MAGNETIC AND FERROELECTRIC MATERIALS FOR POWER ELECTRONICS, SENSING, AND ENERGY STORAGE

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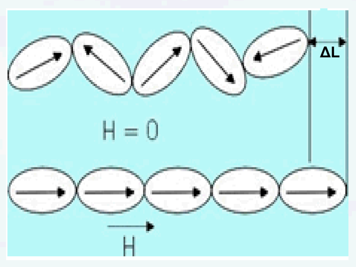
CoFe Micro Magnetoelastic Resonators for Smart Sensors and Tags

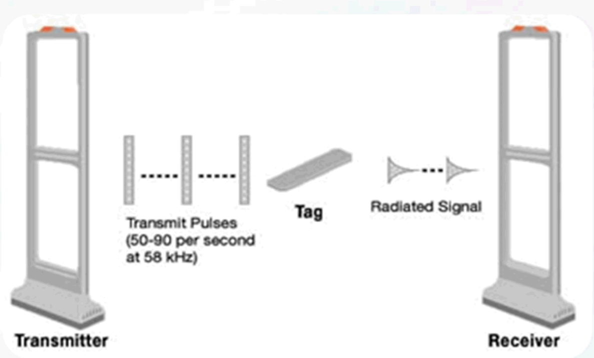
Electrodeposited, highly magnetostrictive, CMOS compatible, rare earth, and oxide free CoFe alloys

Magnetostriction, λ=ΔL/L

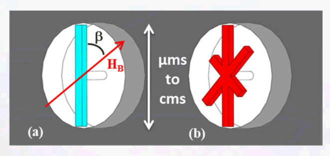


Magnetoelastic Material	λ_s (ppm)
Metglas 2605SA1	26 ± 4
CoFe plated on Cu	172 ± 25
CoFe plated on Au	229 ± 32

"Dumb Tag"



"Smart Tag"



a) Single frequency resonator
b) Multi-Frequency resonator (3)

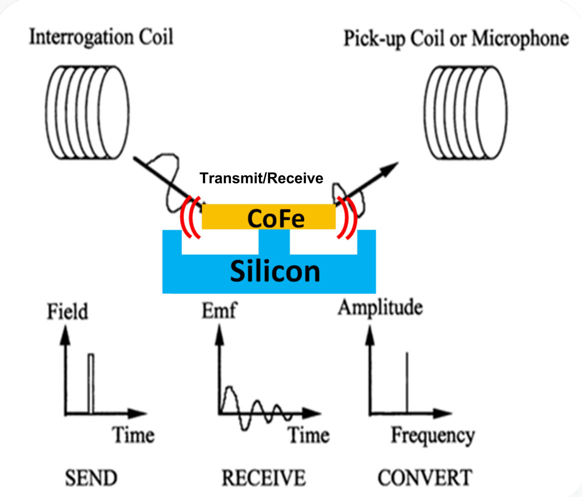
$$f_r = \frac{1}{2L}\left[\sqrt{\frac{\rho}{E_0}+\frac{9\lambda_s^2\rho(\langle|H_B|\cos(\beta)\rangle)^2}{J_s H_A{}^3}}\right]^{-1}$$

$$N_K = \frac{N_T!\,(N_W-1)!}{2N_R!\,(N_T-N_R)!\,(N_W-N_R)!}$$

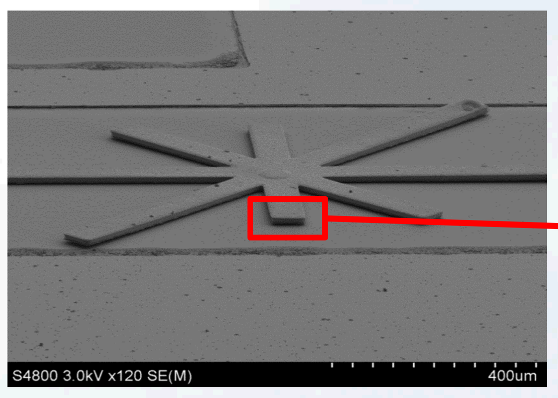
- N_K = # labels
- N_T = # resonator types
- N_R = # resonators
- N_W = # possible angles

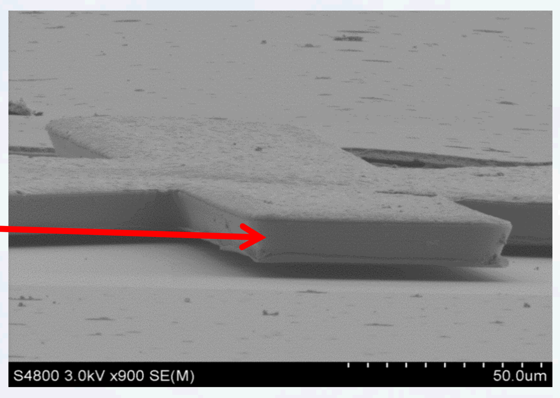
✓millions of different coded sensors
✓Centimeter scale tags

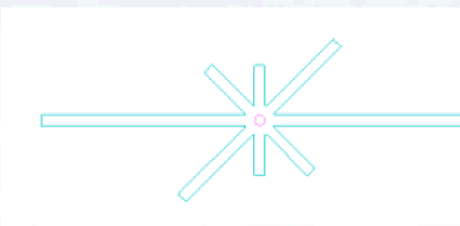
Tag/Sensor method of operation

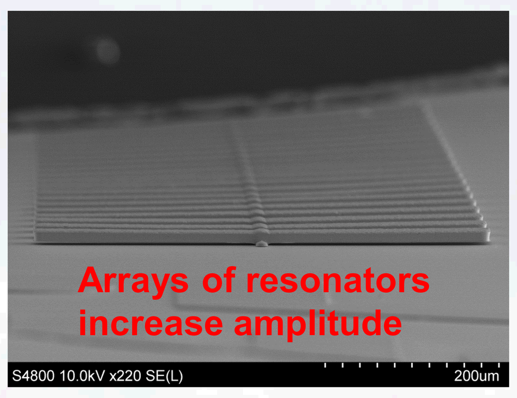


First demonstration of electroplated CoFe released micro resonators



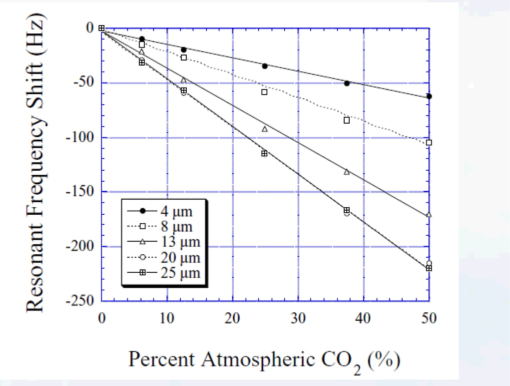




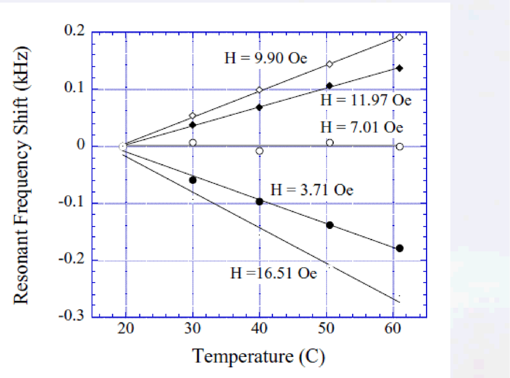


Arrays of resonators increase amplitude

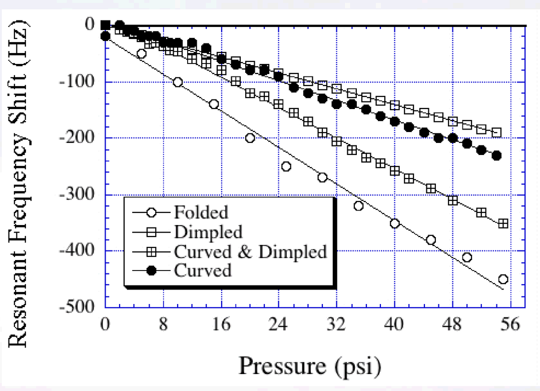
Gas sensing

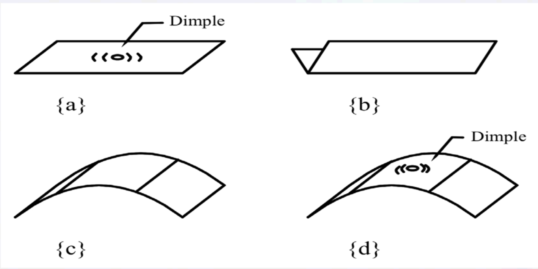


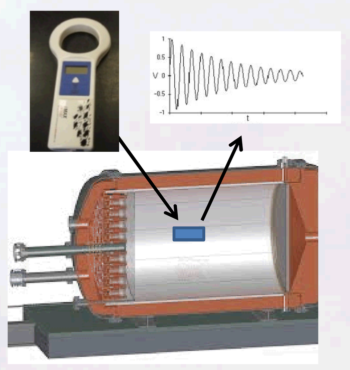
Temperature sensing



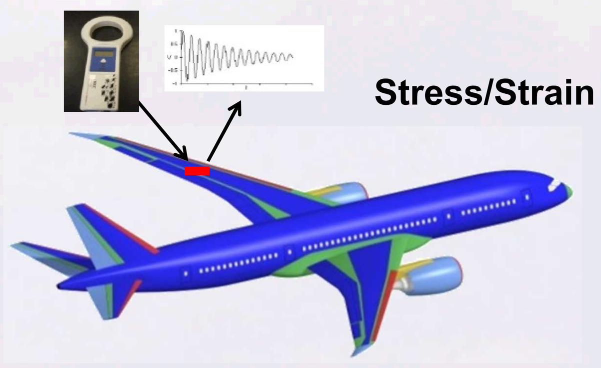
Pressure sensing







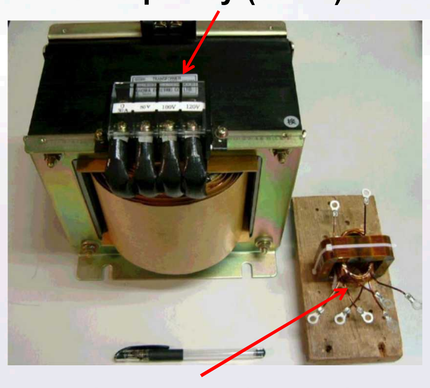
Stress/Strain sensing



1. Grimes, C., et al., *Wireless Magnetoelastic Resonance Sensors: A Critical Review.* Sensors, 2002. 2(7): p. 294-313.
2. Grimes, C.A., et al., *Theory, instrumentation and applications of magnetoelastic resonance sensors: a review.* Sensors (Basel), 2011. 11(3): p. 2809-2844.

γ'-Fe_4N Soft Magnetic Materials for High Power and High Frequency Transformers and Inductors – First ever bulk γ'-Fe_4N materials and devices!

Line frequency (50 Hz) transformer

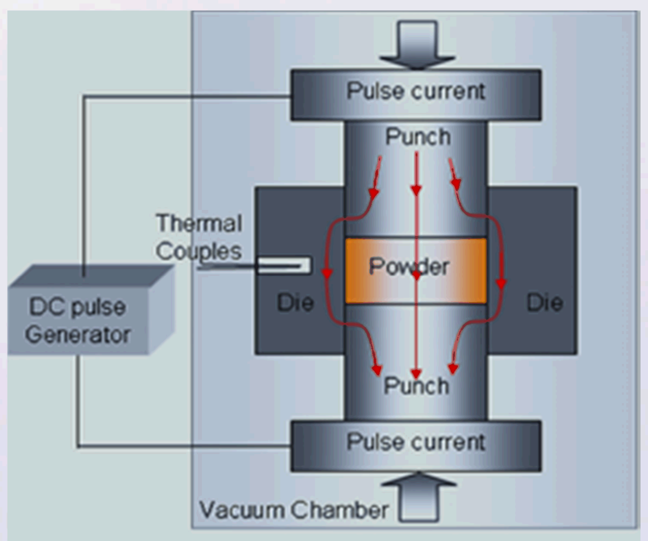


High frequency (20 kHz) transformer

S. Krishnamurthy, Half Bridge AC-AC Electronic Transformer, IEEE, 1414 (2012).

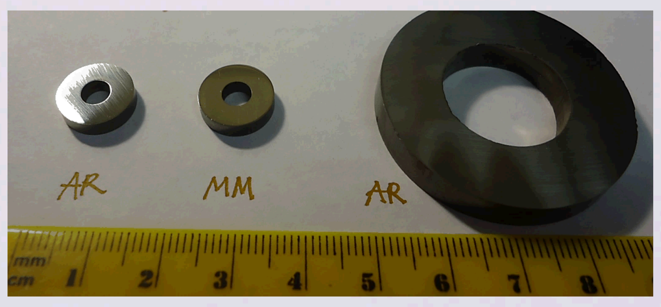
- Higher frequencies reduce inductive requirements
- Materials for high frequency power electronics have been an afterthought

High frequency magnetic materials complement wide bandgap (WBG) semiconductors



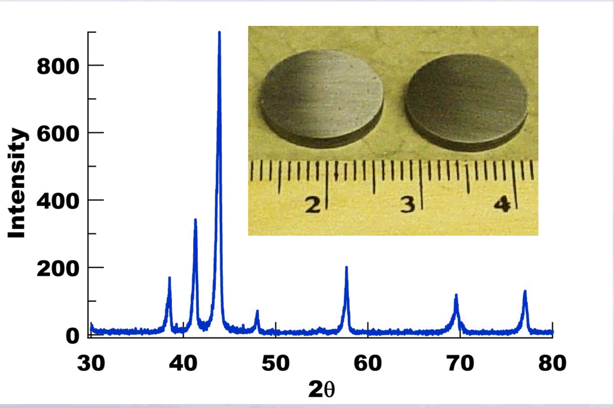
Raw powders are rapidly consolidated using spark plasma sintering (SPS)

- SPS allows for net-shaping by using shaped dies
- Toroids, E-cores, and other shapes can be fabricated directly without the need for any machining

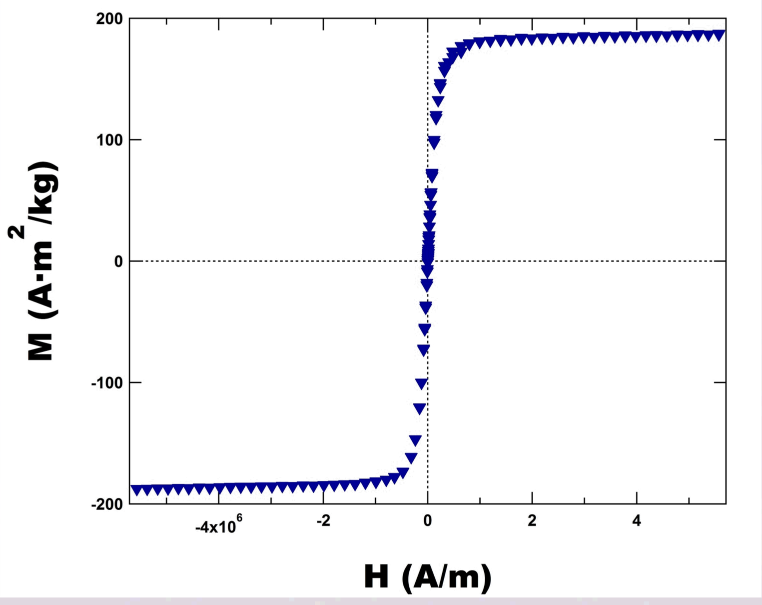


Magnetic Material	J_s (T)	ρ(μΩ·m)	Cost
VITROPERM (Vacuumschmelze)	1.20	1.15	High
Metglas 2605SC	1.60	1.37	High
Ferrite (Fexxocube)	0.52	5x10^6	Low
Si steel	1.87	0.05	Low
γ'-Fe_4N	1.89	~200	Low

γ'-Fe_4N meets all the requirement of high frequency and high power electronics

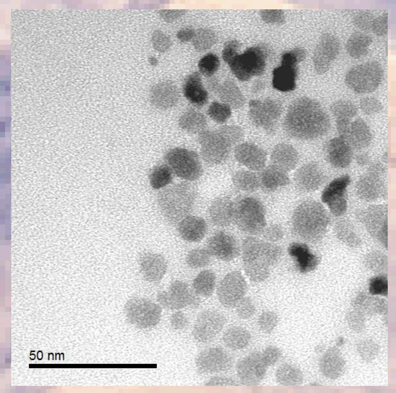


- Fe nitride powders well consolidated with little porosity
- Grain sizes 200 nm – 1 μm → fine grain size = low loss
- γ'-Fe_4N primary phase
- Fe_3N secondary phase from mixed phase starting material

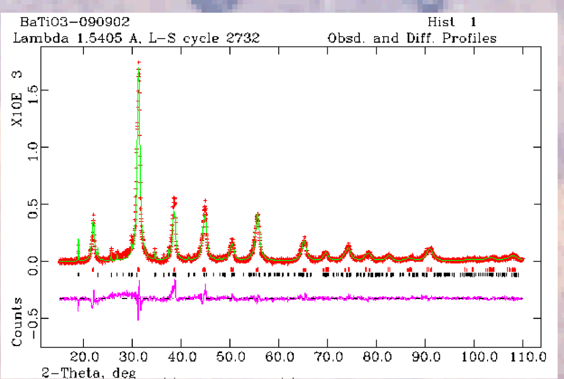


- Fe_4N SPSed at 550°C and 100 MPa achieved an M_{sat} of 188 A·m²/kg.
- Predicted M_{sat} of bulk γ'-Fe_4N is 209 A·m²/kg (Fe is 217 A·m²/kg)
- Negligible coercivity

Ferroelectric ($BaTiO_3$ and PZT) Nanoparticles for Electrostatic Capacitors



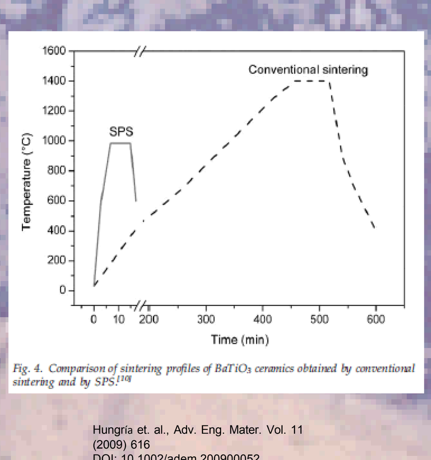
Sandia solution synthesized $BaTiO_3$



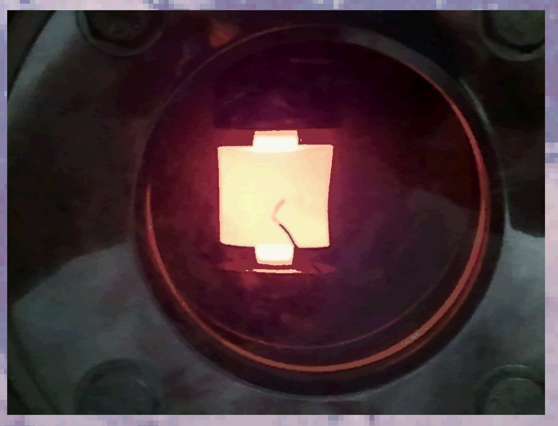
XRD pattern fits tetragonal phase

Spark Plasma Sintering (SPS) of $BaTiO_3$ nanoparticles:

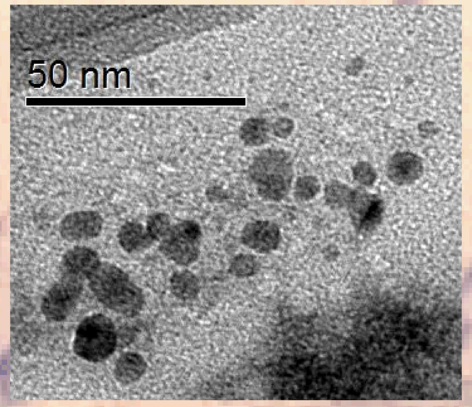
- Dramatically shorter overall sintering times
- Lower sintering temperatures, shorter hold times
- Ability to limit/control grain sizes
  - Porosity and oxygen defects minimized at same time
- Effective in removing resistive grain boundary component commonly observed in conventionally sintered BTO
- Improved frequency response



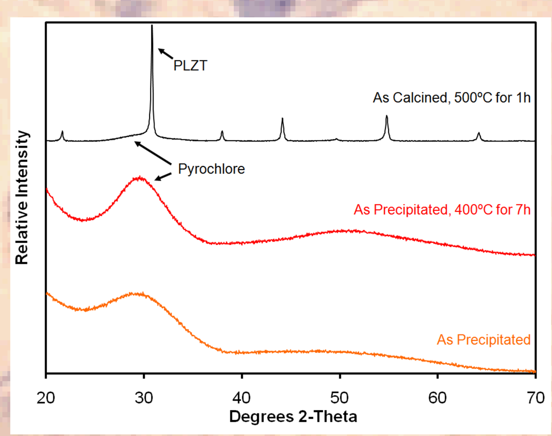
Hongbo et al., Adv. Eng. Mater. Vol. 11 (2009) 616
DOI: 10.1002/adem.200900052



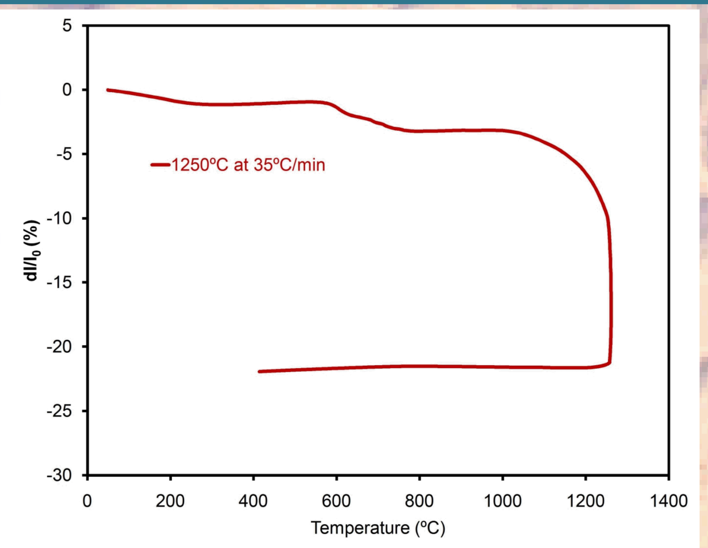
SPS graphite die during sintering

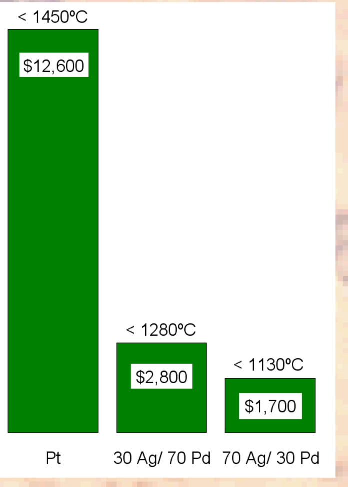


Sandia solution synthesized PZT

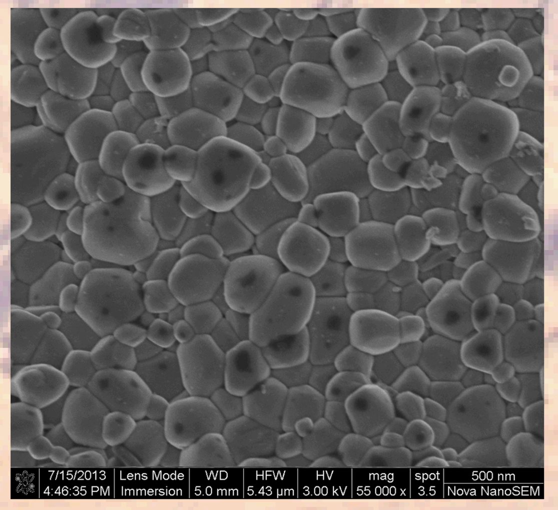


Significant lowering of calcining temperature (300 – 500 °C)





- Reduced PLZT sintering temperature with nanoparticle precursors
- > 4 fold reduction in electrode (and device) cost



SPSed $BaTiO_3$

$BaTiO_3$/epoxy composite with "graceful" failure mode

* Currently supporting TPL, Inc. in Army Phase I SBIR: "Nanoparticle Capacitors for Multi-Point Initiation"

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