



Exceptional service in the national interest

ELECTRODEPOSITED MAGNETOELASTIC SENSORS FOR GROUND FAULT CURRENT DETECTION

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ENERGY RELIABILITY THROUGH GRID RESILIENCY



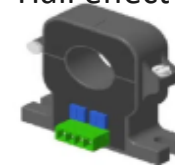
- Power grid resiliency is an important national security concern
- Ground fault creates safety hazard for technicians and for the equipment within the array
- High-energy fault currents can spark fires and melt conductors, which can cascade throughout the rest of the system.
- Existing current sensing approaches do not adequately address the needs of modern grid
 - Low cost sensors (e.g. shunt resistor) – intrusive
 - Medium cost approaches (e.g. current transformers) –insertion, non-linearity
 - Phasor measurement units :sophisticated but too expensive.
 - In general does not address higher harmonics detection
- Sensor approach to detect power frequency current based on coupled NiFeCo based magnetomechanical resonators that is:
 - Low cost, low SWAP
 - Wirelessly operates in real-time potentially capable of detecting harmful power frequency harmonics



Shunt resistor



Hall effect sensor



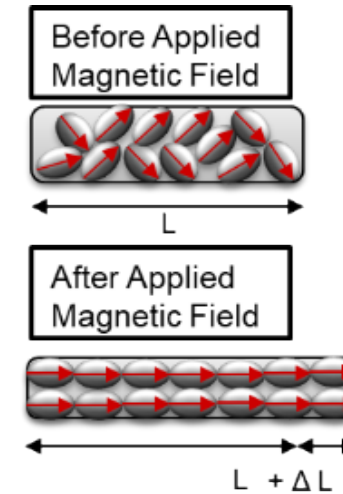
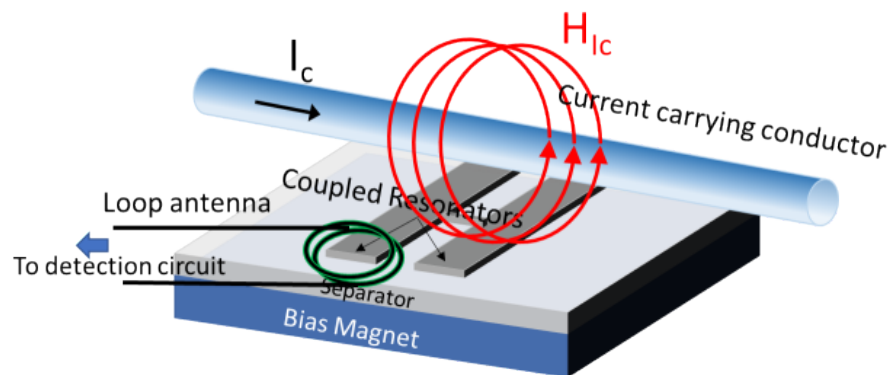
Current transformer



MAGNETOELASTIC SENSOR SOLUTION



- Magnetoelastic sensor for ground fault current detection
 - Ferromagnetic materials composed of magnetic domains
 - Individual magnetic moments of the atoms aligned
 - Magnetic domains rotate in response to applied magnetic field
 - Positive magnetostrictive film → elongation of the material
- Frequency dependance
 - Magnetic field from current shifts frequency
- COMSOL modeling to evaluate material properties for performance optimization



Resonance frequency (f_r) of single resonators

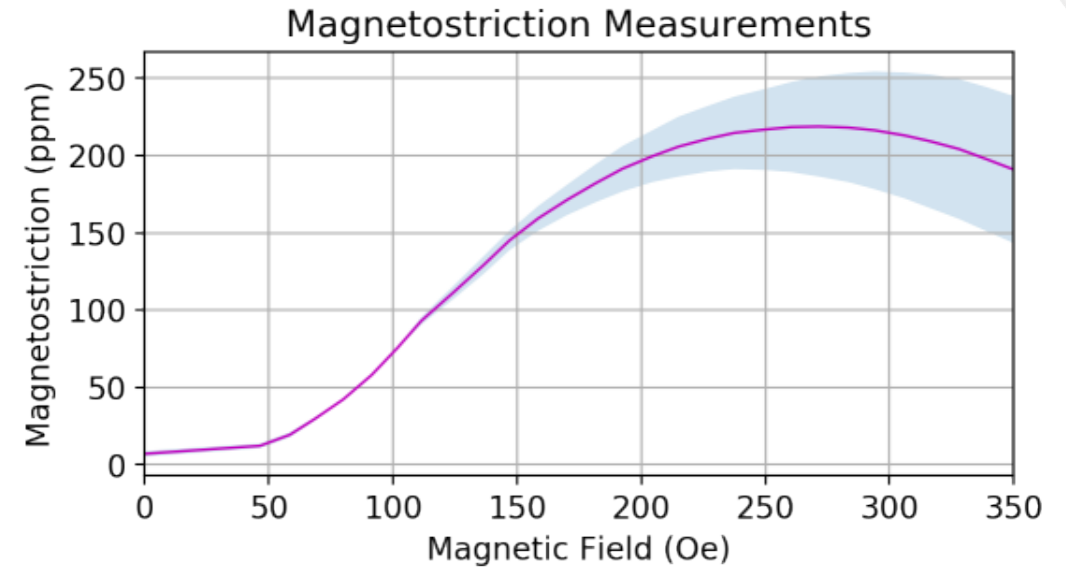
$$f_r = \frac{1}{2L} \left[\frac{\rho}{E_0} + \frac{9\lambda_s^2 \rho (|\mathbf{H}_B + \mathbf{H}_I(t)| \cos(\beta))^2}{J_s H_A^3} \right]^{-1}$$

ρ = Density
 H_B = Bias magnetic field
 H_I = AC field
 L = Resonator length
 E_0 = Young's modulus
 J_s = Saturation magnetostriction
 J_s = Saturation polarization
 H_A = Anisotropy field

INITIAL MAGNETOELASTIC MATERIAL DEVELOPMENT



- Electrodeposition of NiFeCo alloy with dopants - increase magnetostriction while keeping soft magnetic properties
- Composition of approximately 85% Ni, 10% Fe, and 5% Co
- Sulfate salt chemistry
 - Increase permeability with Ho
 - Decrease coercivity with Ge
 - Increase electrical resistivity with B
- Magnetostriction of approximately 210ppm measured at Northeastern University
- Thicknesses of 50nm to over 1mm
- UV tape for sheets of released material
 - Mechanical properties tested for Young's modulus and Poisson's ratio
 - Magnetometry and resonance testing
 - COMSOL modeling

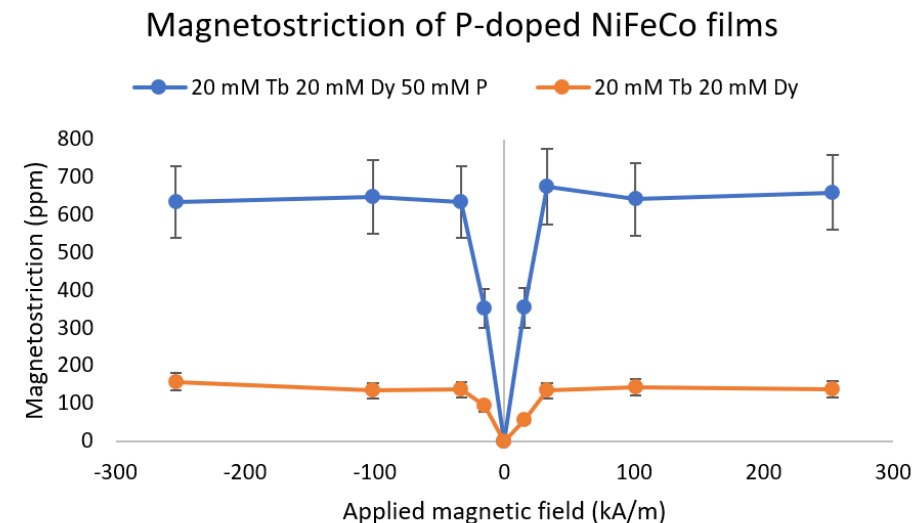
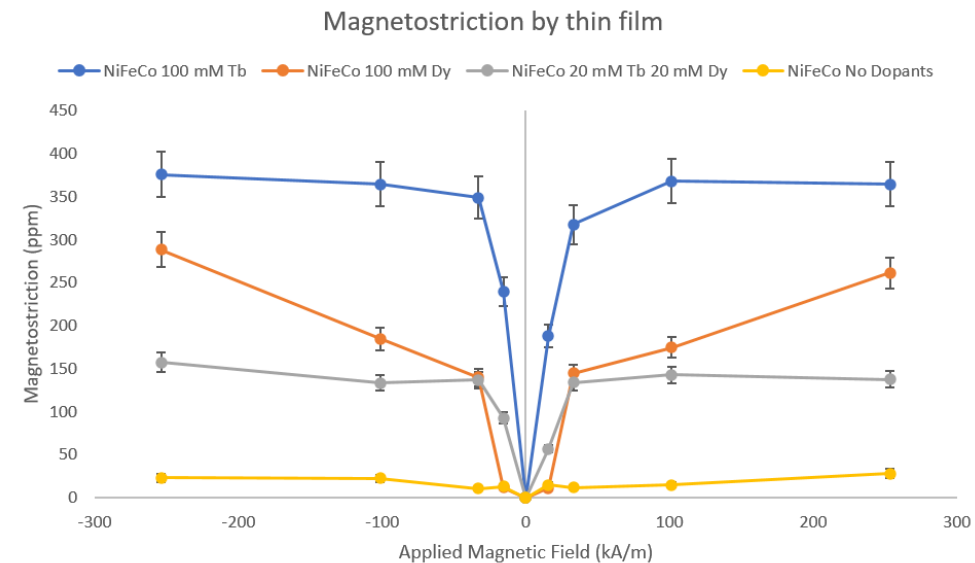


Released sheet of NiFeCo alloy material

INCREASING MAGNETOSTRICTION AND ELECTRICAL RESISTIVITY



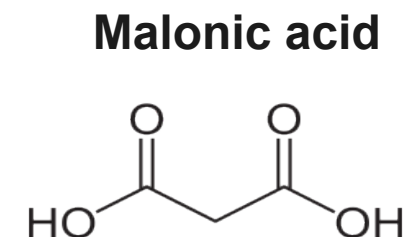
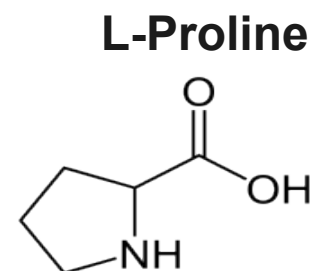
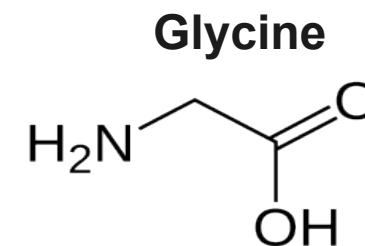
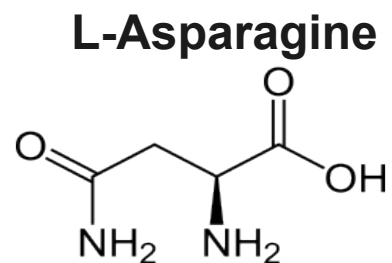
- Increase magnetostriction with Tb and Dy
- Increase electrical resistivity and lanthanide incorporation with P
 - Increase from approximately 1 at% to over 10 at% of lanthanides
- Thin film magnetostriction was measured using an SiO₂ Fiber Bragg Grating (FBG) dilatometry technique coupled with a light depolarization wavelength-based interrogation system
- Further discussion : “Electrodeposited NiFeCo + Tb and Dy for Enhanced Magnetostrictive Properties and Soft Magnetism”
 - Thursday at 11:20 room 304A by Mina Faltas
- Higher magnetostriction alloys had problem with chemical stability and poor deposits



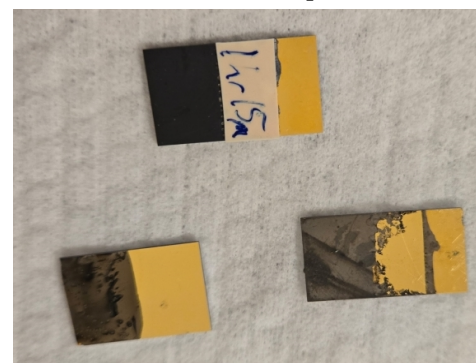
ENZYME COMPLEXING FOR CHEMISTRY STABILITY



- New chemistry developments for better material performance and reliability
- Phosphorous incorporation for electrical resistivity
 - Promotes lanthanide incorporation for increased magnetostriction
 - Causes instability in chemistry and poor mechanical properties
- Looked at enzymes based on previous research
- Zwitterion with positive and negative functional group
- Test across concentration, pH, and current density
 - Molar ratios
 - Function/complex differently as a function of pH
 - Solubility limits



Old samples



Enzyme Chemistry



CONTROLLING STOICHIOMETRY AND MATERIAL PROPERTIES



- Tested at pH 2.0 to 4.0
- Current density varied from 10-40 mA/cm²
- Achieved good deposits from all chemistries
 - Mirror like surface with uniform film
 - XRD performed to look at crystal structure
 - Amorphous material as P is incorporated
- EDS performed for composition analysis
- Malonic promoted Ni films – stopping anomalous codeposition
- Asparagine had best stoichiometry at 2:1 ratio and 40mA/cm²
- Glycine and proline performed well at ≤1 molar ratio of ligand to cation

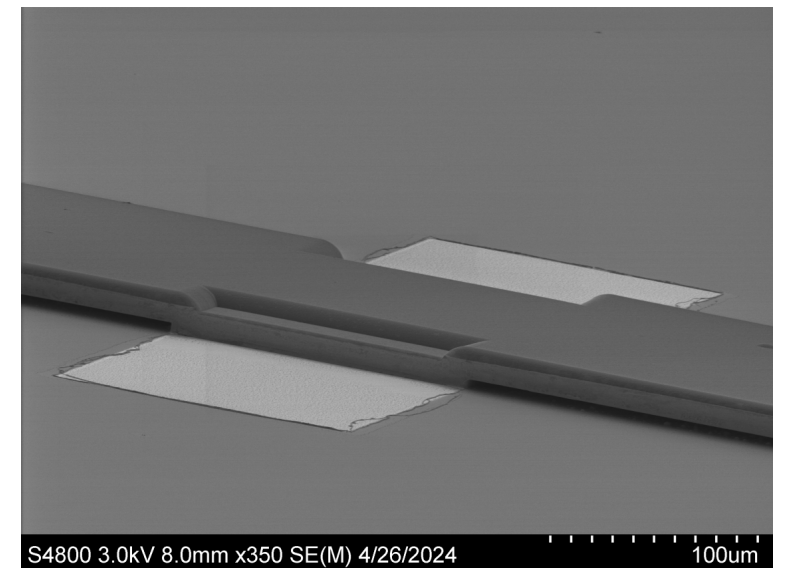
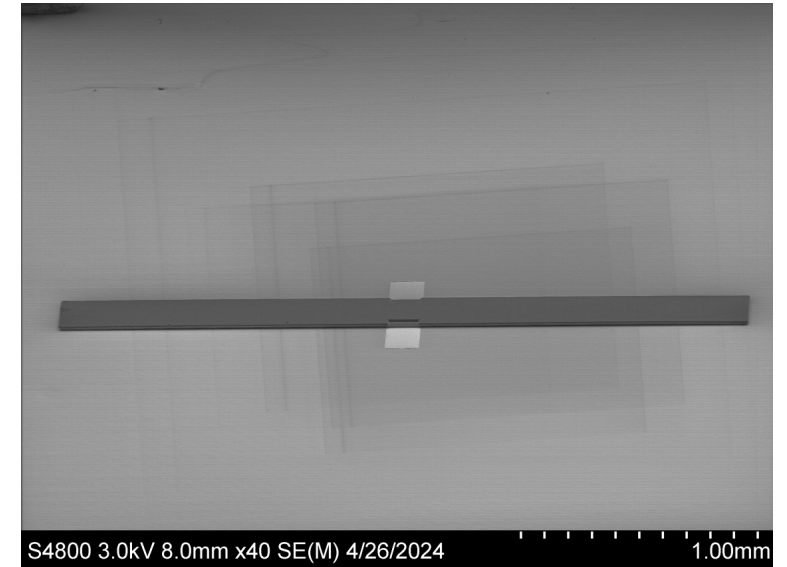
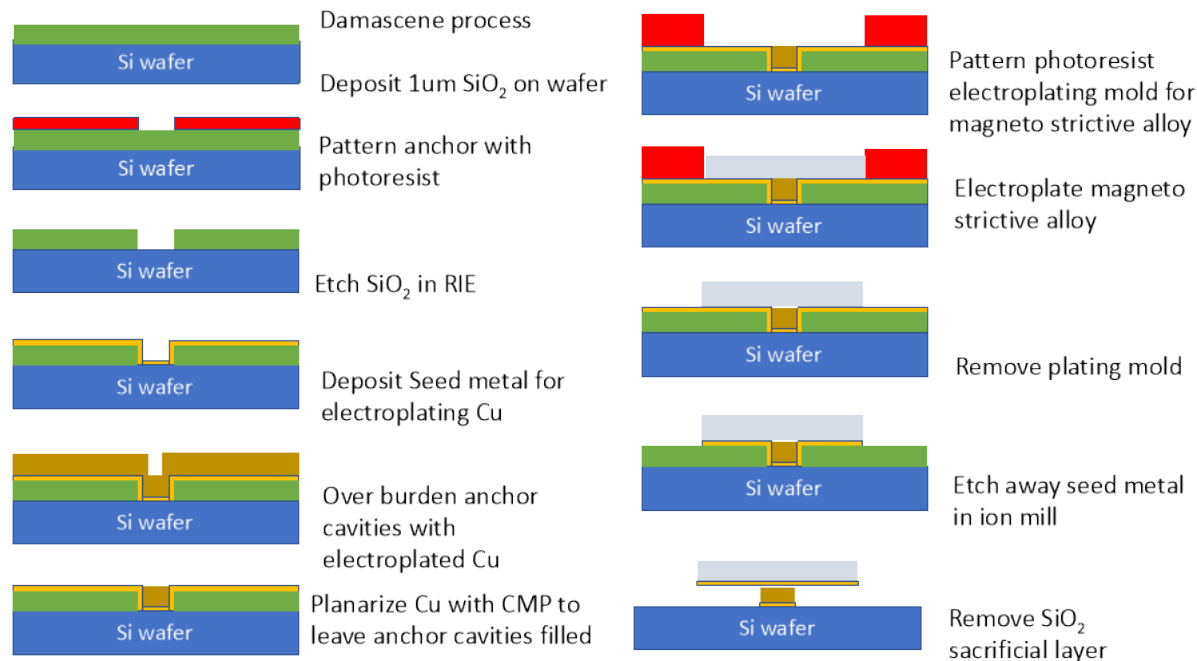
Film Composition Based on Concentration and Current Density

20 mA	1 to 1 L:M	Ni	Fe	Co	Dy	Tb	P
	Proline	56.5	14.9	8.2	1.3	1.3	17.8
	Glycine	71.1	0.3	4.6	0.1	0.2	23.7
	Asparagine	73.6	1.4	6.3	0	0	18.7
20 mA	2 to 1 L:M	Ni	Fe	Co	Dy	Tb	P
	Proline	75	0.1	1.5	0	0.1	23.2
	Glycine	76.8	0.1	1.2	0	0	21.9
	Asparagine	72.7	0.2	3.6	0.1	0.1	23.2
40 mA	2 to 1 L:M	Ni	Fe	Co	Dy	Tb	P
	Proline	80.8	1.8	2.2	0	0	15.1
	Glycine	85.1	0.7	1.1	0	0.1	13
	Asparagine	67.6	2.6	5.9	0.3	0.3	23.4
10 mA	1 to 4 L:M	Ni	Fe	Co	Dy	Tb	P
	Proline	64.1	11	8.9	1	1.1	10.6
	Glycine	79	2.1	2.9	0.1	0.3	15.6

MICROFABRICATED RESONATORS

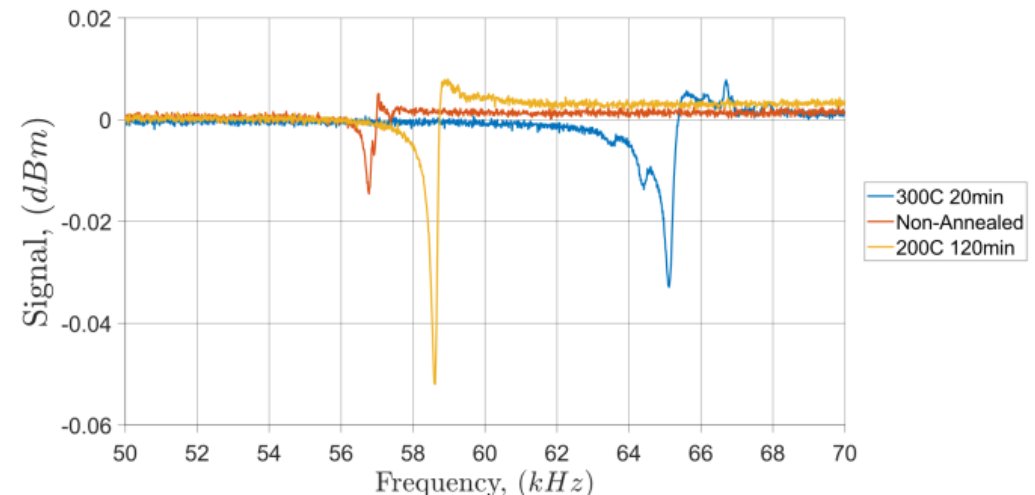
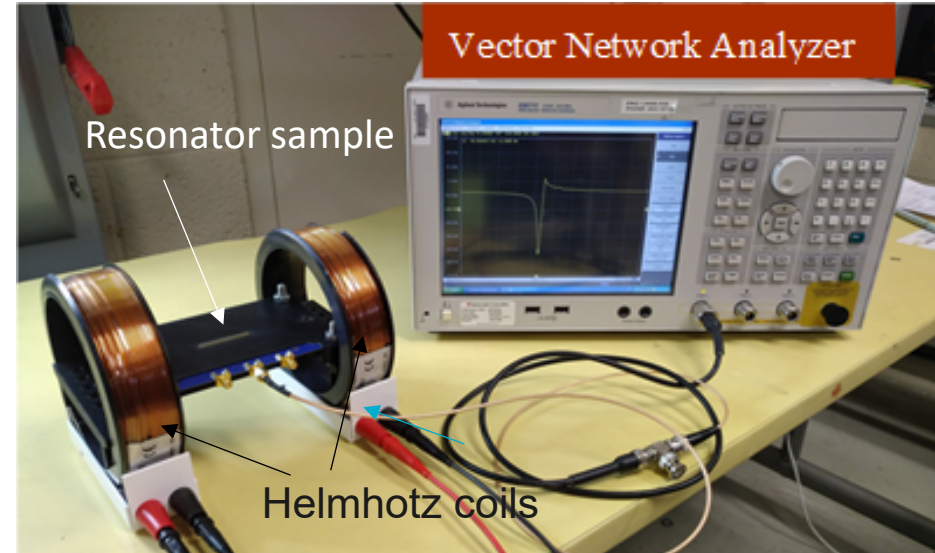


- Microfabrication process for cantilevered, released structures
- Vary anchor geometry, resonator length
- Release process
- Fully released resonators with Tb doping
 - Magnetostriction of approximately 350ppm
- Enzyme chemistries have not been released yet



RESONANCE TEST SETUP

- Resonance testing of materials
- Custom coil setup for transmit and receive
- Vector network analyzer for AC field sweep and signal pickup
- Fully released resonator testing is in process
- Post processing of initial material
 - Anneal at 200°C for 2 hours increases resonant response with initial material
 - No post processing of higher magnetostriction materials yet



CONCLUSION



- Developed initial NiFeCo alloy with Ho, Ge, and B for soft magnetic material with high magnetostriction
- Stabilized chemistries with Tb, Dy, and P
 - Control stoichiometry and stress
- Microfabrication process for fully released resonators
 - Demonstrated with initial NiFeCo alloy
- Next steps:
 - Fully released resonators with proline and glycine chemistries
- Acknowledgements
 - Thank you to Nick Gurule for resonance testing
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