Challenges in magnetics for PwrSoC - Development in high-frequency magnetics, materials and integration

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Overview- Integrated Magnetics

- Background
- Challenges
- Modelling – Thin film
- Integration aiming PSOC
- Developed Nanomagnetic Materials
- Fabricated Inductors
- Test Results

Market Opportunities for Miniaturised Point of Load Power supplies

MP3

Camcorder

Mobile Phone

PDA

PC

Buck Type DC-DC Conversion

Market size billions of € !

In-Store electronics

GPS / Marine electronics

Household Electronics fixed / portable

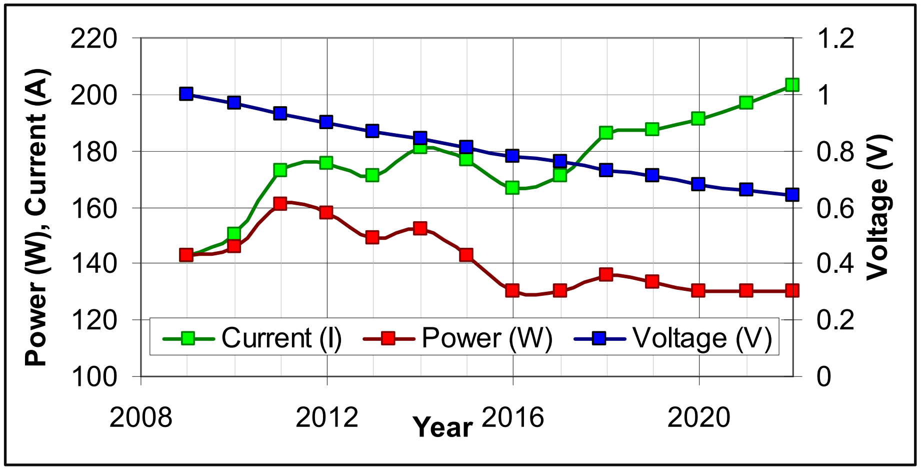
Microprocessor Unit (MPU) Power Trends

Decreasing Voltage

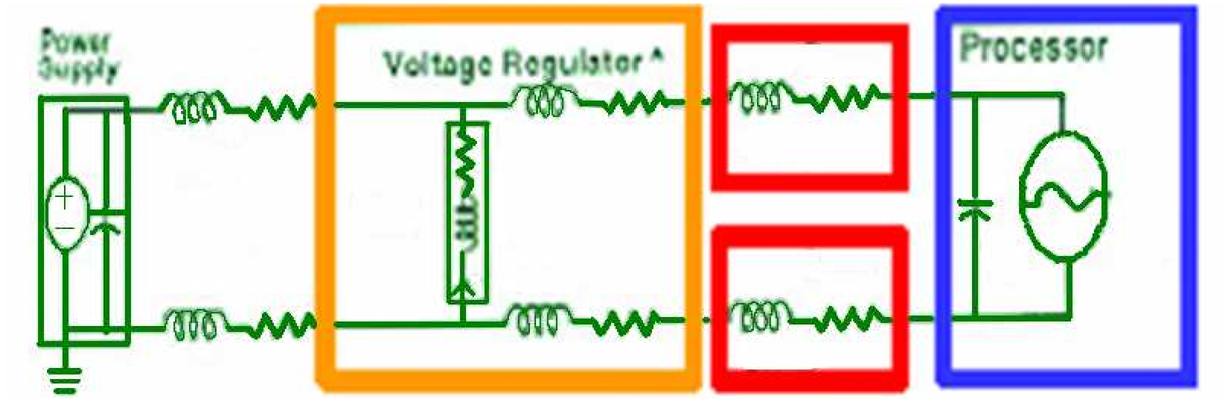
Increasing Current

Increased current will result in increased interconnect losses

$$P = I^2 R$$

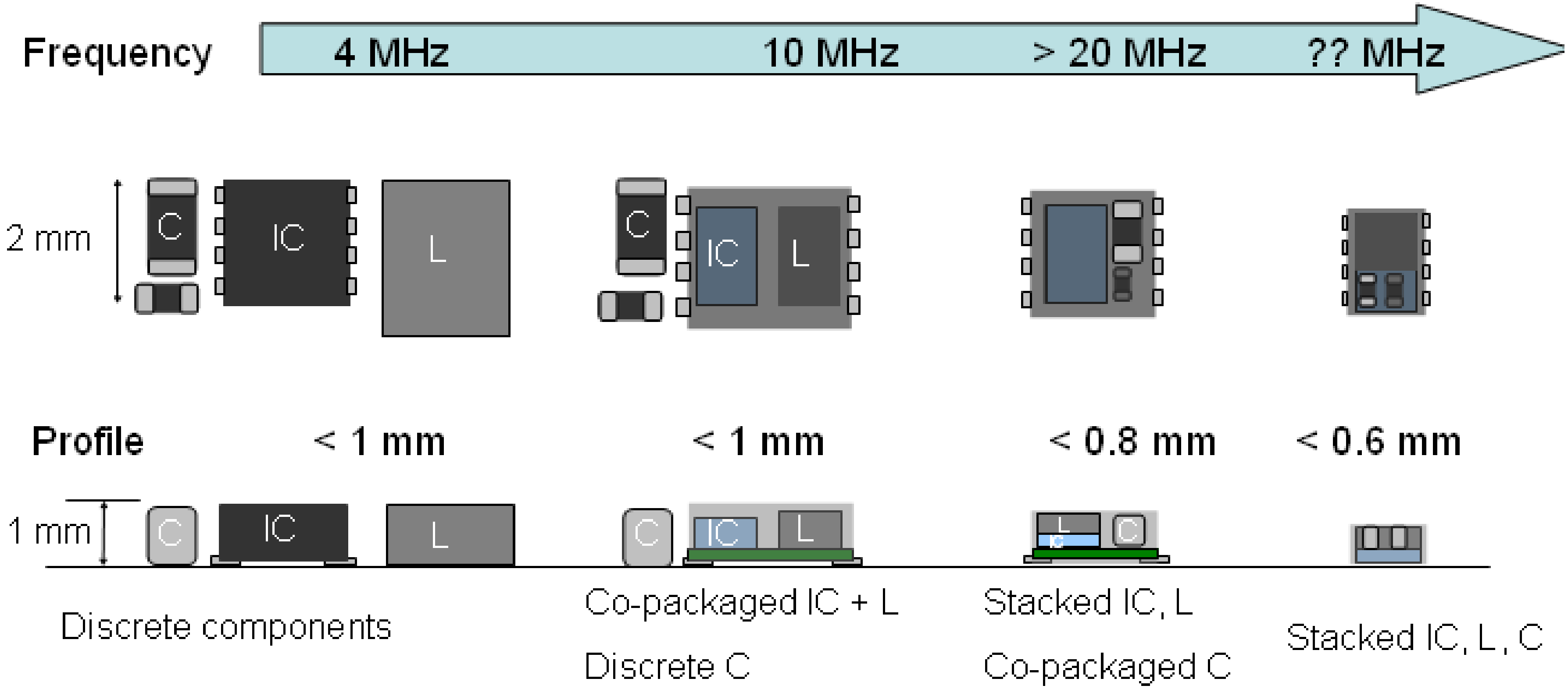


ITRS 2009 Roadmap for the power, voltage, and current requirements of a high-performance MPU with heatsink [1]



Solution: Integrated power conversion module !

Passive Component Size Reduction with Increasing Frequency Enables Functional Integration

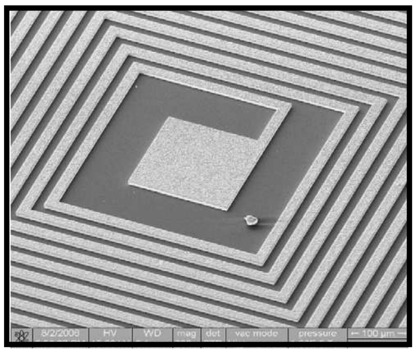


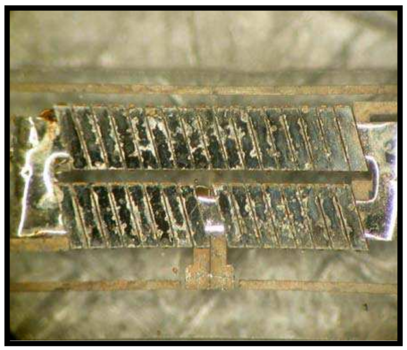
State of the Art

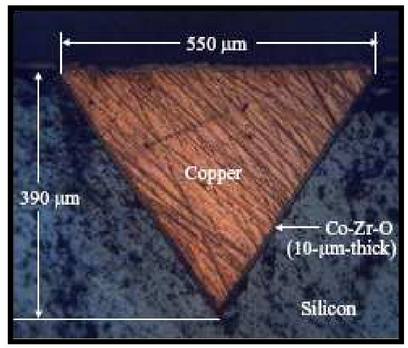
A number of different structures reported in the literature

Constraints limit the usefulness of some structures

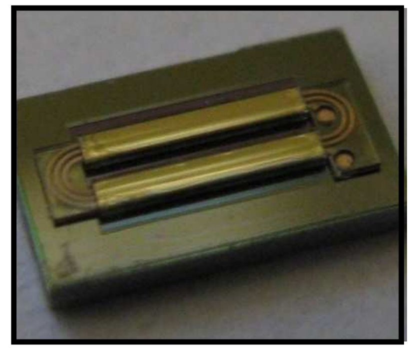
- Out-of-plane flux
- Negative mutual inductance in turns
- Fabrication complexity

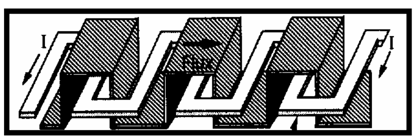

Current Applied Physics **8**, 138 (2008)


Microsyst. Tech. **12** , 923 (2006)

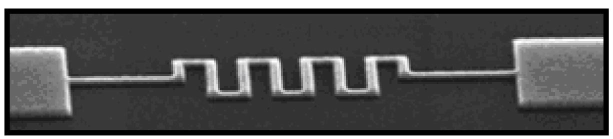


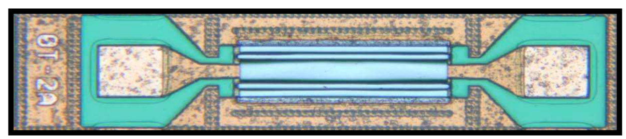
Proc. IMAPS (2002)


Tyndall National Institute, 2009



IEEE Trans. Mag. **30**, 73 (1994)


International Semiconductor Conference 1, 93 (2006)


J. Appl. Phys. **103**, 07E927 (2008)

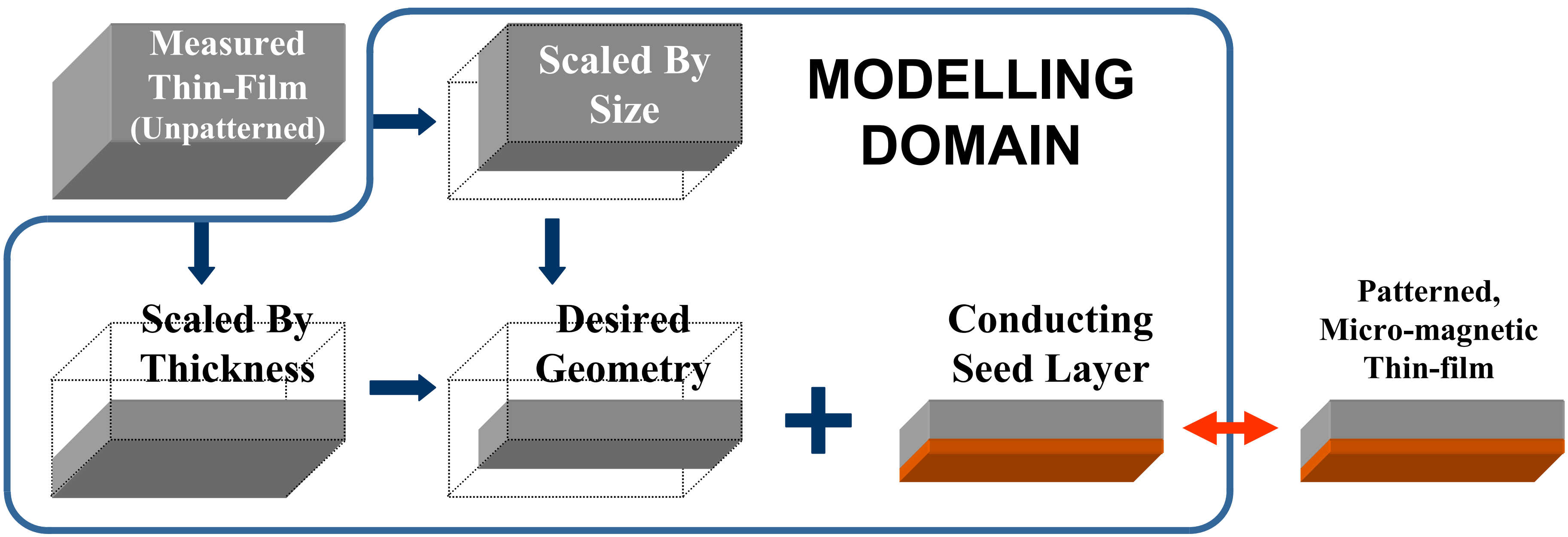
Challenges

- Modelling
  - Magnetic modeling for Micron scale devices
  - Optimisation with converter for higher efficiency
- Integration
  - Low cost & high yield process
  - Non line of sight technique
  - CMOS compatibility
- Materials
  - Reducing Cu winding Loss
  - Magnetic materials with low loss at high frequency
    - Eddy current loss
    - Hysteresis loss
    - Ferromagnetic resonance loss

THIN-FILM MODELLING

Magnetic material properties differ substantially between as-deposited, wafer-scale films and patterned structures in a micro/nano-scale device

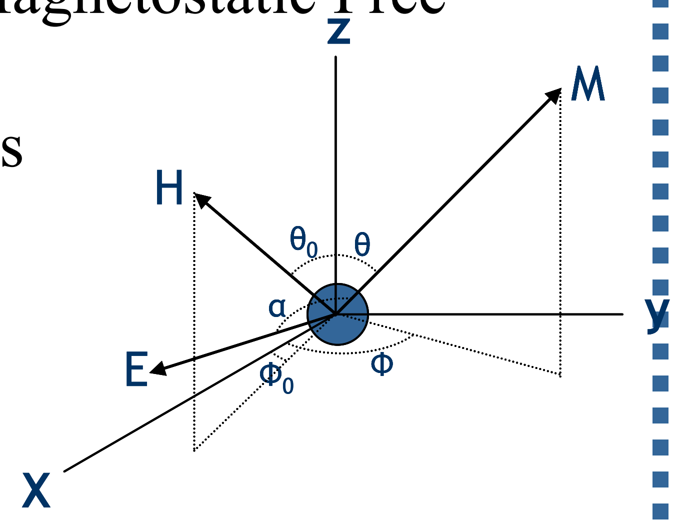
It is easier to measure one film and scale the results using modelling



Shape-Dependent Anisotropy

Modelled via Stoner-Wohlfarth model of Magnetostatic Free Energy- Particle Model

Still a good approximation of larger systems



Total free energy, E_f, along **M** in a system with an induced anisotropy **E** in the presence of an applied field **H**

$$E_f = \underbrace{-K\cos^2\alpha}_{\text{Material Anisotropy}} - \underbrace{Ms^2\left(D_x(\sin\theta\cos\phi)^2 + D_y(\sin\theta\sin\phi)^2 + D_z\cos^2\theta\right)}_{\text{3D Demagnetizing Field}} - \underbrace{\overline{M}\cdot\overline{H}}_{\text{Applied Field}}$$

Material Anisotropy

3D Demagnetizing Field

Applied Field

K – Material Anisotropy Constant
M_s – Saturation Magnetization
D*i* – Shape Demagnetization factor in *i*

H – Applied Field Vector
M – Resultant Magnetization Vector

Shape-Dependent Anisotropy

Shape Demagnetizing Factors Extremely geometry-dependent

For a thin-film, the rectangular prism model may be used:

$$
\begin{aligned}
\pi D_x = {} & \frac{y^2-z^2}{2yz}\ln\left(\frac{\sqrt{x^2+y^2+z^2}-x}{\sqrt{x^2+y^2+z^2}+x}\right)+\frac{x^2-z^2}{2xz}\ln\left(\frac{\sqrt{x^2+y^2+z^2}-y}{\sqrt{x^2+y^2+z^2}+y}\right)+\frac{y}{2z}\ln\left(\frac{\sqrt{x^2+y^2}+x}{\sqrt{x^2+y^2}-x}\right) \\
& +\frac{x}{2z}\ln\left(\frac{\sqrt{x^2+y^2}+y}{\sqrt{x^2+y^2}-y}\right)+\frac{z}{2x}\ln\left(\frac{\sqrt{x^2+z^2}-y}{\sqrt{x^2+z^2}+y}\right)+\frac{z}{2y}\ln\left(\frac{\sqrt{x^2+z^2}-x}{\sqrt{x^2+z^2}+x}\right)+2\arctan\left(\frac{xy}{z\sqrt{x^2+y^2+z^2}}\right) \\
& +\frac{x^3+y^3-2z^3}{3xyz}+\frac{x^2+y^2-2z^2}{3xyz}\sqrt{x^2+y^2+z^2}+\frac{z}{xy}\left(\sqrt{x^2+z^2}+\sqrt{y^2+x^2}\right) \\
& -\frac{\left(x^2+y^2\right)^{3/2}+\left(y^2+z^2\right)^{3/2}+\left(z^2+x^2\right)^{3/2}}{3xyz}
\end{aligned}
$$

Total demagnetizing factor must always equal 1

Each axis in the rectangular prism model can be determined by applying the cyclic permutation

$$\frac{D_x}{4\pi}+\frac{D_y}{4\pi}+\frac{D_z}{4\pi}=1$$

*J. Aharoni, J. Appl. Phys **83**, 3432 (1998)

Shape-Dependent Anisotropy

To determine the effect of shape on permeability, start with the equation for complex permeability (Van de Riet):

$$\mu_r = \left(\frac{\gamma Ms}{(\gamma H_k + i\alpha\omega)} \times \left[1 + \frac{\omega^2}{(\gamma H_k + \gamma Ms + i\alpha\omega)(\gamma H_k + i\alpha\omega) - \omega^2} \right] + 1 \right) \left[\frac{(1-i)e^{(1+i)d/\delta} - 1}{d/\delta \, e^{(1+i)d/\delta} + 1} \right]$$

At sufficiently low frequencies, the low-frequency intrinsic permeability may be simplified as the initial permeability, inversely proportional to anisotropy

$$\mu_i = \frac{M_s}{H_k} + 1$$

Anisotropy is made up of a number of elements

$$H_k = H_i + H_d + H_{mc} + H_{me}$$

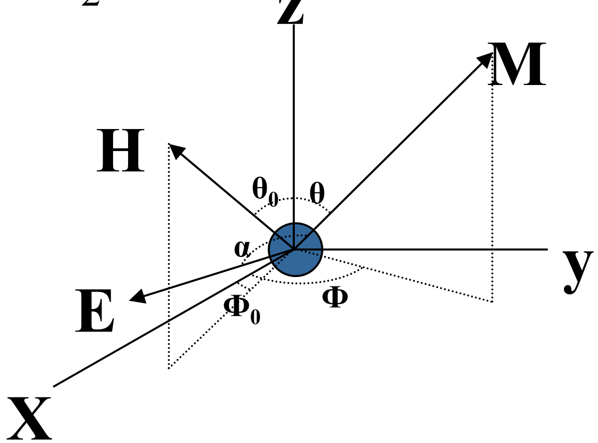
H_i – Induced Anisotropy
H_{mc} – Magnetocrystalline Anisotropy
H_{me} – Magnetoelastic Anisotropy
H_d – Shape Anisotropy

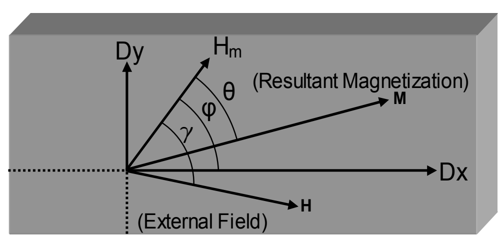
THICKNESS-DEPENDENT ANISOTROPY/PERMEABILITY

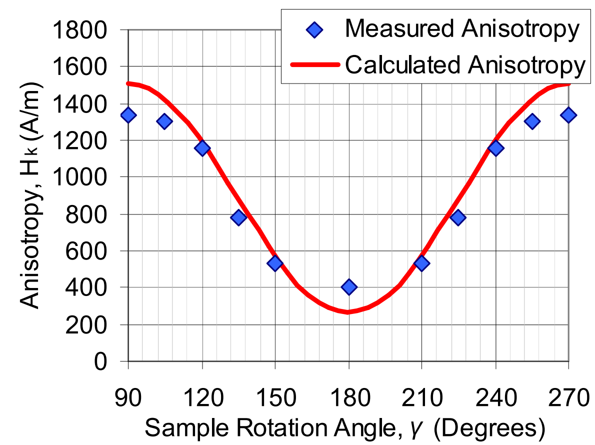
3D Demagnetizing Factors include thickness

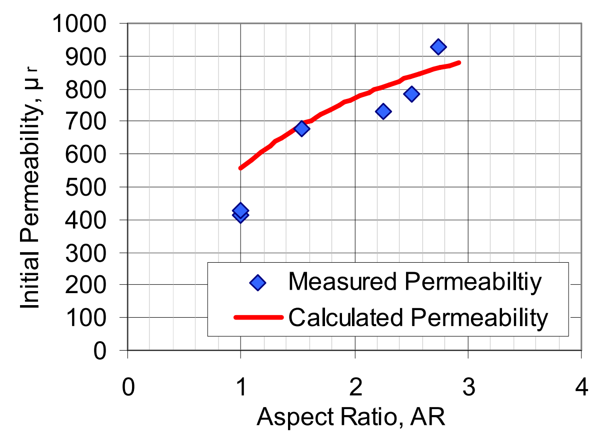
One model for anisotropy contains both thin-film shape and thickness

$$H_k = \frac{Hm}{2}\cos^2\alpha + Ms\left(D_x(\sin\theta\cos\phi)^2 + D_y(\sin\theta\sin\phi)^2 + D_z\cos^2\theta\right)$$





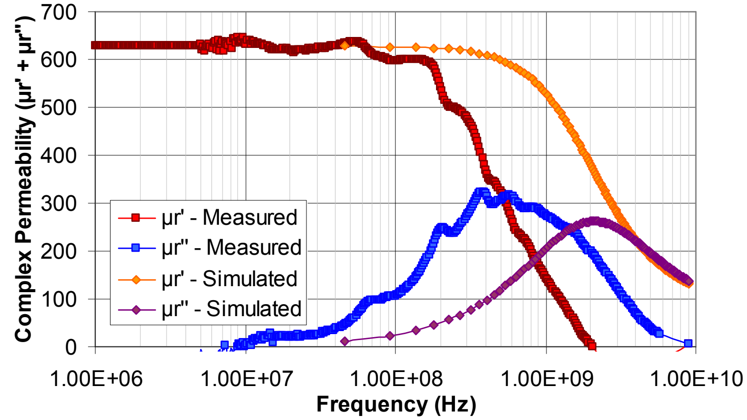




APPLIED PHYSICS LETTERS **96, 202509, 2010**

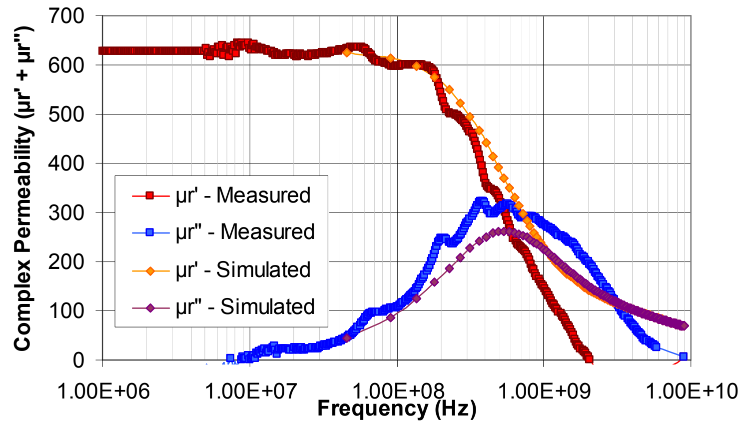
Ferromagnetic Thin-Films

Complex permeability with the modified permeability equation



Measured 1 µm $Co_{91.5}P_{8.5}$ thin-film compared to a simulated CoP thin-film **without** a 50 nm Cu seed layer

Complex permeability with the modified permeability + conductivity equation

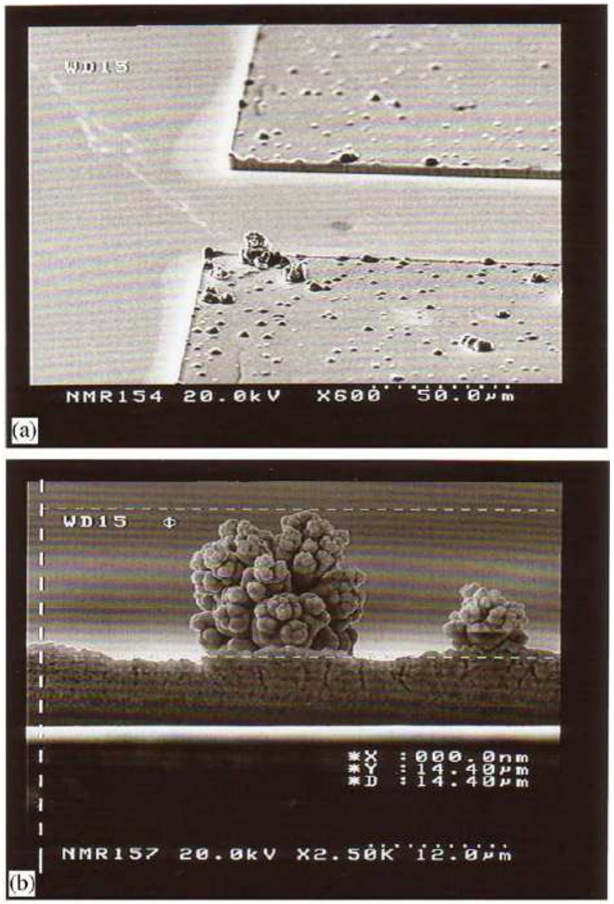


Measured 1 µm $Co_{91.5}P_{8.5}$ thin-film compared to a simulated CoP thin-film **with** a 50 nm Cu seed layer

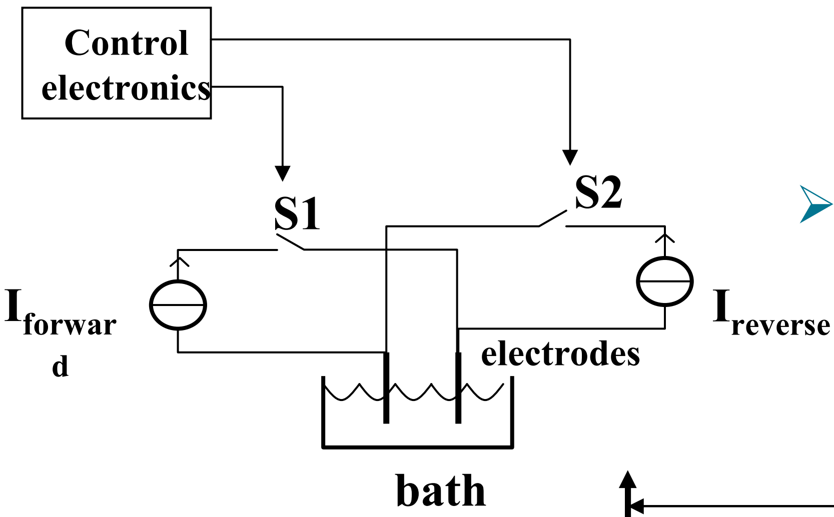
Challenge – Integration aiming PSO

$Ni_{45}Fe_{55}$ DC plated

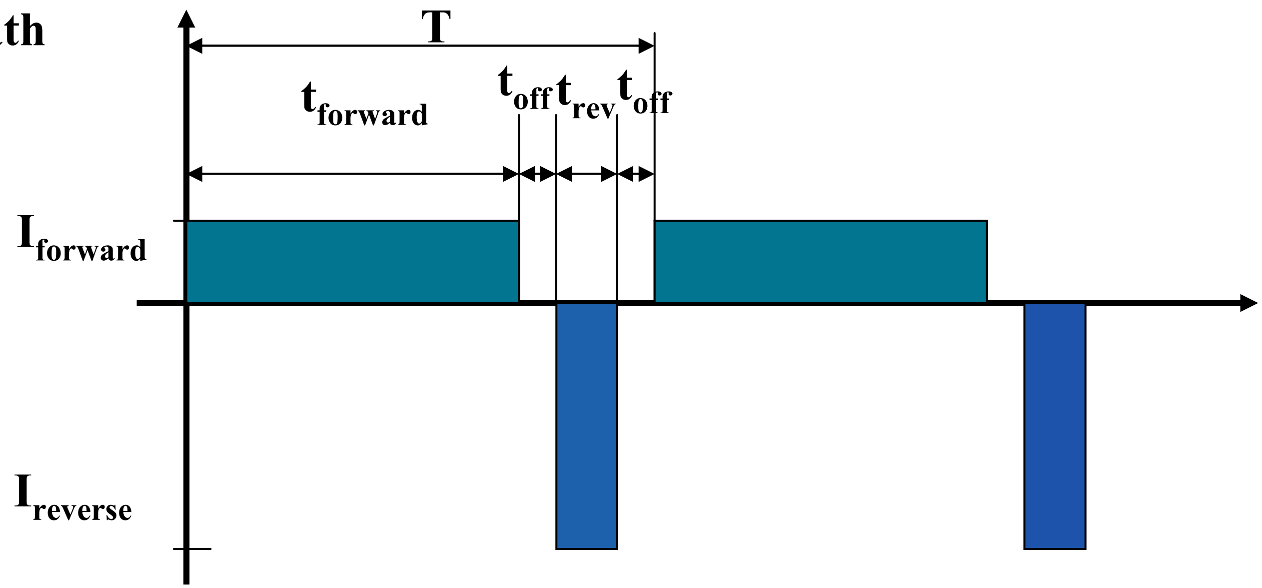
- $NiCl_2.6H_2O + FeCl_2.4H_2O$ +Additives
- Optimised plating current density
- Mechanical agitation
- Plated in magnetic field
- Alloy composition- $Ni_{45}Fe_{55}$
- Non-uniform deposition
- Fractal/dentritic growth across film
- Stressed film → limited thickness



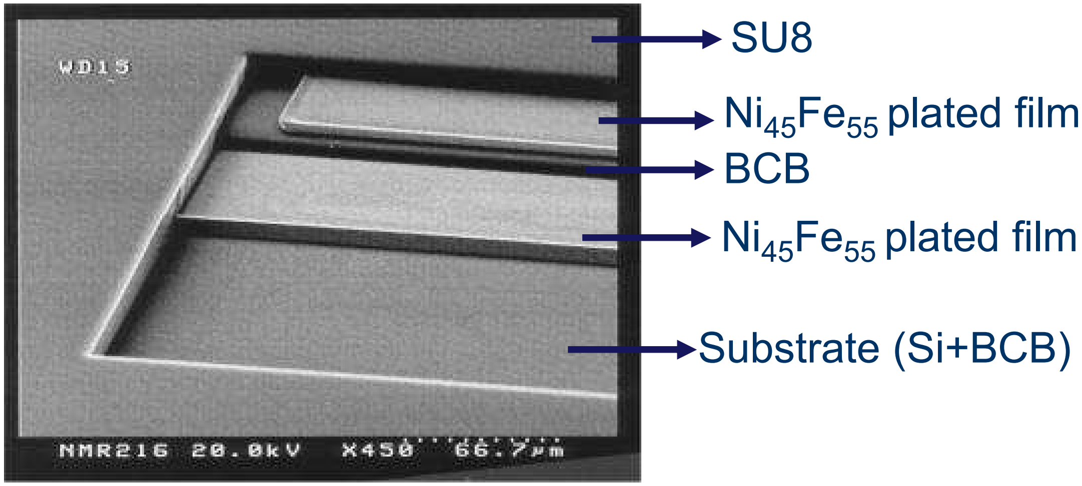
Pulse Reverse Plating

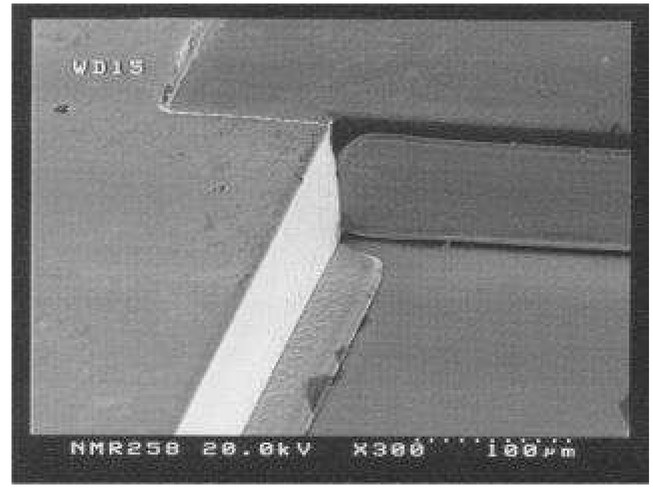


- Voltage regulation & timer circuit
- Rectangular wave at particular frequency
- Milliseconds → Microseconds

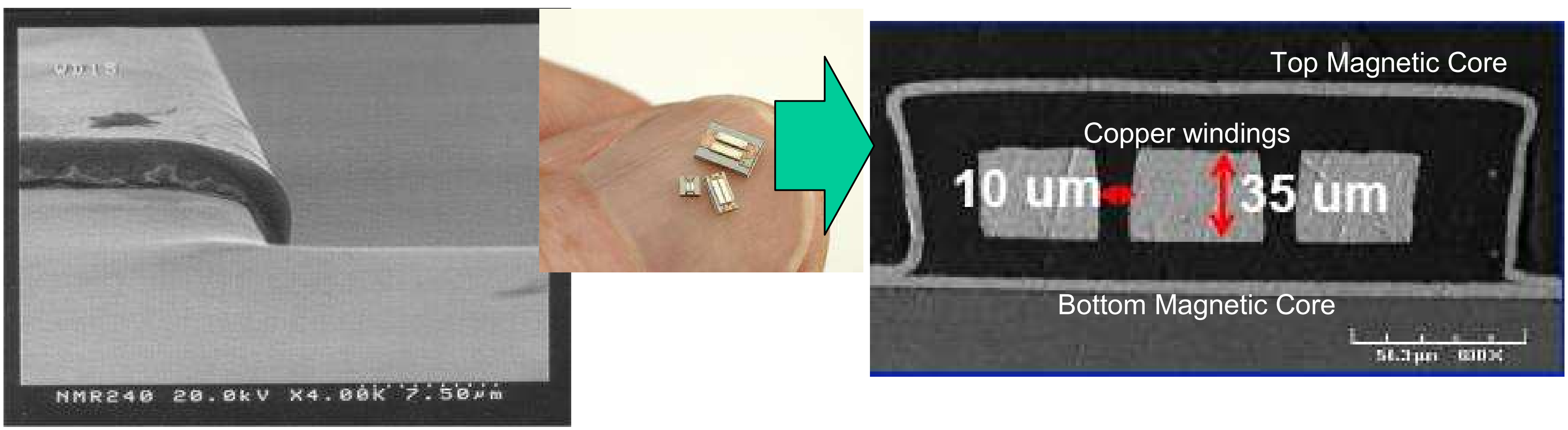


SEM - microfabricated inductors

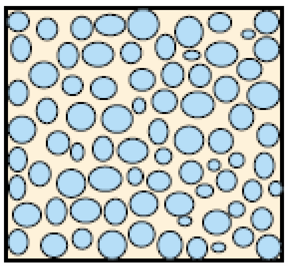


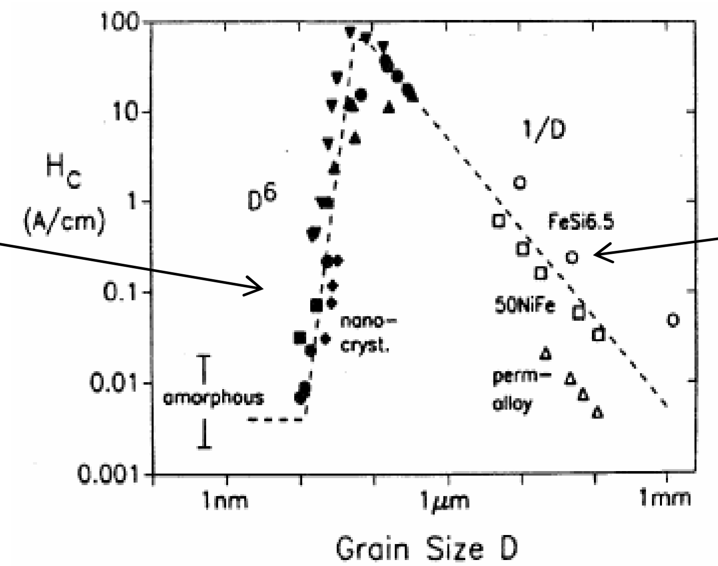


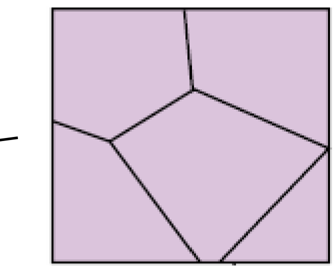
Top cores (over 3D topology)



Challenge – Next generation magnetic materials

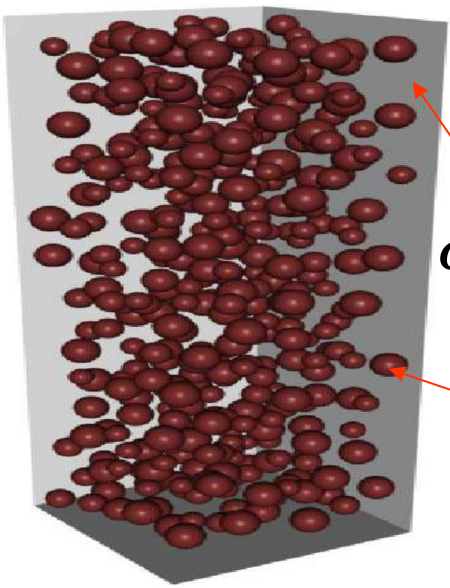






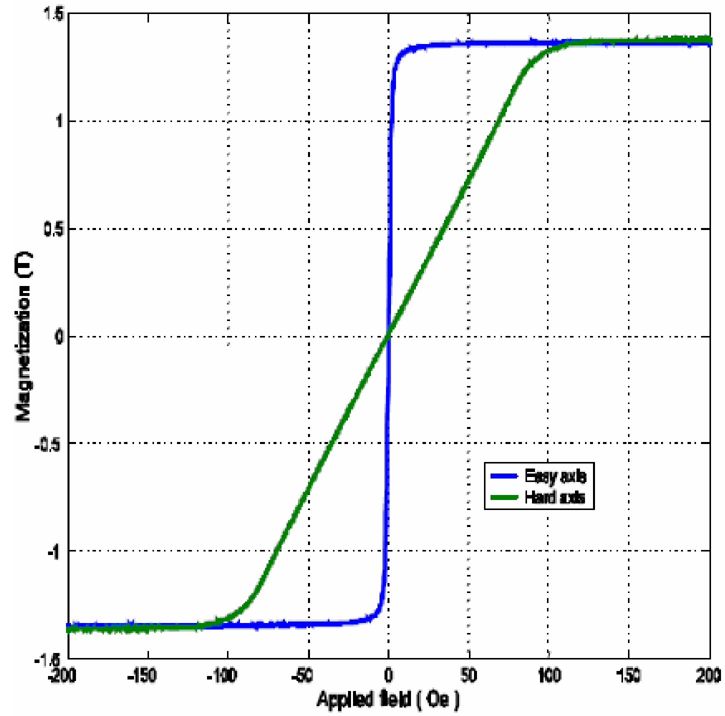
- **Coercivity (Hc) < 2 Oe**
- **Permeability (μ_r) - 300-1000**
- **Saturation Flux density (Bs) – 1.5- 2.4T**
- **Resistivity (ρ) - 30-500 μΩcm**
- **Cut-off frequency for eddy current loss (*f*ed) – 100-500 MHz**
- **Anisotropy field (H_k) – 10-50Oe**
- **Natural ferromagnetic resonance frequency (f_{FMR}) – 1-3 GHz**

Granular Magnetic Materials



Ceramic (SiO_2, Al_2O_3, etc)

Co, Ni, Fe, etc



Advantages: (granular materials)

- **High resistivity of nanocomposite works better than thin film laminations for controlling eddy-current loss.**
- **At subnanometer particle separation distances the magnetic structure changes from dipolar coupled to exchange coupled.**

Drawback: (sputtering)

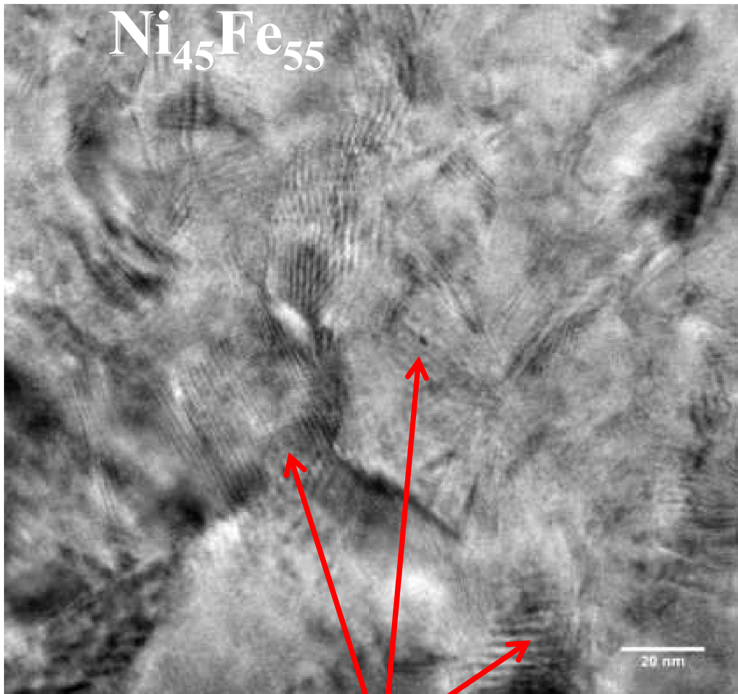
Difficult to produce thicker films, hence, any reasonable power density.

Grand Challenge!

To develop a next generation integratable soft magnetic core material capable of operating at high frequency for Power Applications

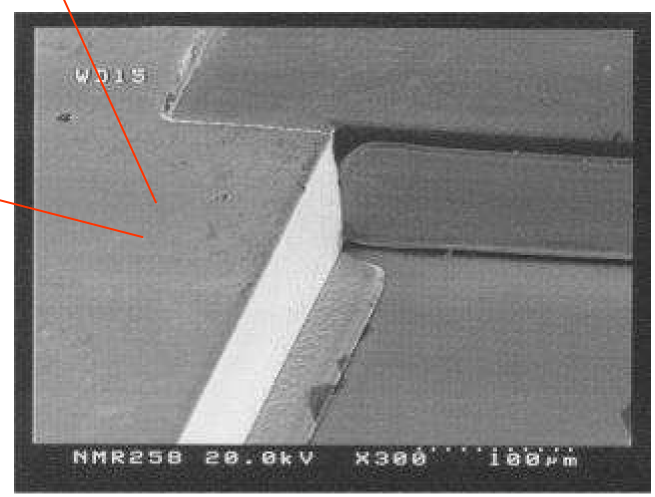
Realisation of power supply on chip (PwrSoc) !

Nano-structured NiFe

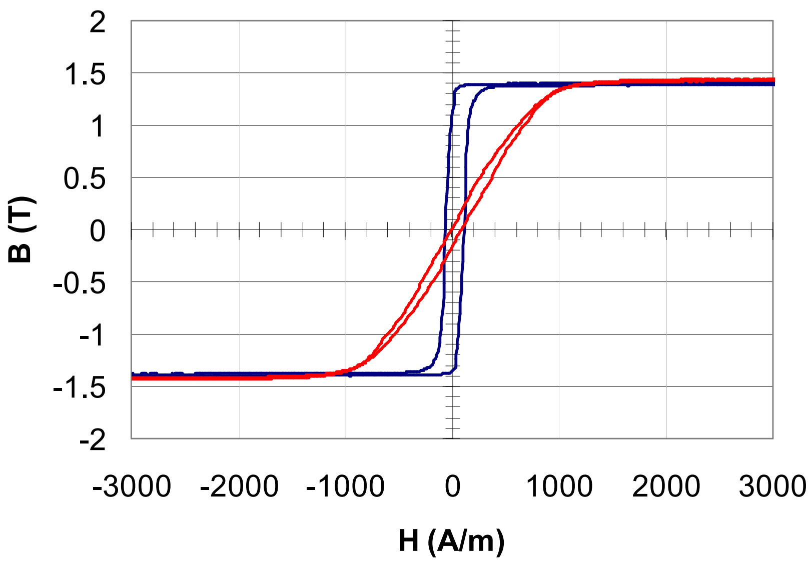


Nanocrystalline grain structure (grains <10nm)

- Create nano-crystalline structure
- Magnetic film for high frequency
- Higher resistivity
- Reduction in Anisotropy dispersion
- Pinning of domain wall in the film
- No Domain wall motion
- Only Domain wall rotation

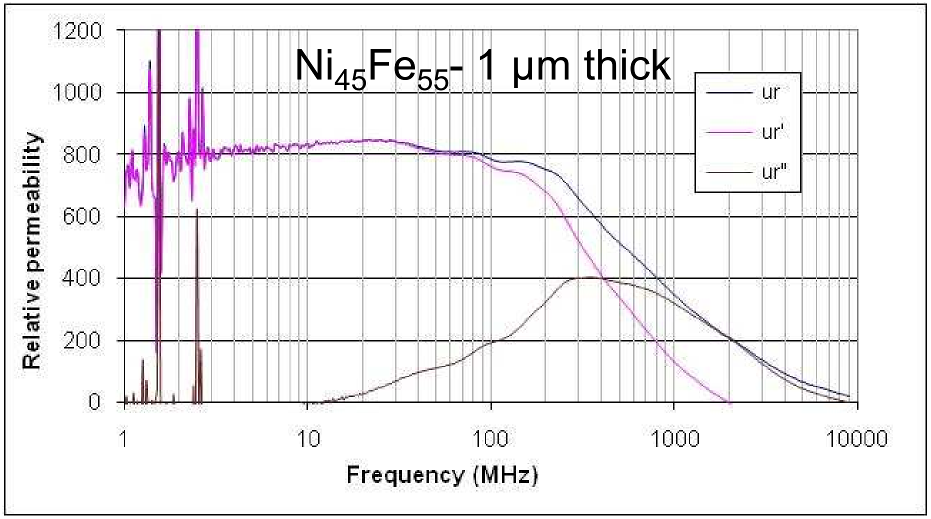


Magnetic characterization of $Ni_{45}Fe_{55}$



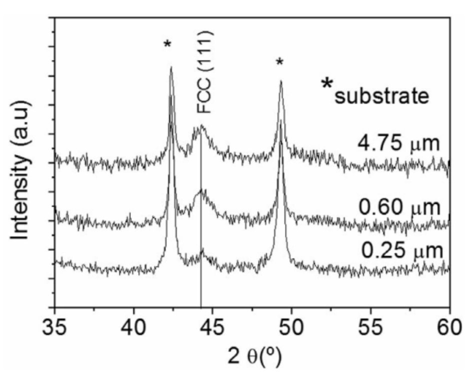
$Ni_{45}Fe_{55}$- 1 µm thick

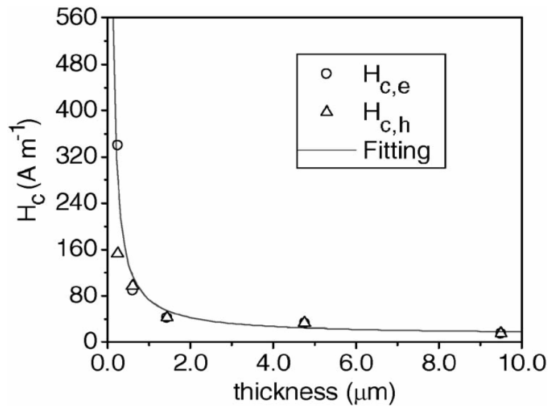
Electroplated $Ni_{45}Fe_{55}$	
Saturation, B_{sat}	1.5 T
Coercivity, H_c	80 A/m
Resistivity, ρ	48 µΩ cm
Anisotropy, H_k	800 A/m

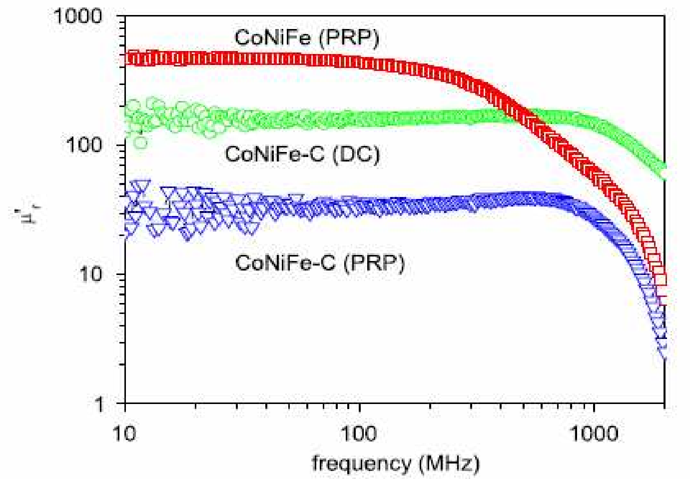


"Electrodeposited anisotropic NiFe 45/55 thin films for high-frequency micro-inductor applications", T. O'Donnell, N. Wang, S. Kulkarni, R. Meere, F. M.F. Rhen, S. Roy, S.C. O'Mathuna, Journal of Magnetism and Magnetic Materials 322, pp. 1690–1693, (**2010**).

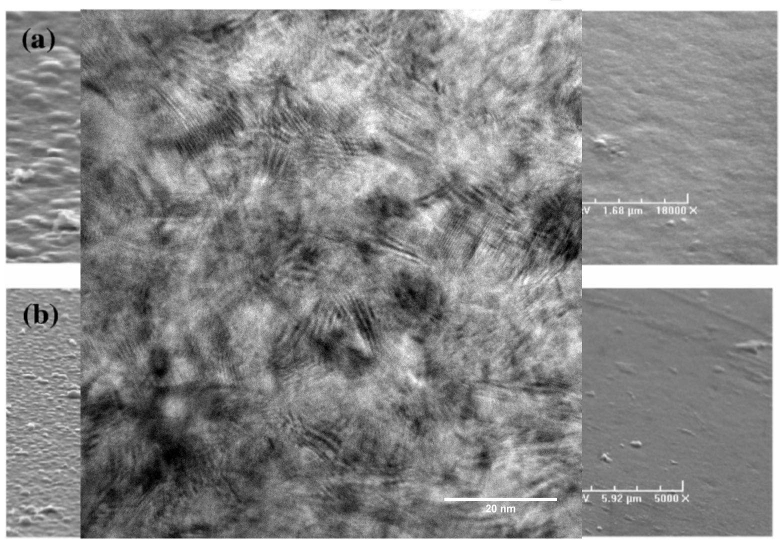
CoNiFe – beyond 100 MHz

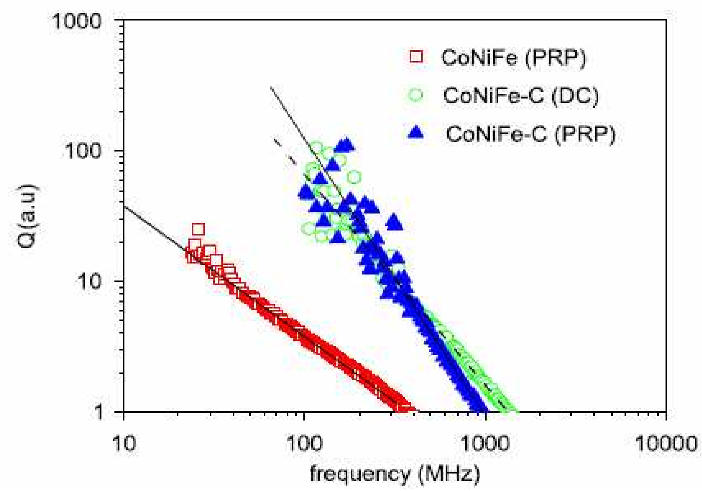






$$H_c = H_{c\,\text{morph}} + H_{c\,\text{anis}}$$

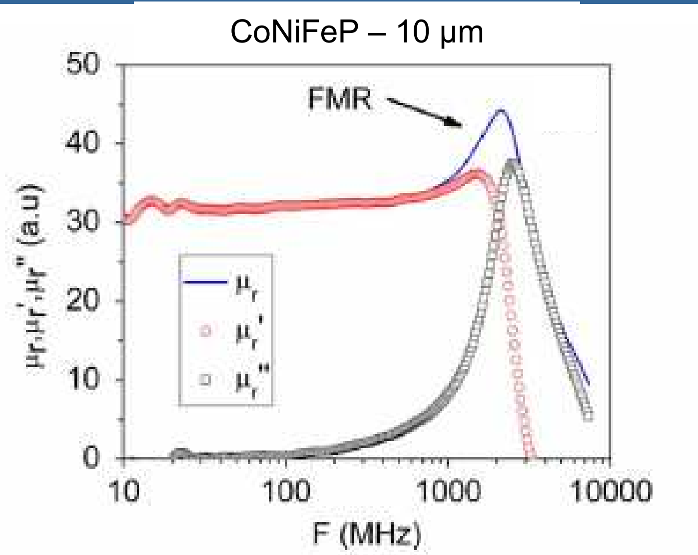


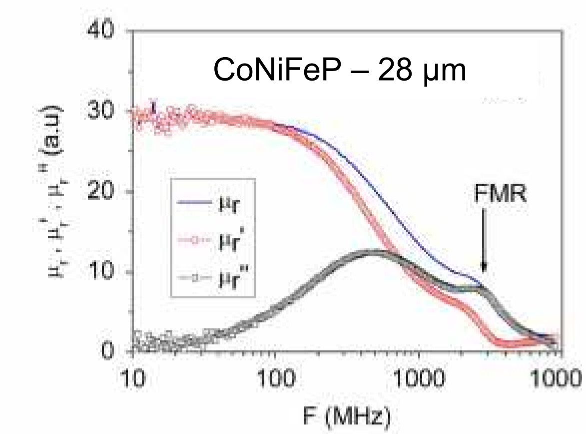


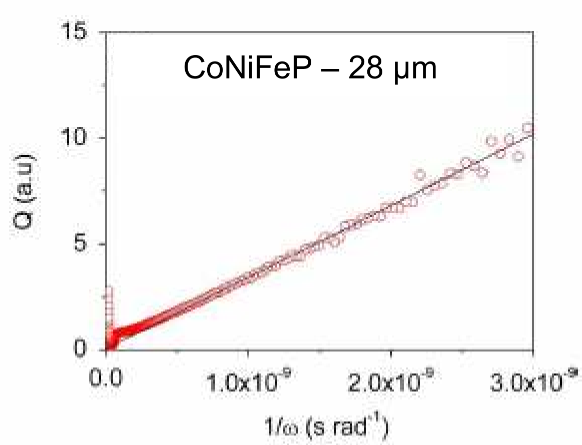
J. Appl. Phys **103, 103901, (2008). Editorially selected for republication in virtual J. of Nanoscience and Nanotechnology.**

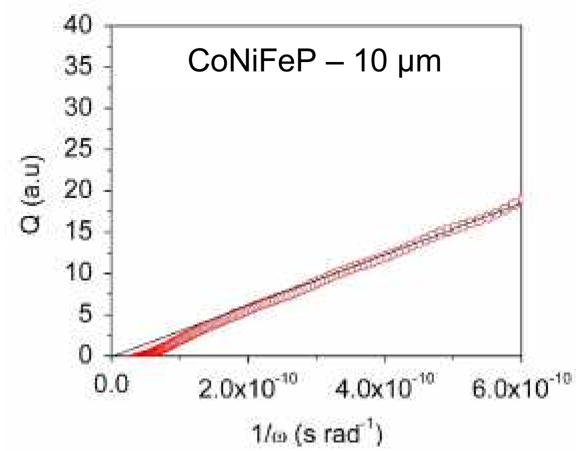
Magnetic characterization of CoNiFeP alloys

Electroplated CoNiFeP	
Saturation, B_{sat}	1.6 -1.8 T
Coercivity, H_c	95 A/m
Resistivity, ρ	24-85 μΩcm
Anisotropy, H_k	2500 A/m





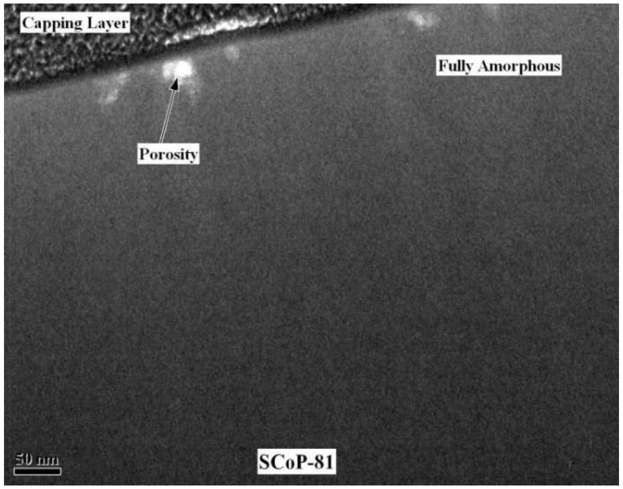


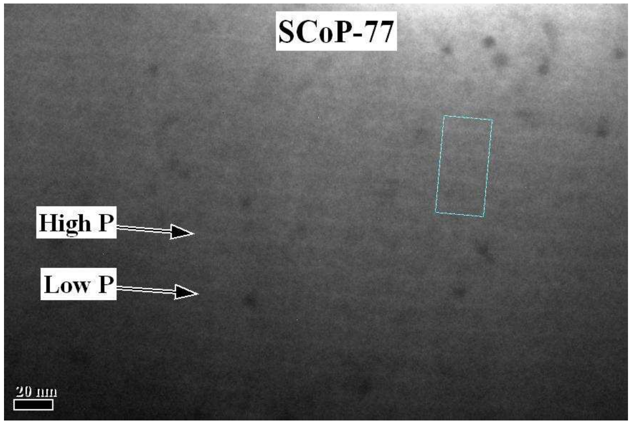


"Dependence of magnetic properties on micro to nanostructure of CoNiFe films", Fernando Rhen, Saibal Roy; ***J. Appl. Phys*** **103**, 103901, (2008)
"Soft-magnetic CoNiFeP alloy films for high frequency applications", Fernando Rhen and Saibal Roy; ***IEEE Trans. Magn. 44,*** No 11, 3917-3920, (2008)

Nanostructured CoP

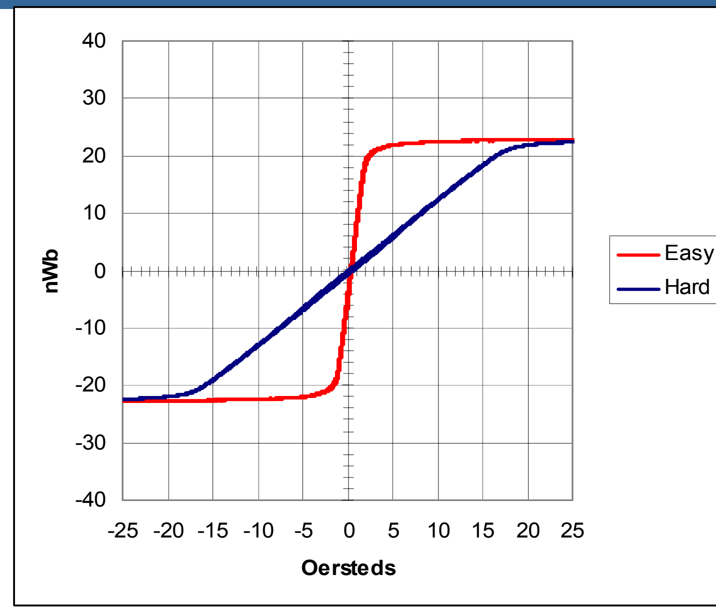
- High resistivity >100 µΩ.cm → Increased skin depth → Increased operational frequency
- DC plated films have perpendicular anisotropy & low permeability
- Use of Pulse Reverse plating to achieve in-plane anisotropy
- To produce multi-nano layer structures
- Pulse Reverse plating;
  - Composition of M layer $Co_{74}P_{26}$, thickness- 30 nm
  - Composition of NM layer $Co_{66}P_{34}$, thickness- 2-5 nm

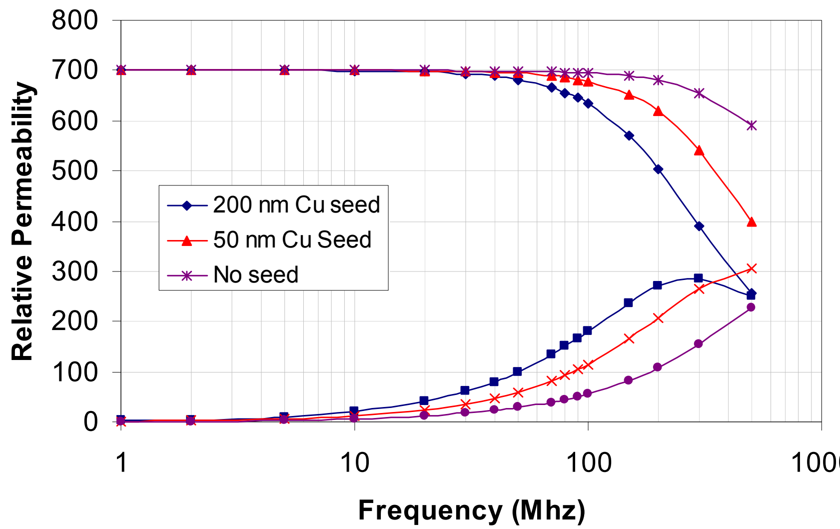


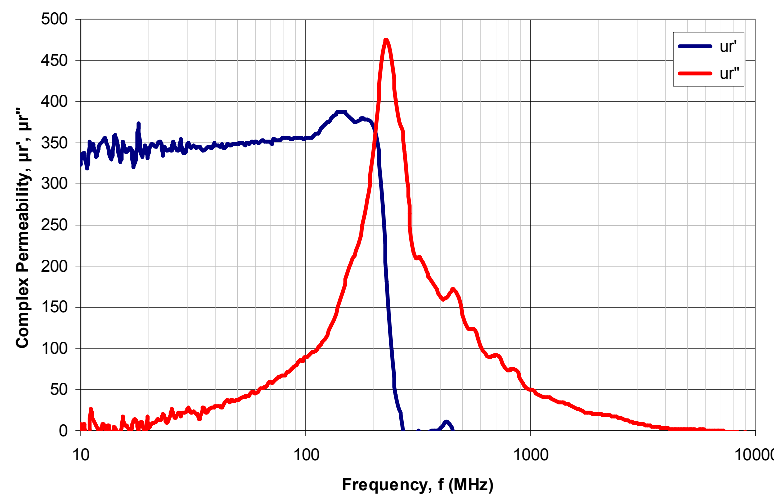


Magnetic characterization of CoP

Electroplated CoP	
Saturation, B_{sat}	1.2 T
Coercivity, H_c	8 A/m
Resistivity, ρ	130 μΩ cm
Anisotropy, H_k	1500 A/m



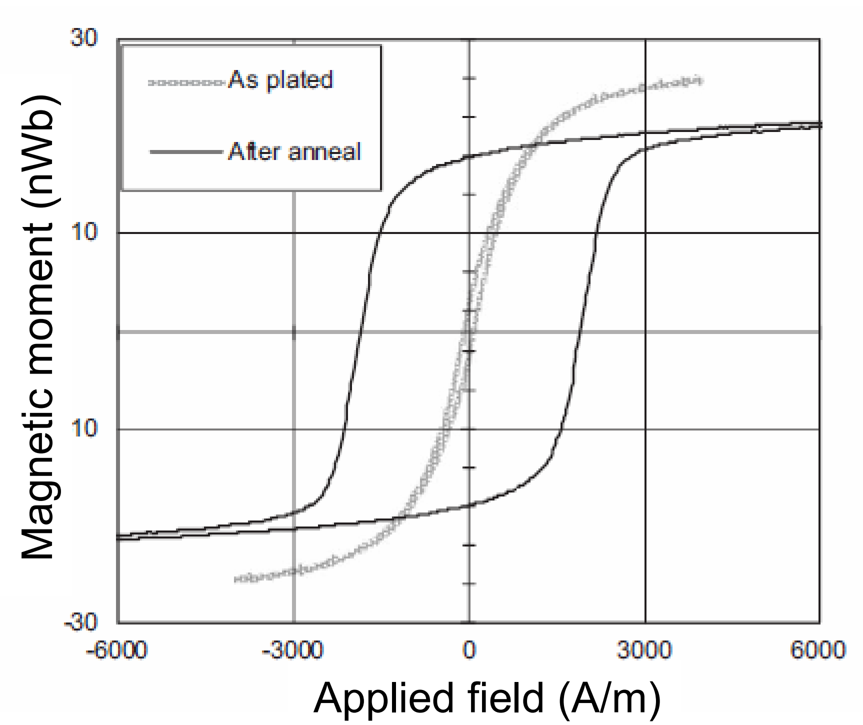




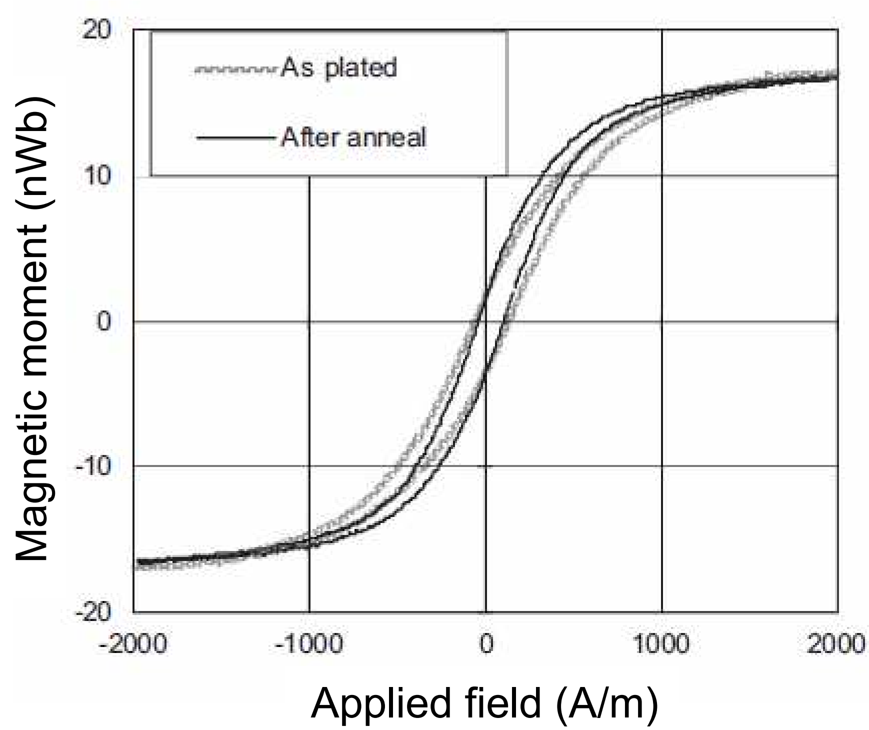
"High Frequency Nanostructured Magnetic Materials for Integrated Inductors", P. McCloskey, B. Jamieson, T. O'Donnell, D. Gardner, M.Morris, S. Roy, Journal of Magn. Magn. Mater., Vol. 320, Issue 20, Pages 2509-2512 (2008)

Nanostructured CoPRe

- Addition of Re to CoP thin films for increased thermal stability
- $Co_{100-x-y}$, P_x, Re_y where; 9.7 at%<x<17.5at% and 0.4at%<y<7.6at%



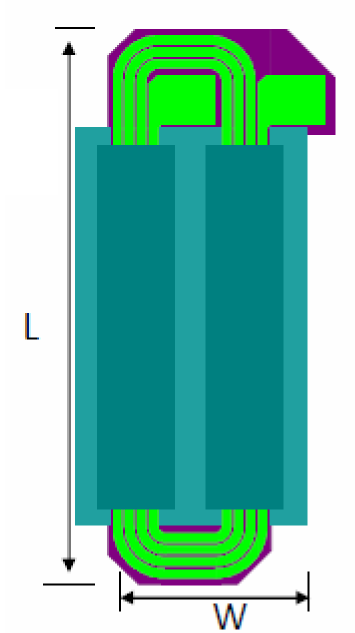
Hard axis measurement for CoP



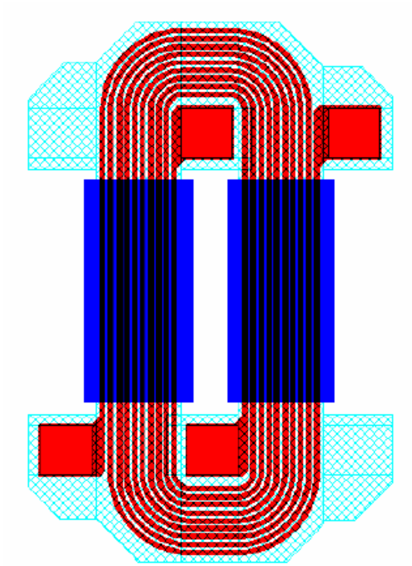
Hard axis measurement for CoPRe

Electrodeposited amorphous Co-P based alloy with improved thermal stability; P McCloskey, B Jamieson, T O'Donnell, D Gardner, M A Morris, S Roy; ***J. Magn & Mag Mat,*** 322, 1536-1539, (**2010**)

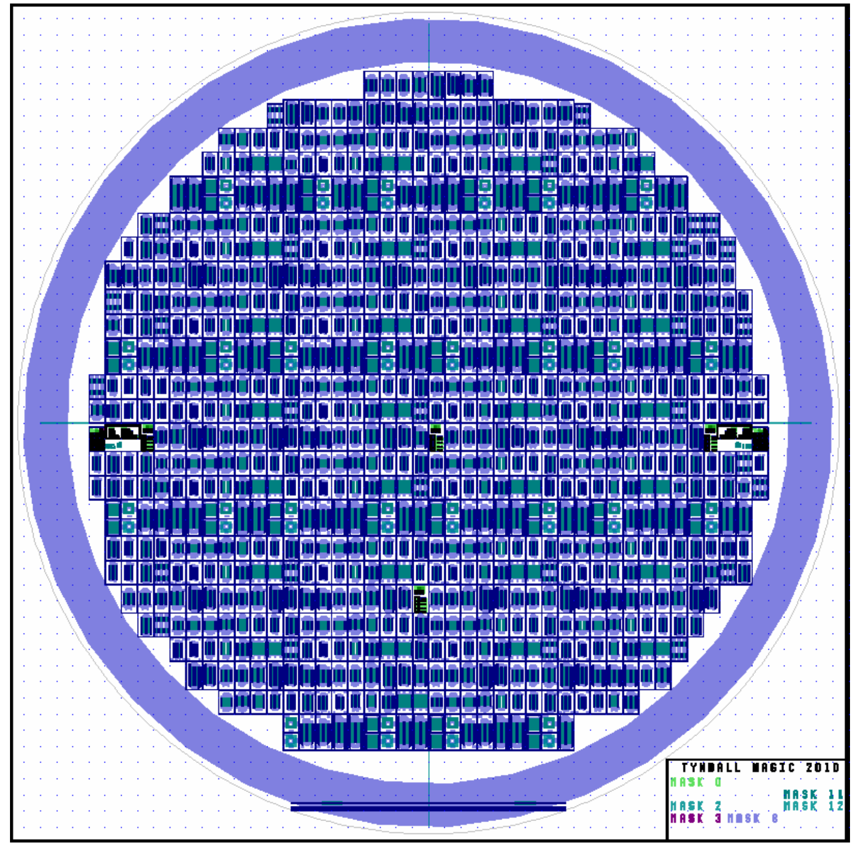
Fabrication- Inductor/Transformer



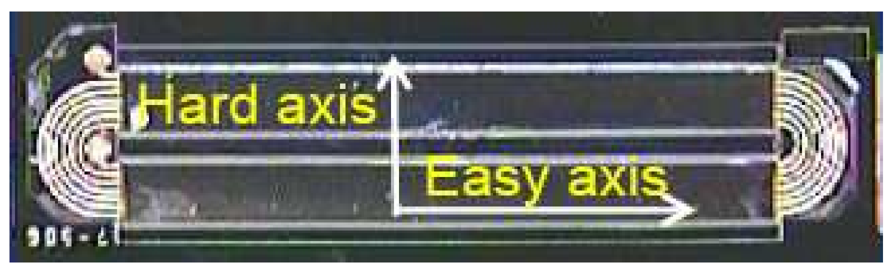
Length, L: 2.50mm
Width, W: 0.85mm



L: 2 mm
W: 1.1 mm

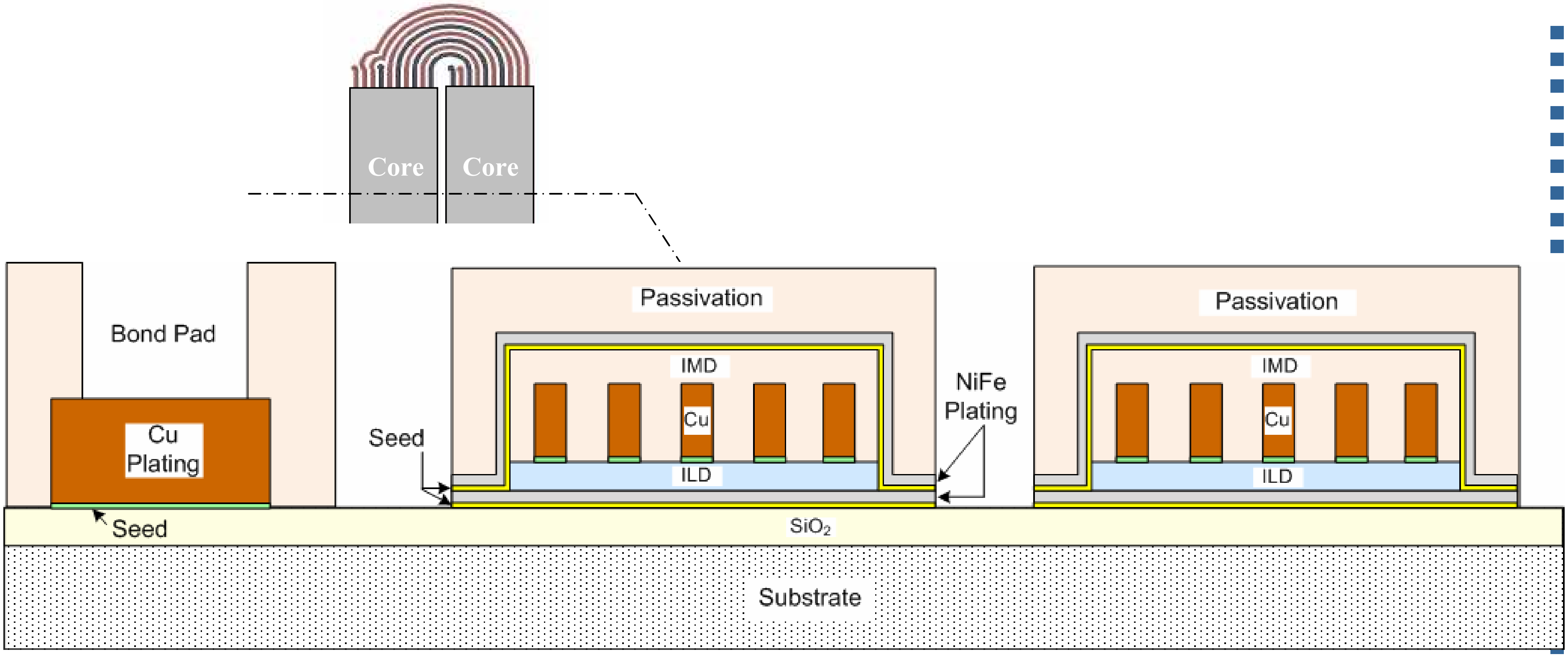


Anisotropy induced in material during deposition



Typical Fabricated inductor

Micro-inductor: Structure



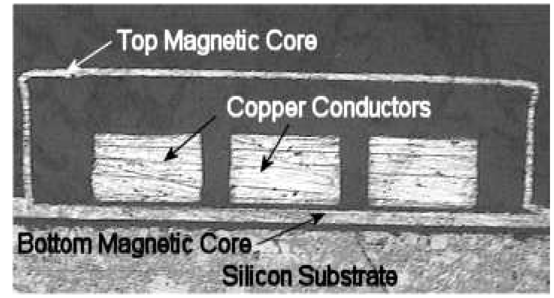
- 5 Mask Layers

Tyndall Fabricated Microinductors

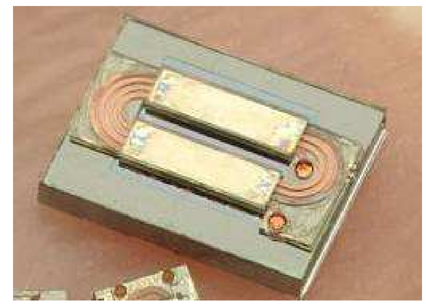
- **Electroplated copper windings.**
- **Thin-film, electroplated magnetic core.**
- **Design optimisation process**
  - **Focus on efficiency and footprint.**
  - **Coupled to validated models.**

- **Race-track shape to achieve:**
  - **good frequency response**
  - **high inductance density**
  - **Low DC resistance**

- **CMOS-compatible process:**
  - **Copper coils deposited by electroplating**
  - **Core consists of thin film of NiFe alloy deposited by electroplating**

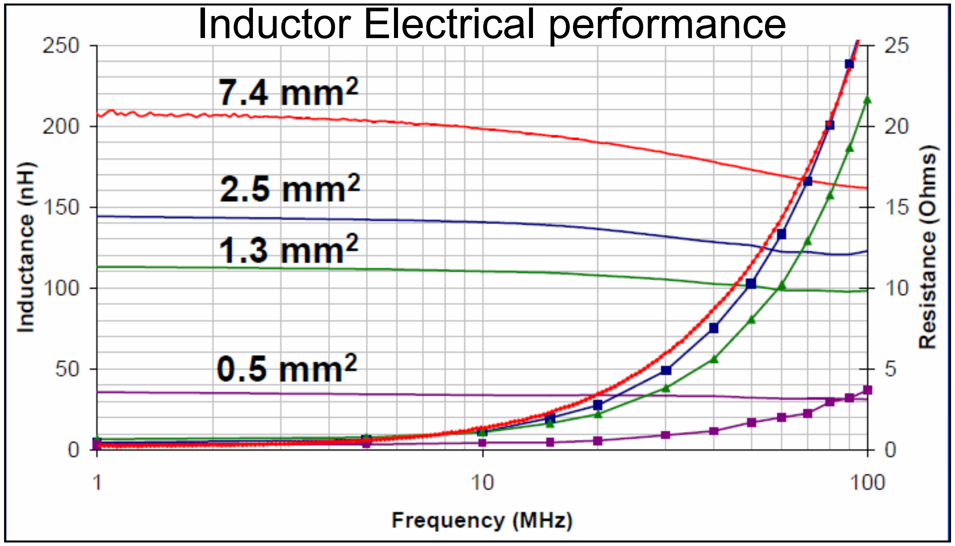


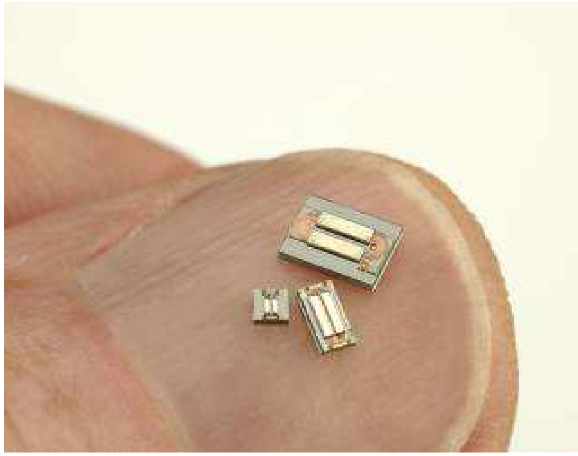
Cross section of a micro-inductor

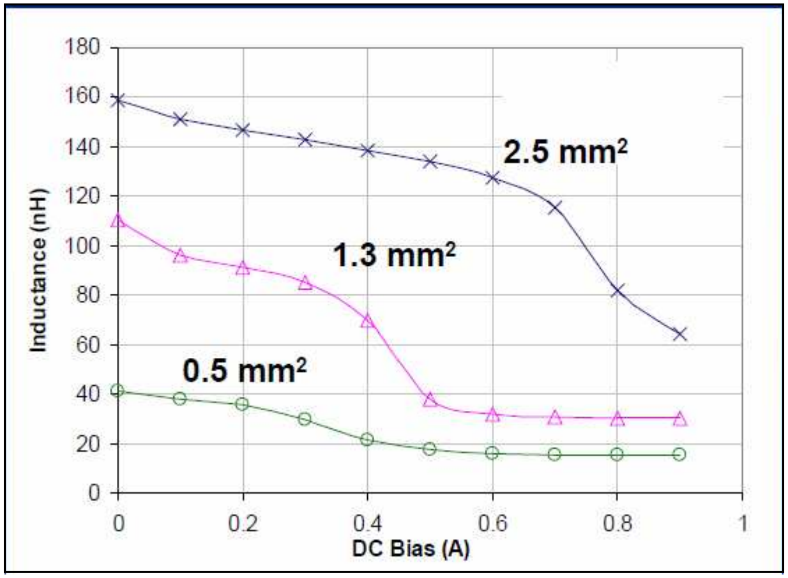


Micro-inductors fabricated on 4 inch Si wafer

Electrical Characterisation of Microinductors







Inductor Current handling performance

Acknowledgement

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Thank you for your attention

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