Tyndall

Integrated Magnetics for PwrSiP and PwrSoc

Paul McCloskey

paul.mccloskey@tyndall.ie

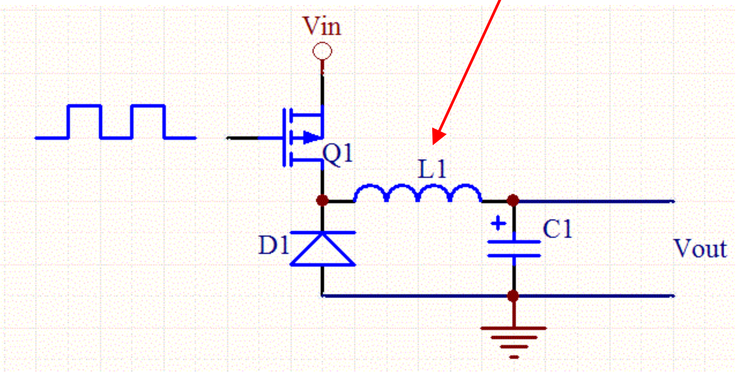
IMPACT FROM EXCELLENCE

Outline

- Evolution of Power Converters
- Integrated Magnetic Structures
- Magnetic core Losses
- Magnetic materials
- Example Devices
- Research Challenges
- Summary

Buck Converter

Typically biggest device



Schematic for a buck converter [1]

- $V_{out} \sim V_{in}\, D$
- Ripple current - controlled by L

$$\Delta i = (V_{in} - V_{trans} - V_{out})D/(Lf)$$

where: D = duty cycle, L= inductance and f = switching frequency

- For small L - need high f
- Switching loss at high f is improving!

[1] Daycounter Inc. Engineering Services, "Buck Converter Design Equations", http://www.daycounter.com

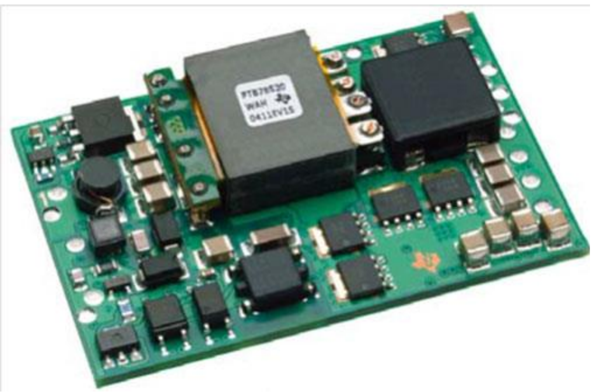
Evolution of Power Converters

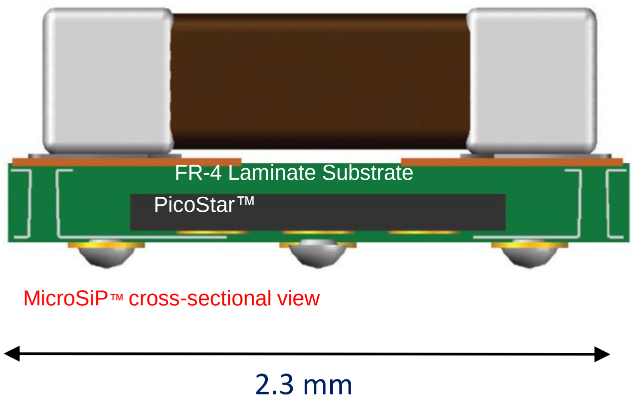
Conventional SMPS

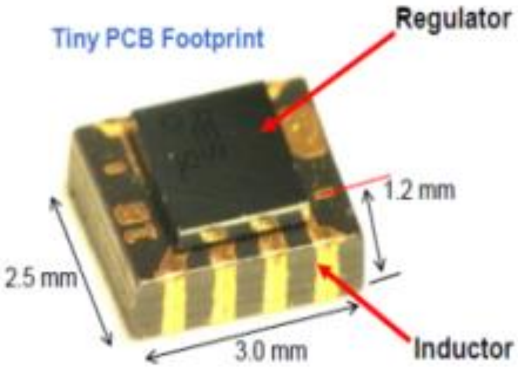
Discrete switches, control, passives & load

PwrSiP

Control, Switches and L integrated in Package





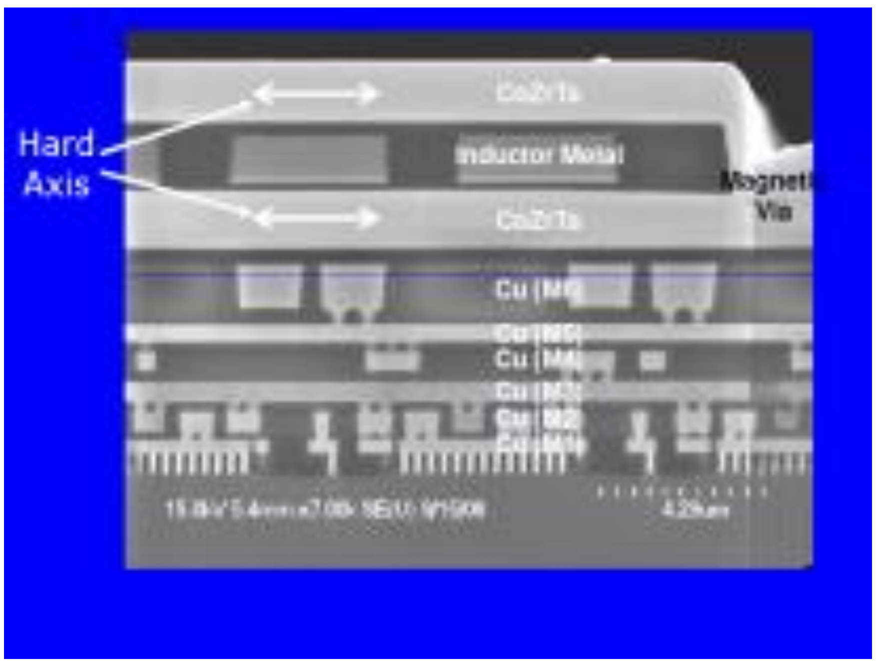


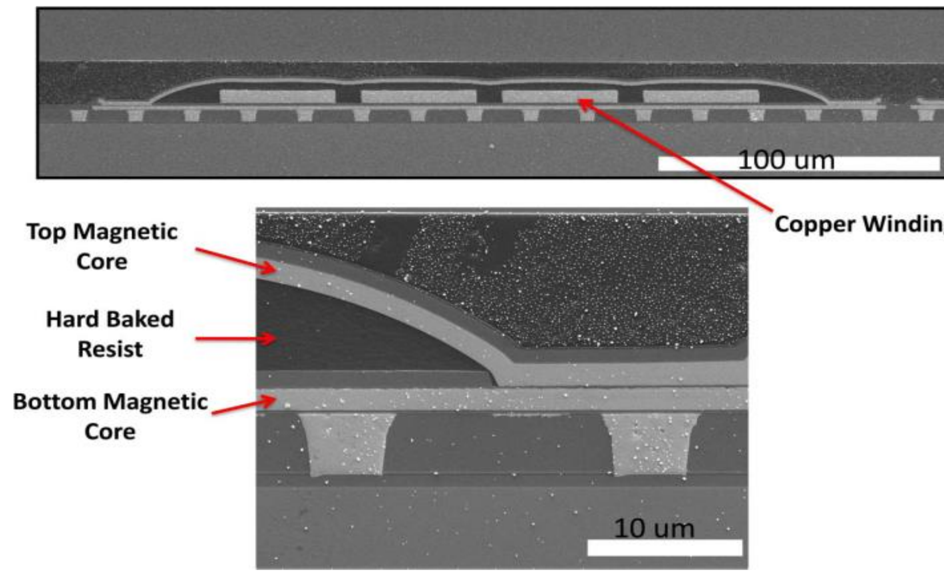
Evolution of Power Converters

PwrSoC

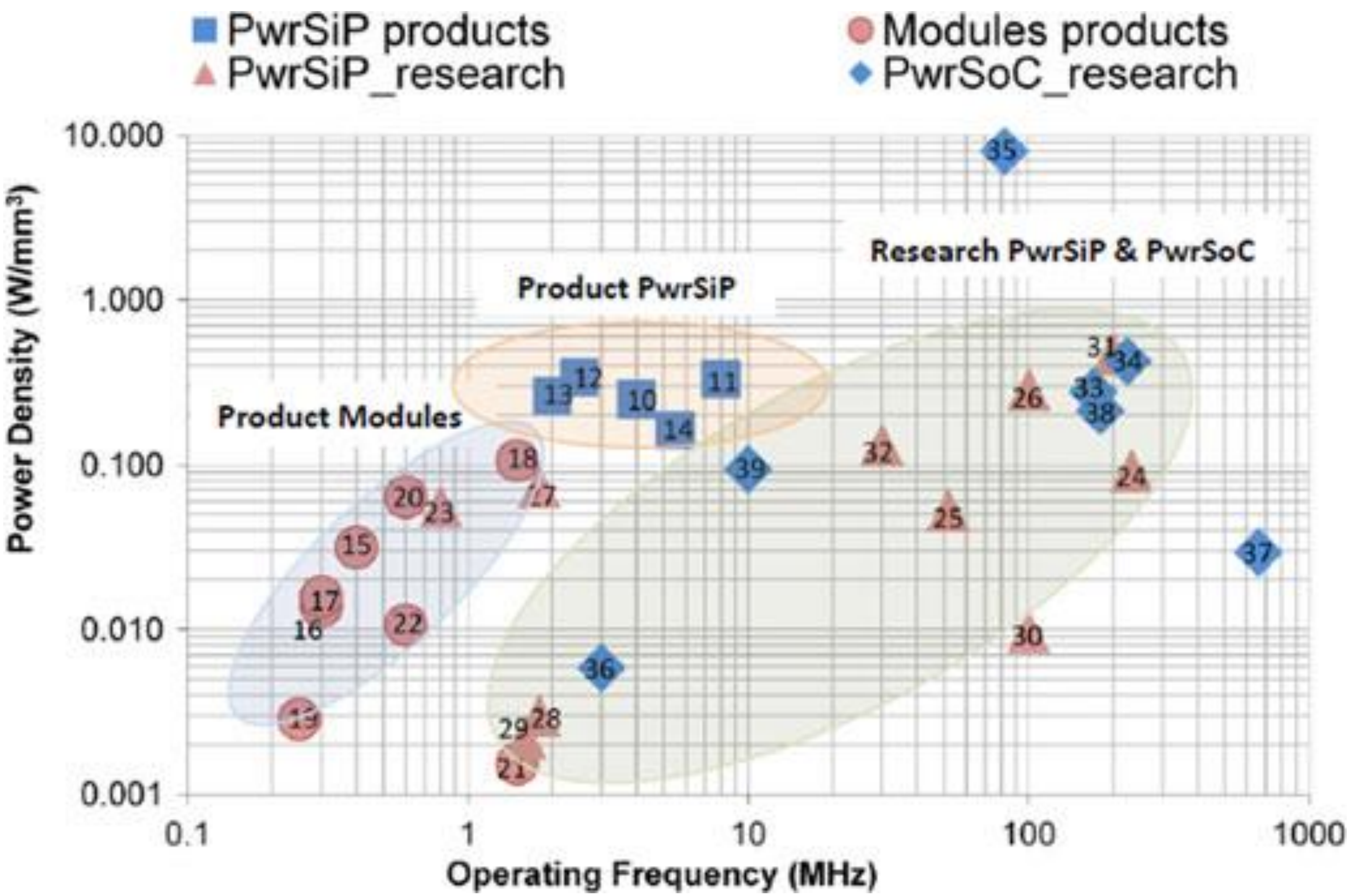
Inductor fabricated on Si die, load may also be integrated

2.5D stacked multi-phase
Buck from IBM (2013)





Evolution of Power Converters



Cian O´ Mathuna et al. "Review of Integrated Magnetics for Power Supply on Chip (PwrSoC)", IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 27, NO. 11, NOVEMBER 2012

Integrated Magnetic Structures

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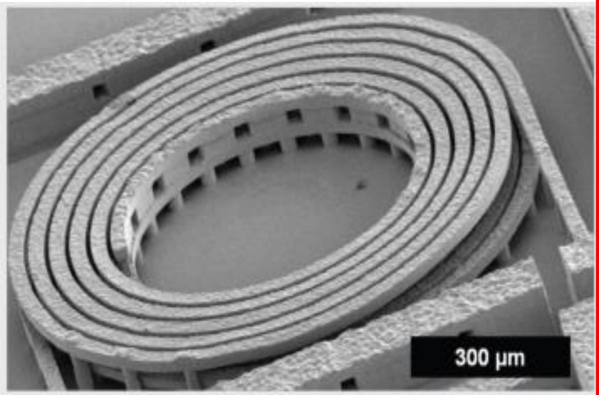
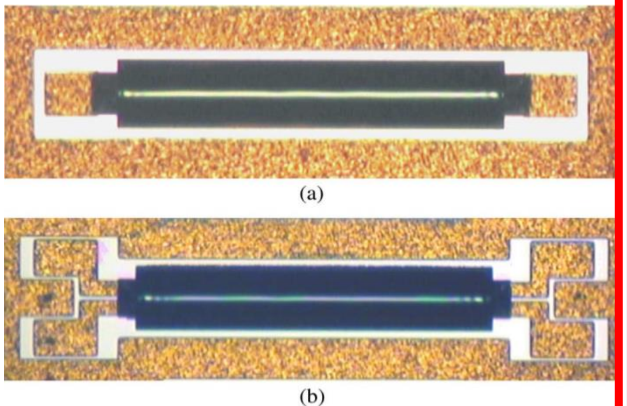
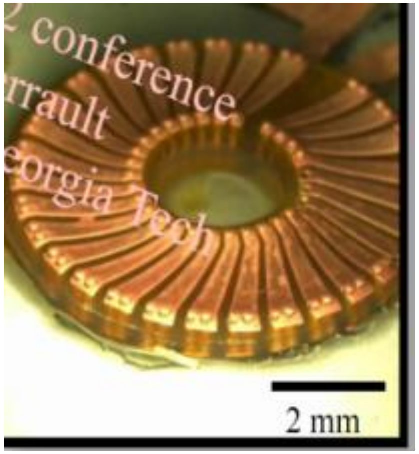
- Spiral: HKUST



- Stripline: Intel, etc.

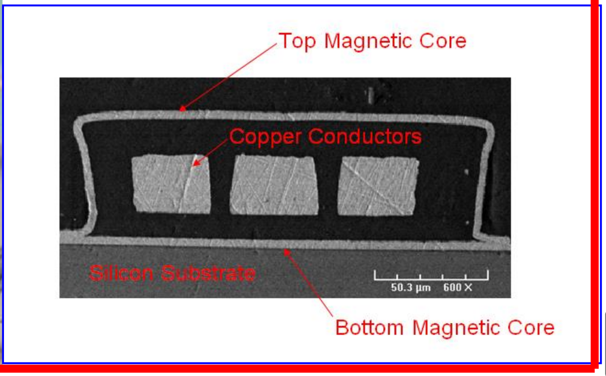


- Toroid: Georgia Tech, etc.



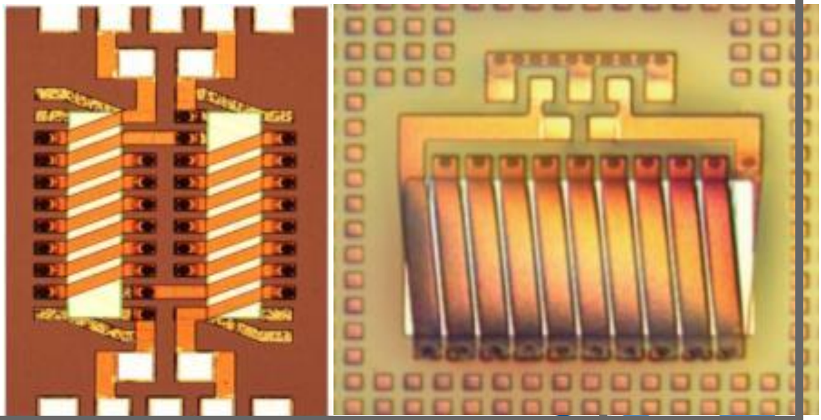
Magnetic cores wrap around windings

- Racetrack: Tyndall, Dartmouth, IBM, etc.



Windings wrap around magnetic core

- Solenoid: ADI, Stanford, etc.



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Magnetic Device - Loss Breakdown

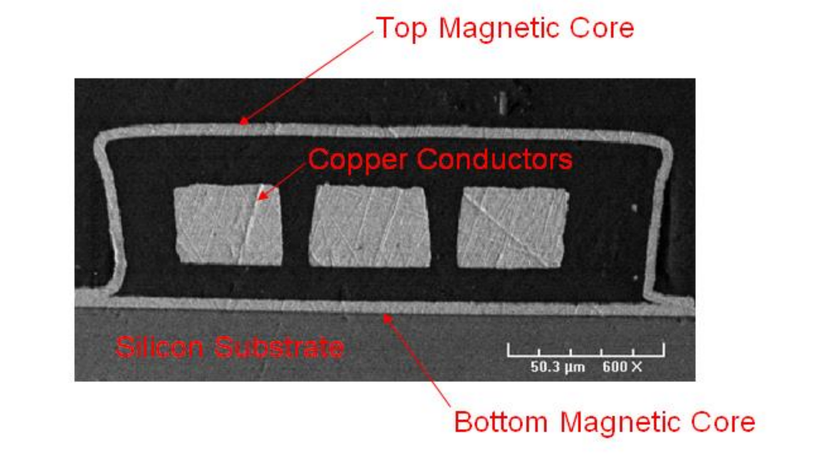
Losses within a magnetic device

- DC conduction loss in windings
- AC conduction loss in windings
- Hysteresis losses in core
- Eddy current losses in core
- Anomalous losses in core

Structure and winding dimensions

⇕

Material property and core geometry



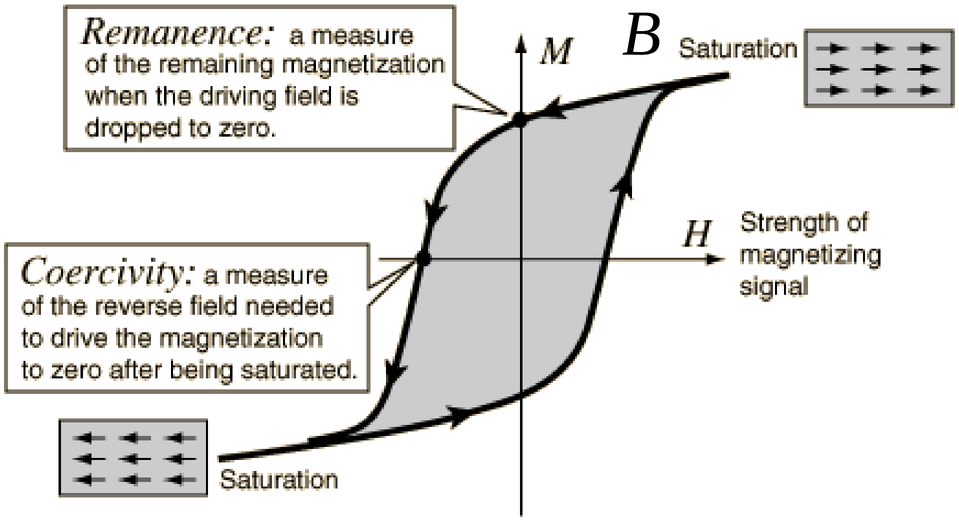
Determined by

- Device structure
- Material properties
- Process constraints

Magnetic Material - Losses

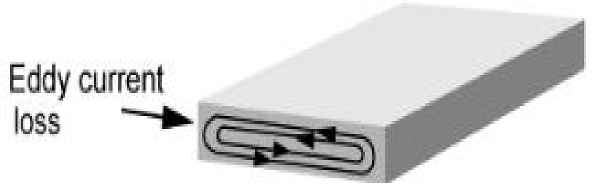
- **Hysteresis Loss**
  - Arise from domain wall motion
  - Area within *B-H* loop
  - $P_{hysteresis} = 4.\ f.B_{ac}^{2}\ H_c/B_{sat}$

  Where; H_c = coercivity, B= Magnetisation, H = Magnetising field, f = frequency



- **Eddy Current Loss**
  - Eddy currents resist change in magnetic field
  - Reduced by keeping thickness below 1 or 2 skin depths
  - Skin depth, $\delta = (2\rho\,/\omega\mu_r)^{0.5}$

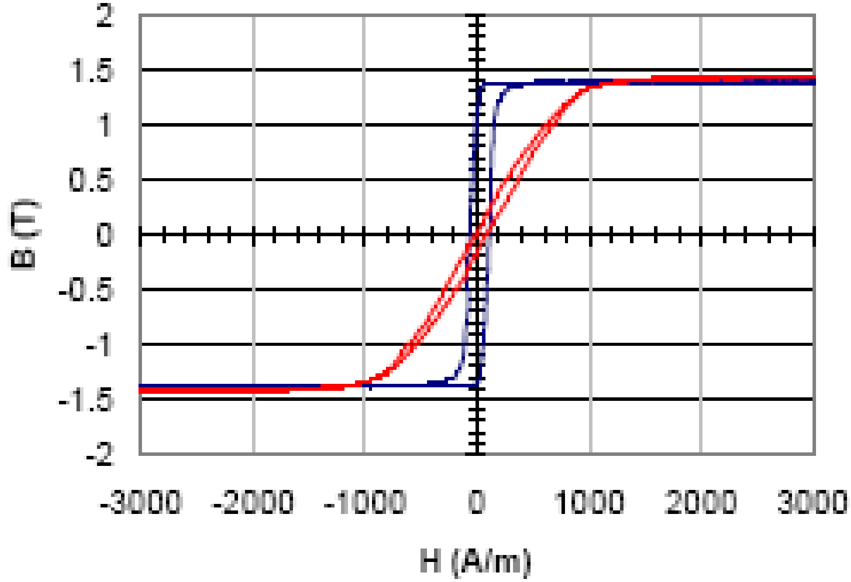
  Where; ρ = resistivity, ω = angular frequency $(=2\pi f\,)$



- **Anomalous Loss**
  - Inconsistencies in domain wall motion
  - Often calculated as; $P_{total} = P_{hysteresis} + P_{eddy\ current} + P_{anomalous}$

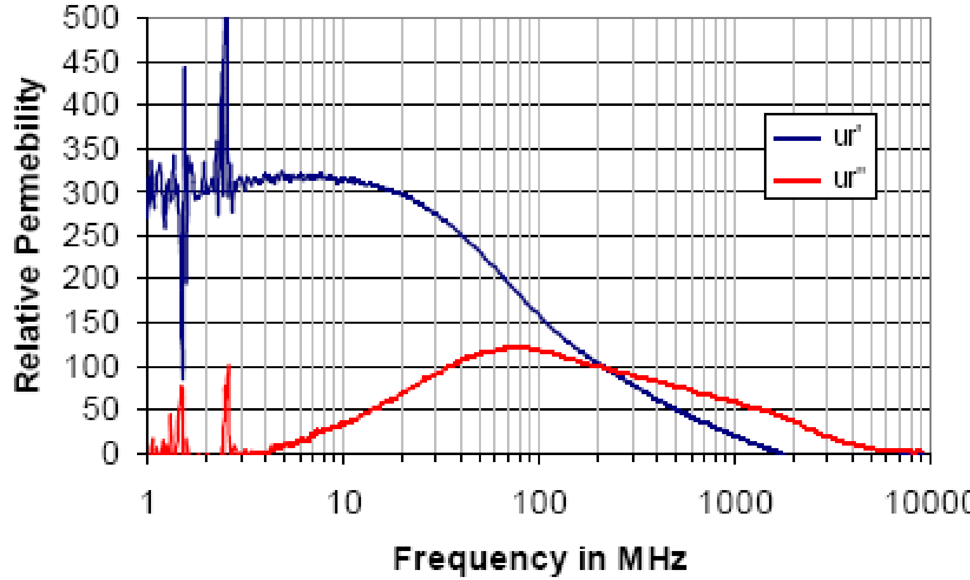
Magnetic Material, Crystalline - Plated $Ni_{45}Fe_{55}$

Saturation, B_s	1.44 T
Coercivity, H_c	80 A/m
Resistivity, ρ	45 µΩ cm
Permeability, μ_r	300



Design impact

- Inductance, $L = (\mu_0 \mu_r N^2 A_c) / I_c$
- Skin depth, $\delta = (2\rho / \omega\mu_r)^{0.5}$

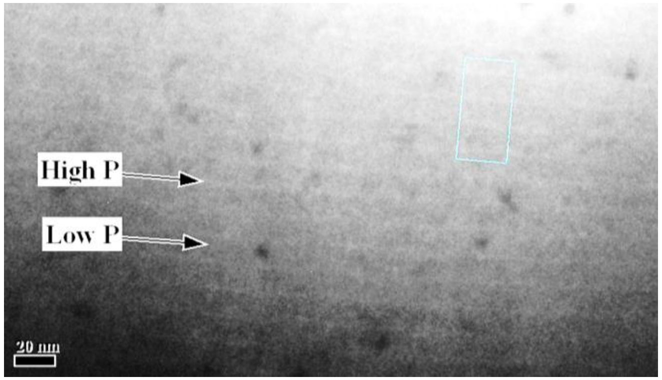


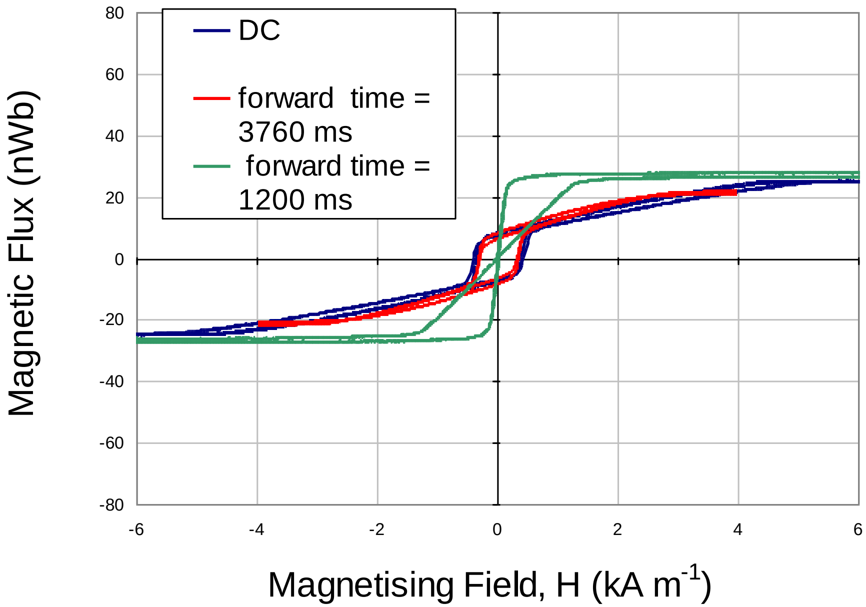
μ_0 = permeability of free space, μ_r = relative permeability, N = number of turns, A_c = CSA of core, I_c = length of core. ρ = resistivity, ω = angular frequency ($=2\pi f$)

Magnetic Material, Amorphous - Plated Cobalt Phosphorous (Co-P)

Requires Pulse Reverse Plating [1] to avoid out of plane anisotropy

- Co-P removed during reverse cycle
- Co removed preferentially from surface => high P layer





Properties [2]

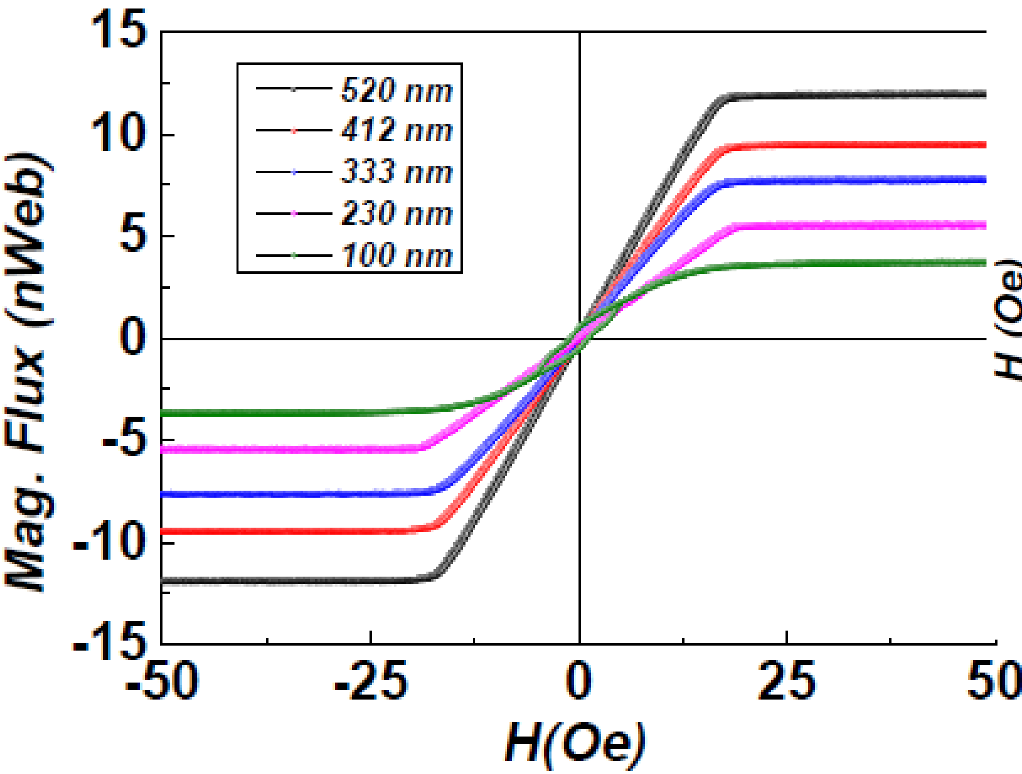
- B_{sat} = 0.9 to 1.2T
- H_c < 40 Am^{-1} with a minimum value of 8 Am^{-1}
- μ_r ~ 700 holding out to a maximum 103 MHz
- 116 < ρ <136 µΩ cm

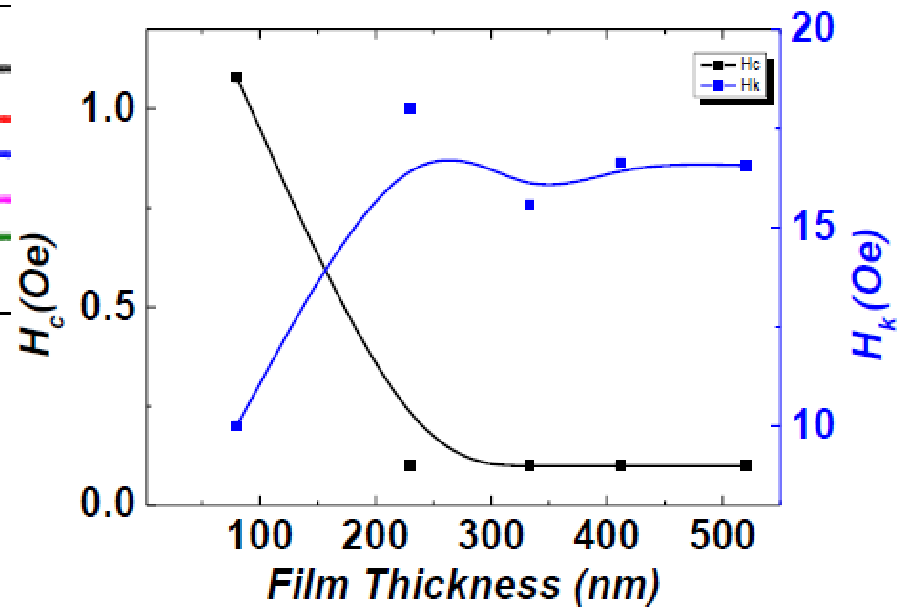
[1] J.M. Riveiro et al, IEEE Trans on Magnetics, Vol. MAG-17, No. 6, November 1981

[2] P. McCloskey et al, "High-frequency nanostructured magnetic materials for integrated inductors", JMMM, Vol 320, Issue 20, p 2509-2512

[3] P. McCloskey et al, "Electrodeposited amorphous Co-P based alloy with improved thermal stability", JMMM, Vol 322, Issue 9-12, p. 1536-1539

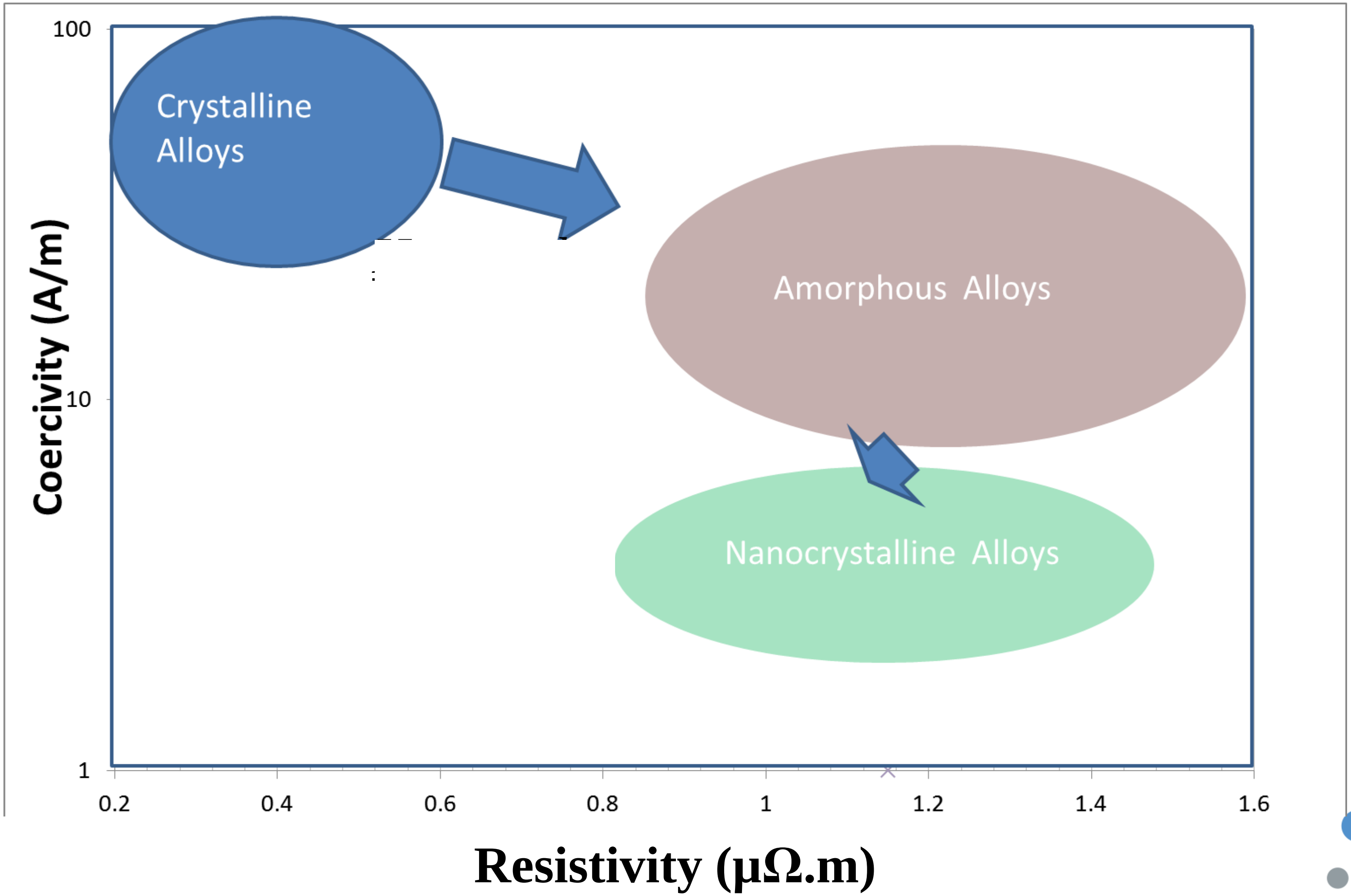
Magnetic Material, Amorphous Sputtered





- **Increasing thickness- lower coercivity (<0.1 Oe)**

Magnetic Materials Development



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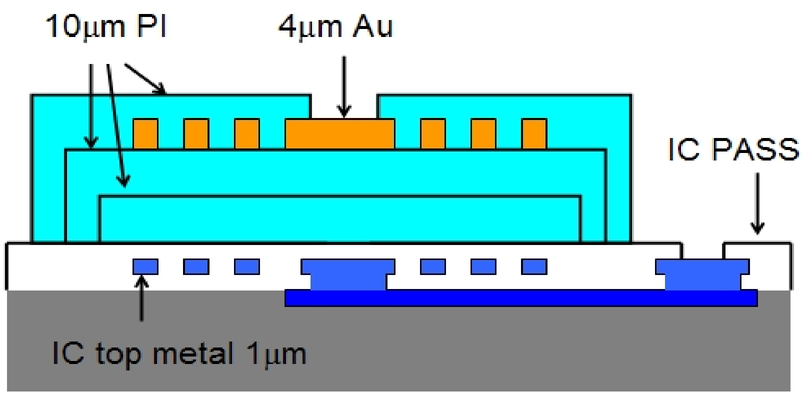
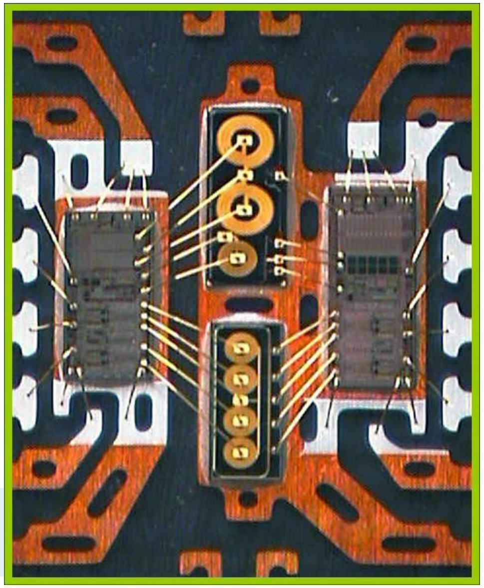
Device 1 - Integrated Transformer for Isolated Power and Signal Transfer



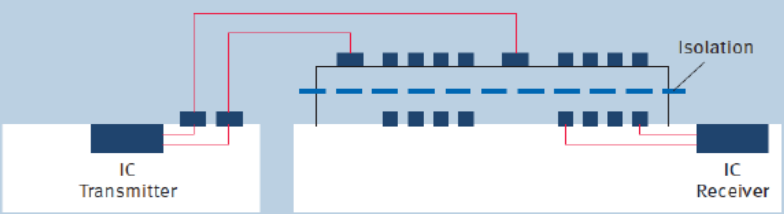


iCoupler

ANALOG DEVICES

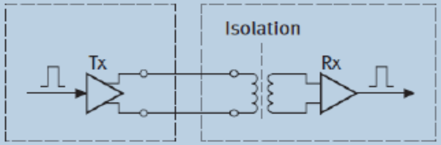
ISOFACE™ PowerSiP

Coreless Transformer Principle



A lot of advantages compared to optocoupler

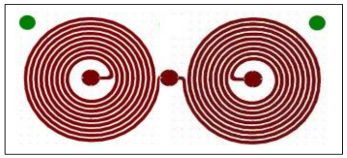
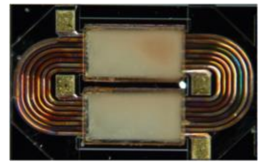
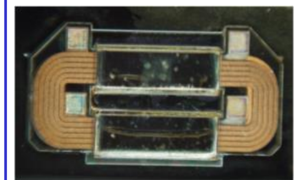
- No degradation over time
- Gain reliability
- High temperature range ... 150°C
- Very fast transmission (10 ... 100MHz)
- Low power consumption



infineon

Commercial products

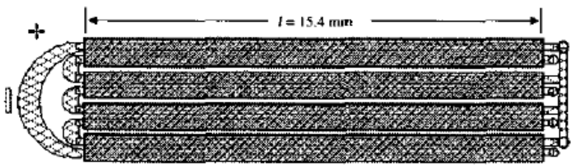
Measured Microtransformer Performance

	Commercial Air Core 	Tyndall Gen1  	Tyndall Gen2  
Device Size	$2mm^2$	$24mm^2$	$3mm^2$
Frequency	180MHz	10MHz	20MHz
Inductance	8nH	440nH	240nH
L Density	$17nH/mm^2$	$18nH/mm^2$	$80nH/mm^2$
Coupling	0.85	0.93	0.97
DC R	0.46 Ohms	0.5 Ohms	0.96 Ohms
µT Effic.	70%	63%	78%
Switch Effic.	<= 60%	80%	80%
Overall Effic.	<= 40%	50%	63%

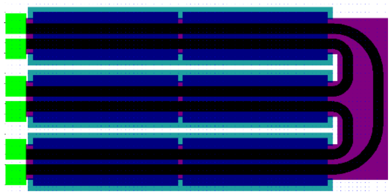
N. Wang et al, IEEE Trans. On Power Electronics (Nov 2014)- Tyndall-TI joint publication

Device 2 - Integrated coupled inductor

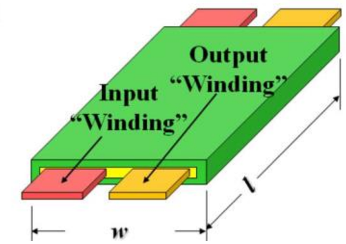
Dartmouth/Tyndall’04



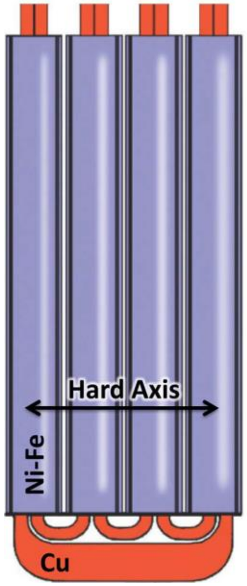
Tyndall’14



INTEL’11

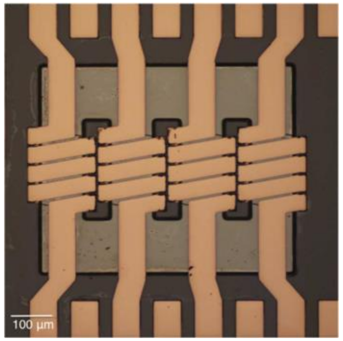


Columbia/IBM/Duke’12

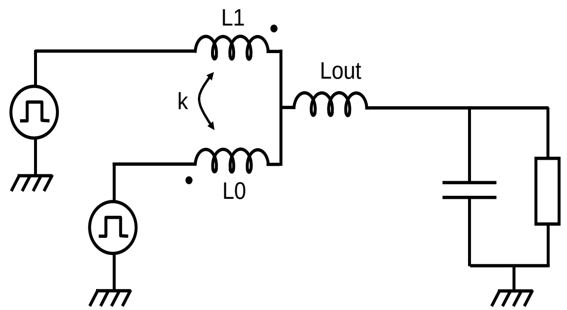


	L self (nH)	DCR (mΩ)	Foot print (mm^2)	Freq (MHz)	Convert Effic (%)
Dartmouth/ Tyndall’04	14	40	80	5	50
INTEL’11	25	14	2.8	>60	76
Columbia/ IBM/Ferric’12	7.4	480	10.9	100	71
Columbia/ IBM/Duke’13	12.5	270	2.5	>40	
Tyndall/ Powerswipe’ 15	35	155	2	100-200	81 Expect!
NUIG/Tyndall’15	23	71	5	20	55

Columbia/IBM/Ferric’13



PowerSwipe Converter Specifications



Comparison single-phase and two-phase dc/dc converter

Inductor design	Freq. (MHz)	L (nH)	Coupling factor	Efficiency (magnetics)	Efficiency (IC)	Total efficiency
Single phase	200	33	--	**95,5 %**	**87,4%**	**83%**
Coupled	**100**	**45**	**~0.4**	**90%**	**90,4%**	**81%**
Coupled +Lout	100	35+21	>0.8	85.6% **(90.25%·94.8%)**	**90,4%**	**77%**

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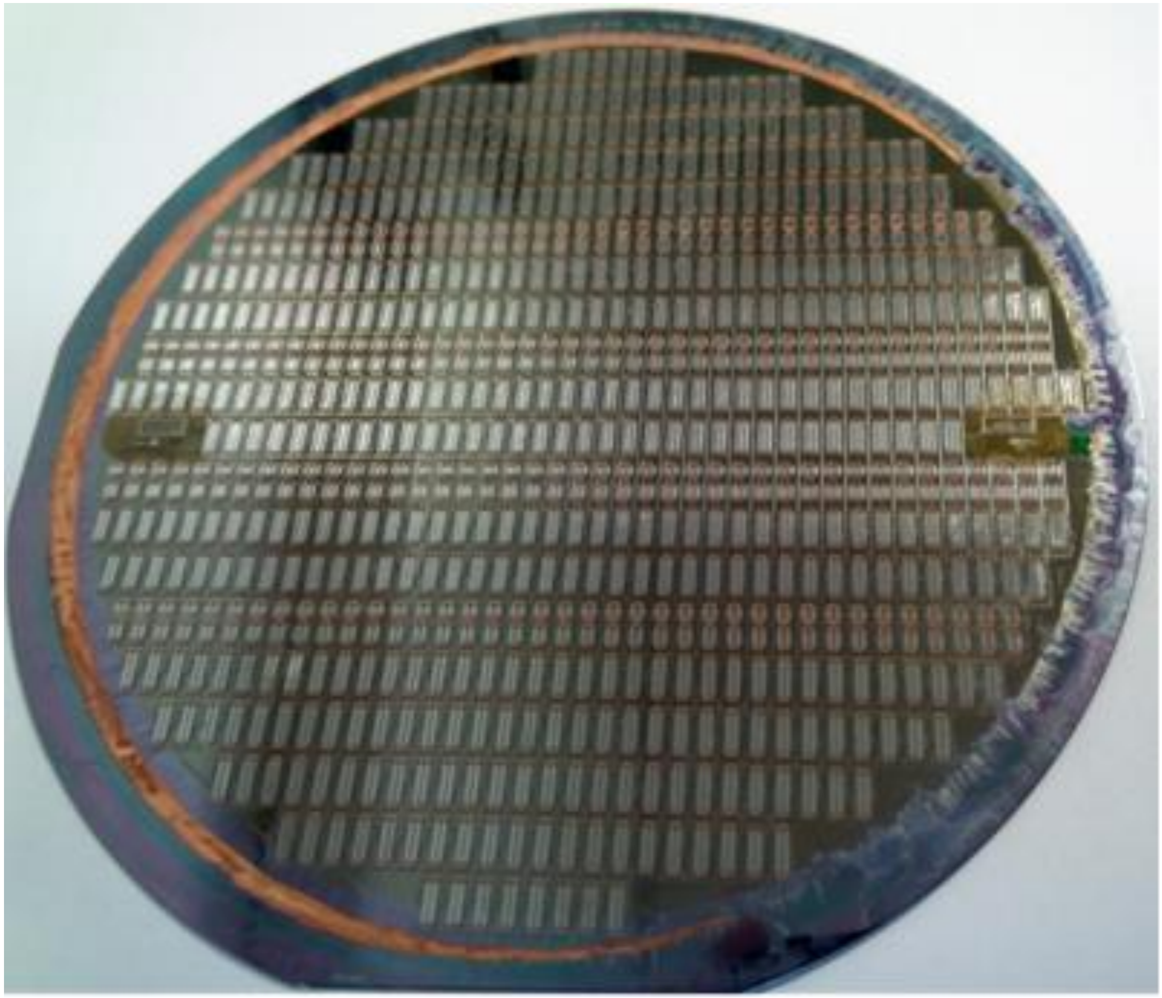
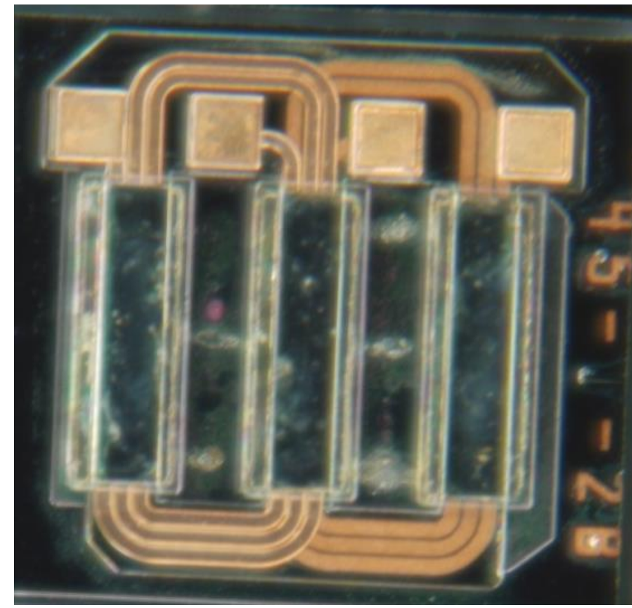
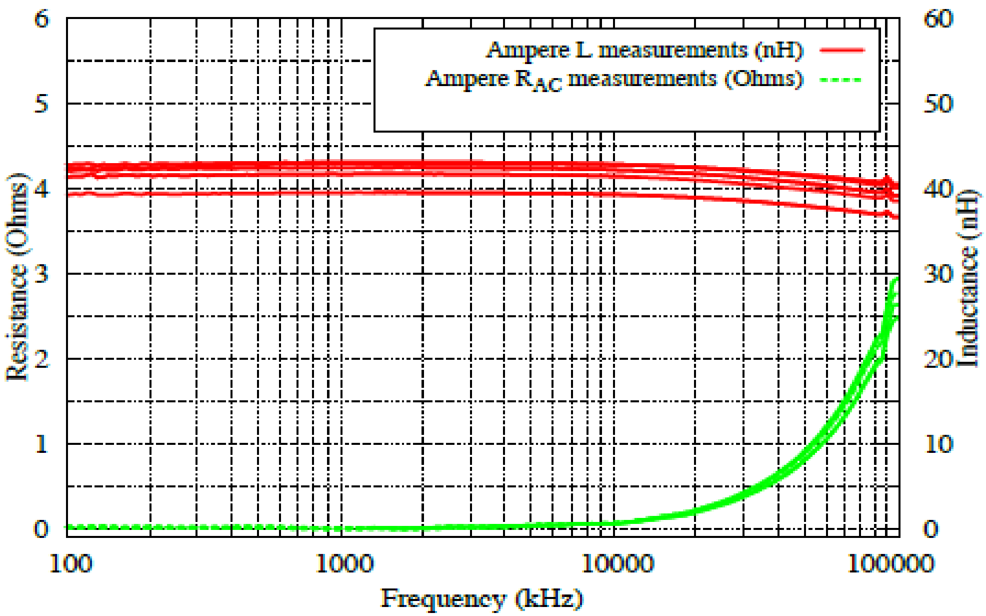
100 MHz coupled inductor- Prototypes

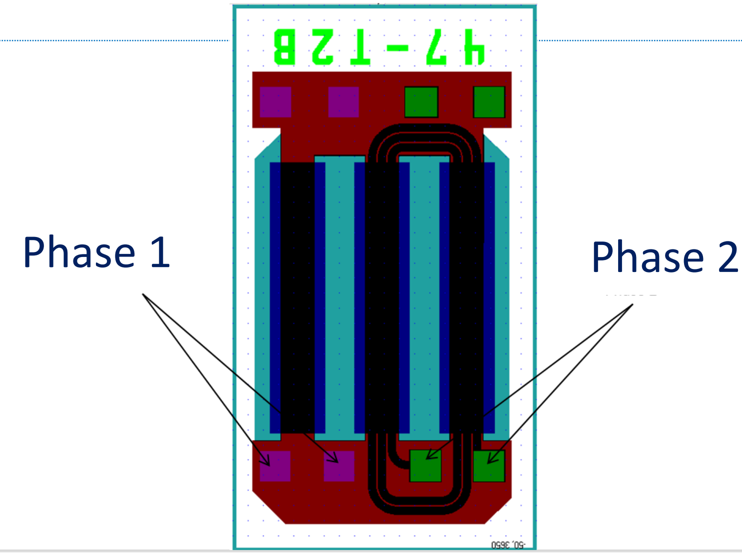


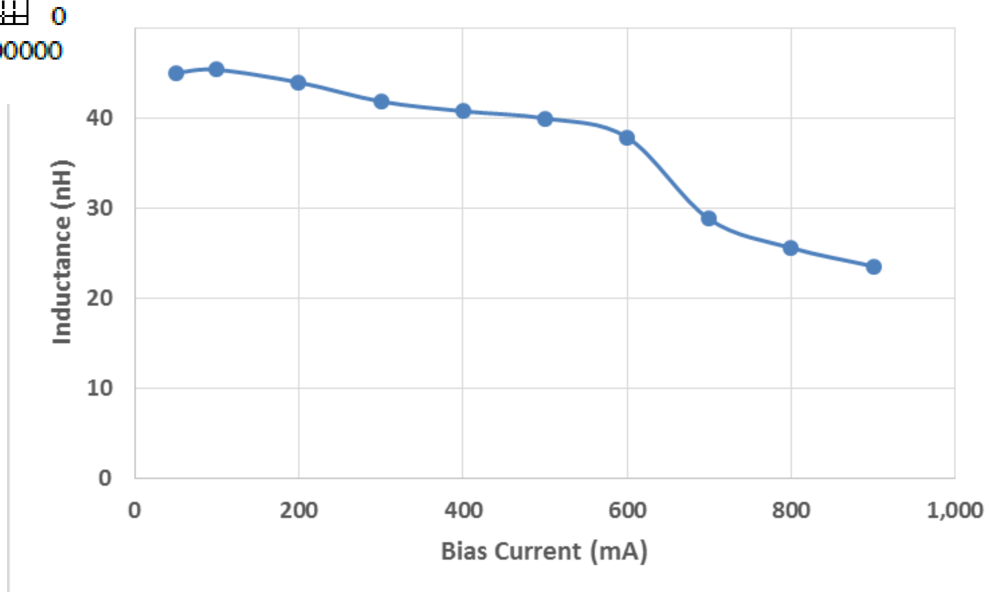


IMPACT FROM
EXCELLENCE

100 MHz coupled inductor- Small Signal Characterization







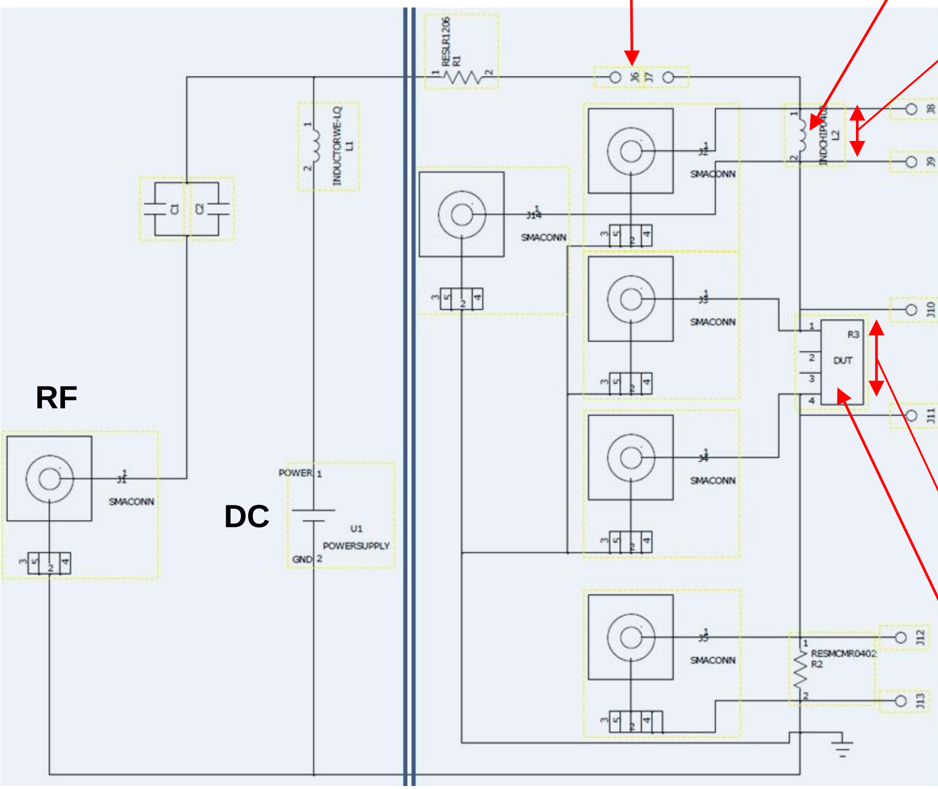
- Good match between design & measured data

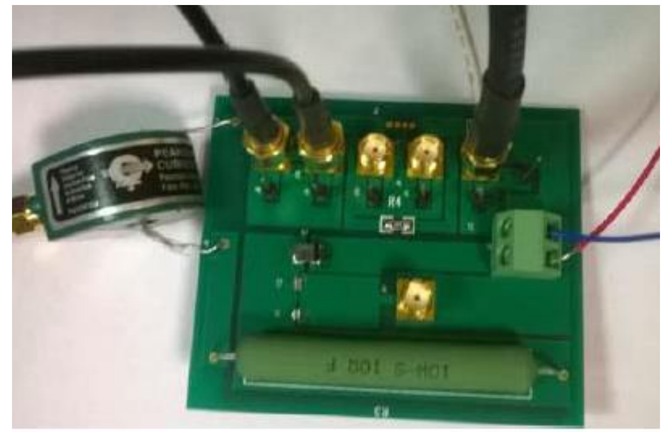
Large Signal Characterization

Current measurement

Known Inductor (20nH)

Voltage measurement





- Large signal generated
  i.e. up to to 0.7A DC + 0.3A ac
- Voltage and current waveforms measured
- Values of L an R_{ac} extracted

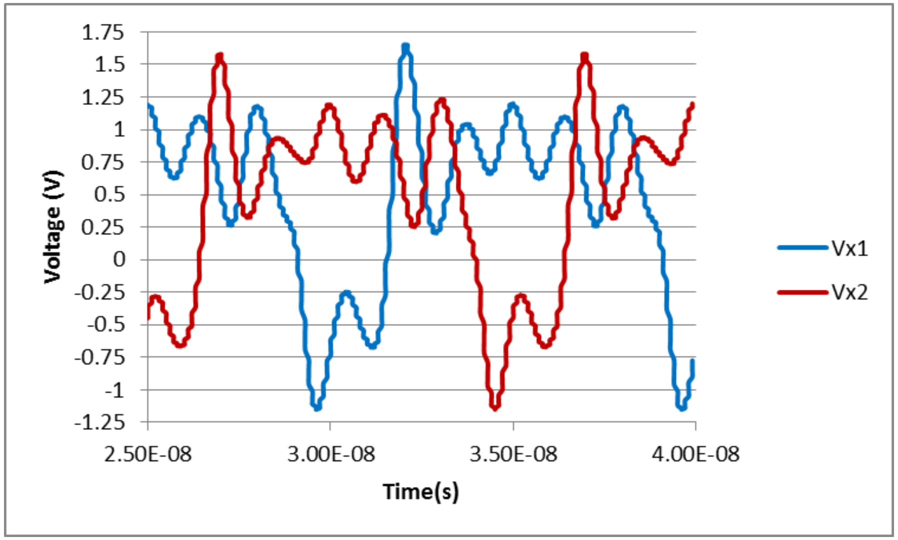
Voltage measurement

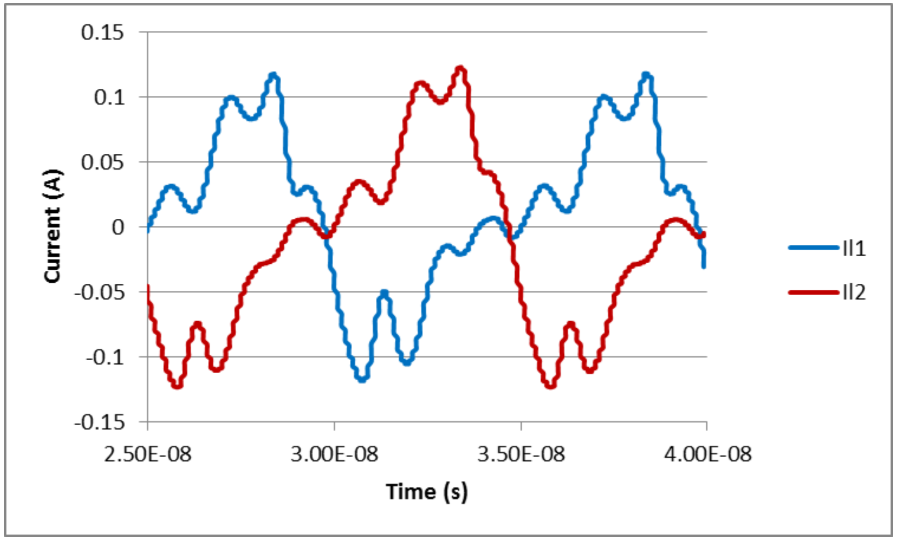
DUT

Signal Generation

Measurement

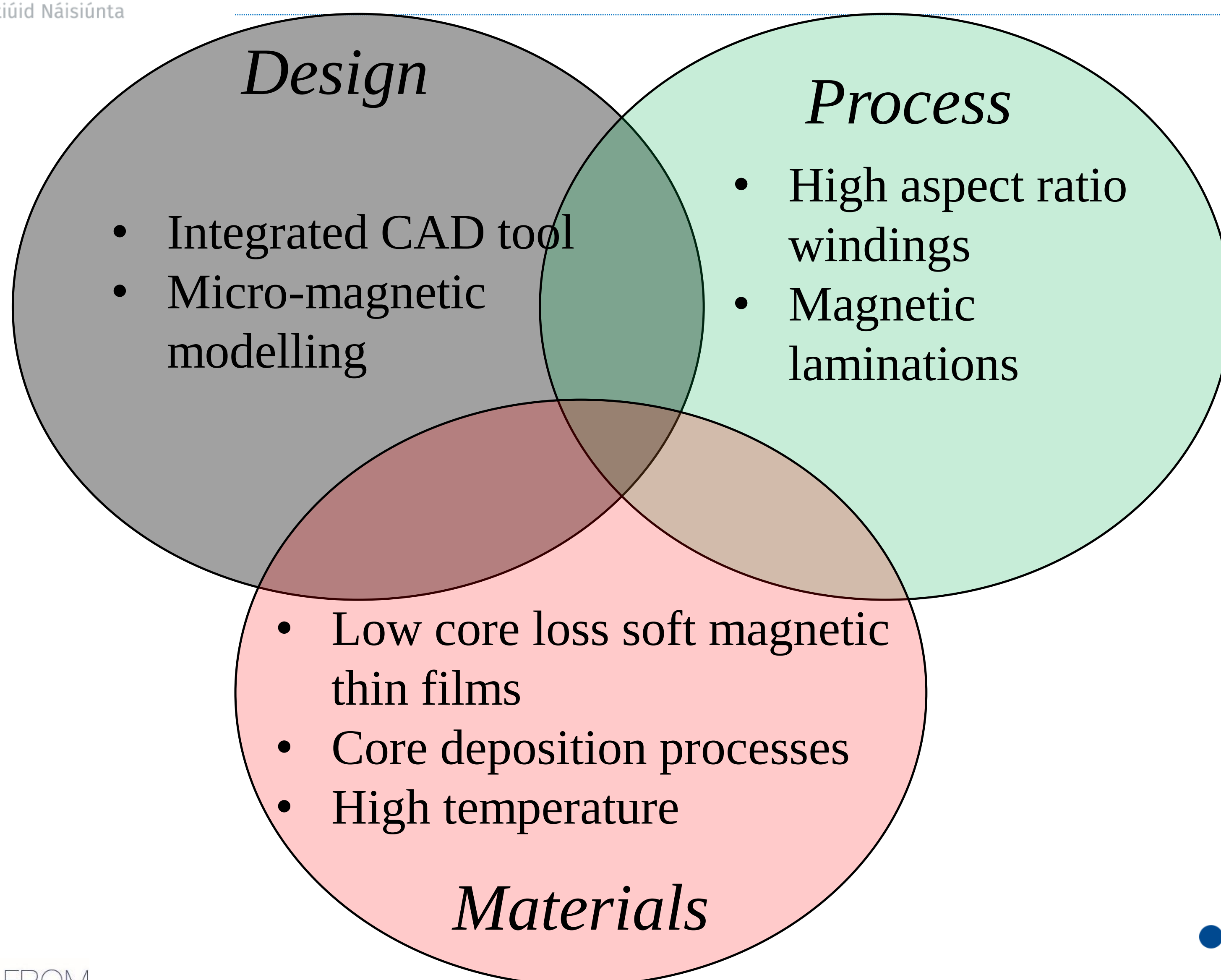
100 MHz coupled inductor - Large Signal Characterization





Vout	Iout	Rac	L-efficiency (est.)
1.2 V	280 mA	889mΩ	90.7%

Research challenges



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Summary

- **Conventional SMPS with discrete components => PwSiP => PwSoC**
- **Greater integration enabled by higher switching frequencies**
- **Range of magnetic structures: Spiral, Stripline, Racetrack, Toroid and Solenoid each with advantages and disadvantages**
- **Magnetic material includes: Crystalline, Amorphous and Nanocrystalline**
- **Example devices:**
  - Microtransformer for isolated power and signal transfer
  - Integrated coupled inductor
- **Research challenges: Design, Materials and Process**

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