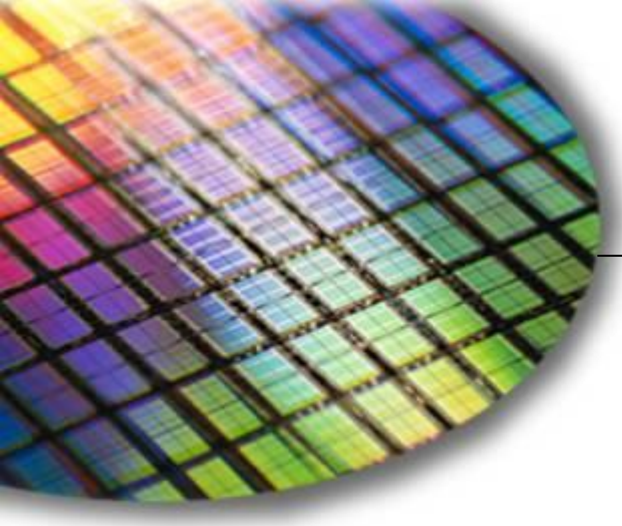


The World Leader in High Performance Signal Processing Solutions

High Bandwidth Low Insertion Loss Solenoid Transformers Using FeCoB Multilayer

Xing Xing, Baoxing Chen

11/18/2012

Analog Devices Inc., Wilmington, USA

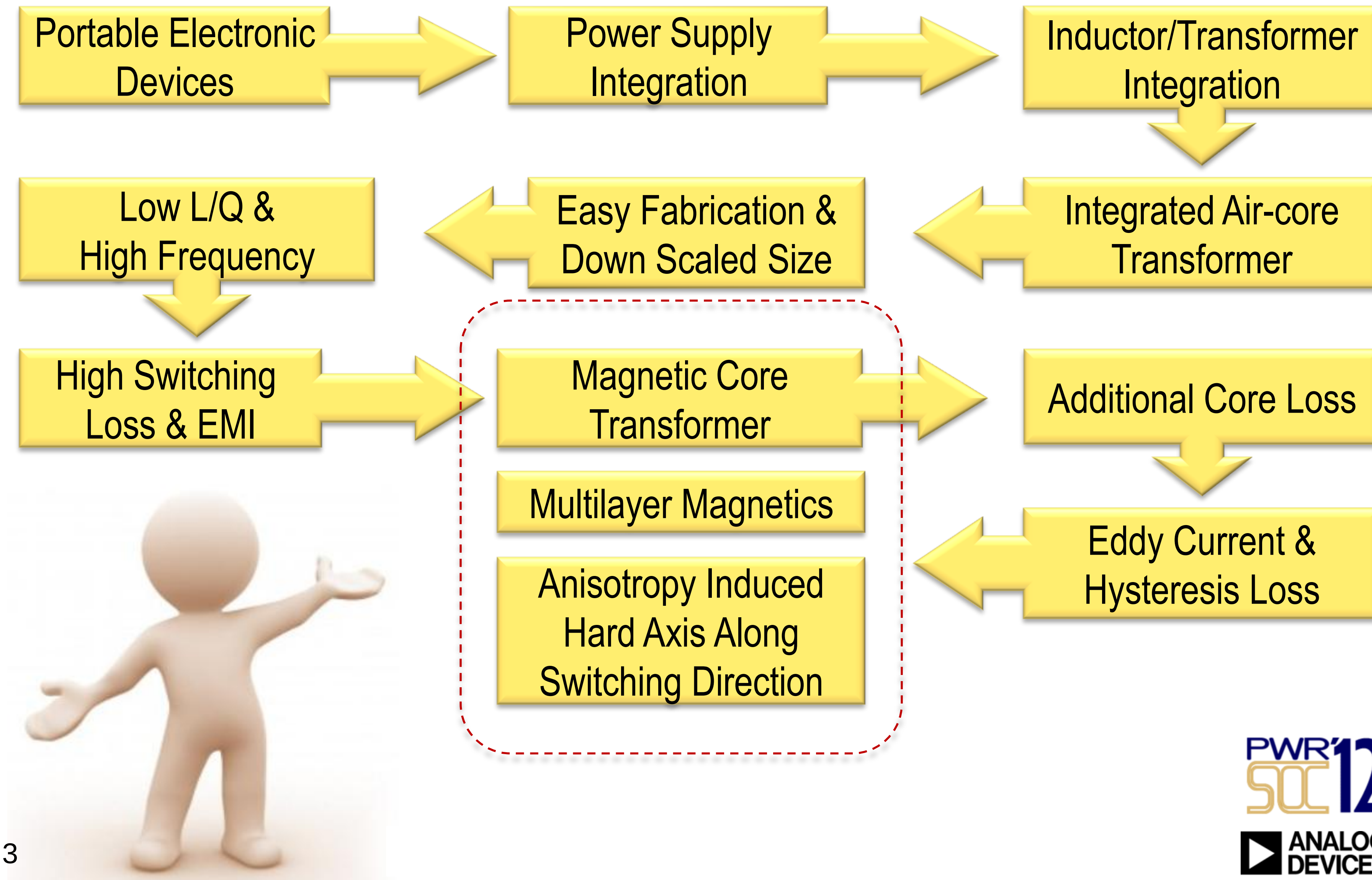
PWR SOC '12

ANALOG DEVICES

Outline

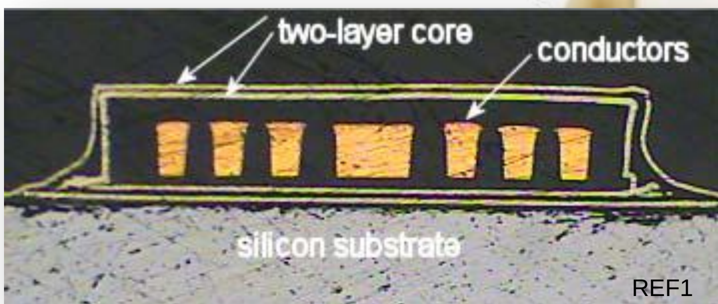
- Introduction
  - Magnetic core transformer integration
  - Developing the Next Generation of isoPower
- Design
  - Converter Design
  - Transformer Design
- Fabrication
- Inductor Modeling, Testing & Results
- Magnetics and Permeability
  - Multilayer study
  - Testing
  - Discussion
  - Saturation Current
- Transformer Performance
  - One side
  - Coupling
- Conclusion

Introduction



Pot-core

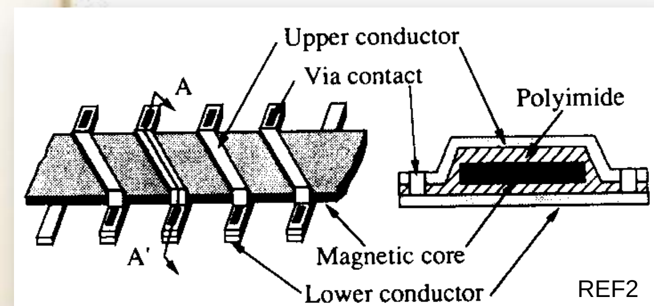
Solenoid



Magnetic Core Transformer

Multilayer Magnetics

Anisotropy Induced Hard Axis Along Switching Direction



- Magnetic layers enclosing spirals
- Complex core structure
  - Limited magnetic permeability
  - Difficulty in domain alignment controlling
  - Significant core loss

- Windings enclosing magnetic core
  - Via complexity
- Simple core structure
  - Higher permeability
  - Easy domain alignment
  - Limited hysteresis loss

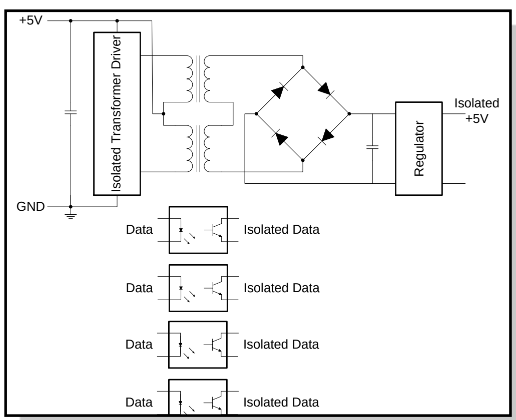
PWR SOC 12

ANALOG DEVICES

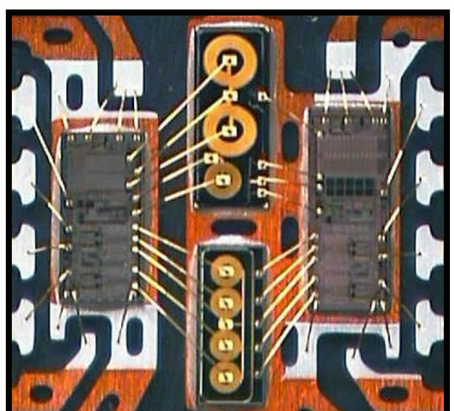
Developing the Next Generation of *iso*Power

Magnetic Core *i*Coupler® Transformers

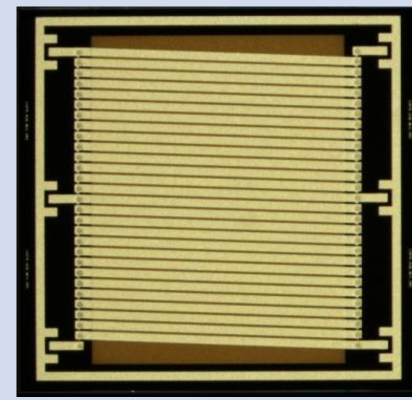
Discrete solutions with optocouplers and external transformers are <u>Large</u>, <u>Custom</u> designs with <u>Poor Reliability.</u>



Proprietary *iso*Power integrates data & power in <u>one package</u>.



Today's air core transformers will be replaced with <u>magnetic core transformers</u>.

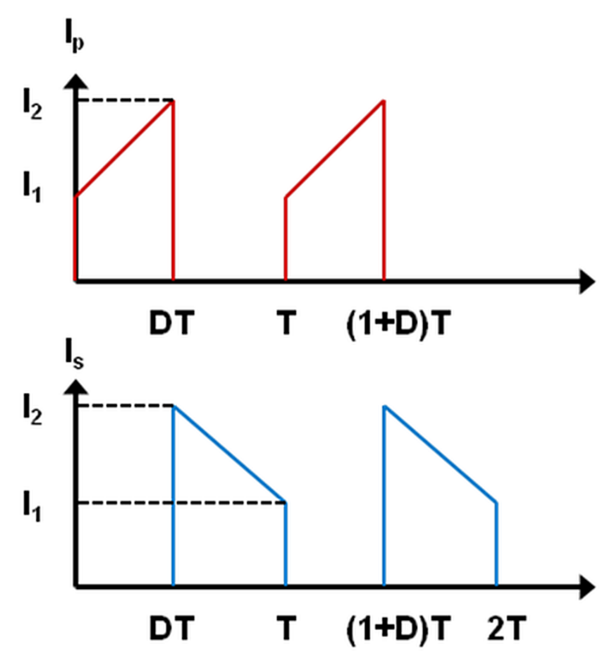


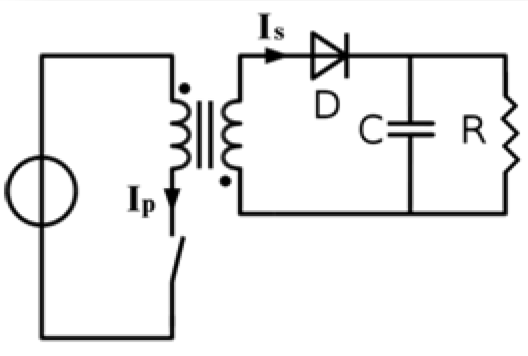
Magnetic Core *iso*Power

- **Better Efficiency & Power**
- **Low Noise Emissions (EMI)**

Converter Design Goal

Design Goal	
Architecture	Fly-back DC/DC Converter
Input Voltage	3 Volt
Output Voltage	3 Volt
Frequency	20 MHz
Power	1 Watt
Inductance	120 nH
Peak Current	0.75 Amp



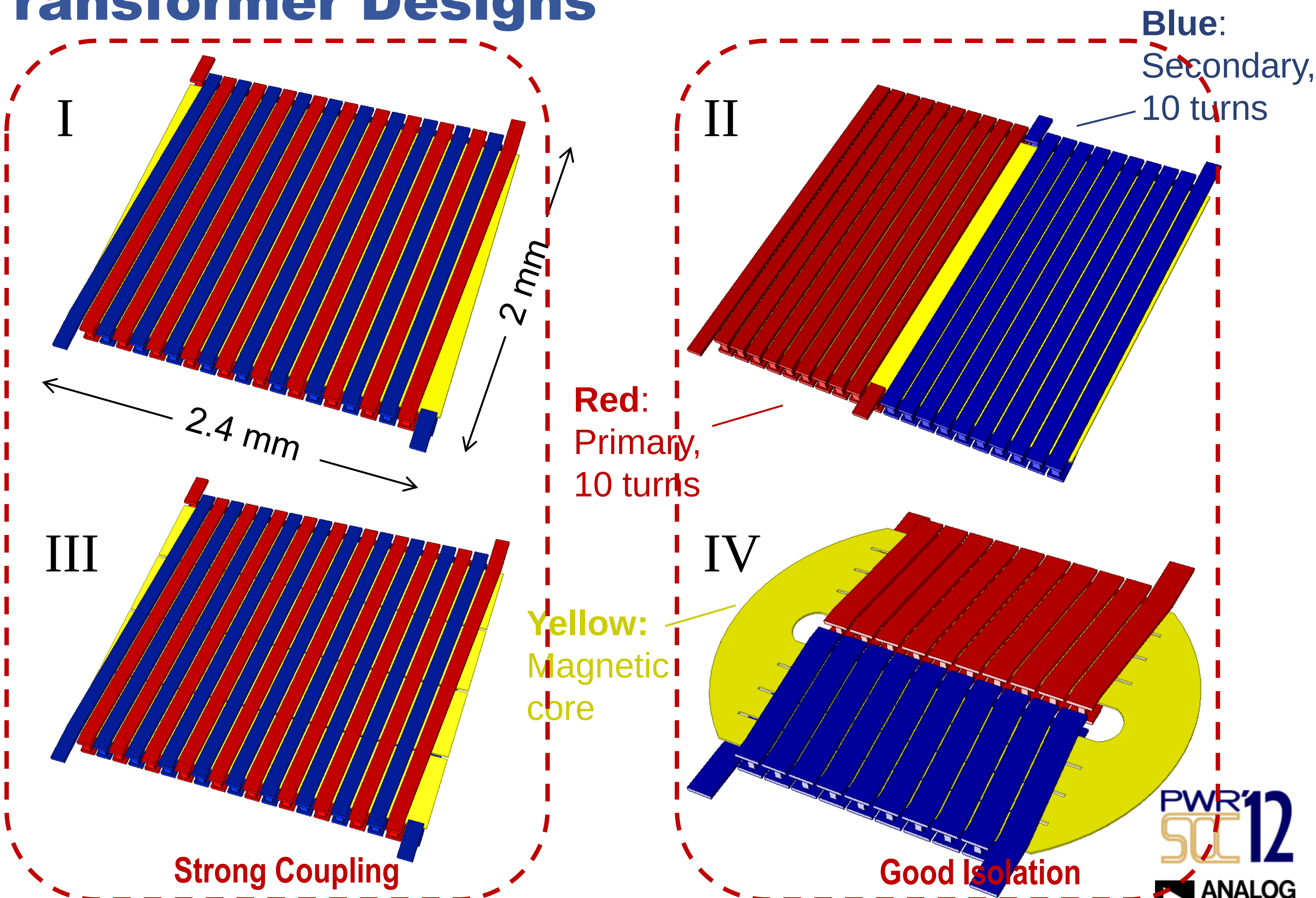


Fly-back Converter

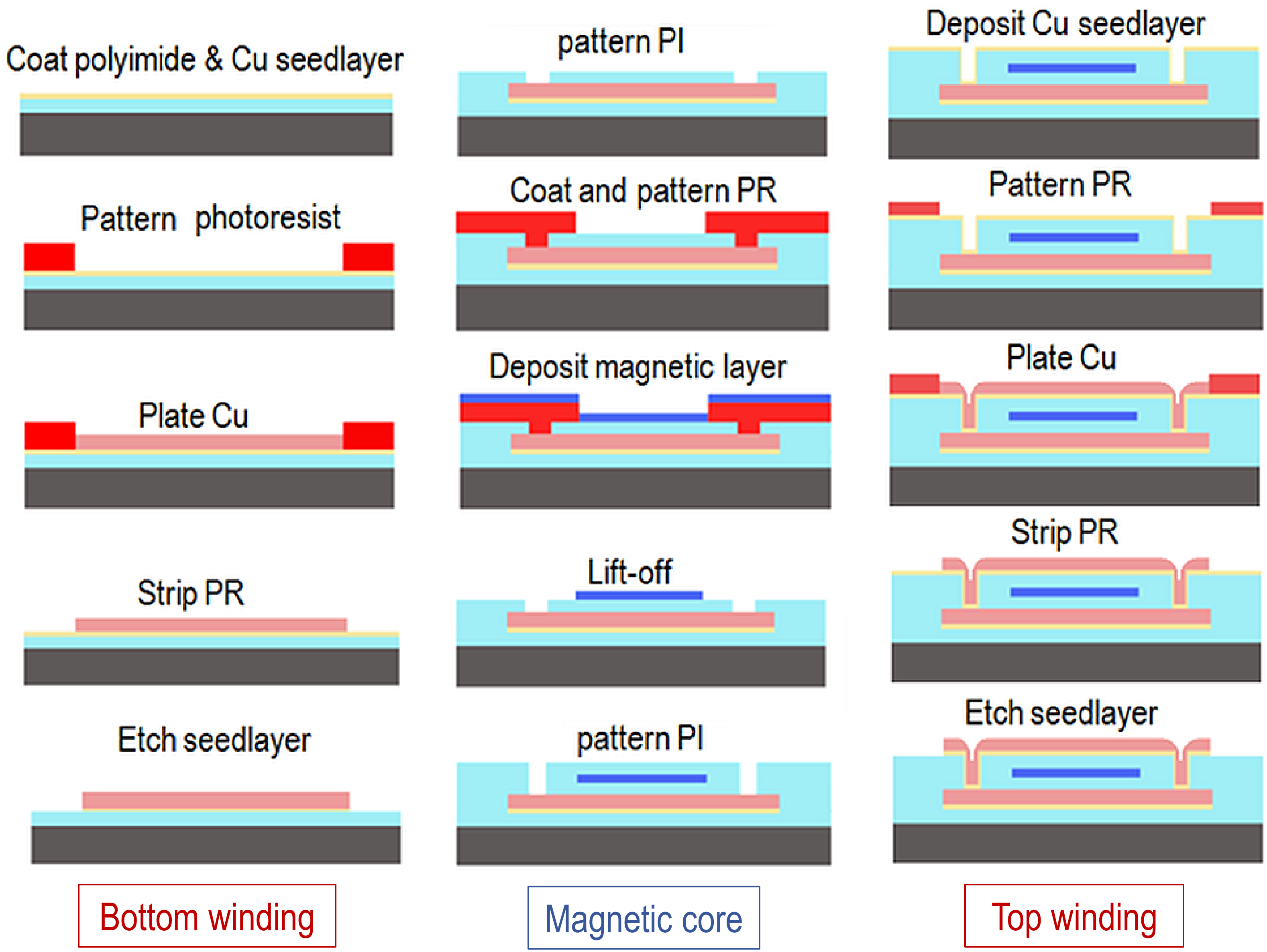
$$V_{IN} = L_p \frac{I_2 - I_1}{DT}$$

$$I_{Load} = D \frac{(I_1 + I_2)}{2}$$

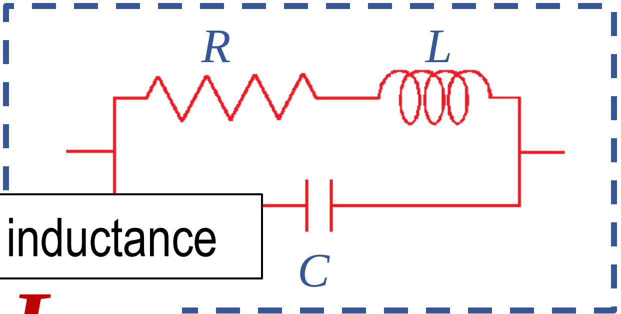
Transformer Designs



Fabrication



Inductor Modeling

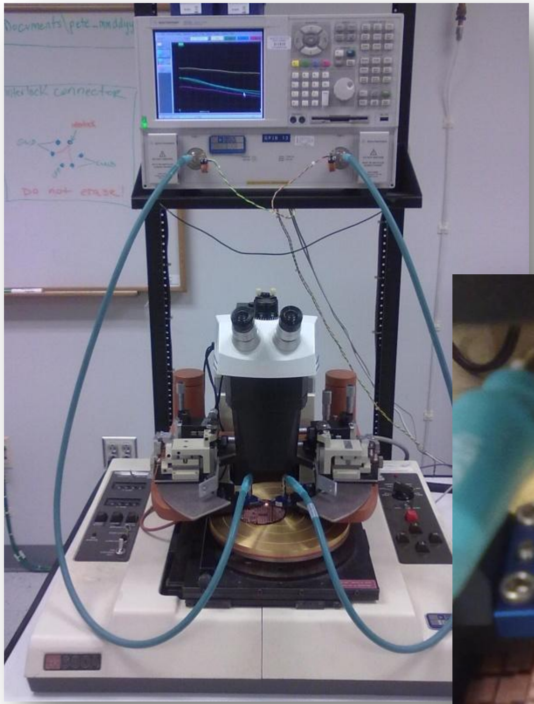


Total inductance		Main inductance		Leakage inductance
L	$=$	L_m	$+$	L_l
		$\parallel$		$\parallel$
		$L_{(dc)} \dfrac{\delta_c}{s} \dfrac{\sinh \frac{s}{\delta_c} + \sin \frac{s}{\delta}}{\cosh \frac{s}{\delta_c} + \cos \frac{s}{\delta_c}}$		$\dfrac{R_w}{2\pi f}$

Total resistance		Winding resistance		Core resistance
R	$=$	R_w	$+$	R_c
		$\parallel$		$\parallel$
		$R_{w(dc)} A \cdot [\dfrac{e^{2A} - e^{-2A} + 2\sin(2A)}{e^{2A} + e^{-2A} - 2\cos(2A)}]$		$\omega L_{(dc)} \dfrac{\delta_c}{s} \dfrac{\sinh \frac{s}{\delta} - \sin \frac{s}{\delta}}{\cosh \frac{s}{\delta_c} + \cos \frac{s}{\delta_c}}$

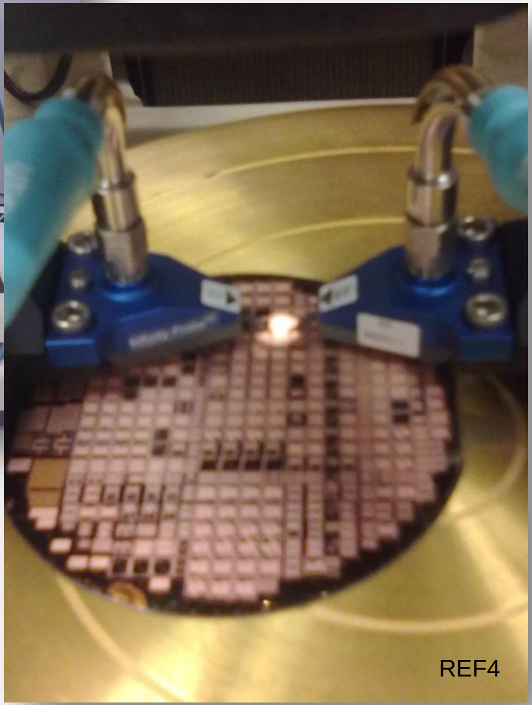
$$Q = \omega L / R$$

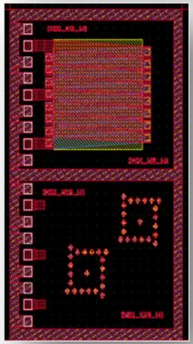
On-wafer Measurement

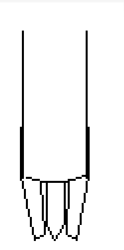


$[S] \rightarrow [Y]$ ➡ $[Y_{de\text{-}embed}]=[Y_{DUT}]-[Y_{PAD}]$

➡ $[Y_{de\text{-}embed}] \rightarrow [Z_{de\text{-}embed}]$







GSG

Π Model of Two-port Measurement

Inductor

$$L = \frac{1}{\omega} \cdot Im\frac{-1}{Y_{12}} \quad Q = -\frac{Im(Y_{11})}{Re(Y_{11})} \quad R_s = Re(\frac{-1}{Y_{12}})$$

Transformer

$$L_1 = \frac{\mathrm{Im}(Z_{11})}{\omega} \quad R_1 = \mathrm{Re}(Z_{11}) \quad Q_1 = \frac{\omega L_1}{R_1}$$

$$L_2 = \frac{\mathrm{Im}(Z_{22})}{\omega} \quad R_2 = \mathrm{Re}(Z_{22}) \quad Q_2 = \frac{\omega L_2}{R_2}$$

PWRSOC'12

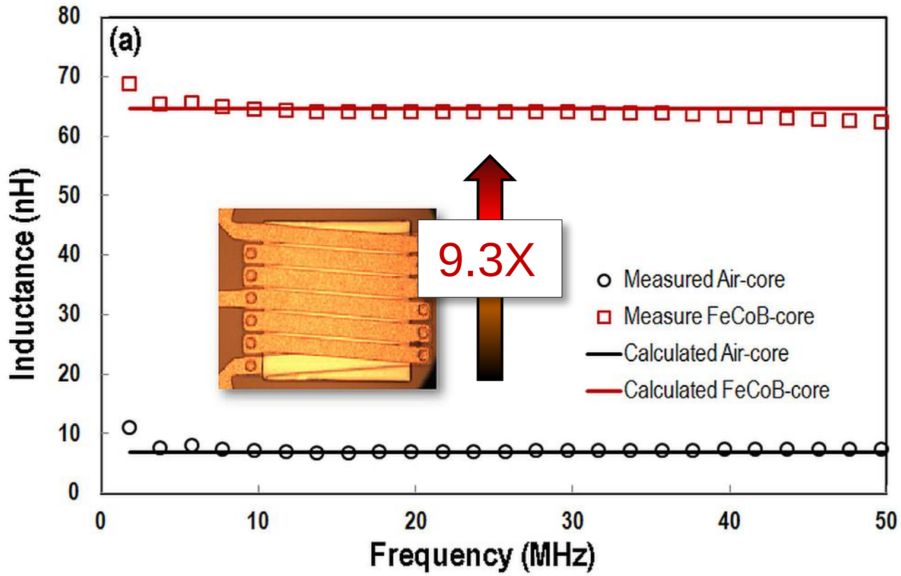
ANALOG DEVICES

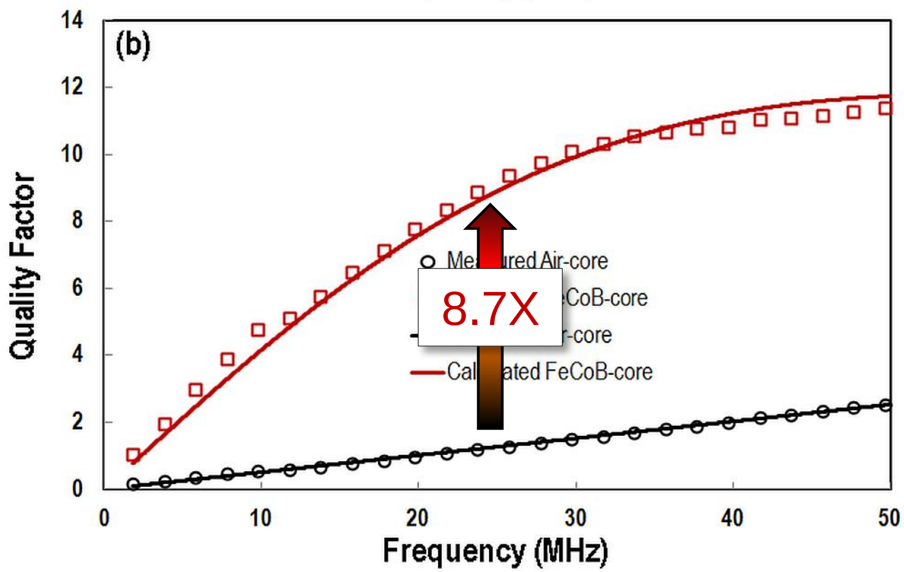
Inductor Results

- Enhancement due to the magnetic core
- Inductance ~ 65nH at 20MHz

  9.3X of the air-core
- Quality factor ~ 8 at 20MHz; 11.5 at 50MHz

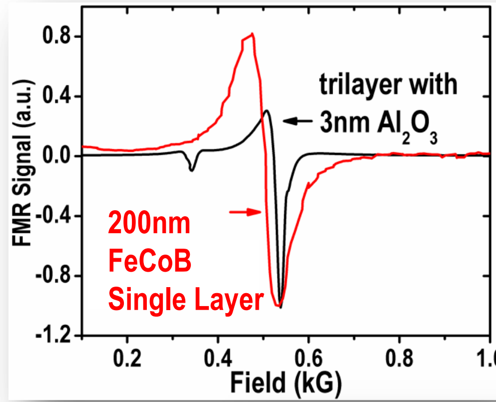
  8.7X of the air-core
- Magnetic permeability of FeCoB multilayer ~ 100

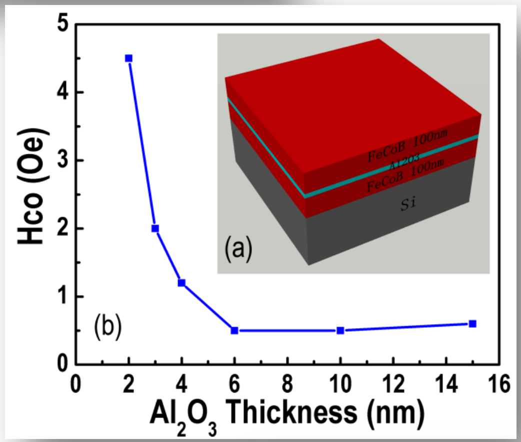


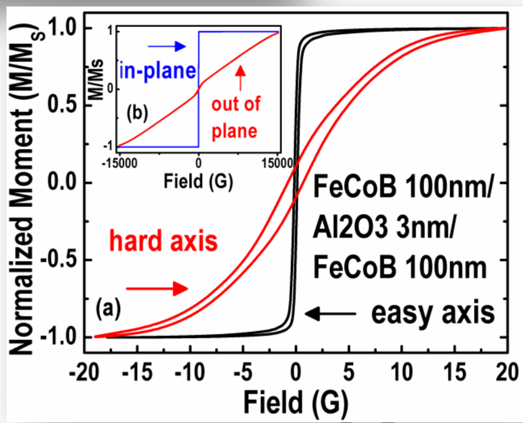


Magnetics

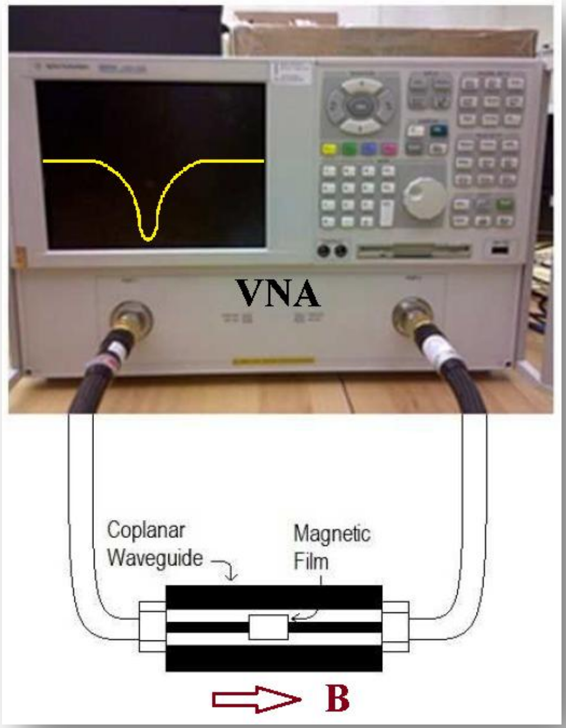
- **FeCoB/Al_2O_3 multilayer**
  - **Reduced FMR linewidth**
    - → Lower eddy current loss
  - **6nm Al_2O_3 spacer**
    - → Minimum thickness above which the anti-ferromagnetic coupling between neighboring FeCoB layers disappears
    - → Very low coercive field
    - → Very low hysteresis loss
  - **Magnetic annealing**
    - → Extremely low hysteresis loss along hard axis
- **[FeCoB (500nm)+Al_2O_3 (6nm)] × 6**





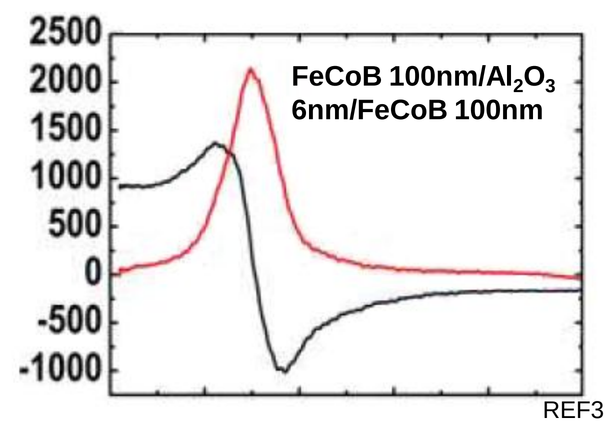


Permeability Measurement



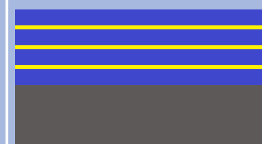
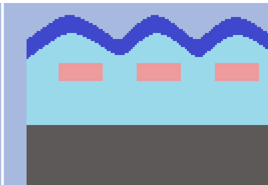
- Testing system
  - Vector network analyzer
  - Waveguide
  - External magnetic field generator
- S11 & S12
  - Magnetic film absorbs microwave energy at frequency *f*, under bias field *B*.

$$\mu_r = Z_0 \frac{\dfrac{1+S_{11H_{bias}} - S_{21H_{bias}}}{1-S_{11H_{bias}}} - \dfrac{1+S_{11H_{ref}} - S_{21H_{ref}}}{1-S_{11H_{ref}}}}{j(klt\mu_0\omega_0)}$$



REF3

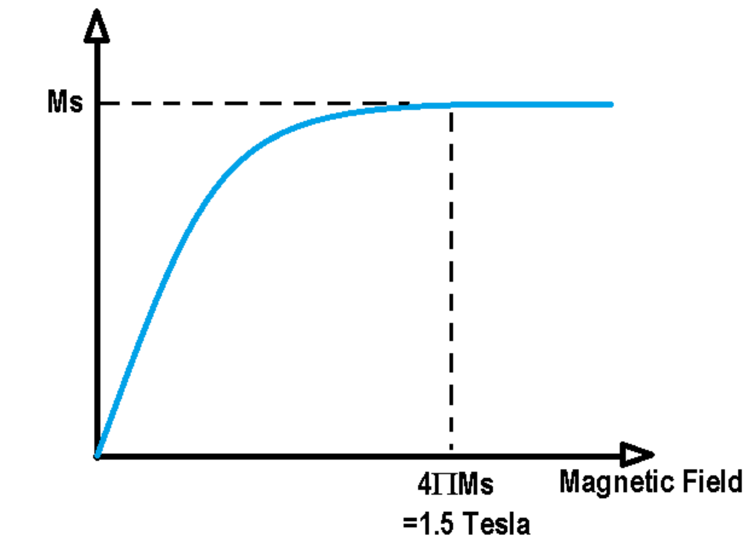
Substrate Surface Condition Dependency of Permeability and Inductance

	200 nm single layer, on bare Si	500 nm single layer, on bare Si	[FeCoB 500 nm/Al_2O_3 6 nm]X6, on bare Si	500 nm single layer, on PI/Si	500 nm single layer, on PI/Cu stripes/PI/Si
					
Relative Permeability	750	350	350	200	100
Inductance of 3um thick core (nH)	470	200	200	115	65

- Permeability decreases as the single layer thickness increases.
- Permeability decreases due to the poor flatness and smoothness of the polyimide surface on which the magnetic deposition was performed.
- [FeCoB 200 nm/Al_2O_3 6 nm]X15 deposited on an appropriately planarized polyimide surface is able to produce an inductance of 470 nH.
- Future work: polyimide surface planarization before magnetic deposition

Saturation Current

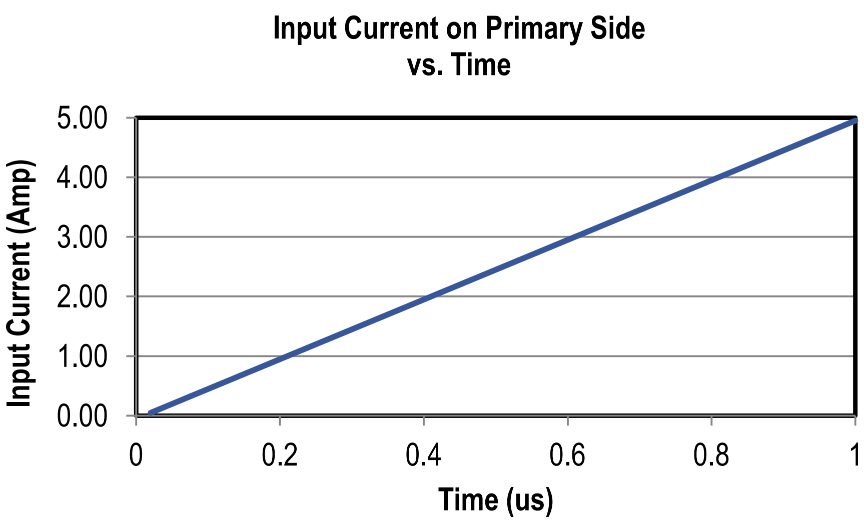
- The magnetic material tends to get magnetically saturated when the field exceeds a critical value.
- The saturation magnetization of FeCoB is **$4\Pi Ms=1.5$Tesla**.
- The magnetic core stops contributing to the inductance when it gets saturated -- $\mu\sim1$.
- Higher initial permeability → lower saturation current in the coil
- The saturation current at **70%Ms** is estimated to be **1.4 Amp** for Inductor Type I.

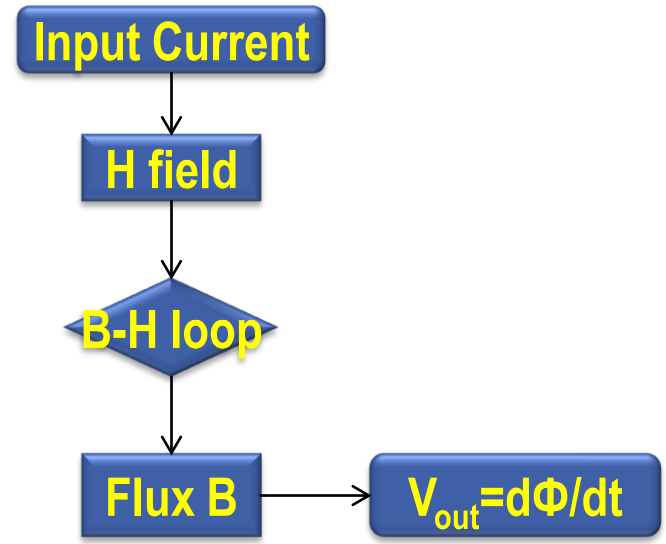


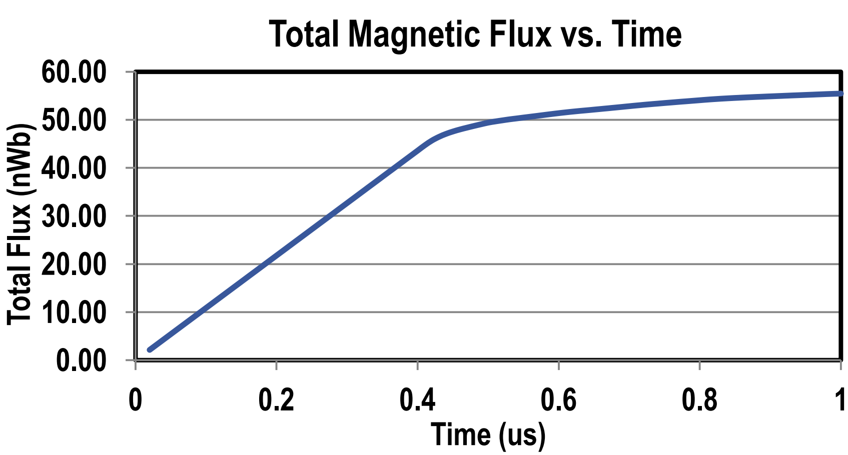
Magnetization Curve of FeCoB along Hard Axis

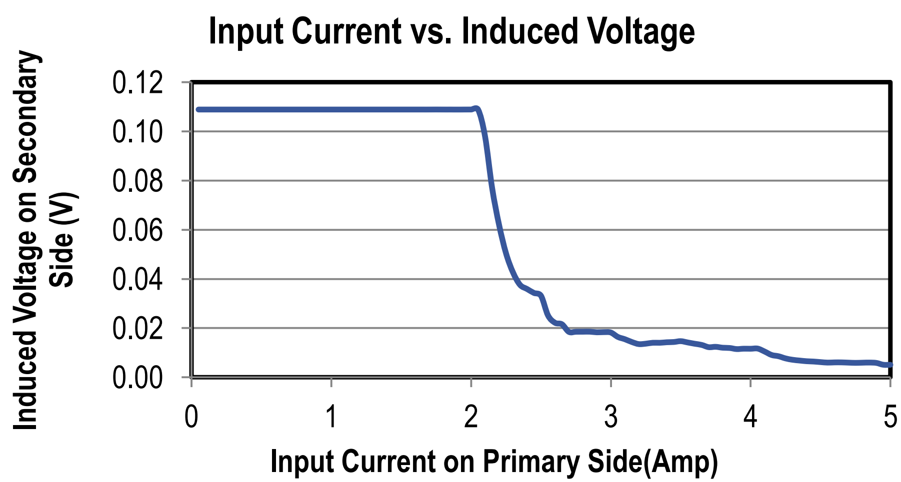
Cross section of a solenoid with FeCoB core

Saturation Current Modeling of [FeCoB 500 nm/Al_2O_3 6 nm]X6 Core

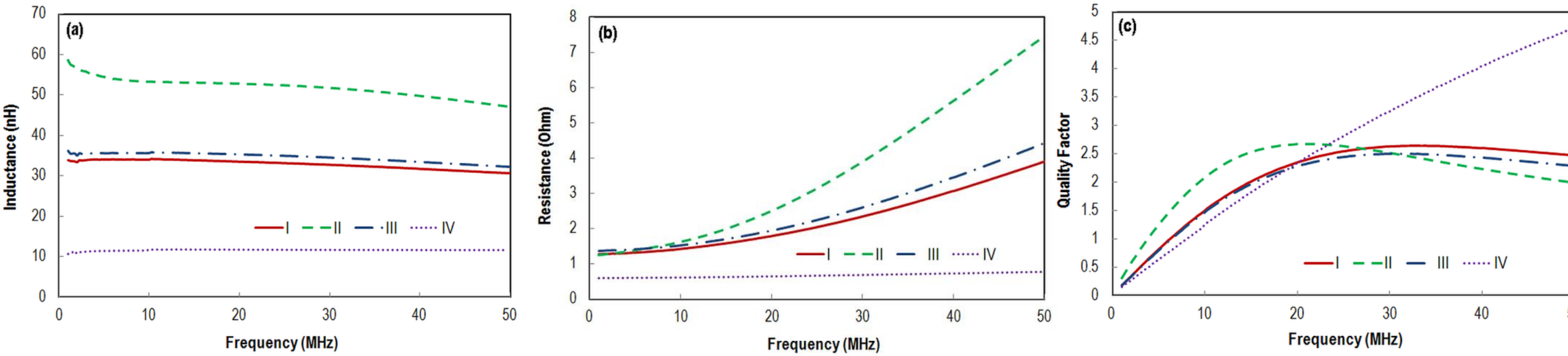


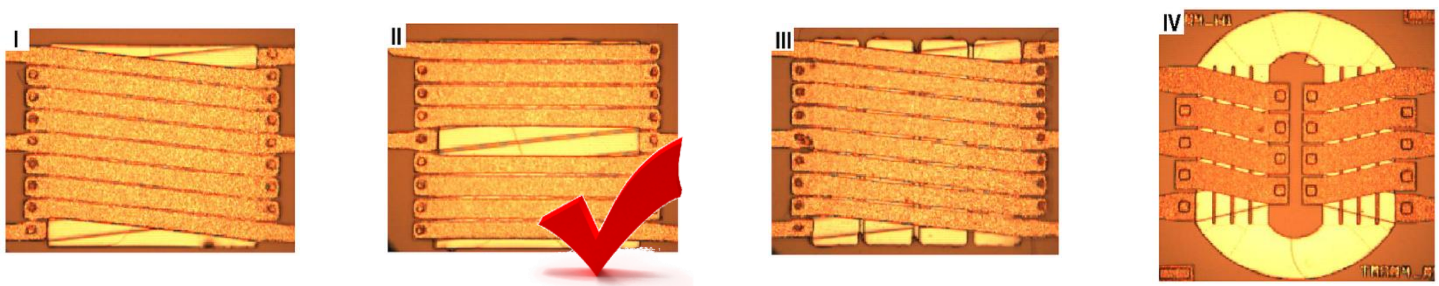






Transformer Performance – Looking at One Side



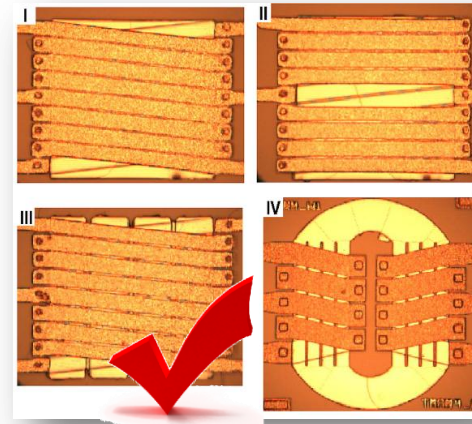


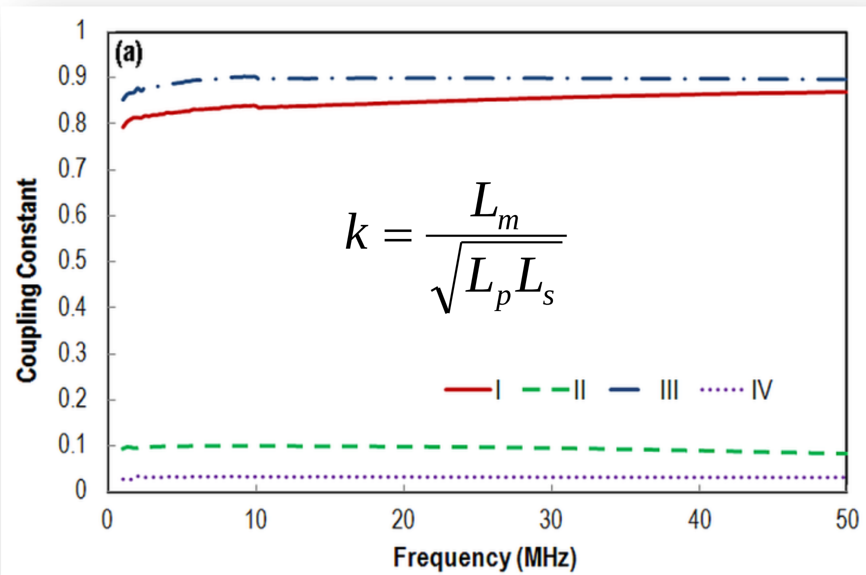
- Transformer II: highest inductance, ~ 53nH; highest total loss due to denser flux; quality factor of 2.7 at 20MHz.
- Transformer III: slightly higher inductance (~ 35.3nH) & resistance than I (~ 33.5nH), due to shape anisotropy inside core.
- Transformer IV: inductance ~ 12nH, due to small core width

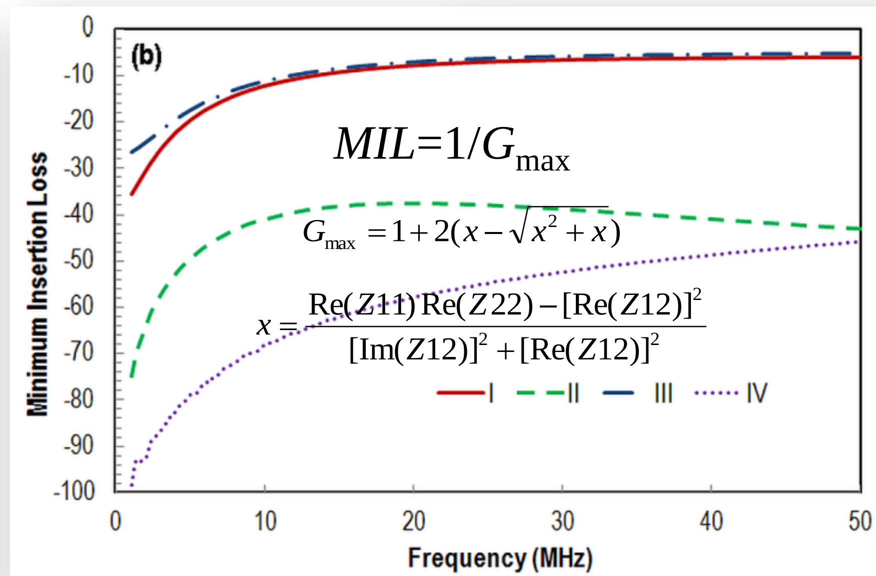
ANALOG DEVICES

Transformer Performance – Coupling

- Transformer II: low coupling constant of 0.1 due to separated windings.
- Transformer III: strongest coupling (~ 0.9) & lowest minimum insertion loss (-7dB at 20MHz).
- Transformer IV: poor coupling, no like bulk magnetic core







Reference

- [1] T. O'Donnell, N. Wang, M. Brunet, S. Roy, S., A. Connell, J. Power, C O'Mathuna, P. McCloskey, Thin film micro-transformers for future power conversion, IEEE Applied Power Electronics Conference, pp. 939-944 (2004).
- [2] C. H. Ahn,Y. J. Kim, and M. G. Allen, A fully integrated planar toroidal inductor with a micromachined nickel-iron magnetic bar, IEEE Trans. Comp., Packag., Manufact. Technol. A, no. 3, pp. 463–469, Sept. (1994).
- [3] X. Xing, et al, RF Magnetic Properties of FeCoB/Al2O3/FeCoB Structure with Varied Al2O3 Thickness, Magnetics, IEEE Transactions on 47 (10), 3104-3107 (2011)
- [4] X. Xing, Soft Magnetic Materials and Devices on Energy Applications, PhD Dissertation, (2011).
- [5] M. Yamaguchi, M. Baba, K. Suezawa, T. Moizumi, K. I. Arai, A. Haga, Y. Shimada, S. Tanabe, And K. Itoh, Improved RF Integrated Magnetic Thin-Film Inductors by Means of Micro Slits and Surface Planarization Techniques, IEEE TRANS. MAGN., BOL. 36, NO. 5, SEPTEMBER (2000).
- [6] G. Grandi, M. K. Kazimierczuk, A. Massarini, U. Reggiani, and G. Sancineto, Model of Laminated Iron-Core Inductors for High Frequencies, IEEE Trans. Magn., VOL. 40, NO. 4 (2004).
- [7] M. K. Kazimierczuk, G. Sancineto, G. Grandi, U. Reggiani, and A. Massarini, High-Frequency Small-Signal Model of Ferrite Core Inductors, IEEE Trans. Magn., VOL. 35, pp. 4185–4191 (1999).
- [8] David C. et al, LATERAL MICROWAVE TRANSFORMERS AND INDUCTORS IMPLEMENTED IN A Si/SiGe HBT PROCESS.
- [9] D. W. Lee, K. Hwang, and S. X. Wang, Fabrication and analysis of high performance integrated solenoid inductor with magnetic core, IEEE TRANS. Magnetics, pp. 4089-4095, VOL. 44, NO. 11, November (2008).

Conclusion

- **Fly-back DC/DC converter**
- **Four solenoid integrated transformers with FeCoB multilayer cores**
  - Different winding
  - Different core structures
- **3µm FeCoB/Al_2O_3 multilayer film → a factor of 9.3 and 8.7 improvements in the inductance and quality factor, respectively**
- **Material study on the FeCoB/Al_2O_3**
  - Multilayer film has reduced eddy current loss
  - [FeCoB 500 nm/Al_2O_3 6 nm]X6 has very small hysteresis loss
  - permeability of the magnetic thin films depends very much on the substrate surface roughness.
  - Saturation current
- **Transformer III interleaved winding and sliced magnetic core, exhibited the lowest insertion loss as well as the best comprehensive performance.**
- **Polyimide surface planarization before magnetic deposition.**

Thank you!
&
Questions?