SAND2021-5808C

Advancements in Magnetic Materials for Microdevices

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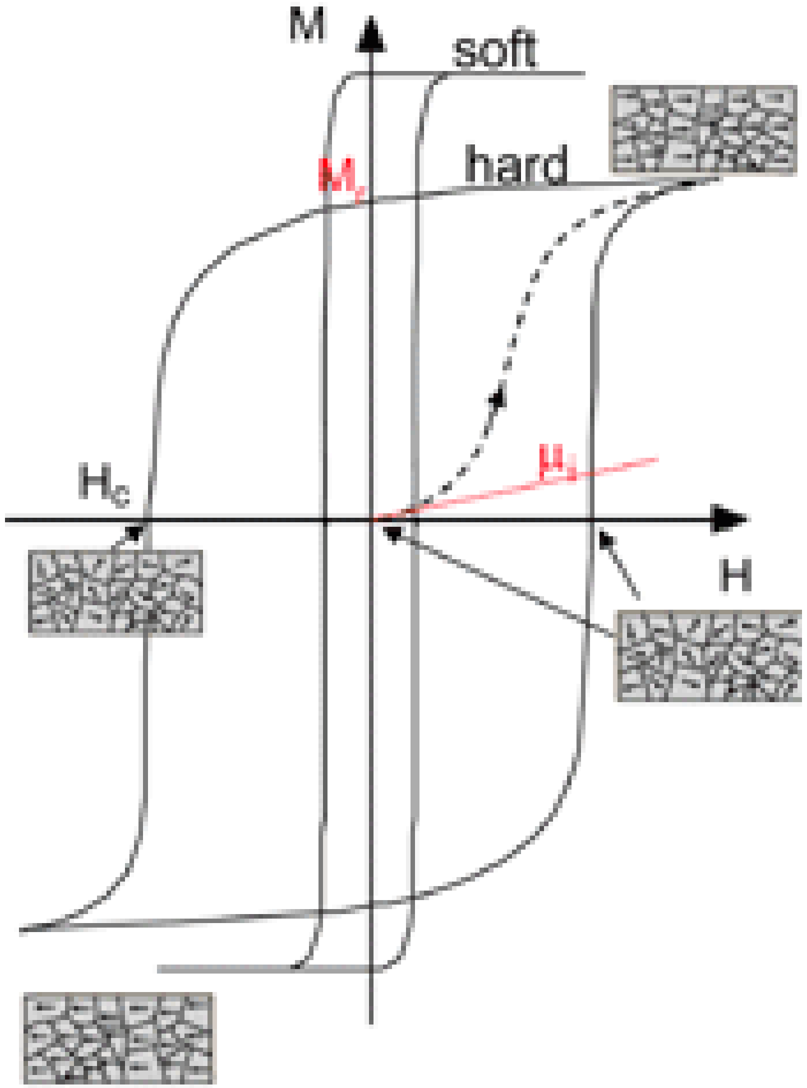
Outline

- Introduction
- Motivation – Magnetic Material Needs and Challenges
- Electrodeposition and Magnetostrictive NiFeCo
- Magnetic Smart Tag (MaST)
- Superparamagnetic Fe_3O_4 Nanocomposite
- Nano-Enabled μ-Inductors
- Conclusion

Hard vs. Soft Magnetic Materials



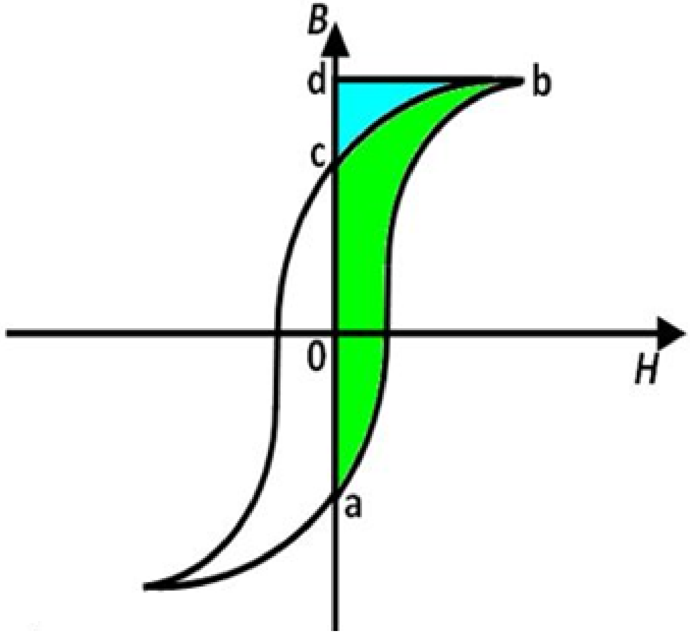
Soft Magnets

- H_C < 1 kA/m
- Flux concentrators, improved magnetic energy density, magnetostriction-based devices
- Fe, NiFe, NiFeCo

Hard Magnets

- H_C > 10 kA/m
- Contactless restoring/biasing force
- NdFeB, SmCo, AlNiCo
- Not microfabrication-friendly currently, 3-D printing?

Core Loss Mechanisms

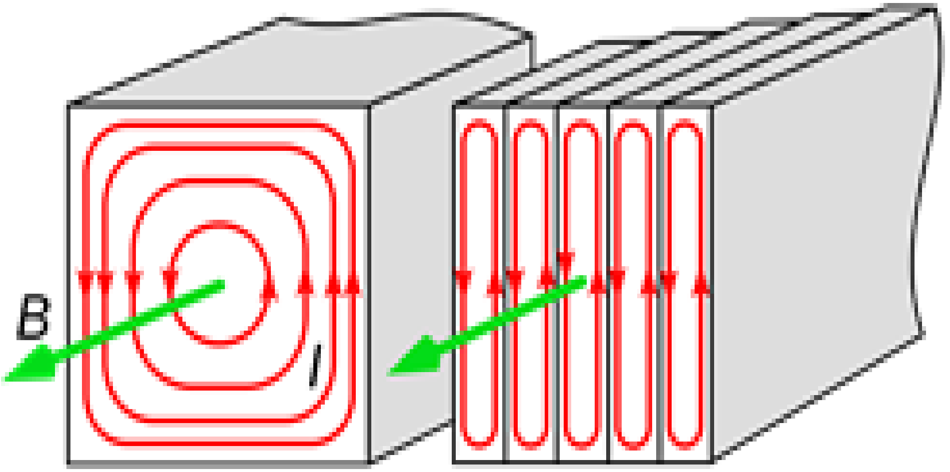


$$\frac{P_{hys}}{V} = \oint H(t)dB$$

Hysteresis

Eddy Current

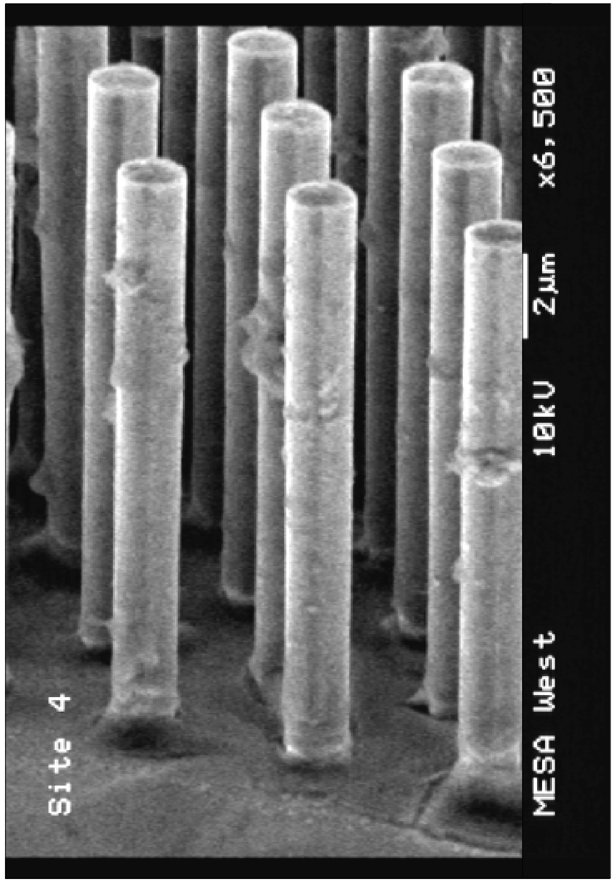
$$\frac{P_{eddy}}{V} = \frac{\omega B^2 A}{48\rho}$$



Manufacturing Issues

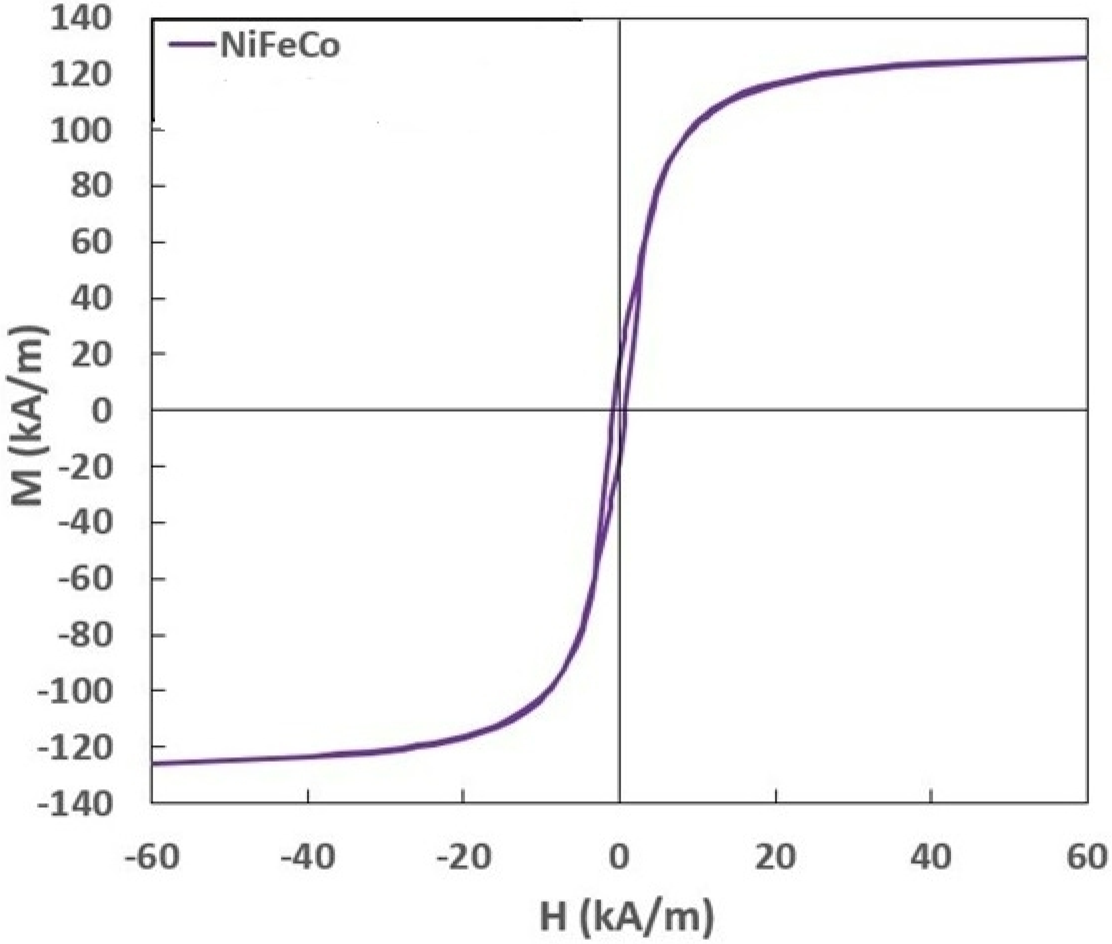
- Integration with CMOS electronics
  - –Ni and Fe known gate oxide contaminants
  - –Low thermal budget required
- Thick (> 1 micron) films
- Fast deposition times
- Anisotropic etches
- Stress-free films

Electroplating – Soft Magnetic Alloys



45/55 wt% Ni/Fe
Plated Lattice

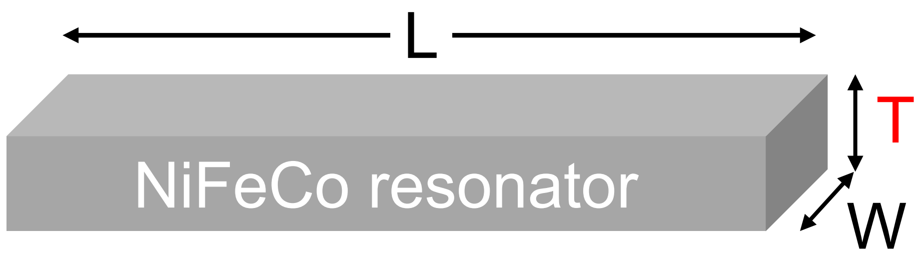
Post width = 13 μm,
Post diameter = 1 μm
Post pitch= 4 μm



Magnetostrictive NiFeCo

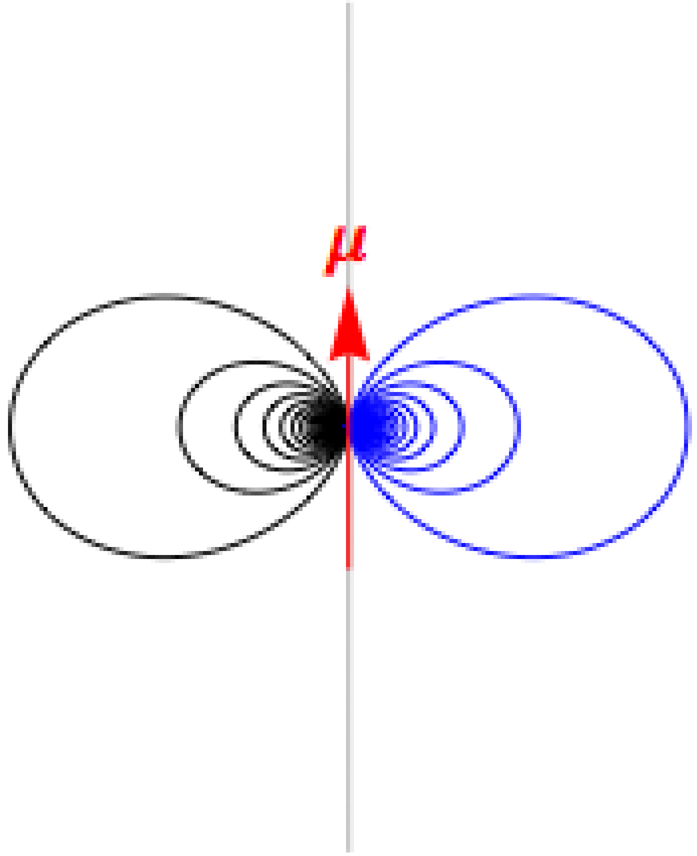
Electroplating –Enhanced Dipole Radiation

Magnetic Dipole Radiation, $Power = \frac{\mu_0 \omega^4 |m|^2}{12\pi c^3}$



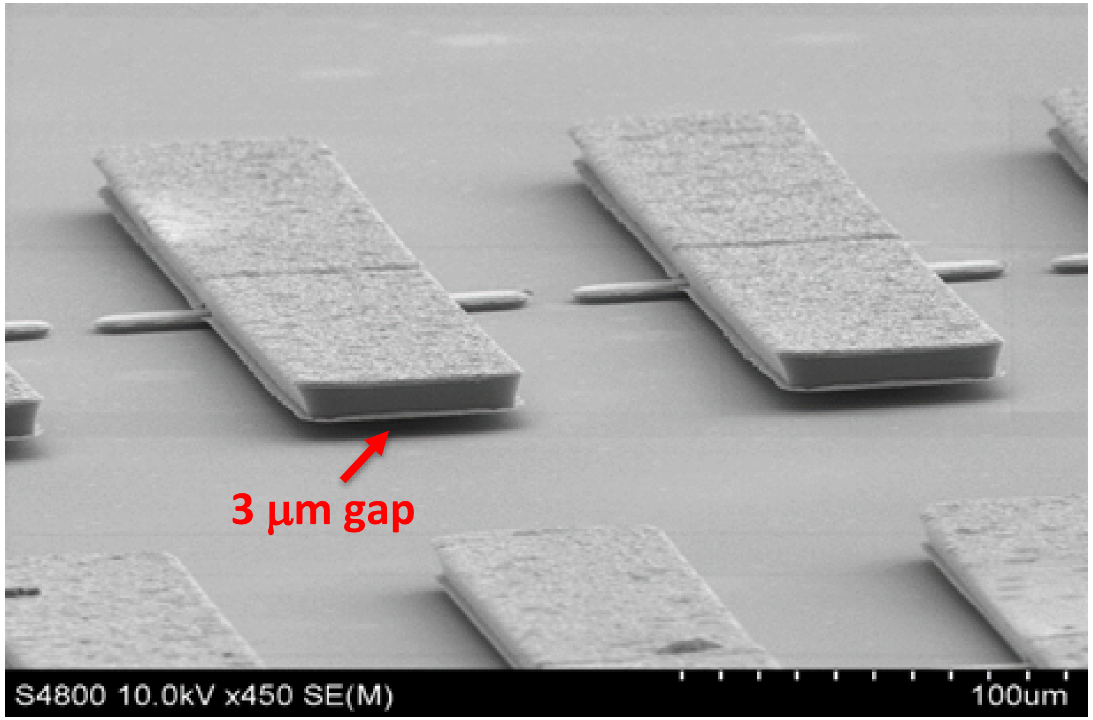
Magnetic moment, $m = MV = MLWT$

- M is the magnetization, V is the magnetic volume, L is the resonator length, W is the resonator width, T is the resonator thickness
- **Thicker, i.e., larger dipoles emit / absorb stronger signals!**



Lorentzian

Electroplating –Manufacturing and Mechanical Advantages



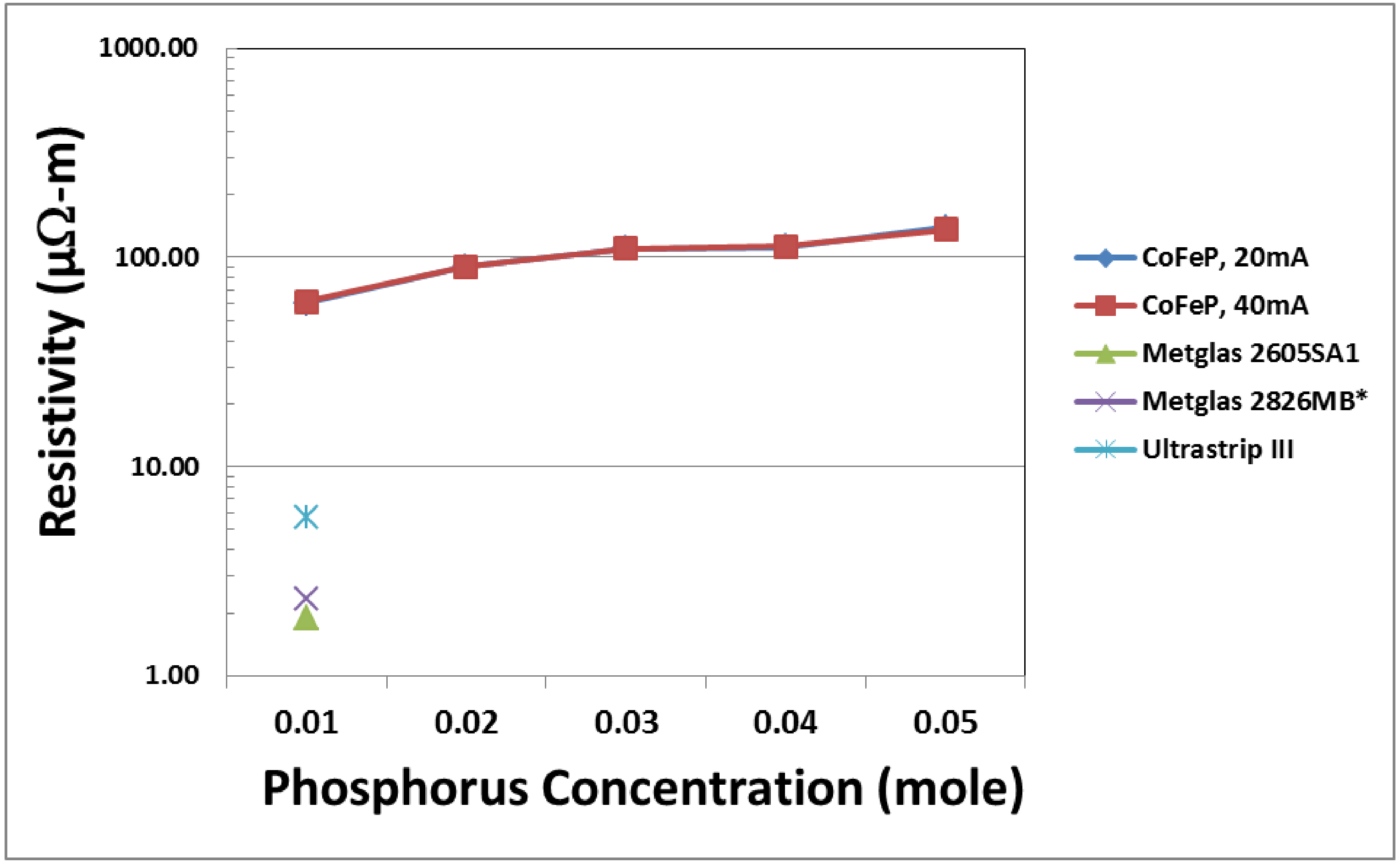
Electroplating

- Thick (µm to mm), photoresist-mold-patterned metal structures
- Fast deposition times (~micrometers/min)
- Eliminates the need for an anisotropic etch
- Stress decreases with increased thickness

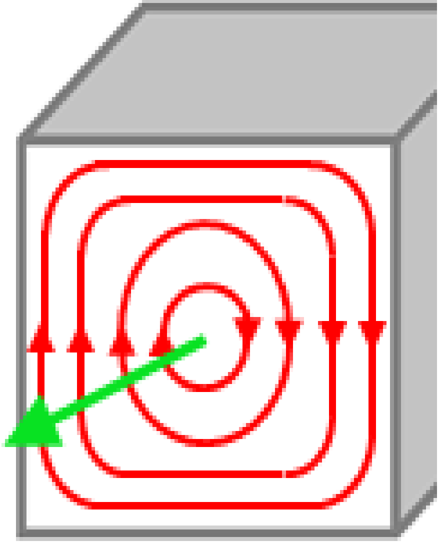
Sputtering/E-Beam evaporation

- Thin films only (< 1 µm)
- Difficult to control stoichiometry of multi-constituent films
- Intrinsic stress increases with thickness

Electroplating – Parameter Tunability

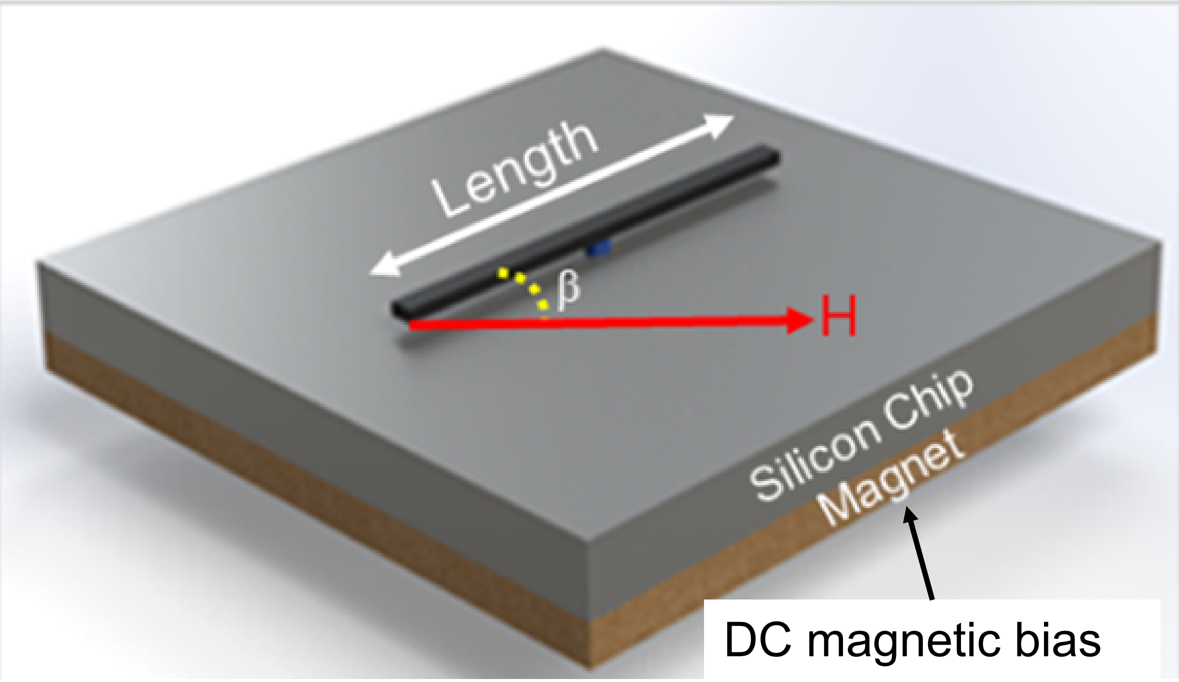


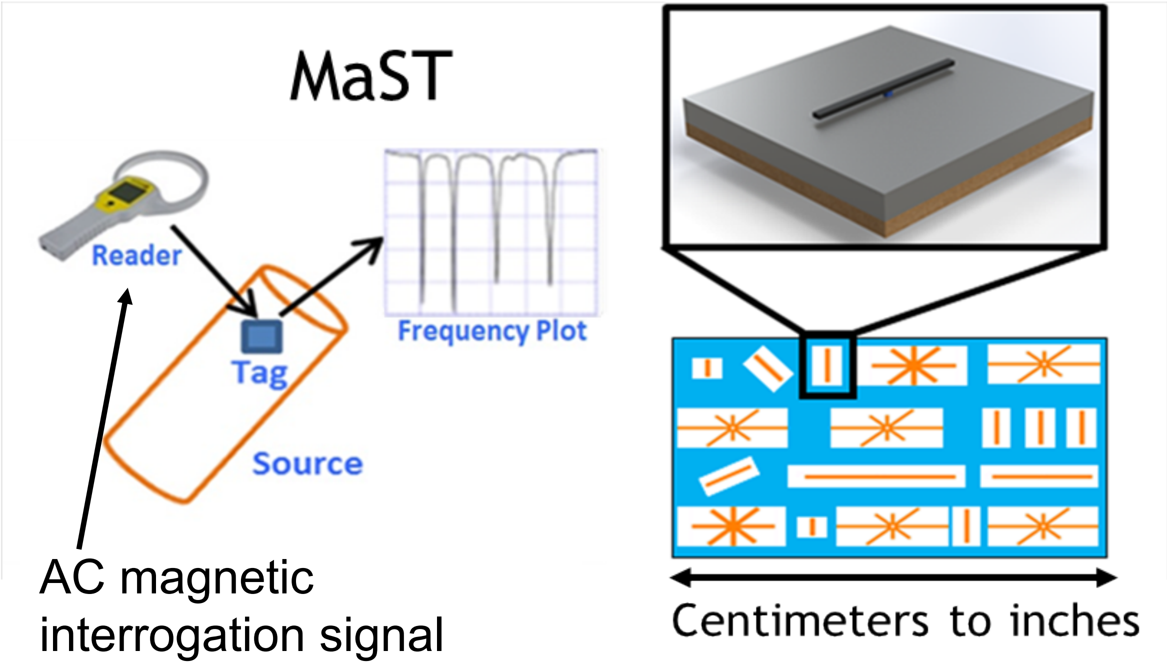
$$\frac{P_{eddy}}{V} = \frac{\omega B^2 A}{48\boldsymbol{\rho}}$$



High resistivity reduces eddy current loss!

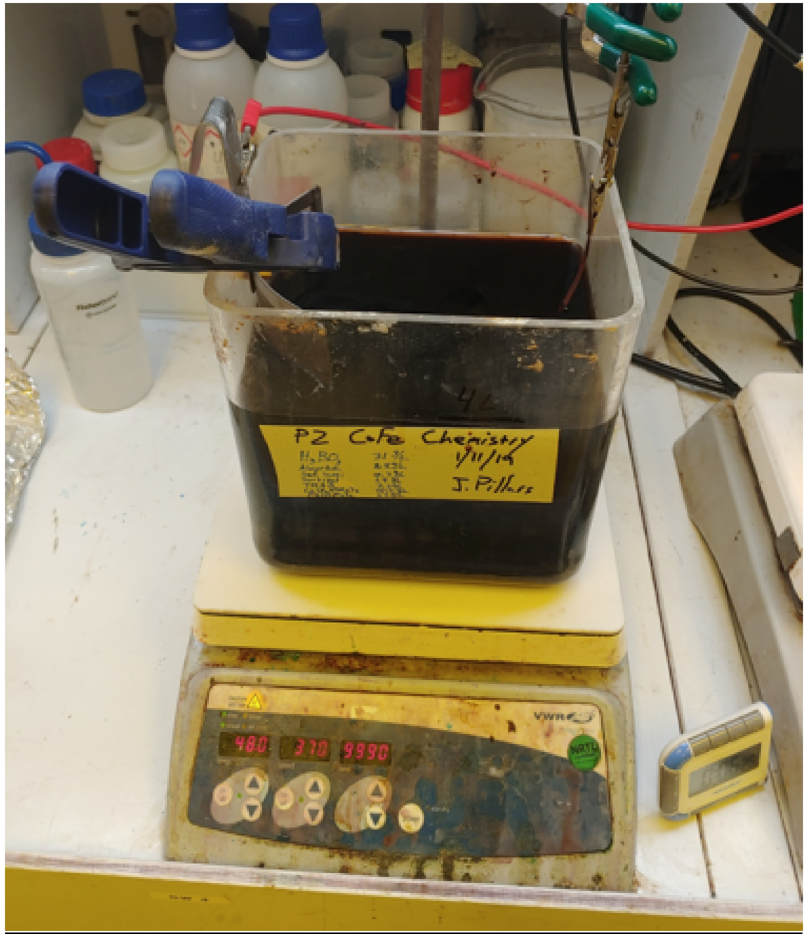
Magnetic Smart Tag (MaST)



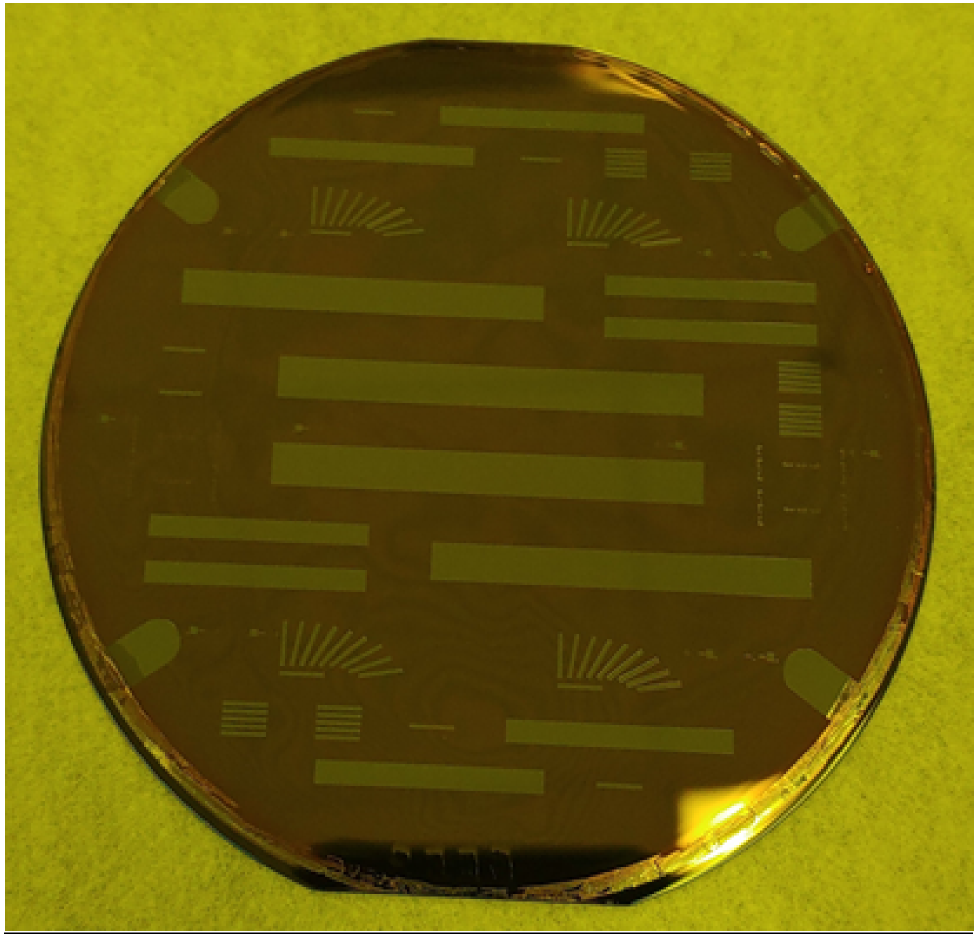


- MaST is comprised of an array of magnetic resonators and a bias magnet
- Operates by the Joule magnetostriction effect
- Passive, wireless, unique identifiers (UIDs) for high value assets

Electroformed NiFeCo Resonators

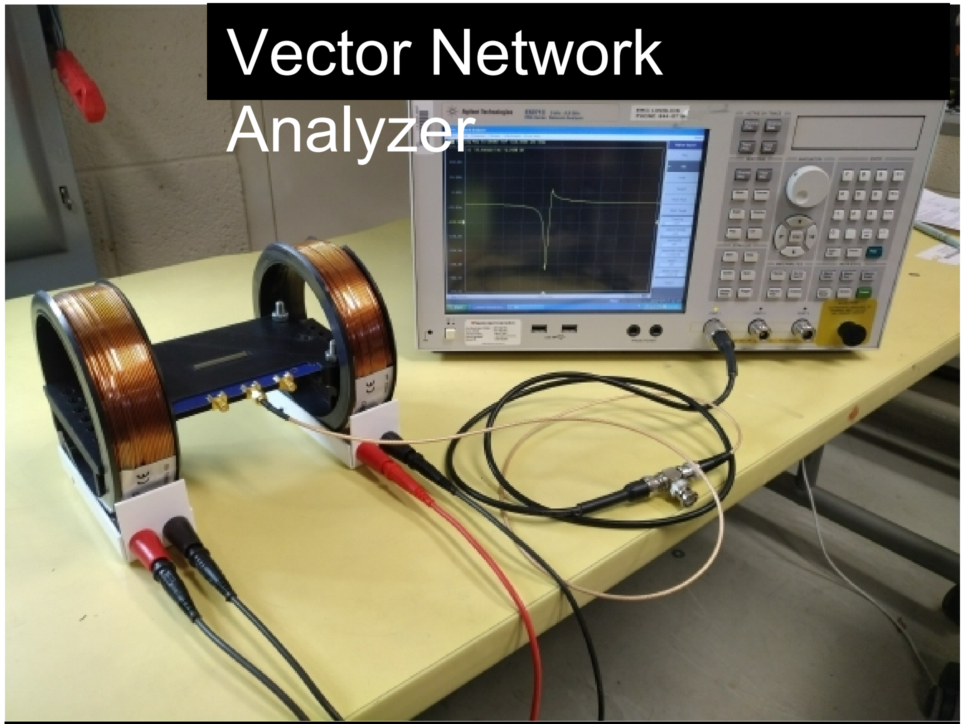


Plating Setup

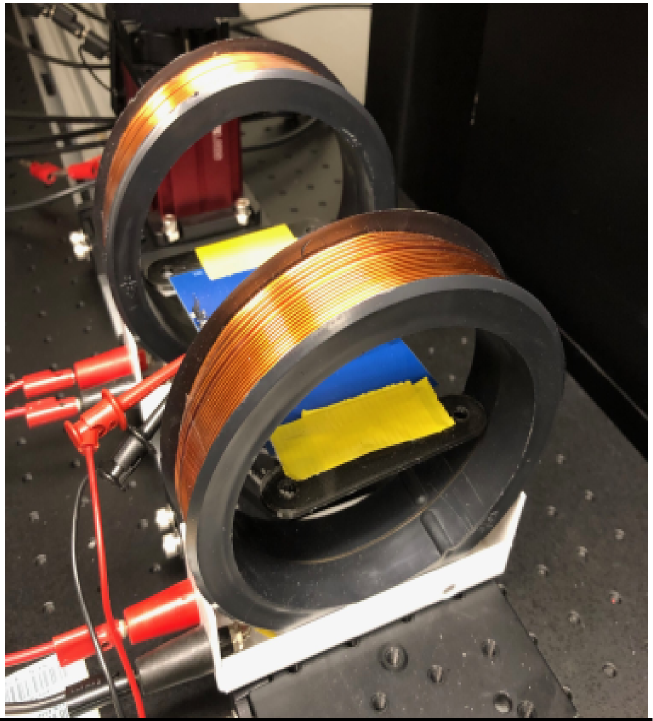


Resonator Wafer

Bench Top Interrogation

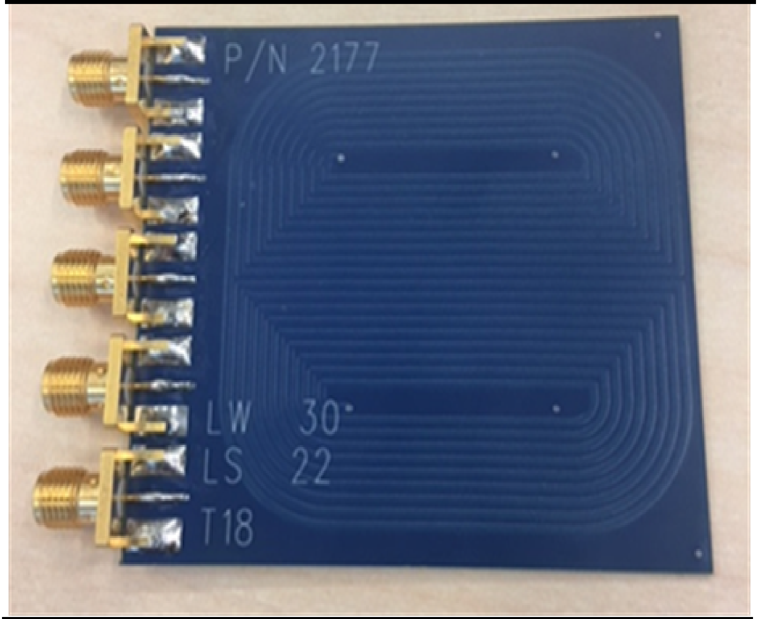


Bench Setup



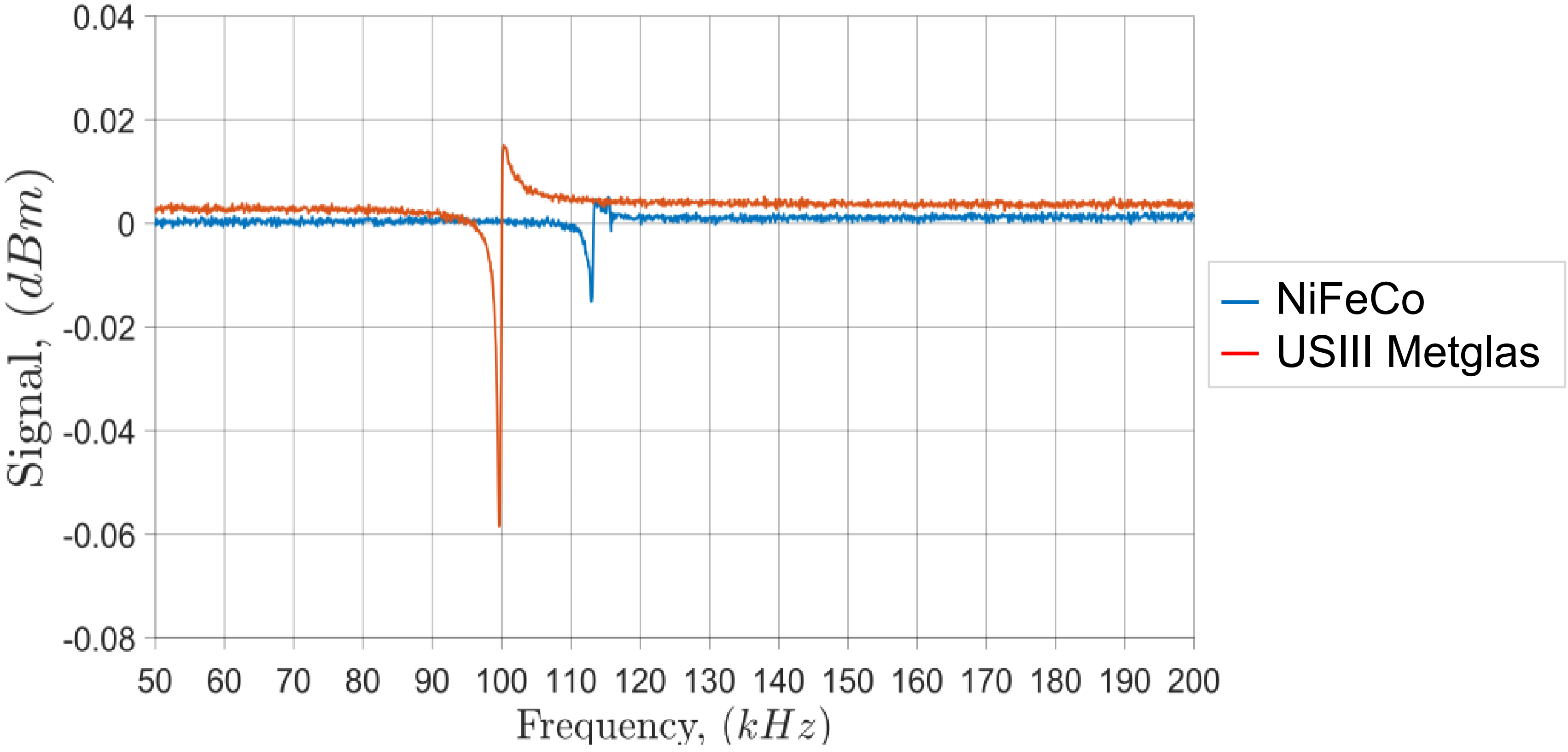
Bias Antenna

← 68 mm →

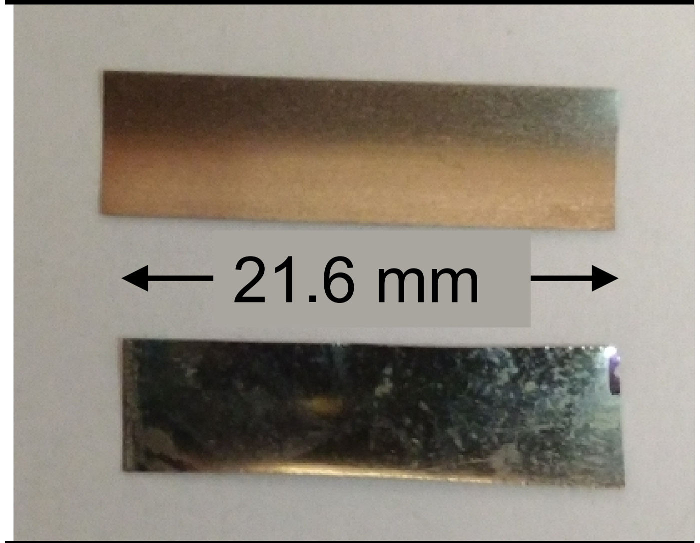


AC Planar Antenna

NiFeCo Magnetic Resonance Achieved



USIII Metglas Alloy Resonator



E-plated NiFeCo Resonator

VNA Measurement – USIII & NiFeCo

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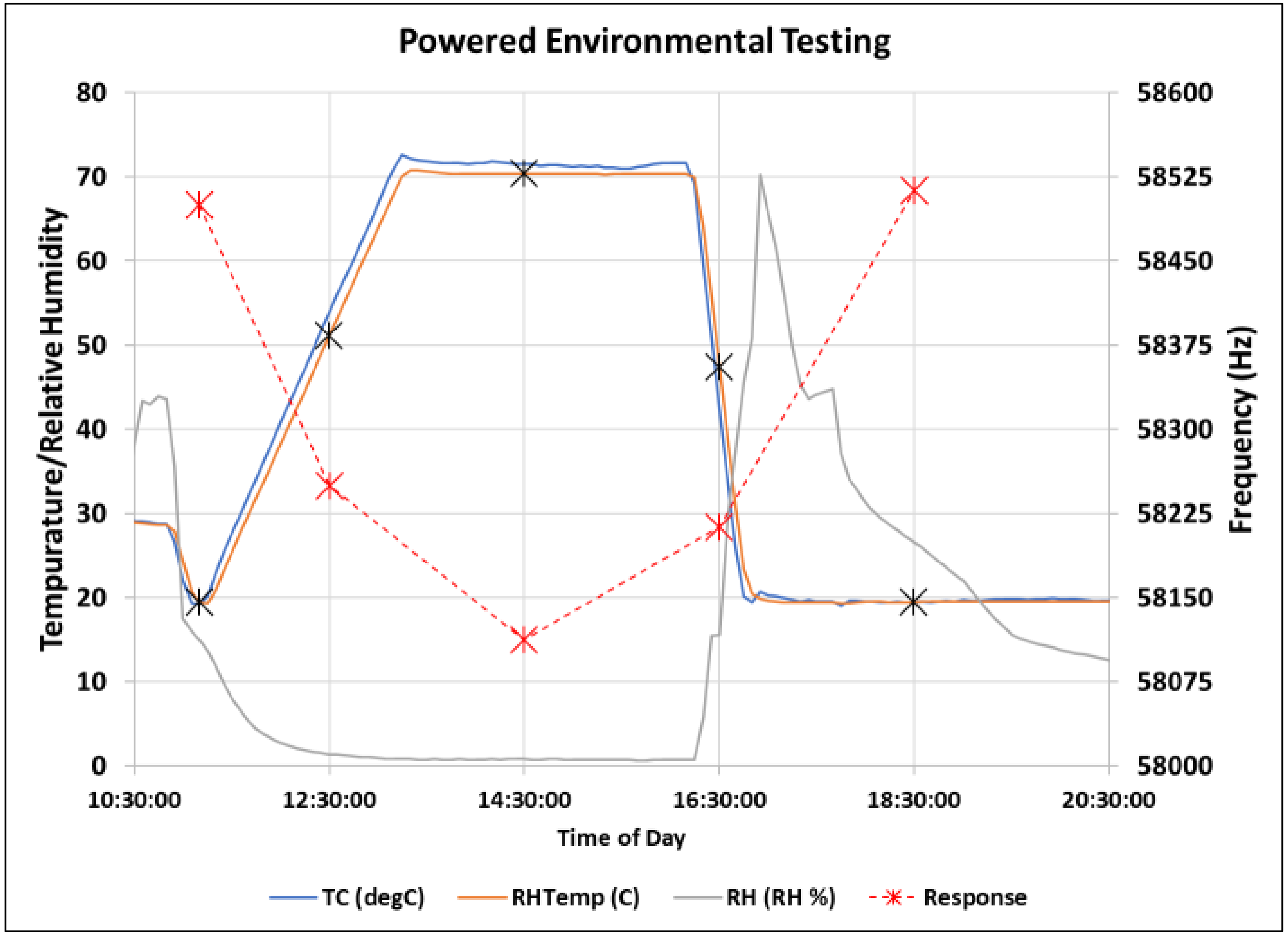
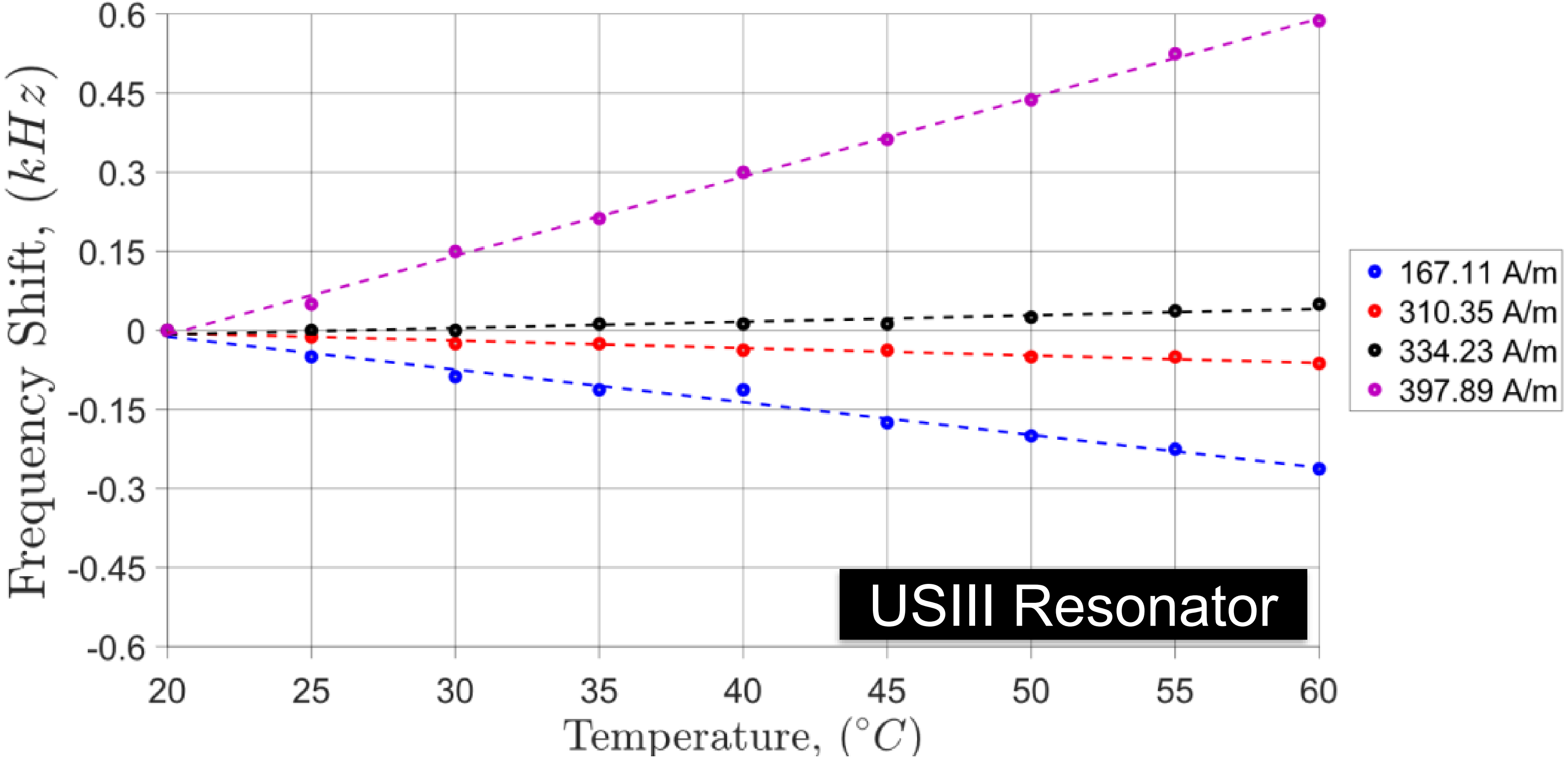
Operation Temperature and Humidity



< 400 Hz resonant frequency shift above 50°C

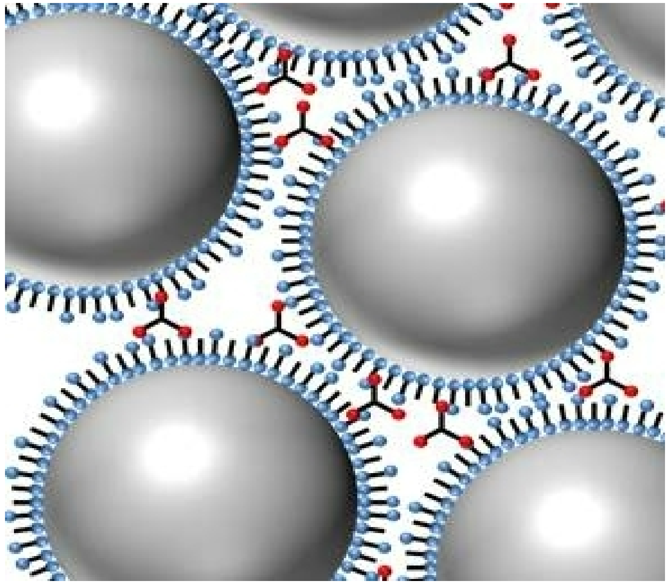
Operation Temperature and Humidity



- Bias magnetic field frequency shift cancellation
- Experiments underway for NiFeCo resonators

Superparamagnetic Fe_3O_4 Nanocomposite

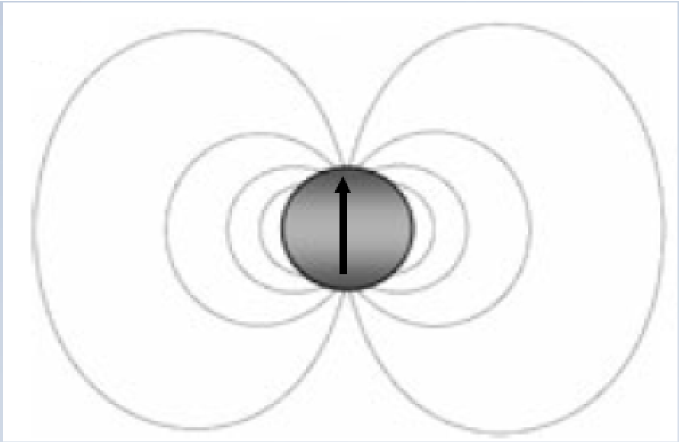
Nanoparticles are crosslinked and separated with nanometer precision



- **Low temperature curing (60 °C)**
- **Molding**
- **3-D printing**

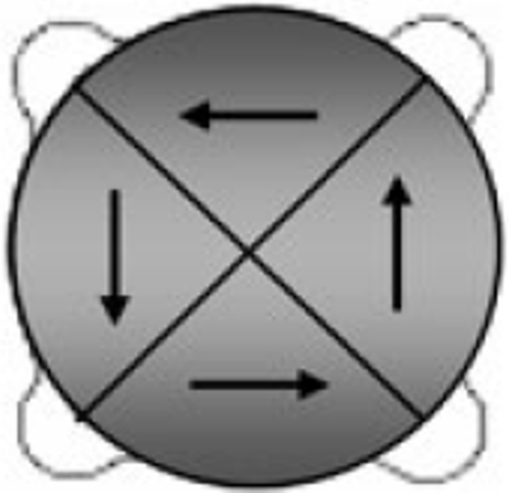
Single Domain:

- No energy spent creating domain walls
- No lossy magnetization processes present, i.e., no hysteresis.

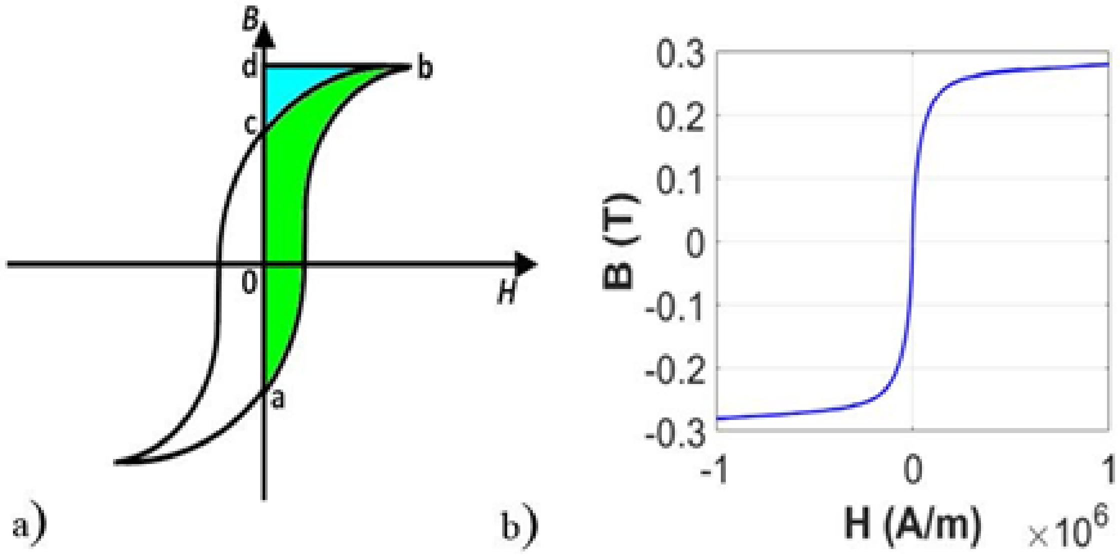


Multidomain:

- Energy required to create domain walls
- Domain wall motion creates hysteresis.



Reduced Core Loss



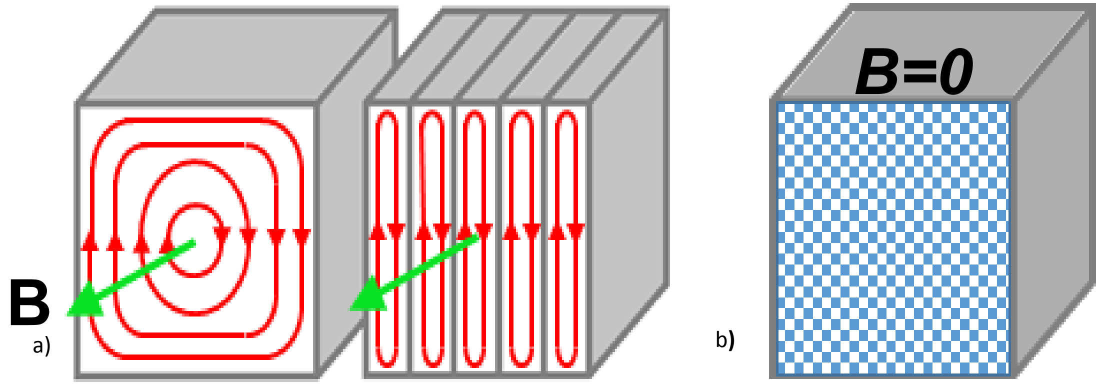
$$\frac{P_{hys}}{V} = \oint H(t)dB$$

Zero core hysteresis!

$$\frac{P_{eddy}}{V} = \frac{\omega B^2 A}{48\rho}$$

$$\rho > 1\ M\Omega{\cdot}m;\ \frac{P_{eddy}}{V} \sim 0$$

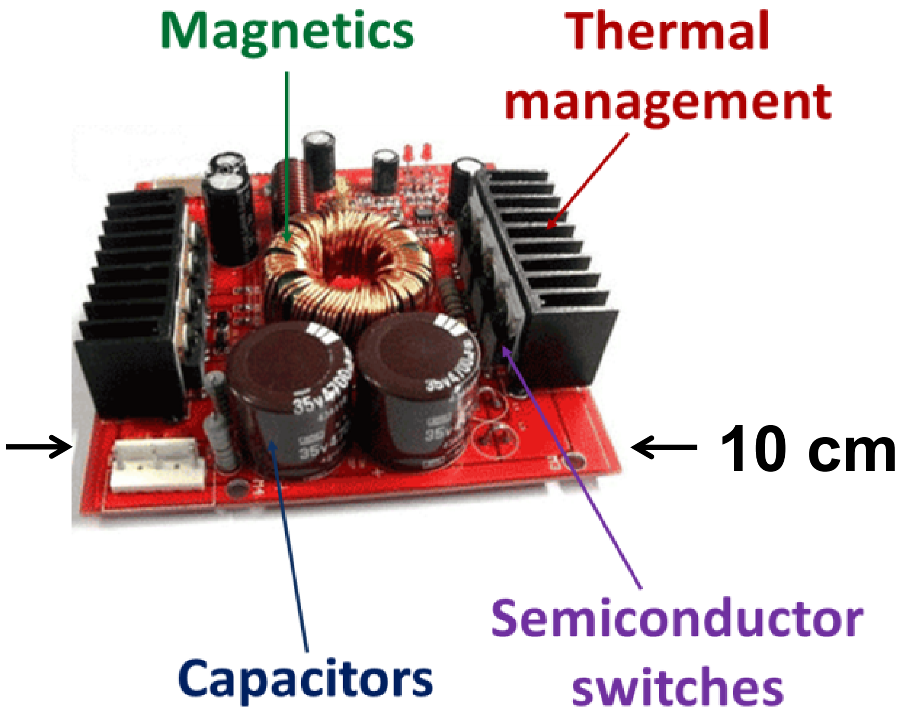
Zero eddy currents!



Core loss, P_v = 100's of kW/m^3 @ 0.5 MHz and ρ = 1 $\Omega{\cdot}$m for ferrites

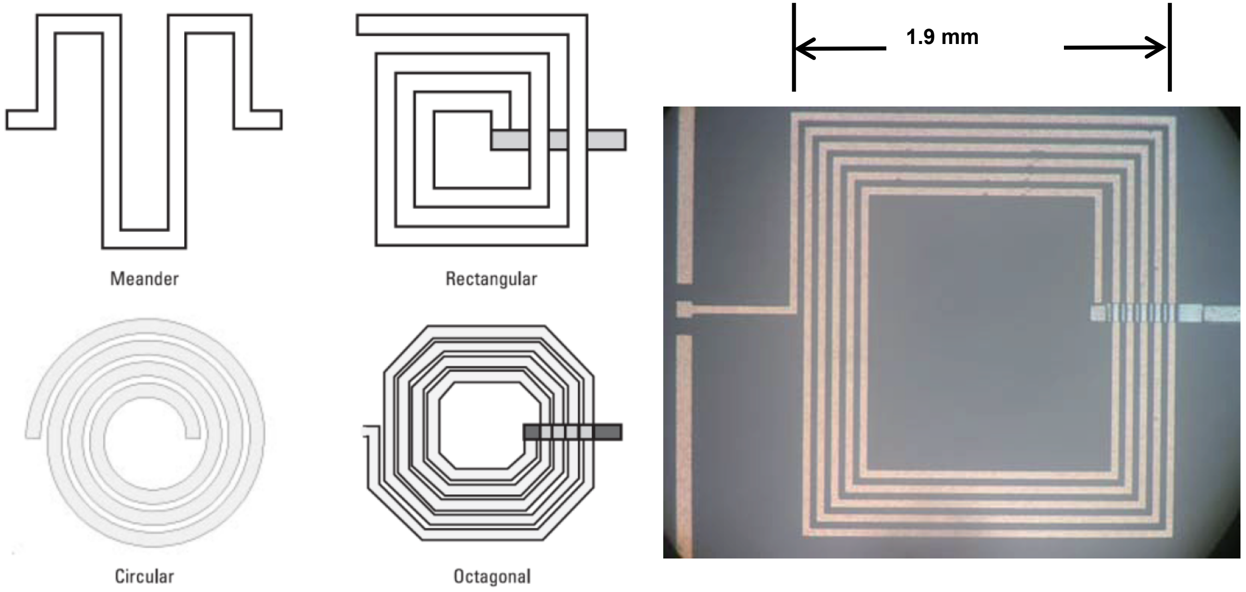
Nano-Enabled μ-Inductors

Status Quo - Power



Discrete components on PCB

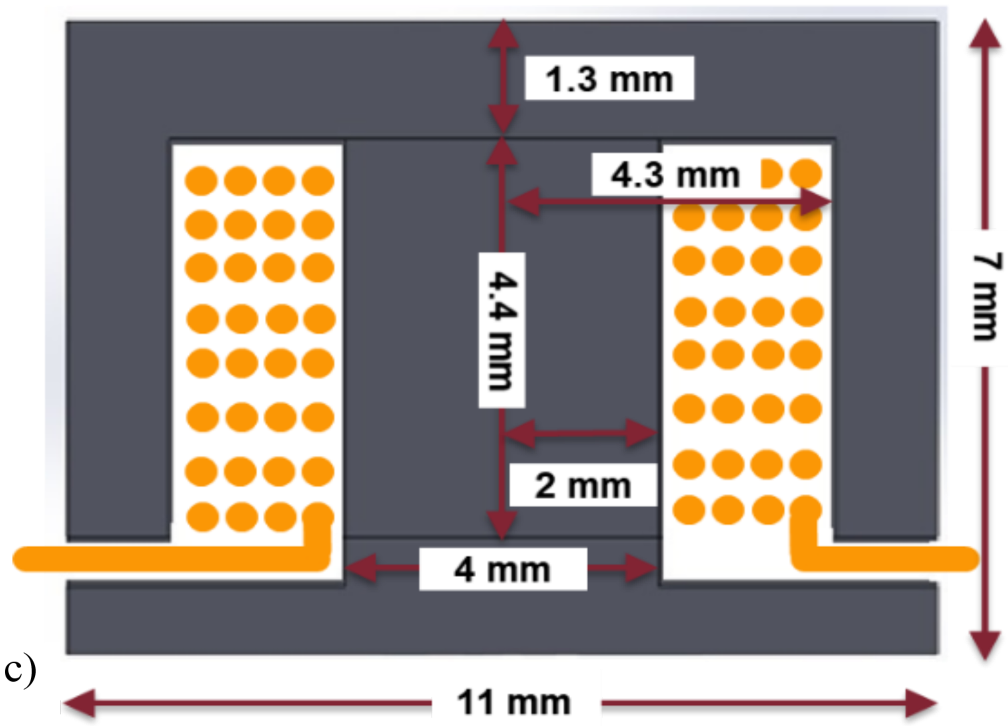
Status Quo - RF



Microfabricated planar air-core inductors

Figures of merit: reduced form factor, higher L, Q and SRF needed!

Prototype Nano-Enabled Inductor



c)

Nanocomposite e-core inductor cross section

Measured Parameter	***Nanocomposite Inductor***
Inductance @ 1 kHz (μH)	4.38
Inductance @ 2 MHz (μH)	3.37
DC Resistance (mΩ)	56
AC Resistance @ 2 MHz (Ω)	2.41
Volume (mm^3)	810
Relative Permeability (μ_r)	5

75 % efficiency measured at 0.9 A using a 3.3 V synchronous buck converter, 1 % greater than a comparable, mature, commercial inductor.

Conclusions and Acknowledgements

- High performing magnetic materials needed
  - Low loss
  - Tunable
  - Microfabrication-friendly
- Electrodeposited NiFeCo alloys and superparamagnetic Fe_3O_4 nanocomposites are good examples

This work funded by NA-22 and by Laboratory Directed Research and Development (LDRD) Project number 170341. This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. LDRD. Team members are Jamin Pillars, Todd Monson, Dale Huber, John Watt, Patrick Finnegan, Barney Doyle, LaRico Treadwell, Heidi Smartt, Nick Gurule, and Ben Lehman.