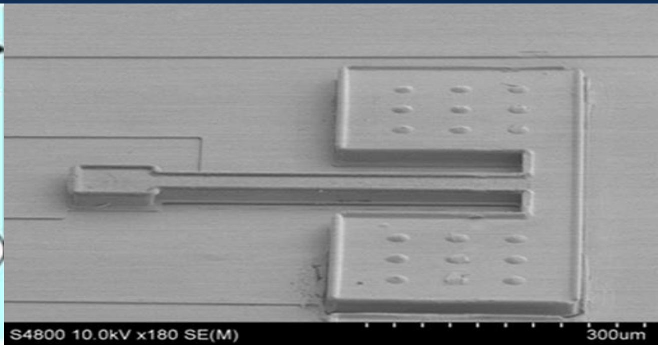

Modeled Electroformed MEMS Variable Capacitor for Cobalt Iron Alloy Magnetostriction Measurements

Eric D. Langlois, Patrick S. Finnegan, Jamin R. Pillars, Todd C. Monson, Mark H. Ballance, Christopher R. St John, Charles J. Pearce and Adam J. Thorpe

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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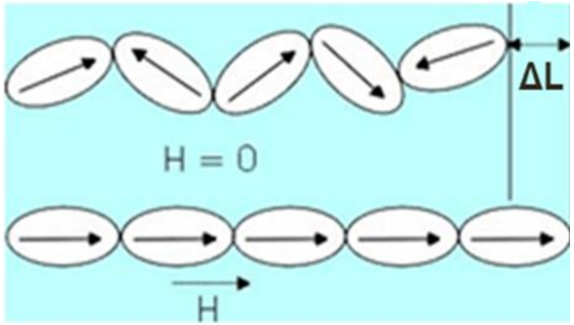
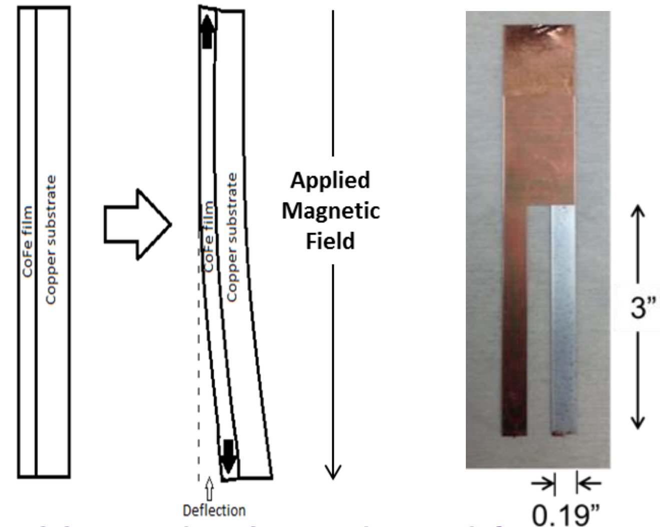
Electrodeposited Magnetostrictive CoFe



$\lambda(H) = \Delta L/L$

Expression du Tremolet de Lacheisserie and Peuzin

$$\lambda_{eff}(D_{sat}) = \frac{2(D_{\parallel} - D_{\perp})E_s {t_s}^2(1+\upsilon_f)}{9E_f L^2 t_f(1+\upsilon_s)}$$

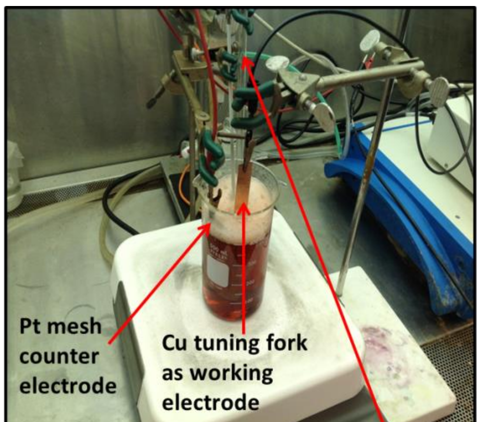


Previous work:

Hunter, D., et al., *Giant magnetostriction in annealed $Co_{1-x}Fe_x$ thin-films.* Nat Commun, 2011. 2: p. 518.

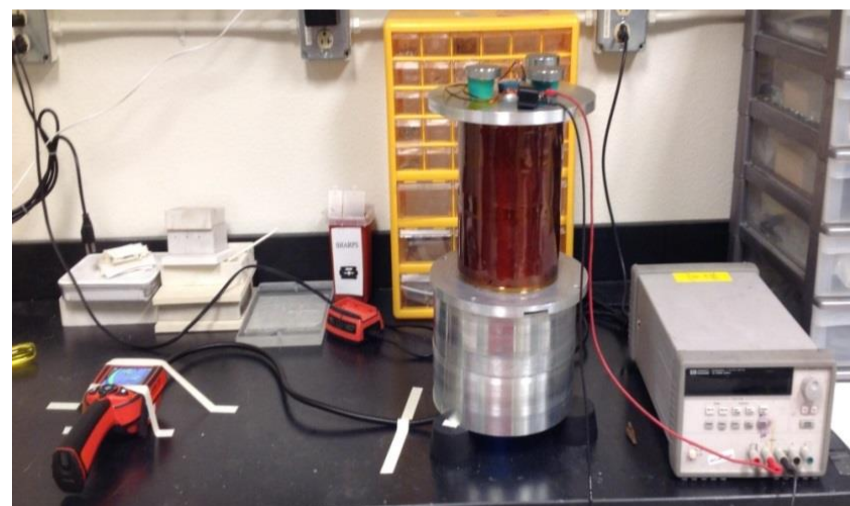
Our work:

Jamin Pillars, Eric Langlois, Christian Arrington, Todd Monson, “Electrodeposition Processes for Magnetostrictive Resonators,” U.S. Patent Application #14876652, October, 2015.



Bubbler with N_2 gas

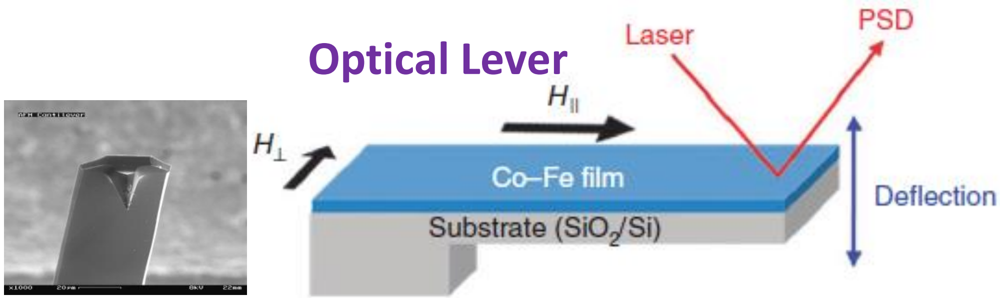
Calibrated solenoid used for testing



Need a method for measuring λ to obtain fundamental performance metrics λ_s and $d_{33,m}$ for magnetostrictive materials.

Motivation – Existing Measurement Techiques Insufficient

Optical Lever

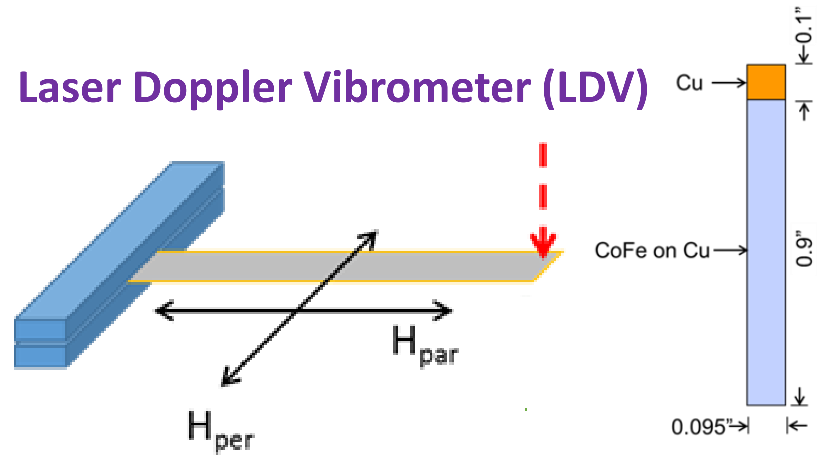


Hunter, D., et al., Giant magnetostriction in annealed Co1−xFex thin-films. Nat Commun, 2011. 2: p. 518.

- Strain resolution (pε)
- Compatible with electrodeposition
- Torsional effects

- Strain resolution (nε)
- Incompatible with electrodeposition

Laser Doppler Vibrometer (LDV)

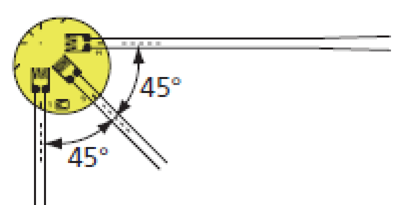


Staruch, M., NRL, communications

Triaxial, 0°/90°/45°

Resistance: 120 Ω

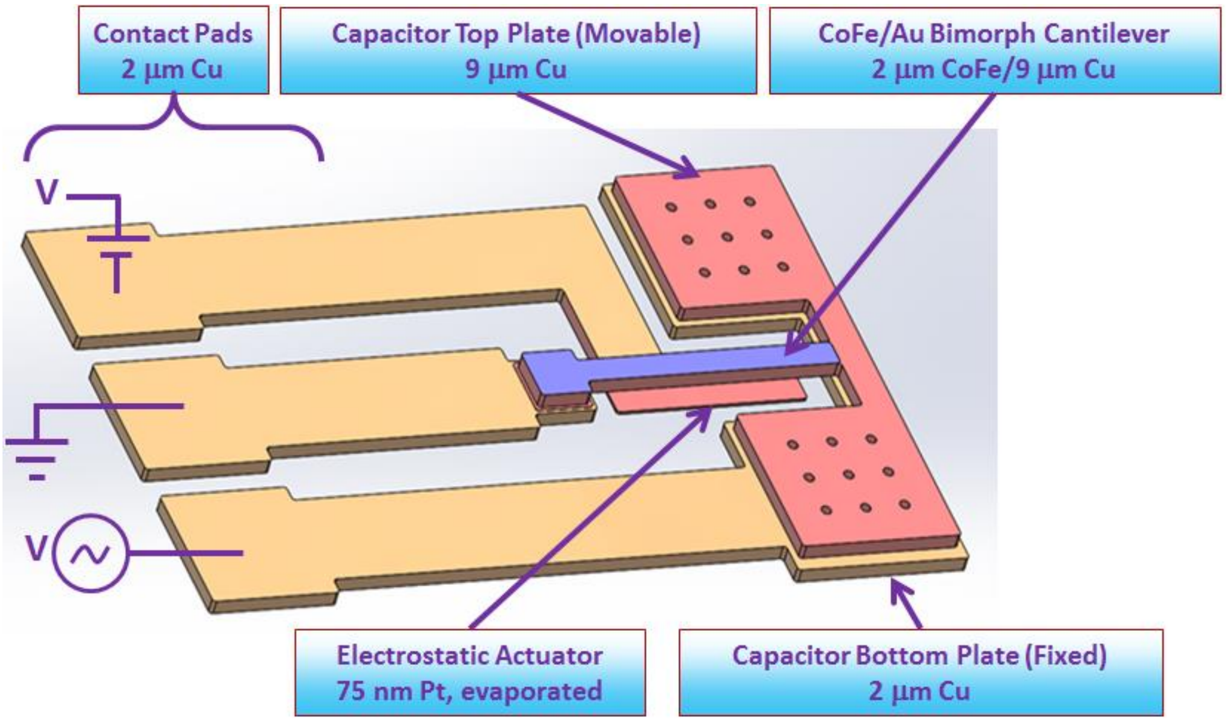
Gage factor: Approx. 2.1



- Strain resolution (± 5με)
- Not good for thin films
- Film adhesion poor

Resistive Strain Gauge

Simulation – Geometry and Materials



Model courtesy of Adam Thorpe, Sandia National Laboratories

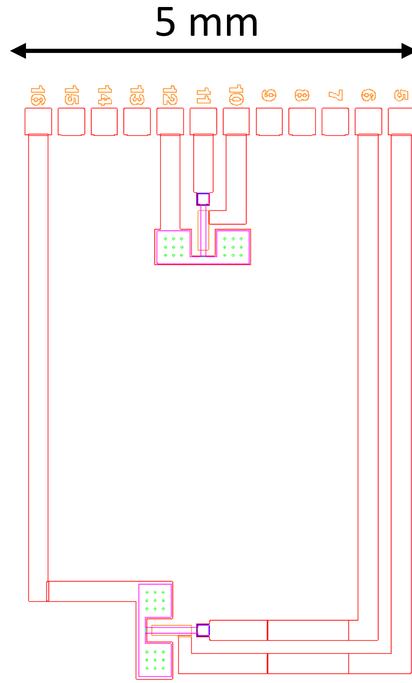
Device Feature	Geometry
Electrostatic Actuator	Width: 300 µm Depth: 80 µm Height: 50 nm
Bimorph Cantilever: Top Film	Width: 400 µm Depth: 40 µm Height: 2µm
Bimorph Cantilever: Bottom Film	Width: 400 µm Depth: 40 µm Height: 9µm
Top Capacitor Plate	Area: 0.135 mm^2 Height: 9µm
Bottom Capacitor Plate	Area: ~0.16 mm^2 Height: 9µm
Air Volume	Sphere: R = 1.2 mm

Both magnetoelastic and electrostatic models were created. Only magnetolastic model will be presented.

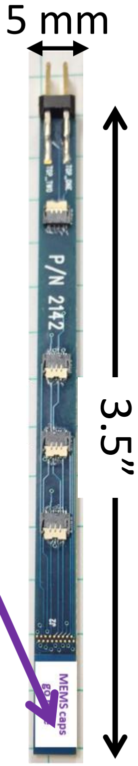
Design Features

Advantages
- **Chip-scale** (5mm (W) X 10mm (L))
- **Orthogonal** (patterned by photolithography)
- **Parallel sensors possible** (boosts signal)
- **Less prone to torsional effects** (improves accuracy)
- **Reduced instrumentation complexity**

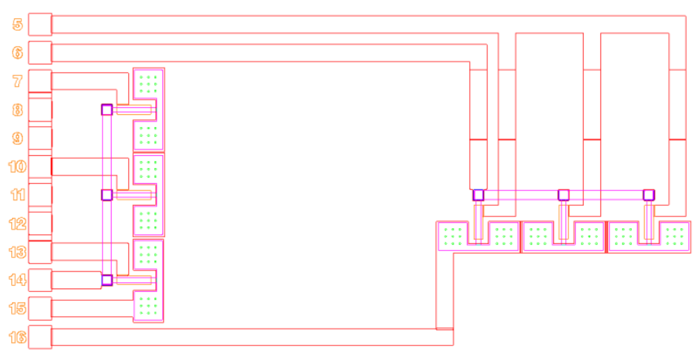
Disadvantages
- **Complex fabrication** (Sandia is good at this!)



Single orthogonal pair

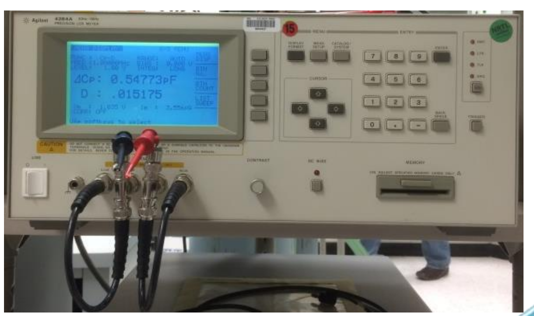


Custom PCB



Triple orthogonal pair

Agilent 4284A 20Hz-1MHz Precision LCR Meter



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Simulation – Physics Interfaces and Mesh

Solid Mechanics (solid)

1) $0 = \nabla \cdot S + F_V$

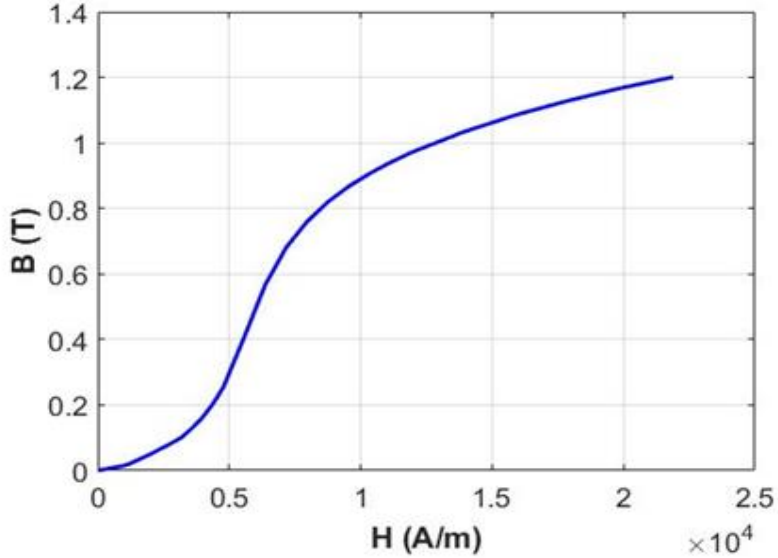
S = stress tensor
F_V = body force per volume

2) $\varepsilon_{me} = \frac{3}{2}\frac{\lambda_S}{M_S^2} dev(\boldsymbol{M} \otimes \boldsymbol{M})$

λ_S = saturation magnetostriction
M_S = saturation magnetization

I.C.'s: u = (0, 0, 0) m
$\delta u/\delta t$ = (0, 0, 0) m/s

B.C.'s: cantilever anchor



Initial B-H curve (measured)

Magnetic Fields (mf)

2) $B = \nabla \times (A_b + A_r)$

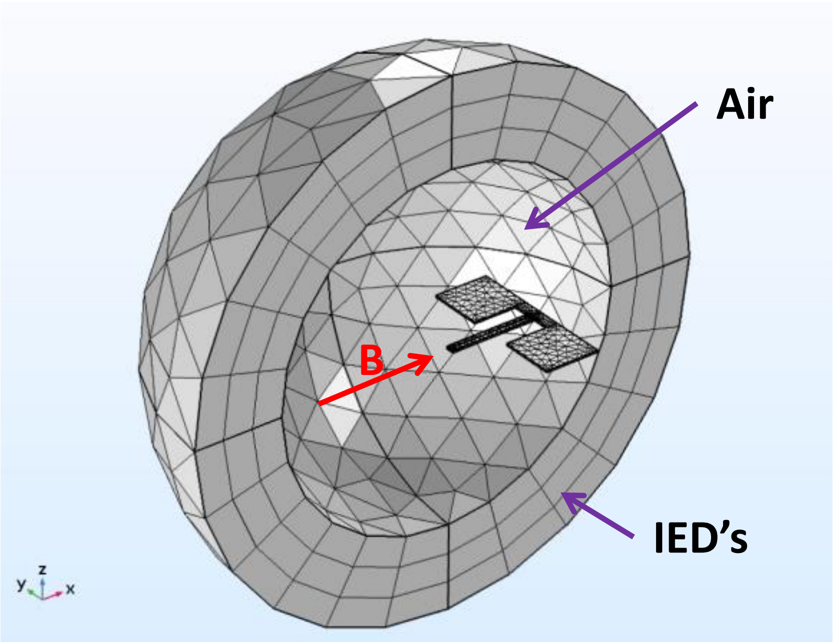
A_b = $B \cdot y$ = vector potential

I.C.'s: A = (0, 0, 0)

B.C.'s: n x A = 0 (mag insulation)

Magnetostriction (pzm1)

Coupling Type: Fully Coupled

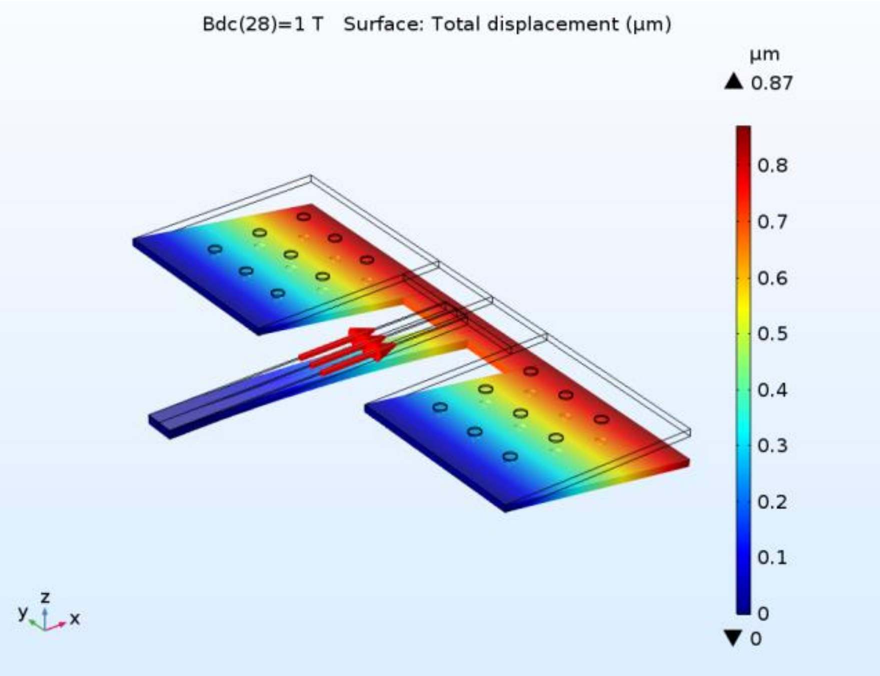


User controlled mesh with free tetrahedrals of size "Normal".

Simulation – Study and Results

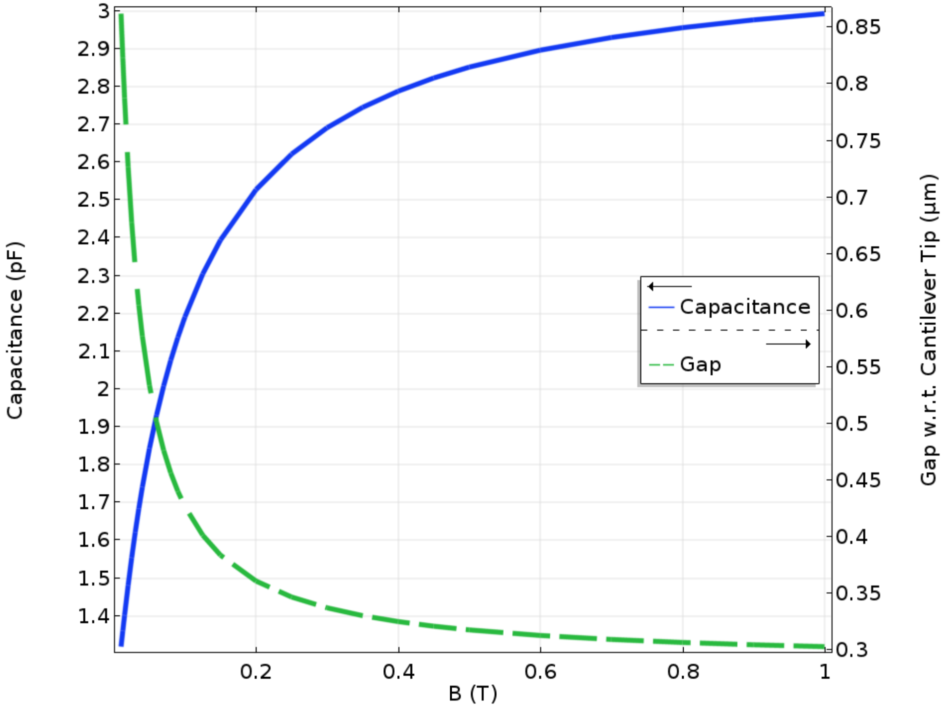
Stationary Study

- Parametric sweep: λ_s = 50-100 ppm @ B = 1 T
- Intent: magnetically saturate film without touching bottom plate
- Parametric sweep: B = 0 to 1 T



3D surface displacement plot (MEMS Cap 1)

Capacitance and gap spacing as a function of applied magnetic flux ramp

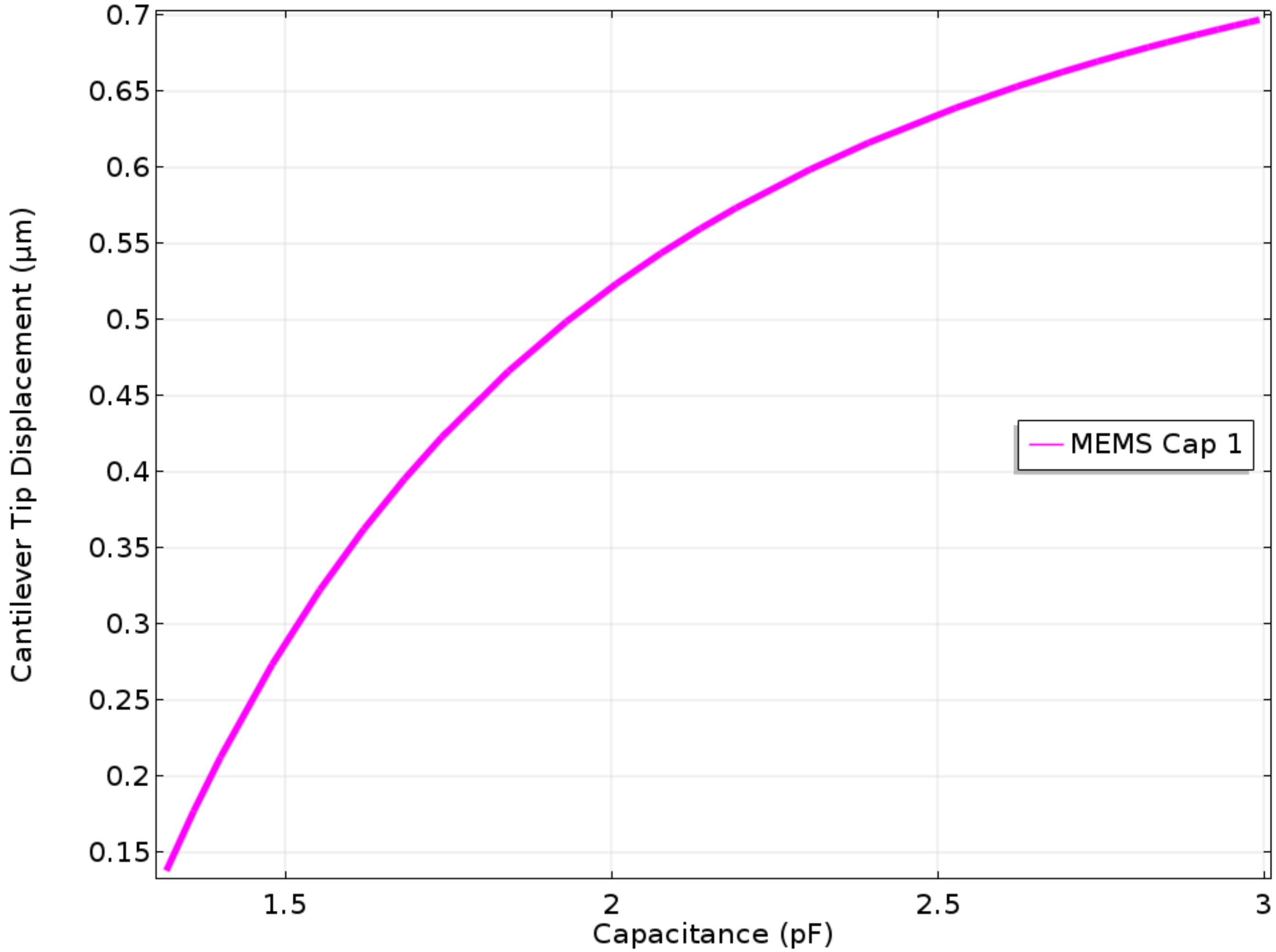


$$C = \sum_{i=0}^{n} \alpha\varepsilon_0 depth \int_0^{width} \frac{dx}{1+w}$$

n = number of block types used
α = symmetry (2)
depth = block dimension (y-axis)
width = block dimension (x-axis)
w = z-displacement

Sensitivity and Range

MEMS Cap 1 sensitivity plot



Device	Quasilinear Range (B = 0.01 to 0.1 T)	Sensitivity (µm/pF)	λ_S (ppm)
MEMS Cap 1	0.14 to 0.57 µm 1.3 to 2.2 pF	0.48	100

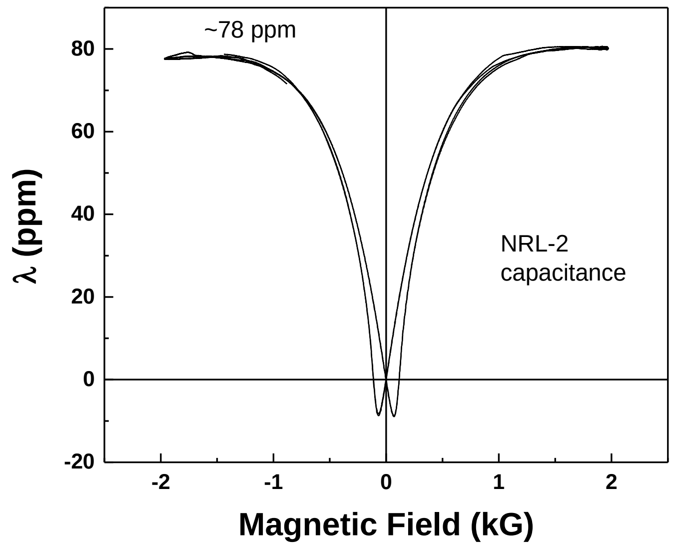
Conclusions

- New method for measuring magnetostriction in electroplated CoFe alloy films needed → MEMS variable capacitors.
- Sensitivity of 0.48 μm/pF was achieved with the MEMS Cap 1 design.
- Capacitor was designed to measure films with saturation magnetostriction values ranging from λ_S = 1 to 100 ppm.
- Alternative designs under consideration.
- 1st pass capacitors under development.

Thank You!

Acknowledgements:

- Individuals for their support and contributions to the vision of this work: Dianna Blair, (Project Manager), Keith Ortiz, Wahid Hermina.
- Metglas Inc. for providing free samples of magnetostrictive alloy ribbon used for calibration of our magnetic test equipment.
- This project was supported by Laboratory Directed Research and Development (LDRD) Project numbers 150356 and 200169. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.



Independent verification of magnetostriction in Sandia bimorph CoFe/Copper cantilevers confirmed by Margo Staruch, Ph.D., Naval Research Labs (NRL).

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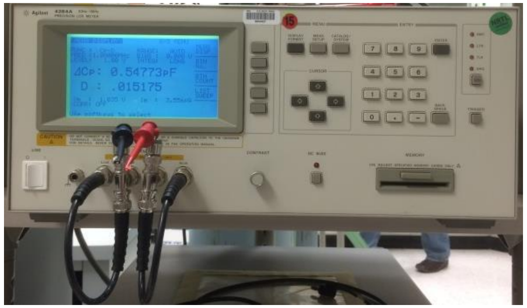
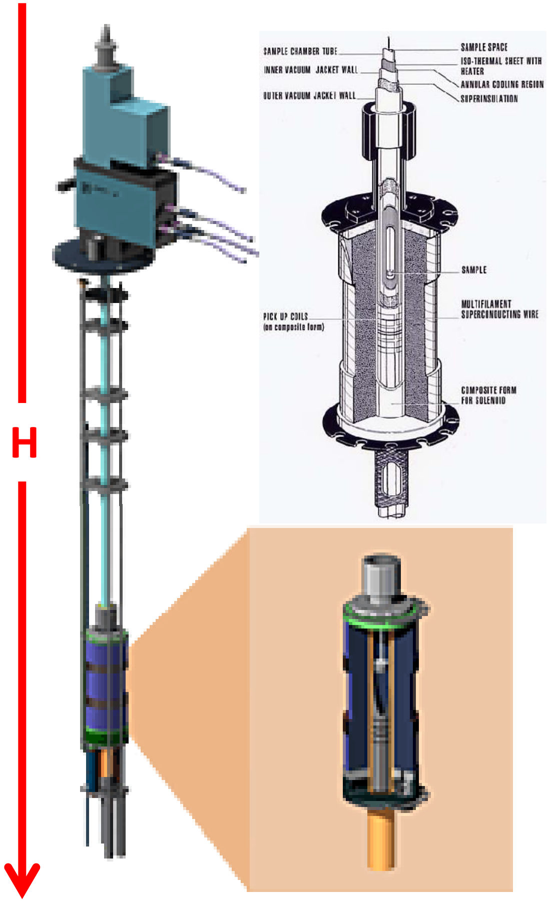
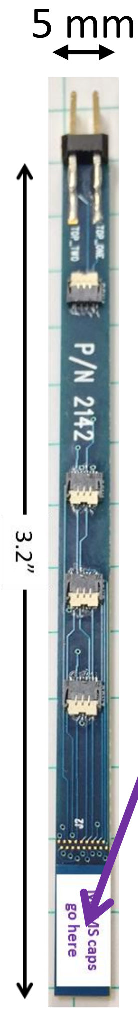
Measurement Apparatus: (MPMS-7) superconducting quantum interference device (SQUID) magnetometer.

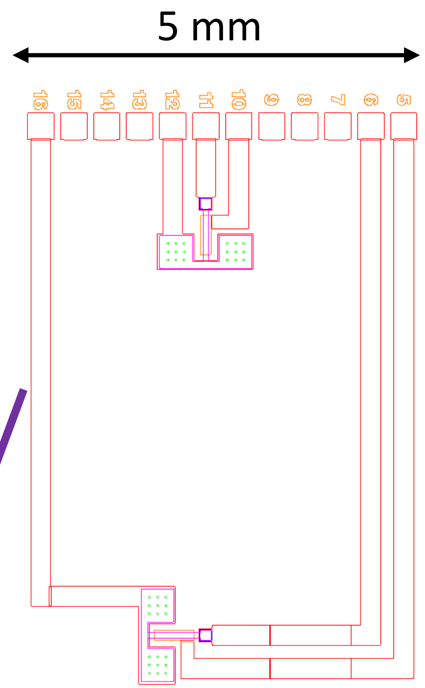
Agilent 4284A 20Hz-1MHz Precision LCR Meter



Quantum Design Magnetic Property Measurement System (MPMS) probe assembly





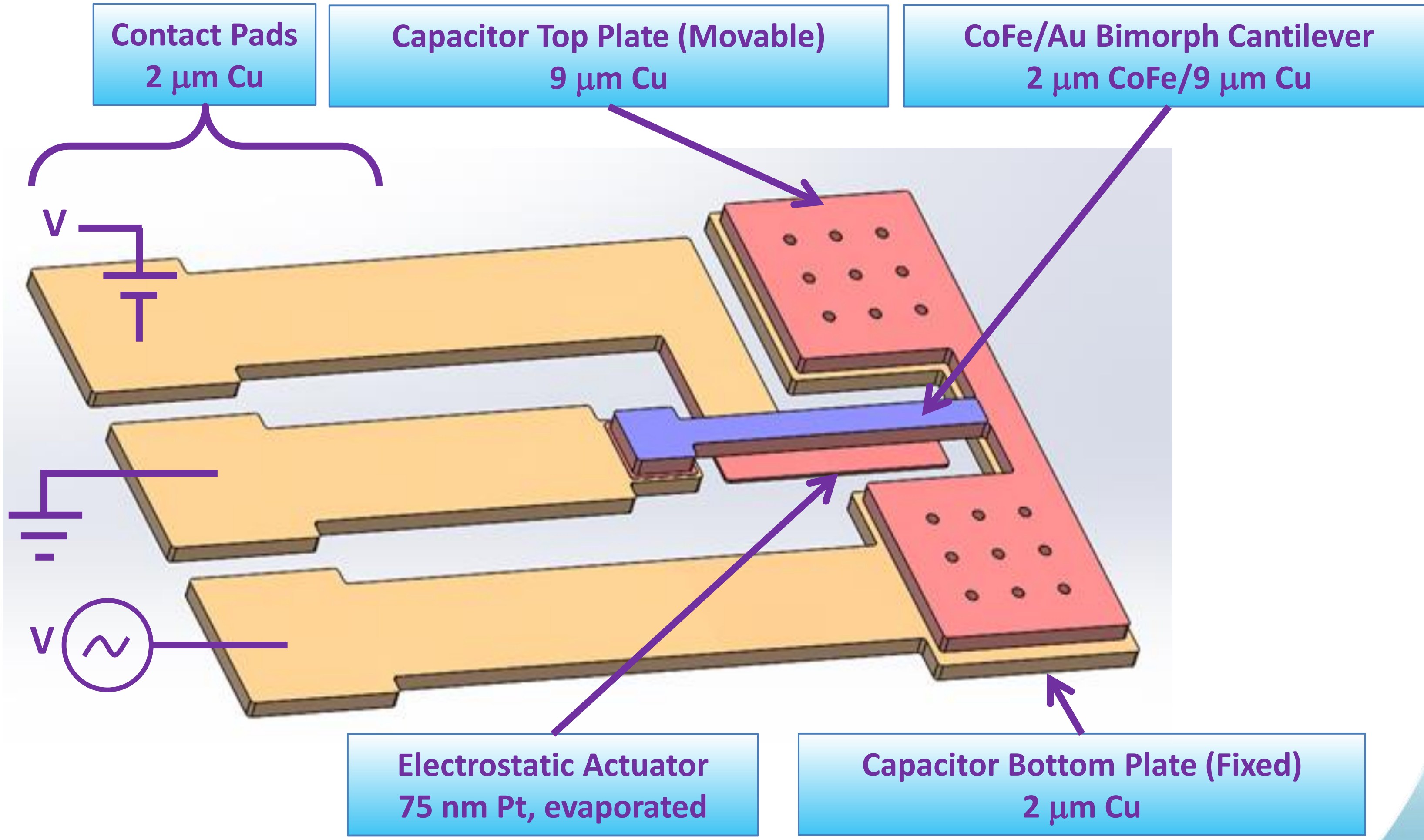


Custom PCB

Plating Bath

CoFe	Chemicals	H_3BO_3	$Co(H_2SO_3)_2$	TMAB	Sorbitol	Na Saccharin salt	Ascorbic acid	$Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$
	Conc. (mol/L)	0.5	0.4	0.1	0.01	0.05	0.05	0.08
Au	Chemicals	Neutronex 309i Gold – 2.4 troy oz gold/gal, 40 ppm thallium						
	Conditions	700 Hz pulse			25% duty cycle		2 mA/cm2	

*CoFe: Bath ph=2.0; Bath temperature=50°C
Au: : Bath ph=9.5; Bath temperature=50°C



**Model courtesy of Adam Thorpe, Sandia National Laboratories*