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Cork, Ireland

# RF Magnetic Films and Their Applications in Integrated Magnetic Devices

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PWR'SoC 10

DC-DC convertors on silicon
*next generation technology for emerging business opportunities*

new technologies new applications new markets

# Group Introduction

Visiting Prof.
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- Shawn Beguhn
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- Ming Li
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- Xi Yang
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**Research Areas:**

- ➢Magnetic, ferroelectric and multiferroic materials for RFIC and MMIC
- ➢RF/microwave devices and subsystems
- ➢Magnetic sensors, spintronics, energy harvesting technologies, solar cell materials, etc.

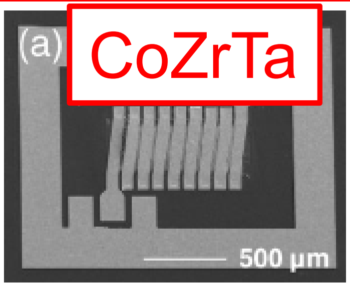
**Financial Supports:**

•NSF, ONR, AFOSR, MIT/LL, Draper Lab, Analog Devices, Northrop Grumman

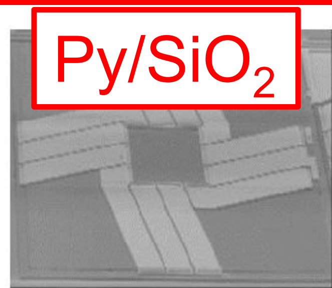
# Outline

- **Challenges of integrated magnetic inductors and RF magnetic materials**
- **Loss mechanisms and micromagnetics of:**
  - **Metallic magnetic films and multilayers**
  - **Ferrite films and multilayers**
- **Recent progress of RF metallic magnetic films and ferrite films and multilayers**
- **Summary**

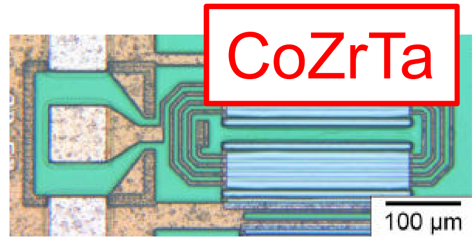
# Status and Challenges on Integrated Magnetic Power Inductors



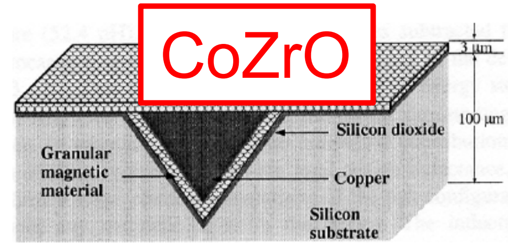

*Lee, et al. IEEE Trans Magn. (2008)*



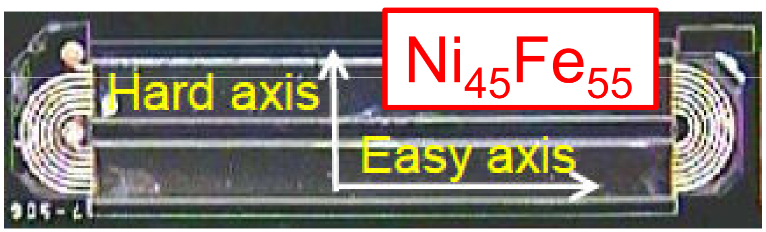

*Orlando, et al. IEEE Trans Magn. (2006)*



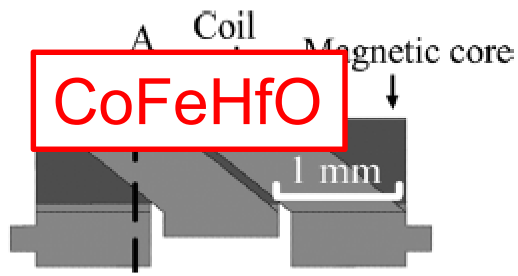

*Gardner, et al. IEEE Trans Mag 2009.*



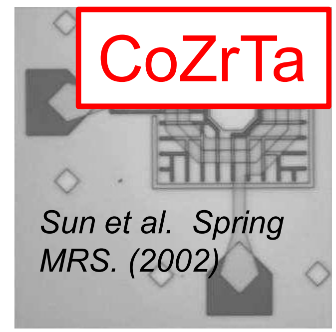

*Dhagat, et al. IEEE Trans Magn. 2004*




*O'Donnell, et al, APEC, 2008.*




*Li, et al. IEEE Trans Adv Pack. (2009)*




*Sun et al. Spring MRS. (2002)*

- ➢**Five types of magnetic inductors.**
- ➢**Hundreds of magnetic material compositions and microstructures**
- ➢**Performance of integrated power inductors are limited by magnetic materials.**


*Sato, et al. IEEE Trans Magn. (2004)*

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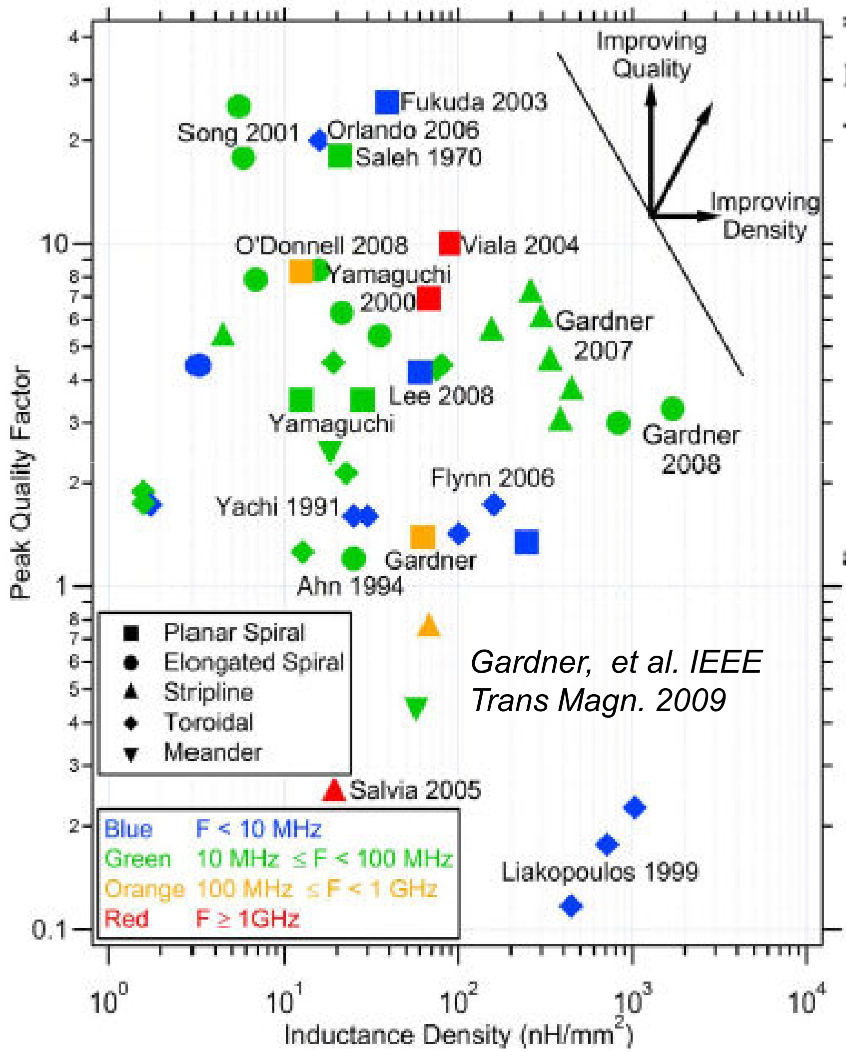
# Integrated Magnetic Inductors for Power: SOA and Challenges

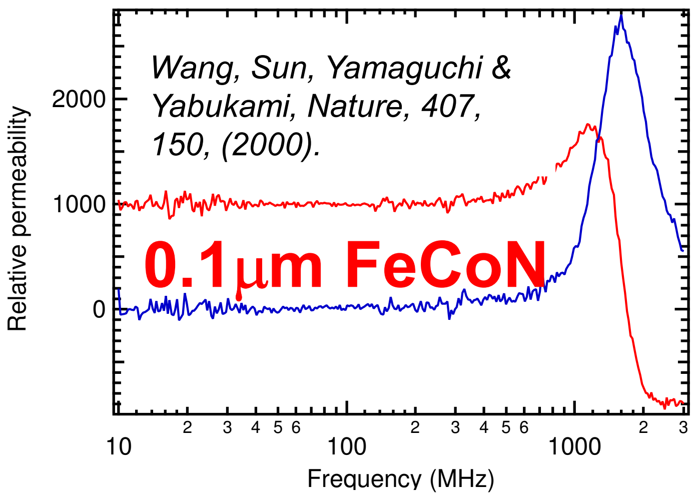


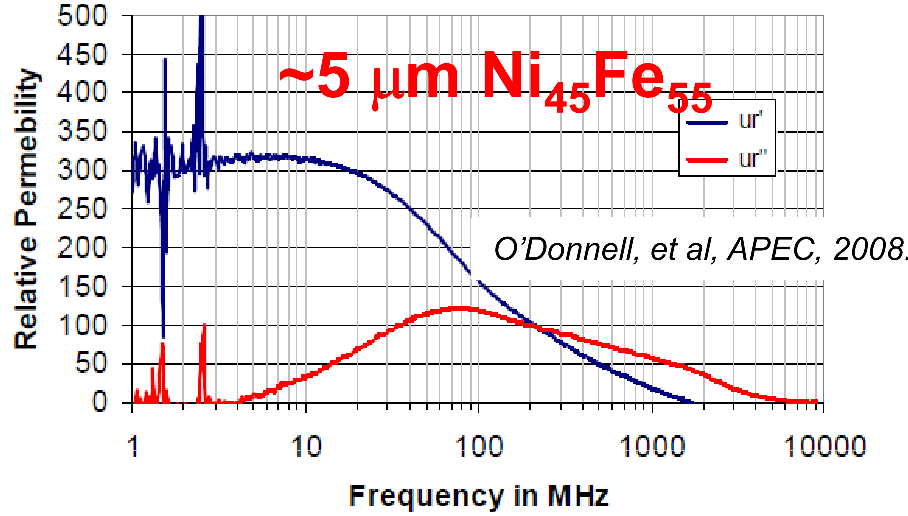

| Magnetic material | Substrate | $R_{DC}(\Omega)$ | $Q_{max}$ | Inductance Enhancement |
|---|---|---|---|---|
| NiFe | Si | 0.095 | ~20 @ 2 MHz | 810 % |
| CoTaZr | Si | | ~3.8 @ 170 MHz | 1900 % |
| CoNbZr | Si | ~5 | 3~12 @ 1 GHz | 7~71 % |
| $CoZrO_2$ | Si | 0.014 | | |
| FeHfN | Si | ~0.9 | ~10 @ 1 GHz | 30 % |
| CoTaZr | Si | 0.67 | 6.3 @ 26 MHz | 3400 % |
| Ferrite-polymer | Polyimide | 2.6 | 18.5 @ 10 MHz | |
| NiFe-based | Polyimide | 1.76 | 10.1 @ 1.4 MHz | |
| NiFe | PCB | 1.477 | | 120 % |
| CoFeHfO | PCB | 0.012 | 23 @ 200 MHz | 12 % |

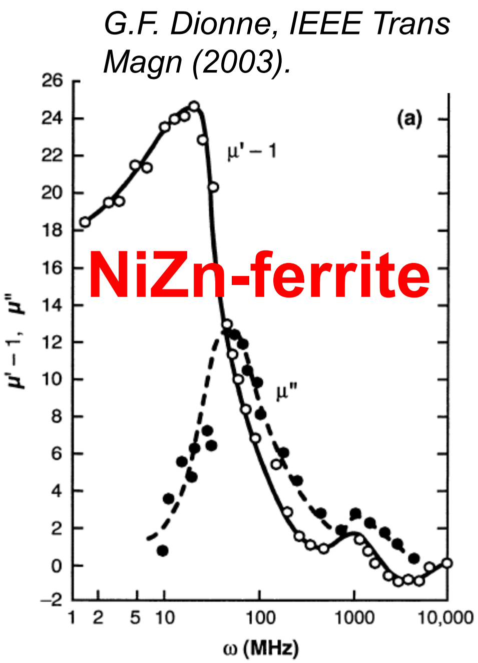
*L. Li, et al, IEEE Trans.. Adv. Pack. (2009).*

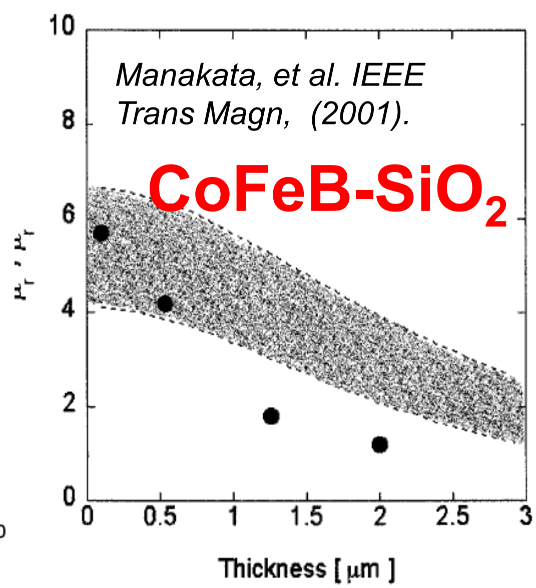
- ➢**Inductor challenges: high Q, high L (10~200nH) and L/area (or large ΔL/L) at 10~100 MHz!**
- ➢**Magnetic materials challenges: high $\mu_r$, large t, low tanδ<2%, high $M_s$, and high ρ.**

# Loss Mechanisms and Thickness Effects on Permeability Spectrum of Magnetic Films



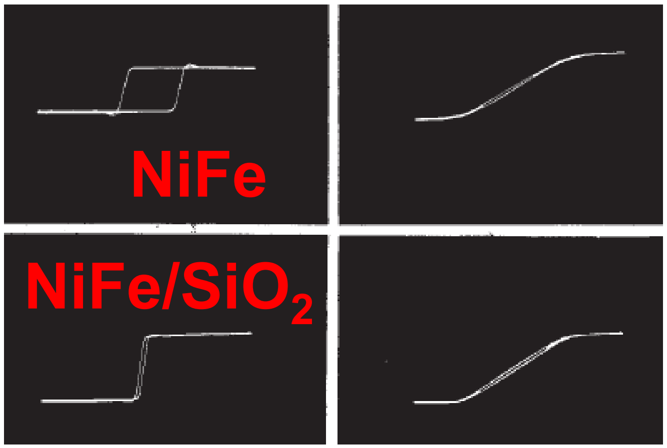




- ➢Ferromagnetic resonance
- ➢Eddy current loss
- ➢Domain wall resonance
- ➢Thick films lead to excessive eddy currents
- ➢Out of plane anisotropy grows with film thickness

- ➢Magnetic multilayers!

# Micromagnetics of Magnetic/Non-magnetic Multilayers: Enhanced RF Magnetism



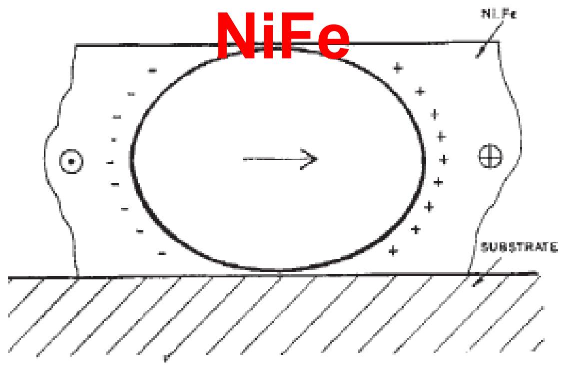
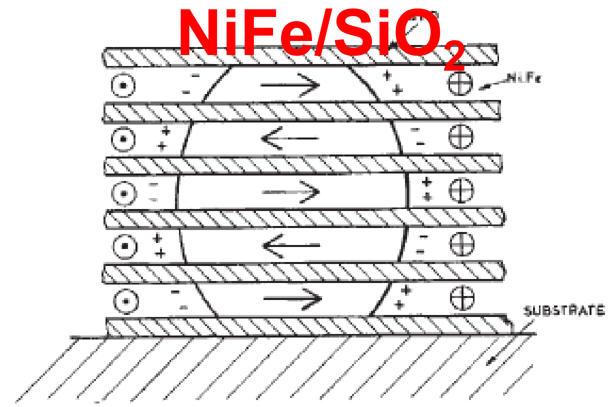



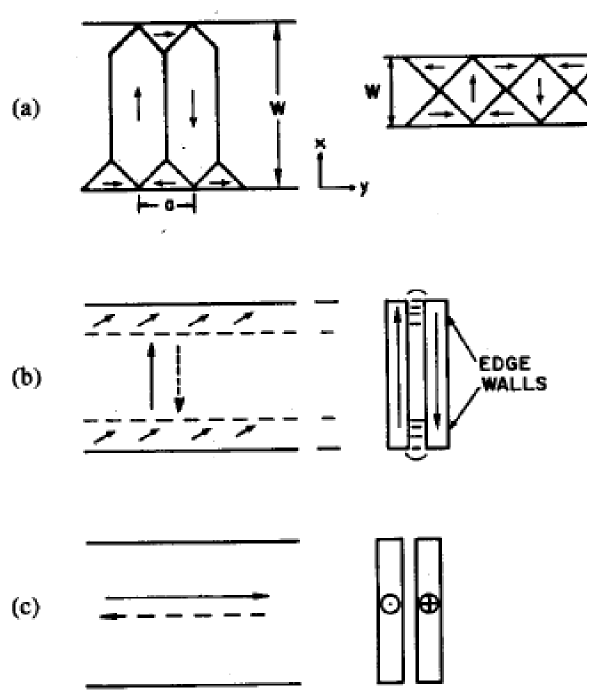

Fig. 2. Néel wall

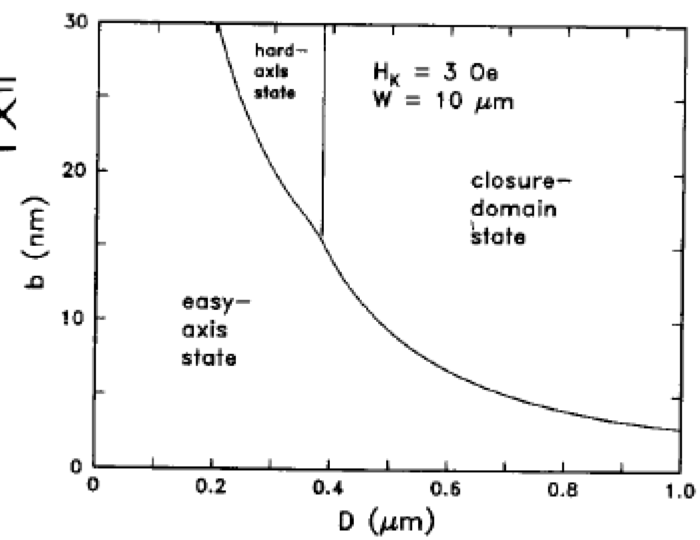



*Clow, Nature (1962).*

**How to achieve the easy axis state:**

- **Low b and low D**
- **High b so that no-pinhole**
- **High D for high average permeability**




*Slonczewski, et al. IEEE Trans Magn. (1988).*

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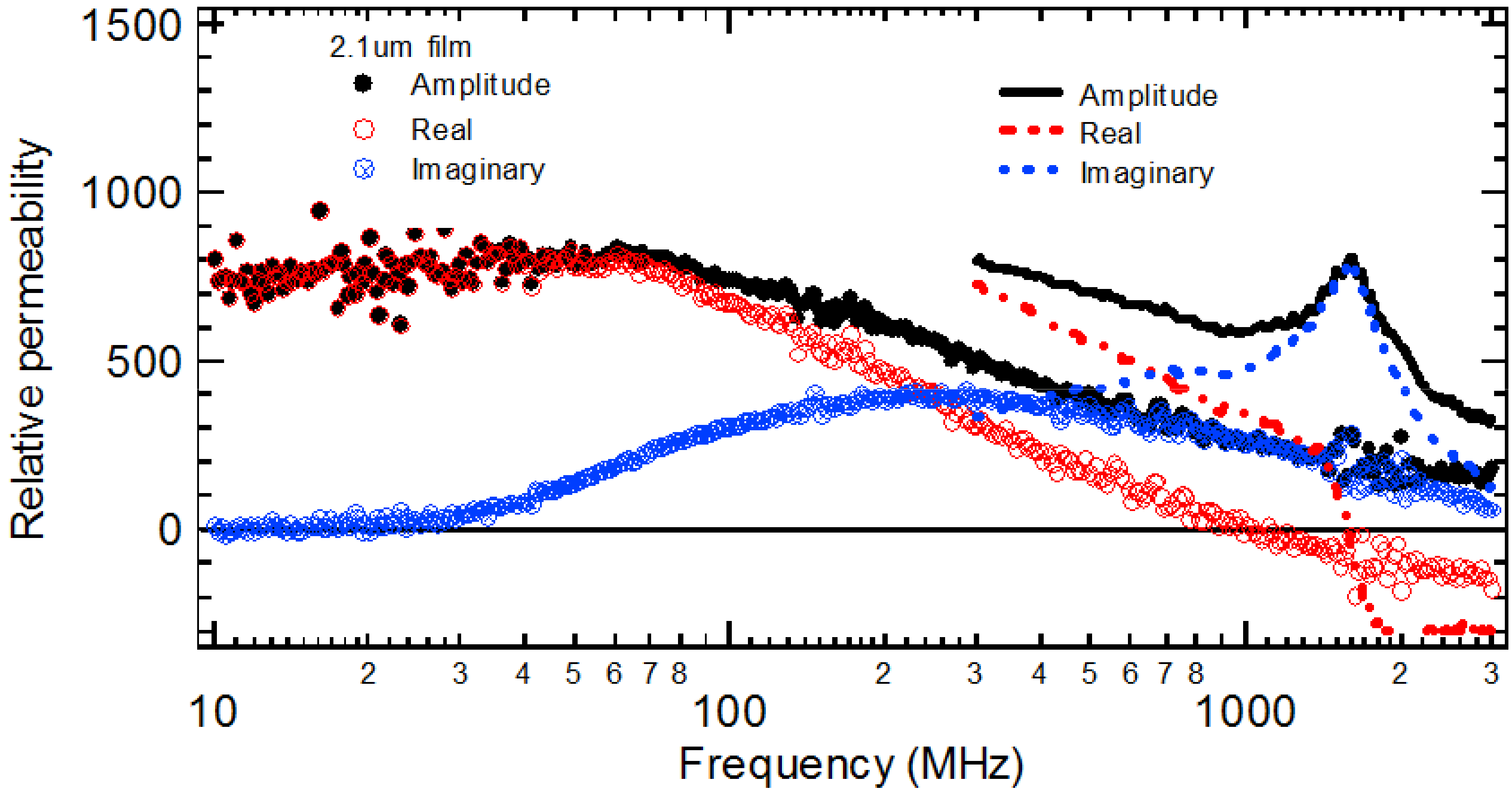
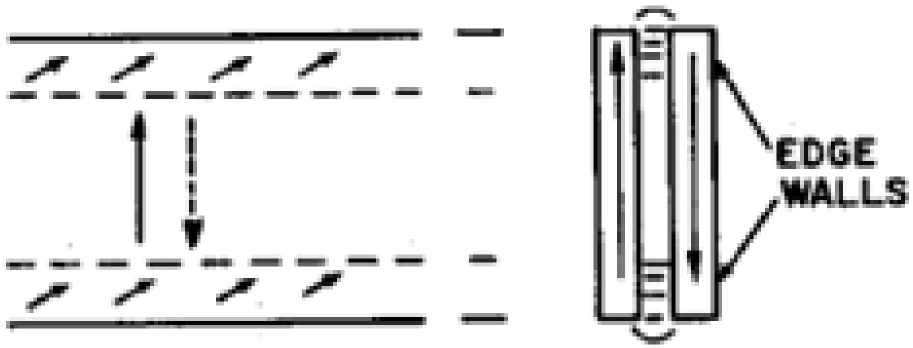
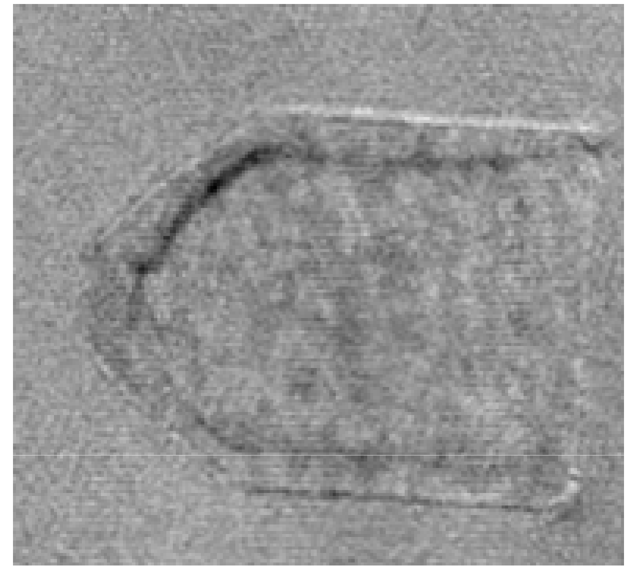
# Permeability Spectra of 2μm Thick Metallic Magnetic films: Single Layer and Multilayer




- ➢**Eddy current dominated permeability of single layer film**
- ➢**Ferromagnetic resonance dominated permeability spectrum for the multilayer!**

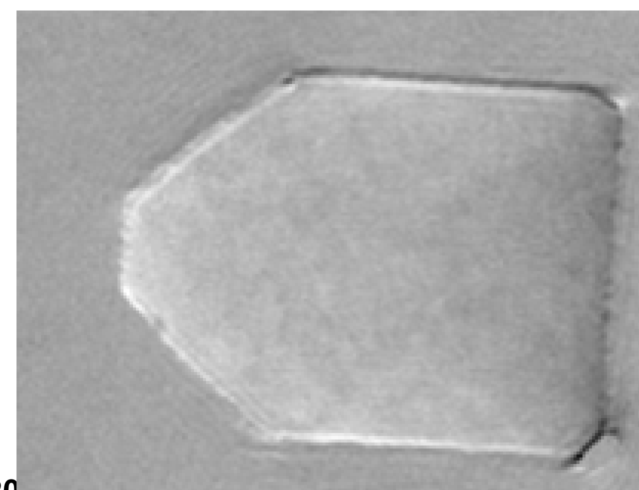
# Edge Closure Domain Walls in Patterned Magnetic/Non-magnetic Islands



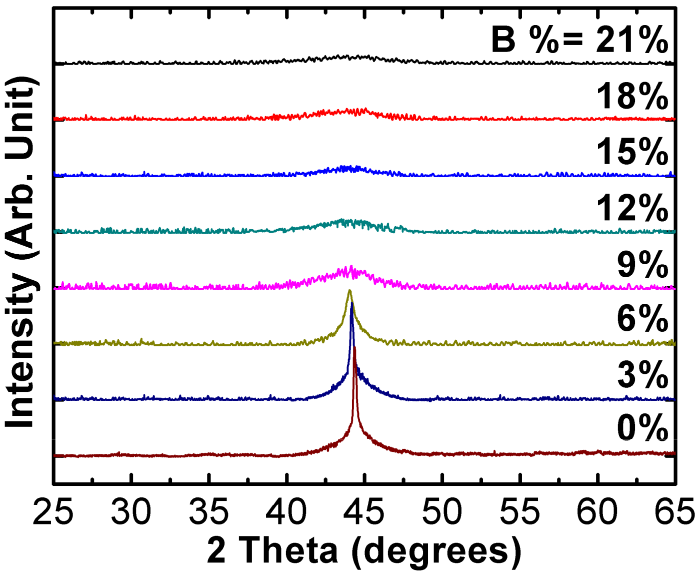



**Magnetic/non-magnetic insulator multilayers:**

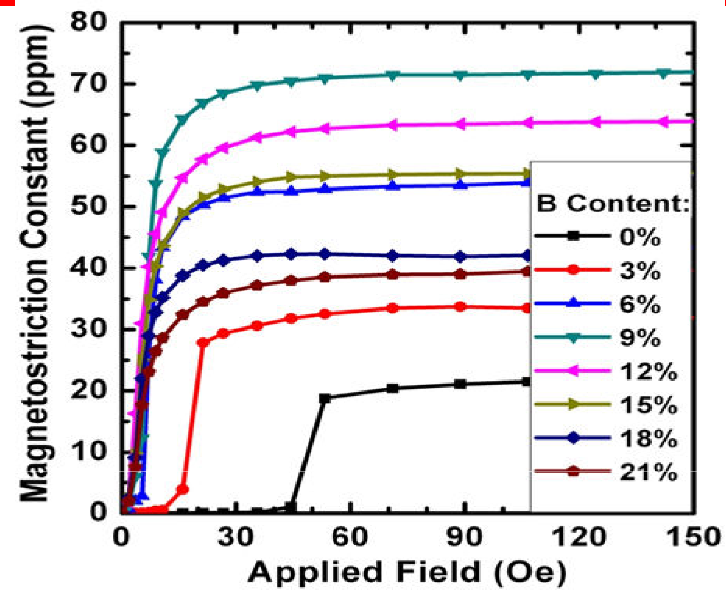
- **Thicker film with significantly reduced eddy current loss**
- **Improved soft magnetism:**
  - **Significantly reduced Hc**
  - **Less out of plane anisotropy**
  - **Lower Gilbert damping.**

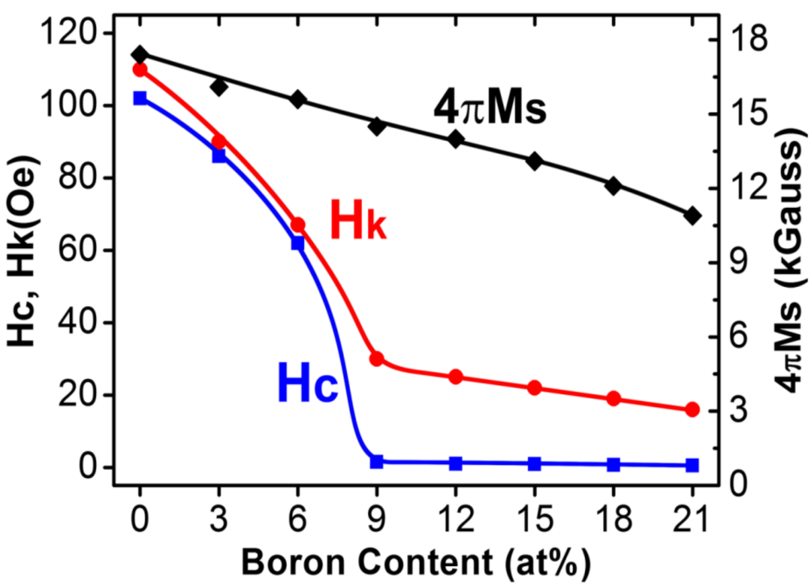


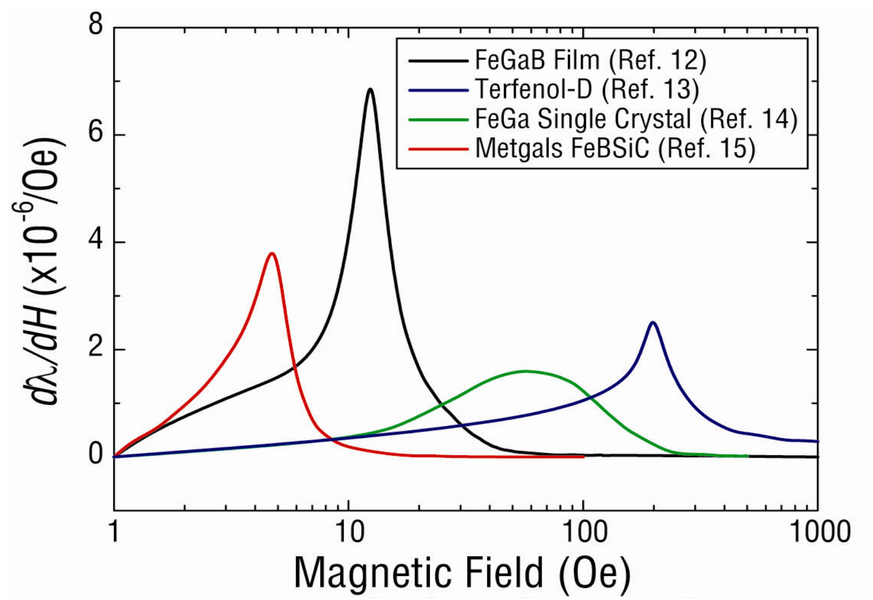
# Novel FeGaB Films: Microstructure, Soft Magnetism and Magnetostriction



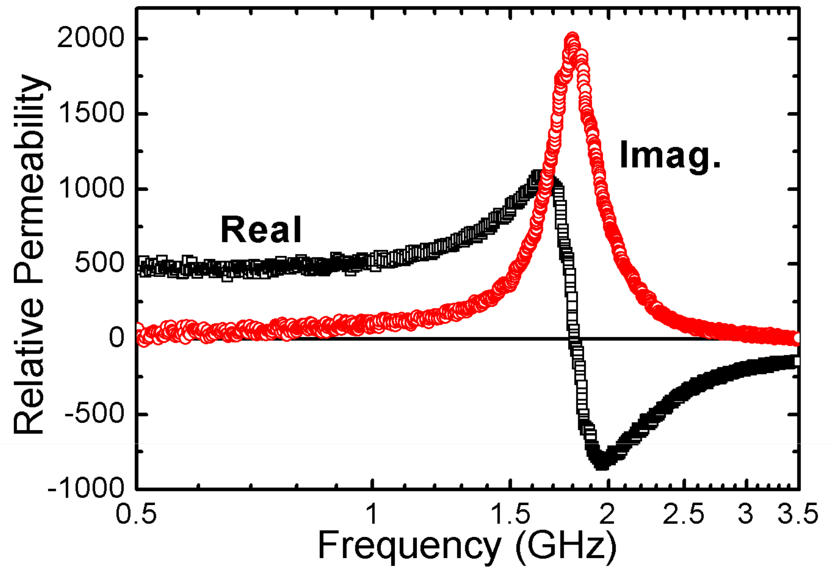

*J. Lou et al., Appl. Phys. Lett., 91, 182504 (2007)*

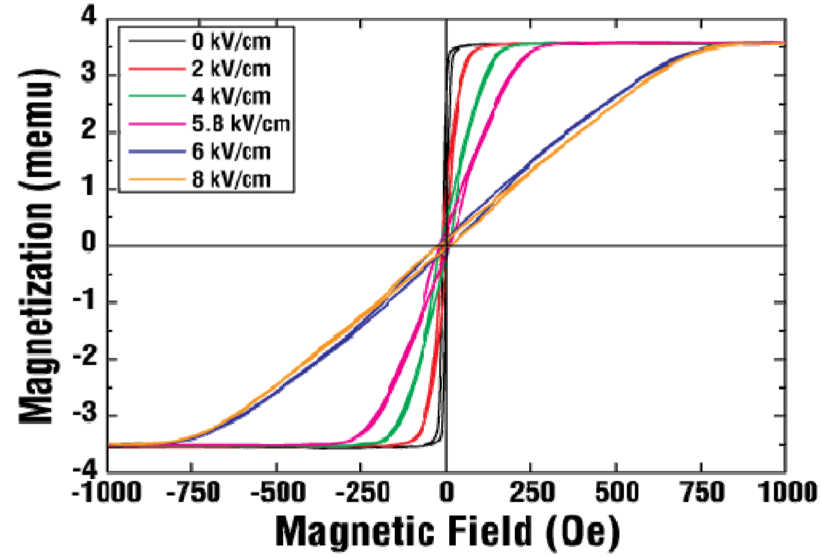


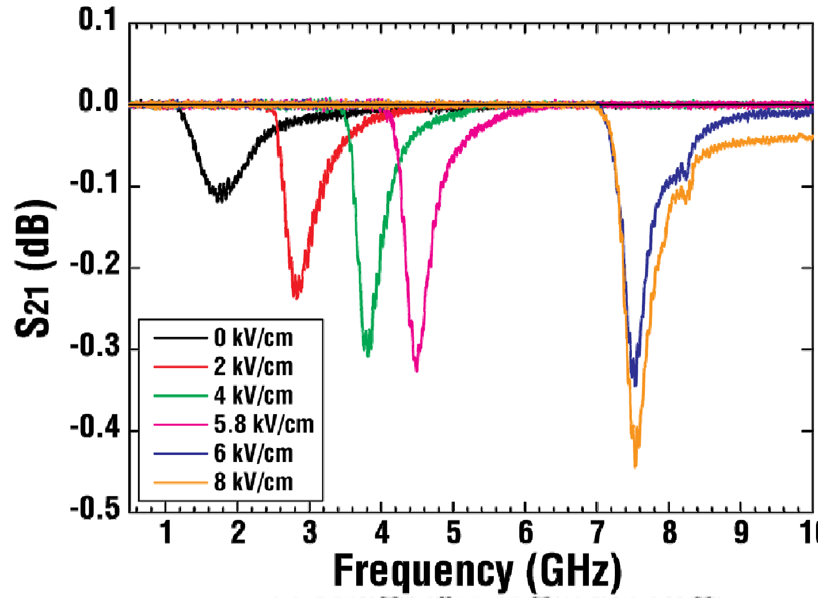



# RF Magnetics of FeGaB and Multiferroic FeGaB/PZN-PT Heterostructures



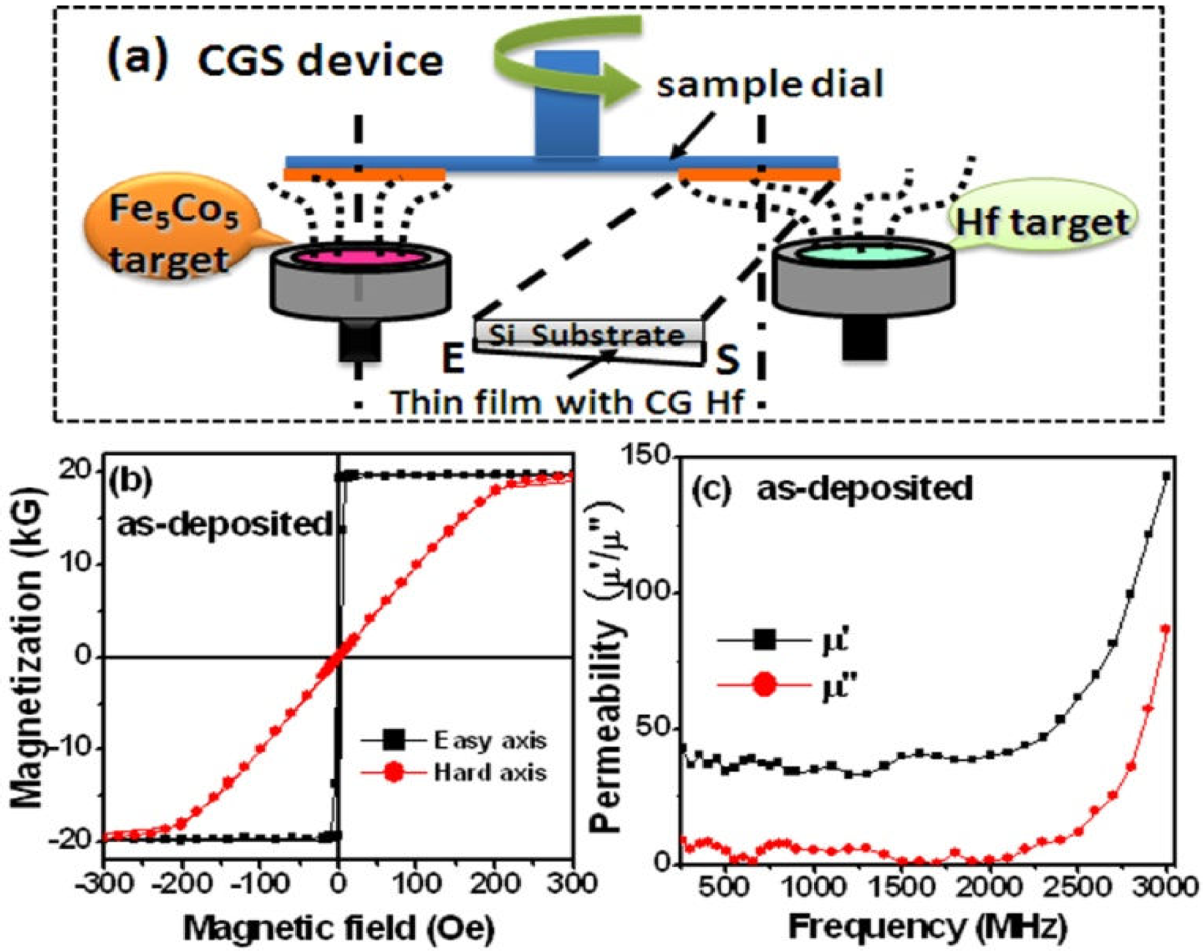




- **High E-field tunable FMR frequency range from 1.75 to 7.57 GHz, or $f_{max}/f_{min}$ = 4.3 at 0Oe.**
- **Dramatic changes in hysteresis loops, ~750 Oe change in anisotropy.**




*J. Lou et al. Advanced Materials, 21, 4711 (2009).*

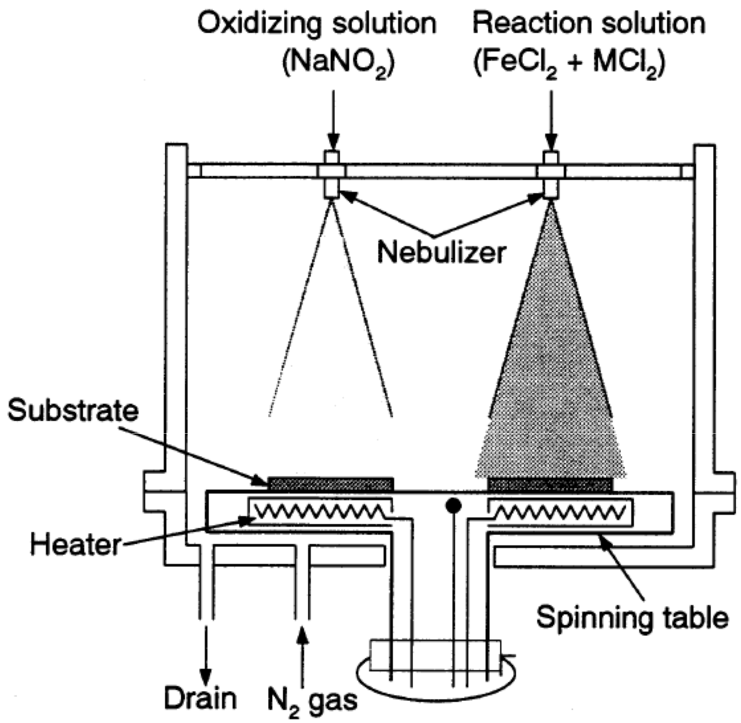
# Soft Magnetic FeCoHf Films with High Uniaxial Magnetic Anisotropy

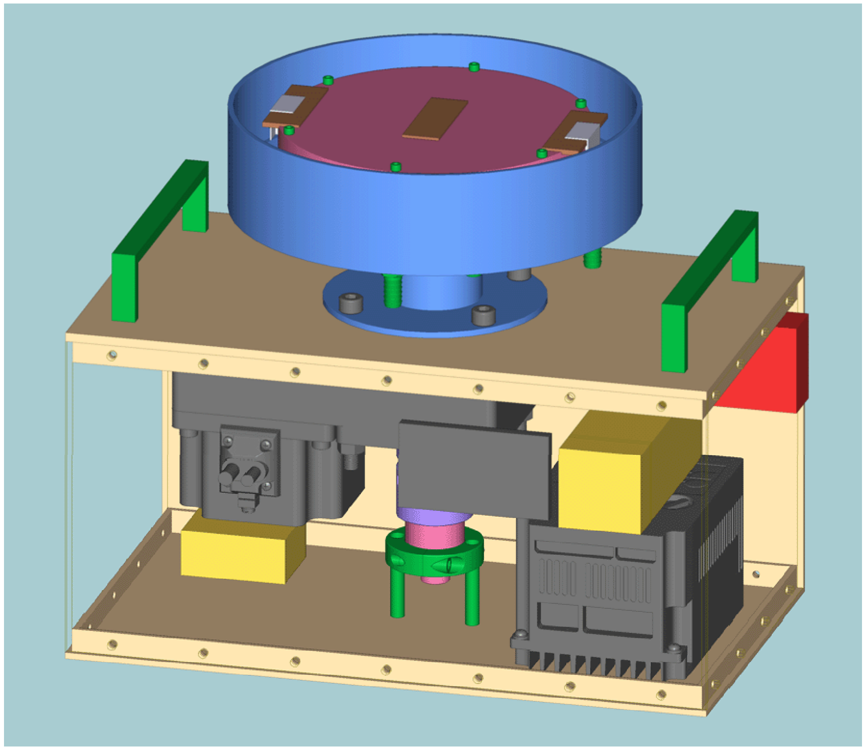



*Li, et al. MMM Conference 2010.*

- **High uniaxial anisotropy induced by composition gradient**
- **Excellent RF magnetic properties!**

# High Quality RF Ferrite Films by Low-Temperature Spin Spray: Process Introduction

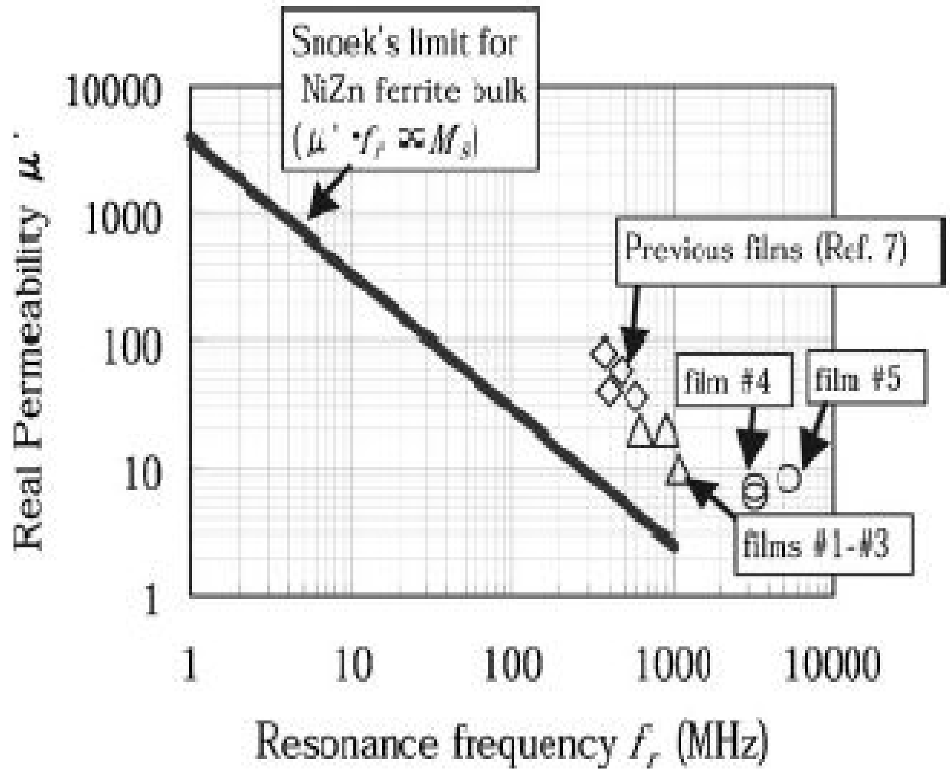


- ➢**Low process temperature of 90°C, high crystalline quality, high deposition rate 50~100nm/min, low RF loss tangent.**
- ➢**Compatible with RFIC and MMIC, even organic substrates.**

*Abe, Electrochimica Acta (2000).*

# Permeability Spectra for Thin Film Magnetic Materials: the Modified Snoek's Limit




*K. Kondo, et al J. Appl. Phys. 101, (2007).*

$$\mu_r = \frac{4\pi M_s}{H_{total}} + 1$$

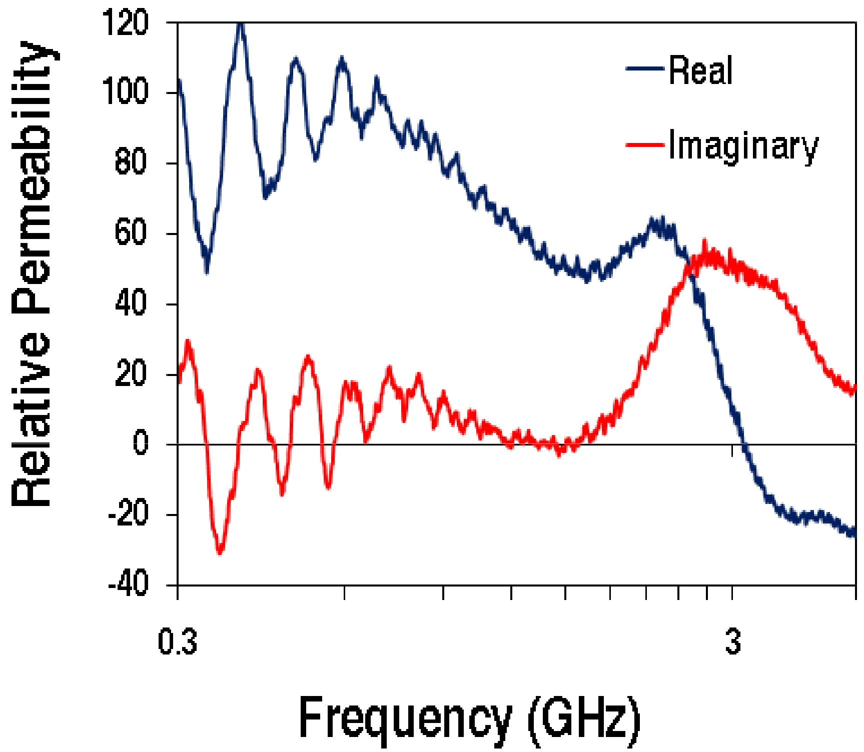
$$f_{FMR} = \gamma \cdot \sqrt{H_{total} \cdot (4\pi M_s + H_{total})}$$

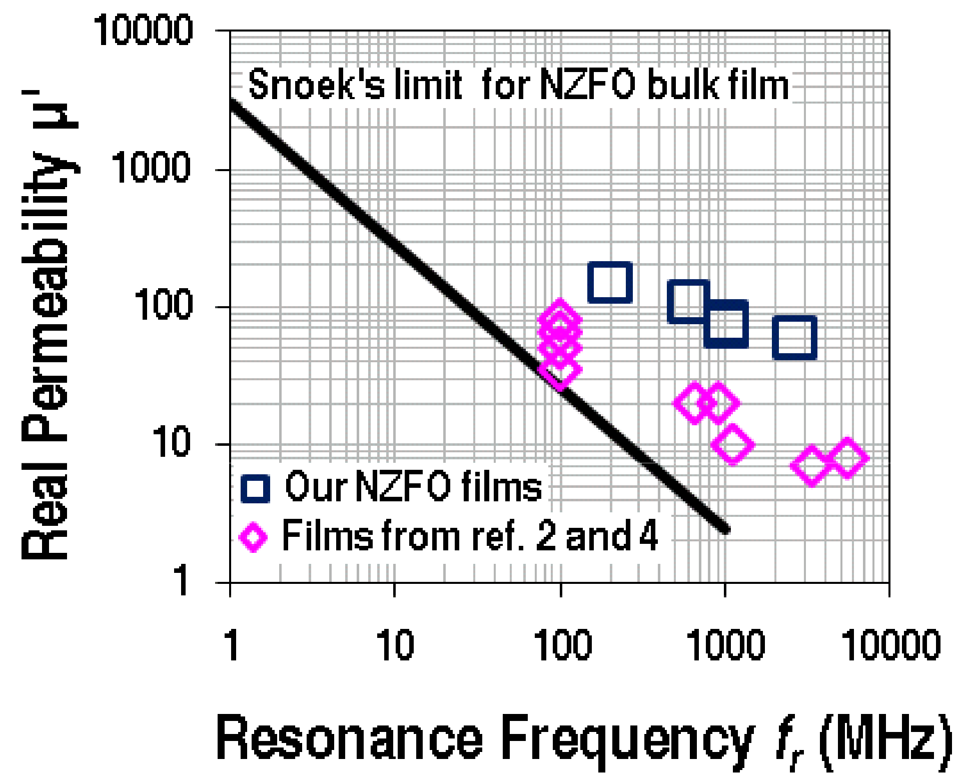
$$f_{FMR} = \gamma \cdot H_{total} \cdot \sqrt{\mu_r}$$

$$\mu_r \cdot f_{FMR} = \gamma \cdot 4\pi M_s \cdot \sqrt{\mu_r}$$

- **Snoek's limit boosted by Sqrt($\mu_r$)**
- **0.5~ 1 order of magnitude enhanced FMR frequency.**

# Permeability Spectrum of Spin Spray Deposited NiCo-Ferrite Films

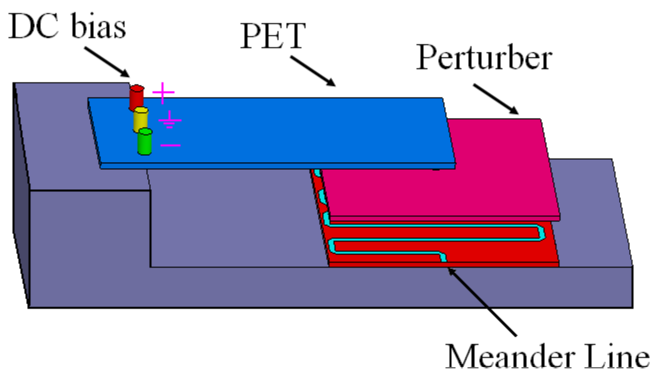


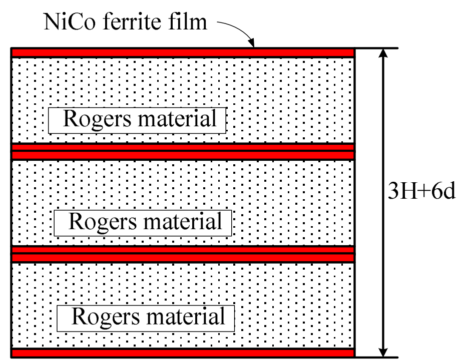



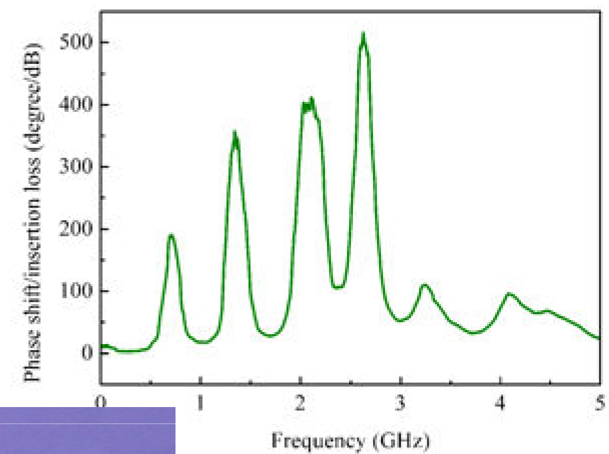

- **Self-biased ferrite films by spin spray deposition at 90°C**
- **High permeability (10~200) and high permittivity (~10) and low loss at GHz.**

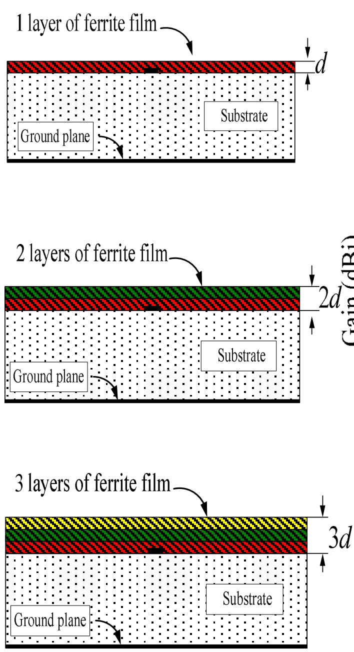
# RF Magnetic Devices with Spin Spray Deposited Ferrite Films Exhibiting Enhanced Performance

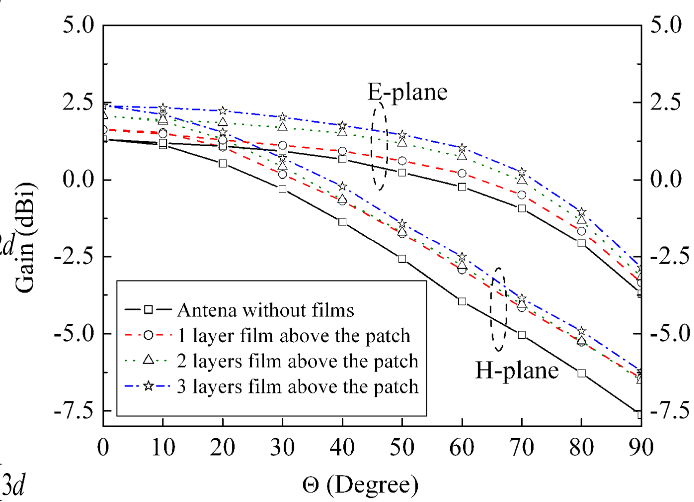
## Monolayer ferrite films

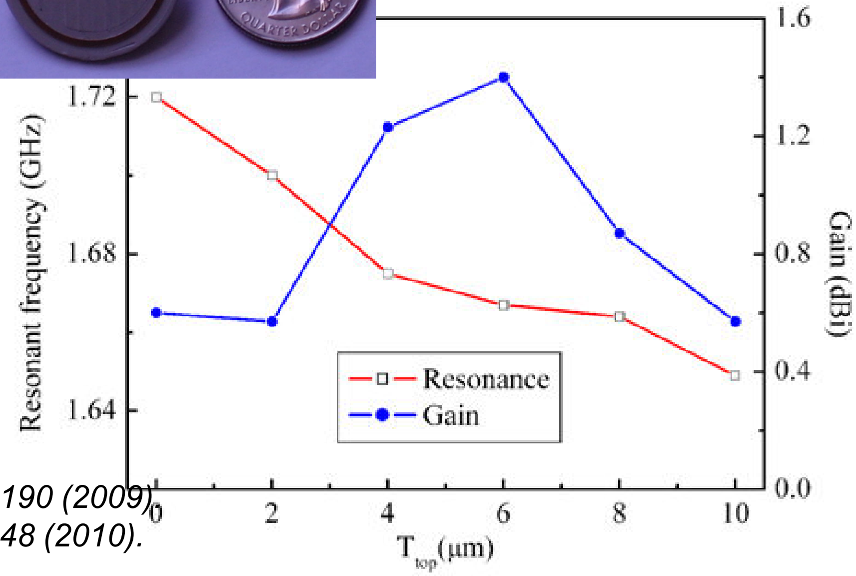


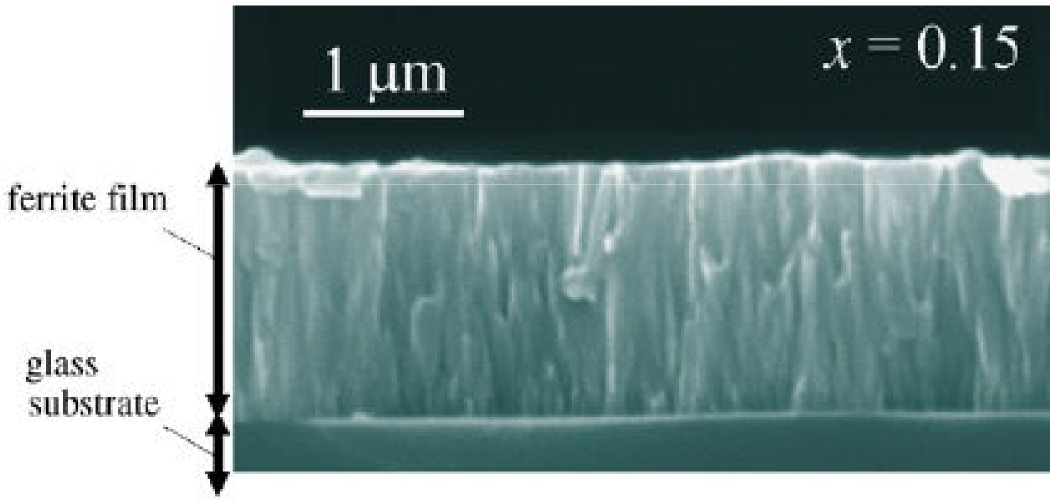




*Yang, et al. IEEE Trans. Antenn. and Prop., 57, 2190 (2009).*
*Yang, et al., IEEE Trans. Antenn. and Prop, 58, 648 (2010).*

# Need for Thick Ferrite/Non-Magnetic Films for RF Devices

- **Hard to achieve thick RF ferrite monolayer films > 3~5 um by spin spray, which also exhibit degraded RF performance.**




*Fujiwara, et al JMMM, (2008)*

- **Need ferrite/non-magnetic insulator multilayers!**

- **No demonstration showing improved RF performance in ferrite/non-magnetic insulator multilayers!**

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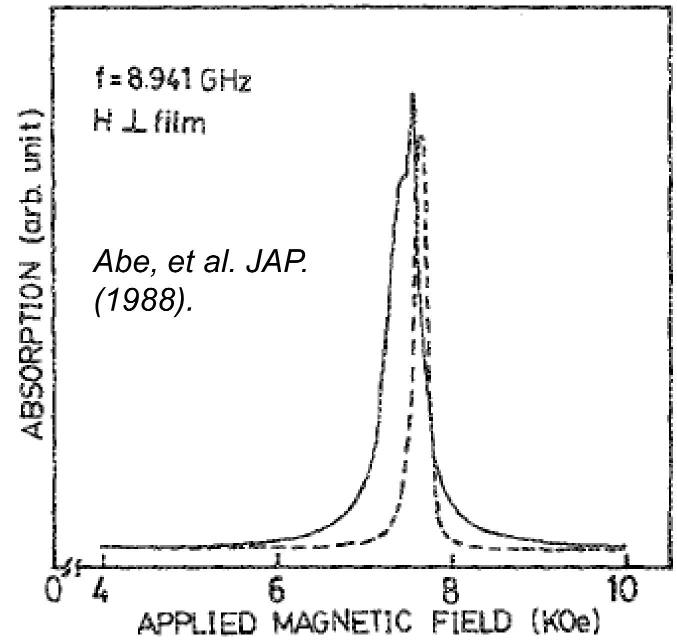
# Performance of Ferrite/Non-Magnetic Multilayers

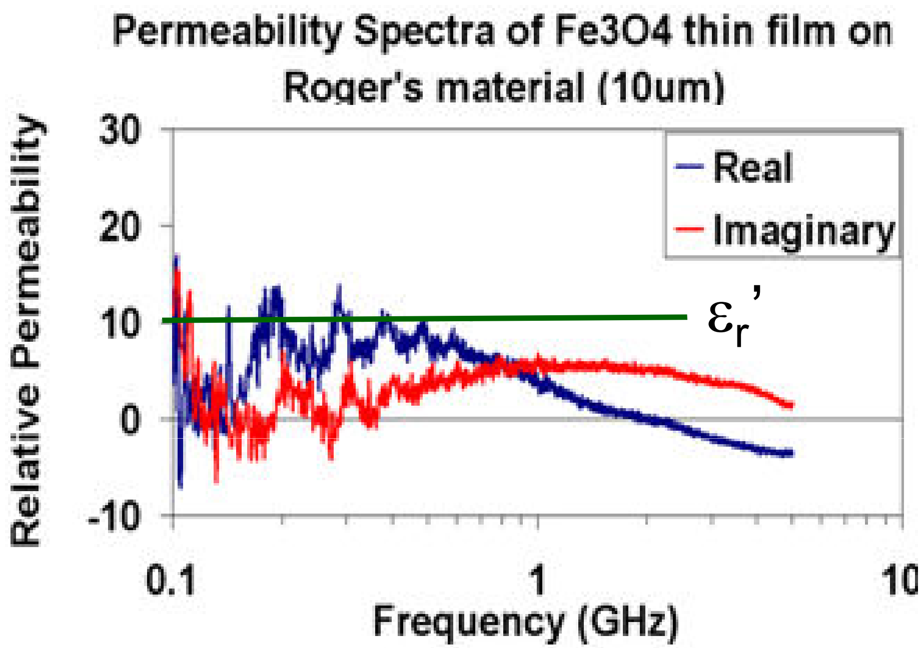
| Type of film | NiZn-ferrite layer: Plating time (min) | NiZn-ferrite layer: Number | Total thickness[a] ($\mu$m) | Magneti-zation (emu/g) | Coercive force (Oe) |
|---|---|---|---|---|---|
| F-5 | 5 | 20 | 5.2[b] | 92[b] | 79[b] |
| F-10 | 10 | 10 | 3.7[b] | 93[b] | 67[b] |
| F-20 | 20 | 4 | 3.0[b] | 90[b] | 56[b] |
| Monolayer | 30 | 1 | 0.8 | 81 | 31 |

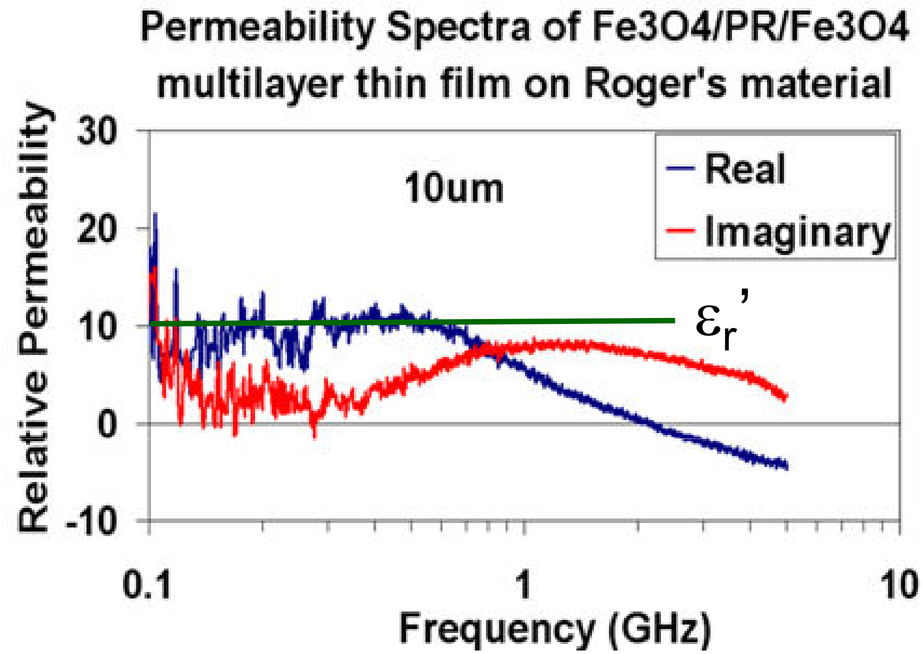


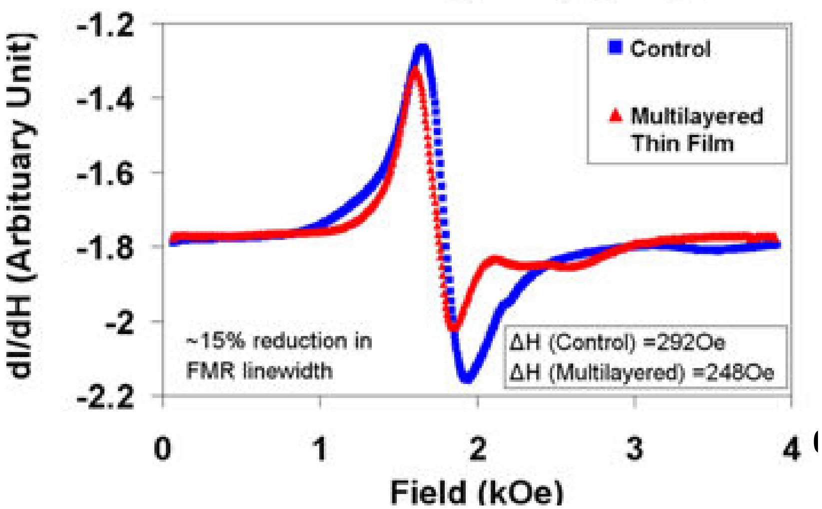

**Spin spray deposited [NiZn-ferrite/Dextrar]xn, failed in achieving improved RF performance!**

- **Enhanced coercivity, which went up with the number of periods.**
- **Degraded RF performance with much higher FMR linewidth.**

# Improved Microwave Magnetic Properties in Spin Spray Deposited Ferrite/Insulator Multilayers

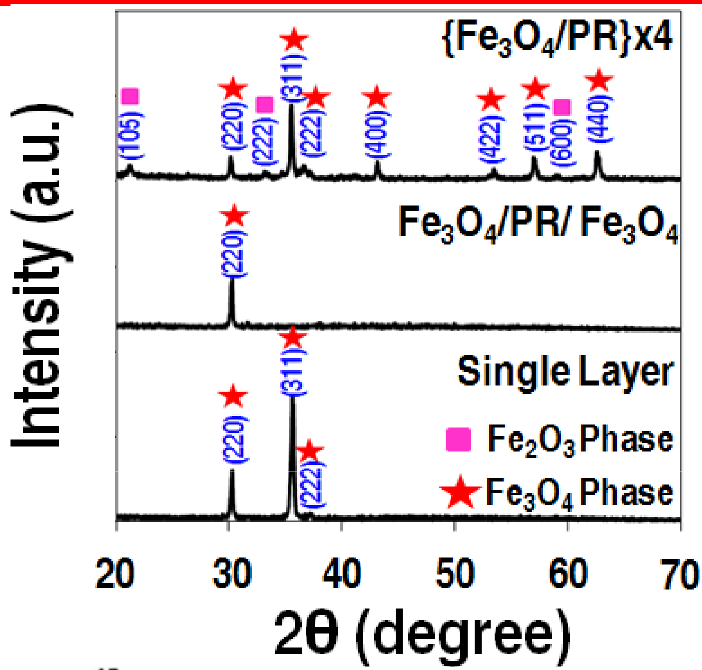


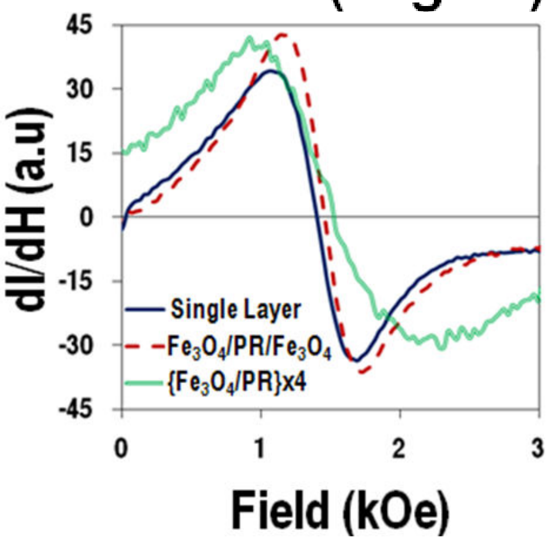



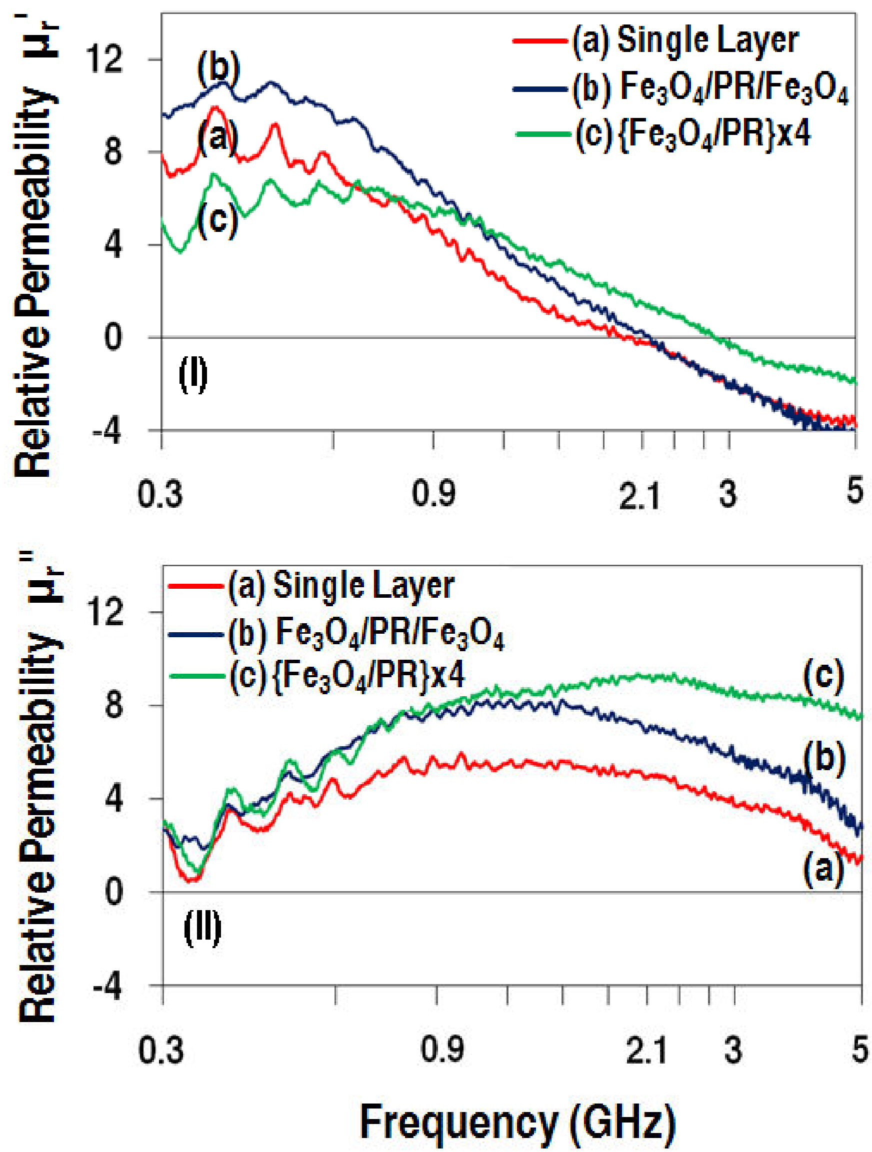




**Ferrite/insulator multilayer leads to reduced FMR linewidth and enhanced permeability!**

# Spin Spray Deposited Ferrite Monolayers and Ferrite/Non-Magnetic Multilayers



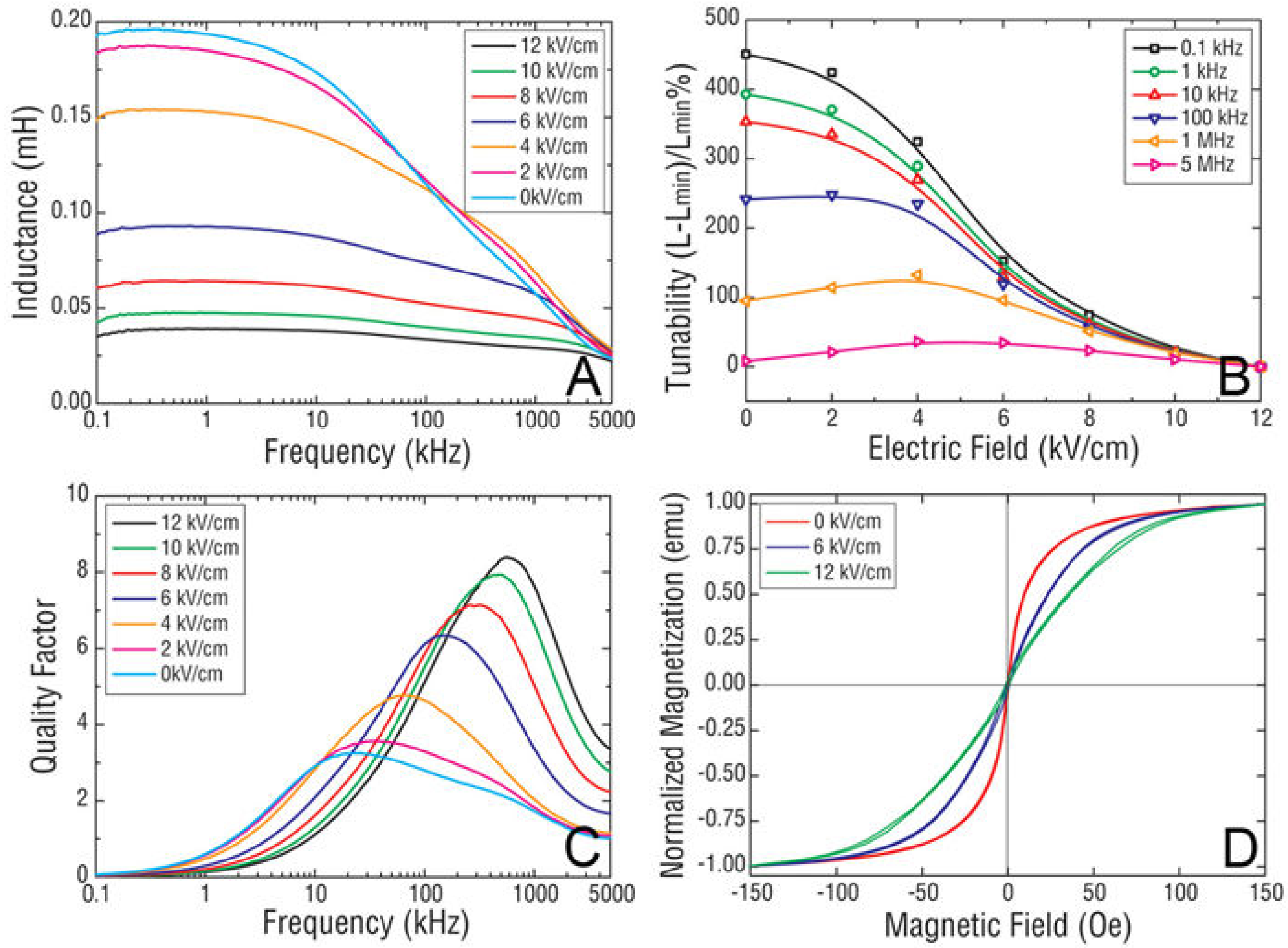
# Improved RF Magnetics in Spin Spray Deposited Ferrite/Non-Magnetic Multilayers

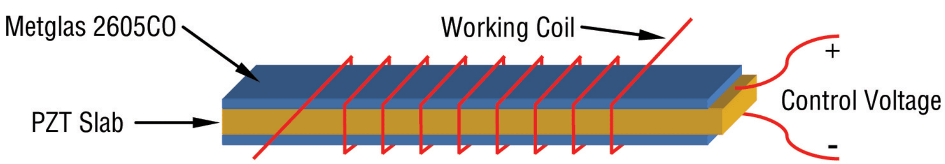
| Film Structure | Thickness (μm) | $M_s$ (emu/cm³) | $H_c$ (Oe) | $\mu_r'$ | $f_r$ (GHz) | $\Delta H$ (Oe) |
|---|---|---|---|---|---|---|
| $Fe_3O_4$ Single Layer | 10 | 318 | 111 | 8 | 1.2 | 618 |
| $Fe_3O_4$/PR/$Fe_3O_4$ | 10 | 318 | 96 | 10 | 1.3 | 589 |
| ($Fe_3O_4$/PR)x4 | 10 | 302 | 140 | 5 | 2.1 | 1398 |
| $Fe_3O_4$ Single Layer | 1.4 | 398 | 134 | 9 | 1.1 | 528 |
| $Fe_3O_4$/PR/$Fe_3O_4$ | 1.4 | 398 | 118 | 10 | 1.2 | 464 |
| NZFO Single Layer | 1.2 | 263 | 23 | 19 | 0.9 | 292 |
| NZFO/$Al_2O_3$/NZFO | 1.2 | 279 | 21 | 20 | 1.0 | 248 |

➢**Improved RF magnetics in ferrite/insulator multilayers, lower Hc, higher μ, narrower ΔH!**

# New Electrostatically Tunable Inductors with Giant Tunable Range

- **A new class of electric field tunable inductors**
- **Giant tunable inductance range**
- **Novel applications in power electronics!**




**Page :** ***J. Lou, D. Reed, M. Liu, N. X. Sun, Appl. Phys. Lett. 94, 112508 (2009).***

# Summary

- Eddy currents in magnetic film limit the performance of integrated magnetic inductors and transformers.
- Thick magnetic/non-magnetic multilayer films are the key to achieving better performance in power inductors and transformers.
- Open for collaborations!
  - Email: Nian@ece.neu.edu
  - Phone: +1-617-373-3351
  - www.northeastern.edu/sunlab

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