Presented at:

“Power Magnetics @ High Frequency Workshop 2023”

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Low-profile Integrated magnetics for low-power applications

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Cork, Ireland

Outline

- **Introduction**
- **Application challenges in integrated magnetics**
  - Miniaturized coupled inductor for energy harvesting sensor node
  - On-chip planar inductor with a ferrite core for RF applications
- **Key design parameters**
- **Outlook and conclusion**

The Innovation Driver for Integrated Magnetics

Technology PUSH

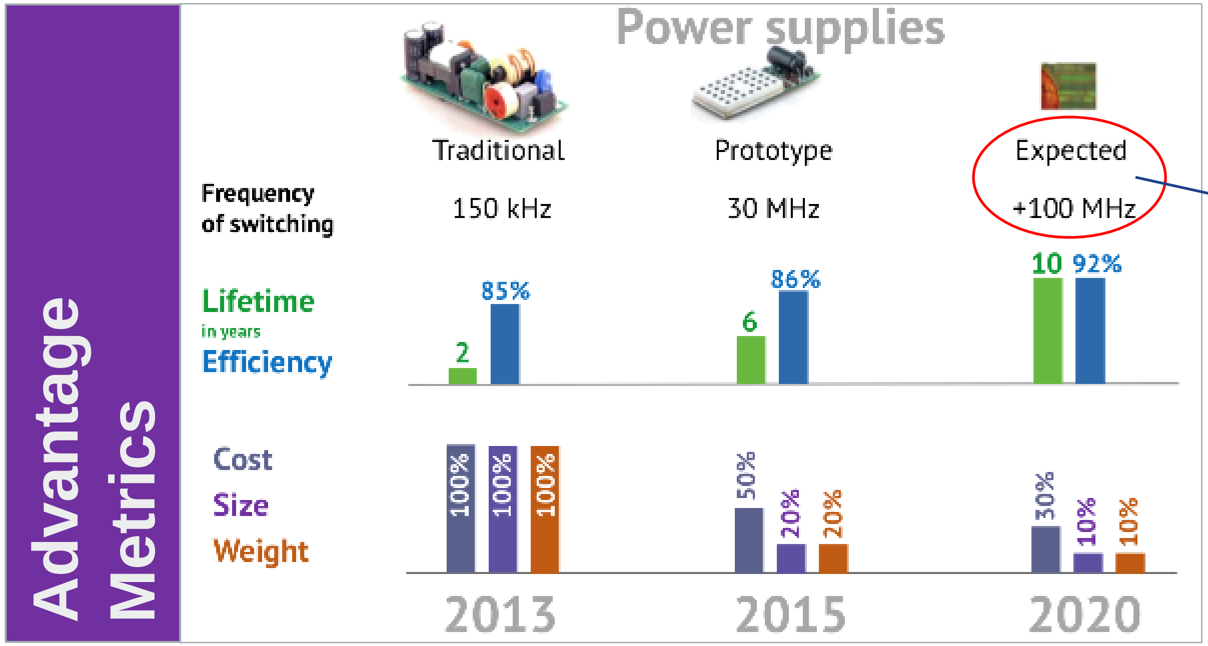
Semiconductor: Si? or GaN, SiC?
Heterogenous (and 3D) **integration**
Diversification: More-than-Moore
High-FOM **materials** for passives

Innovation in Magnetics

Market PULL

Mobility: Affordable power electronics
Energy: Efficient power conversion
Health: Smart implants and wearables
Digital: Powering the processors

This is the way forward



Alex Avron, Power-supply-on-chip conference 2016

Future strategic research focus: to be on 'wafer integration' of magnetics

Magnetics Present and Future Application Space

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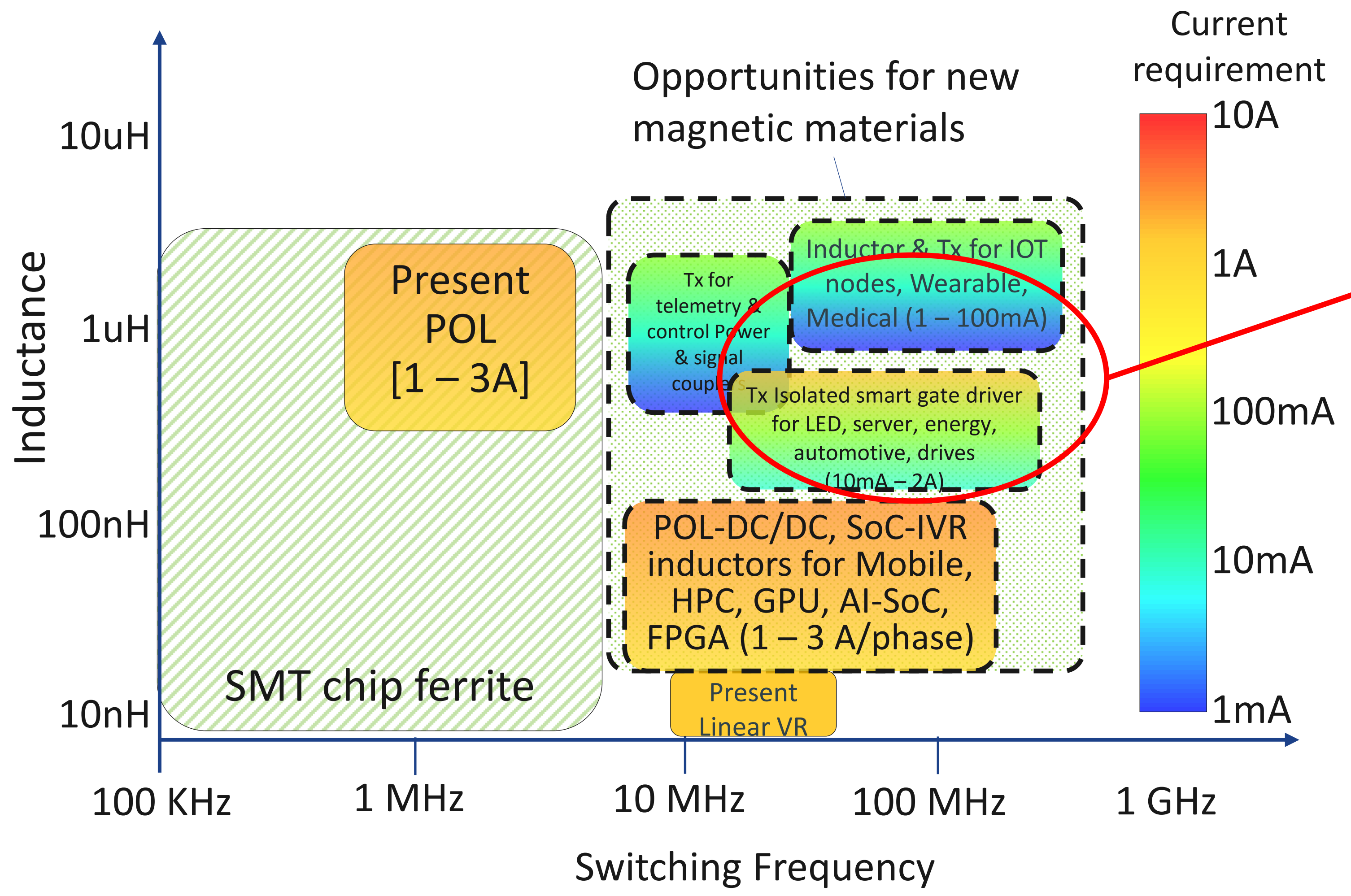


Opportunities for developing devices for applications requiring:

- low-power
- high-frequency
- high-inductance

Need innovation in magnetic materials and their integration

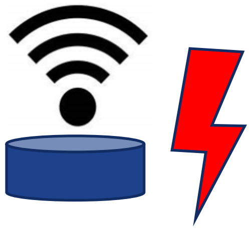
Case study #1:

A miniaturized coupled inductor for a low-voltage cold start circuit designated for integrated energy harvesting smart sensor node

The Power IoT Challenge

We MUST find ways to make batteries last longer – how?

- Make batteries that supply more energy
- Reduce power consumption of the IoT device
- Use ambient energies – Energy Harvesting

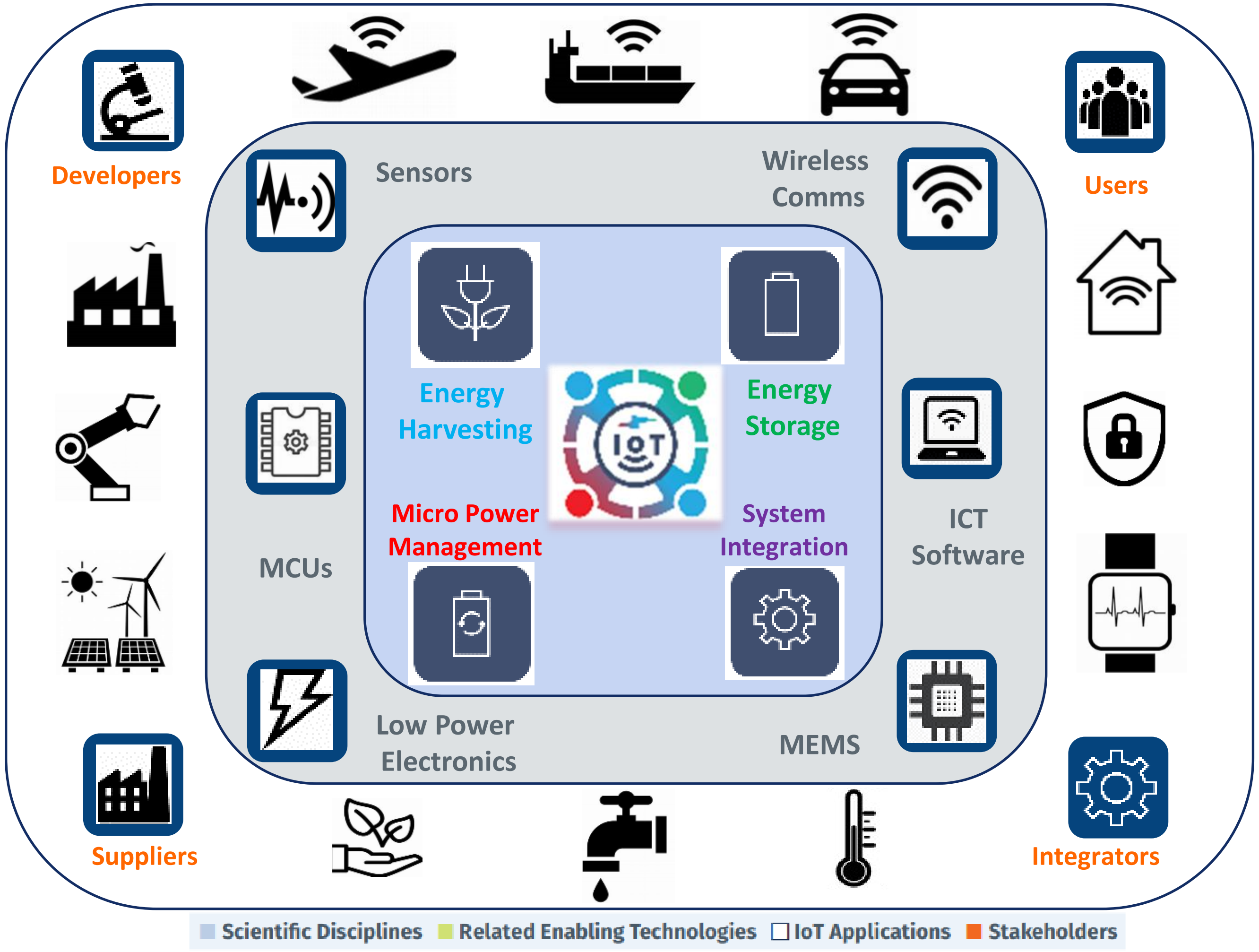


Heat (thermoelectricity)

Vibration/kinetic

Solar (PV)

We need a Power IoT ecosystem

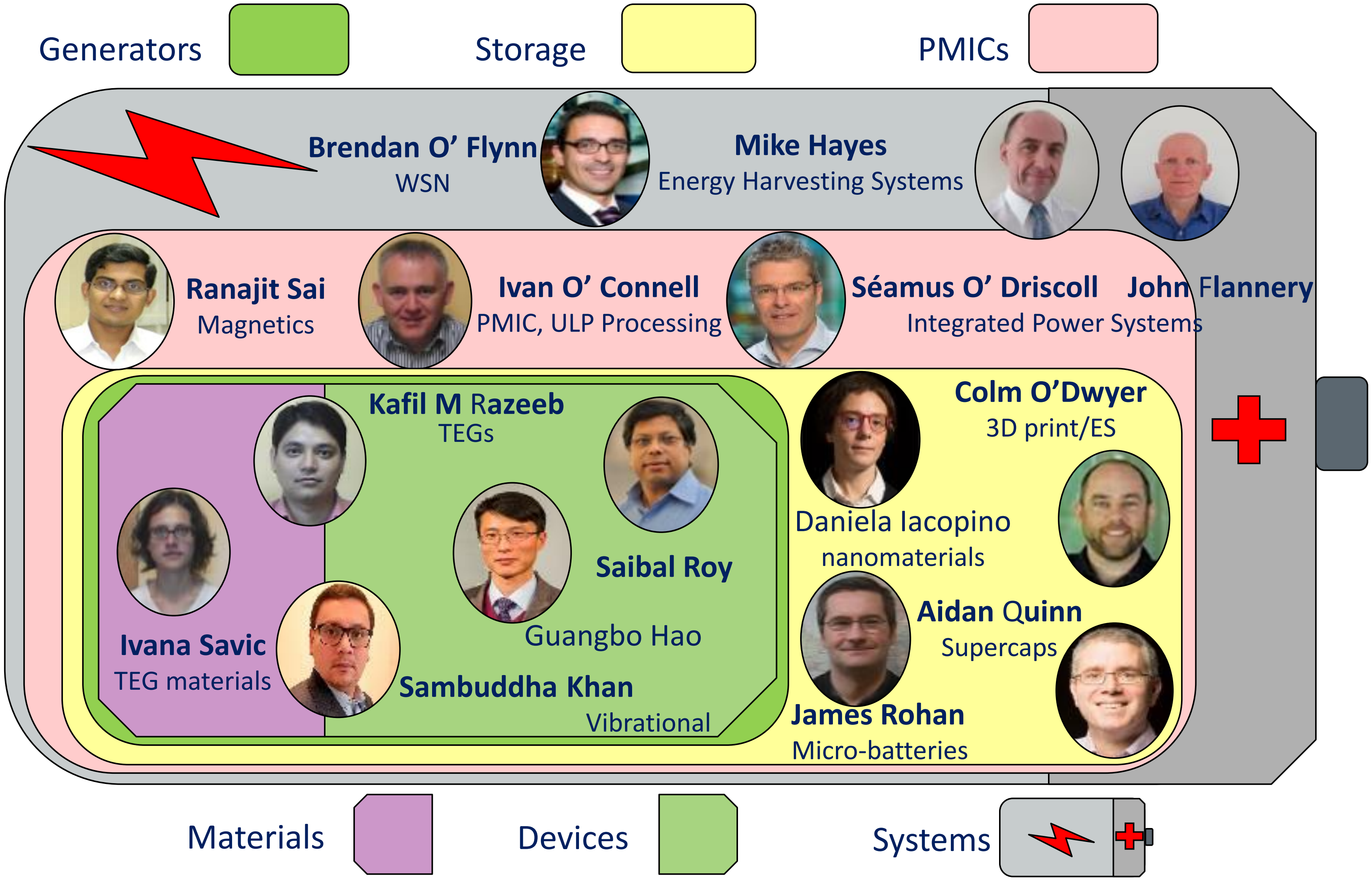


Driven by the EU EnABLES project

PSMA has been a key collaborator in building this ecosystem

Tyndall already has an Ecosystem of ‘Energy for IoT’ PIs

(but we also need external collaborators)

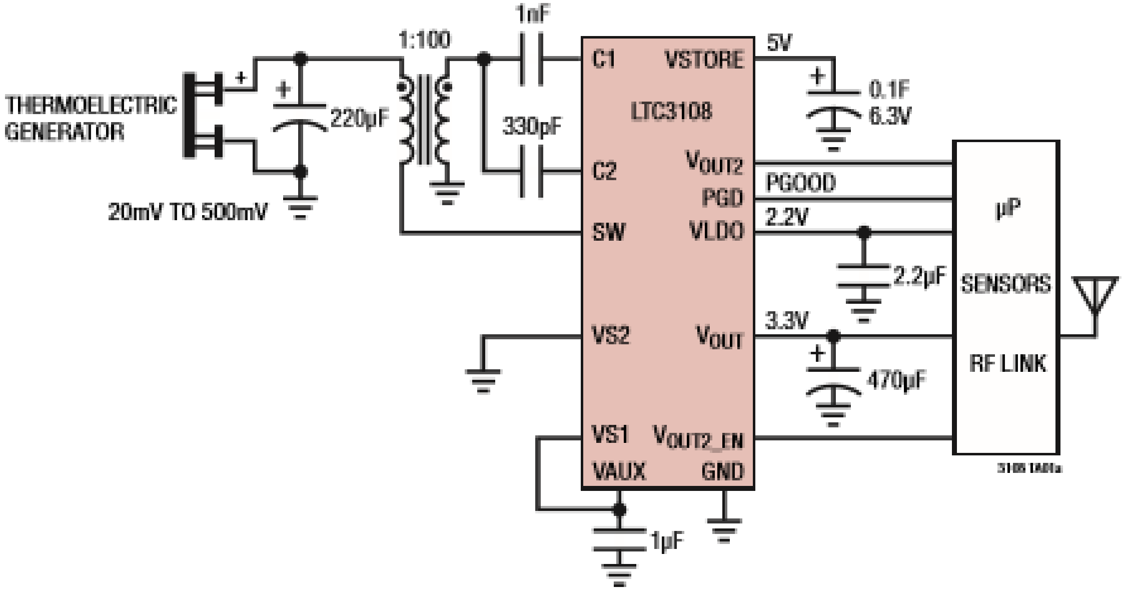


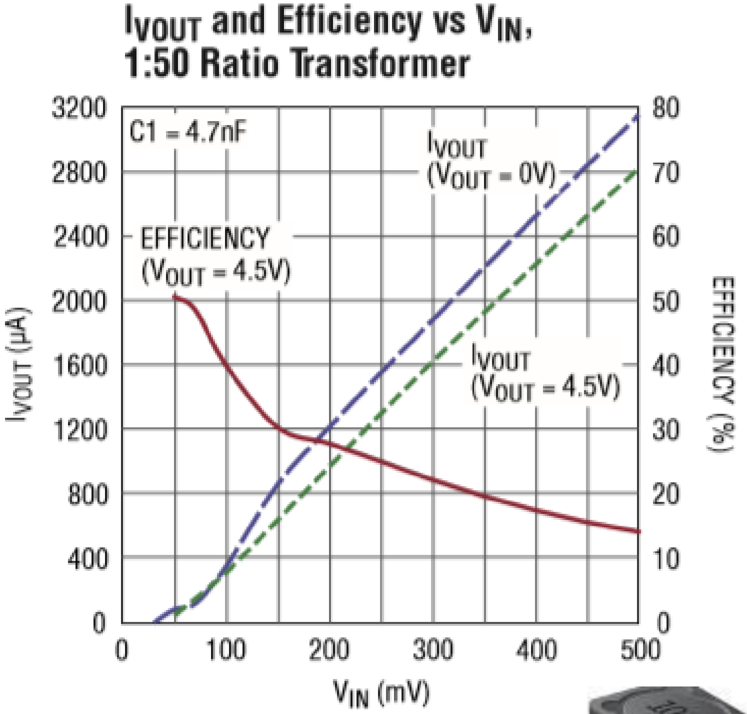
Commercial Low Voltage Cold Start

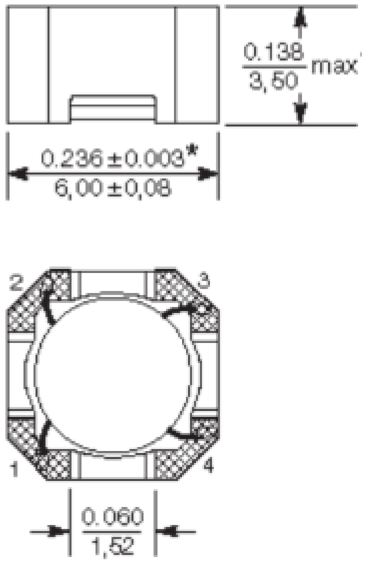
For integrated energy harvesting smart sensor node

ANALOG DEVICES | POWER BY LINEAR

LTC3108







Common commercial solution for 20 mV starting

- 1:100 Tx => Start-up at 20mV, Iin > 3mA
- f0 recommended 10 – 100 kHz
- Resonant 1:N coupled-inductor is relatively huge at 6 X 6 X 3.5 mm

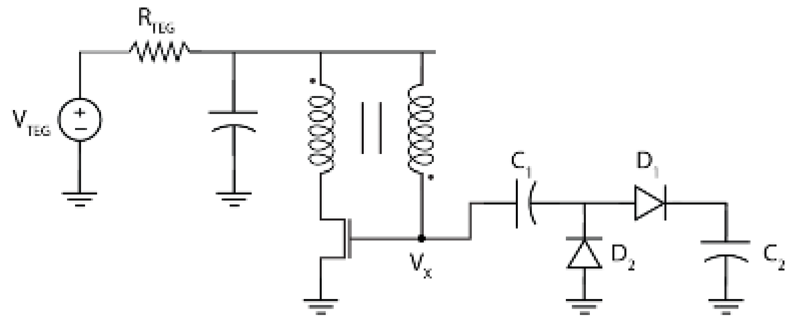
https://www.analog.com/media/en/technical-documentation/data-sheets/LTC3108.pdf

Our goal: to make these coupled inductors disappear..!!

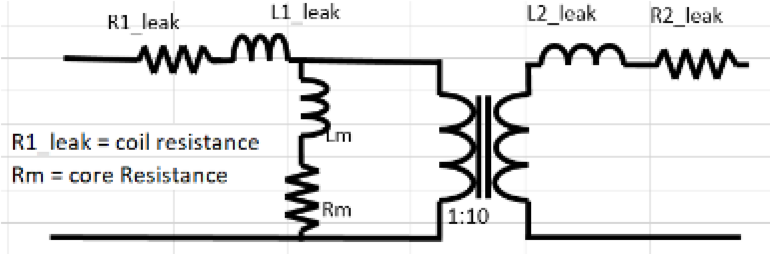
Meissner Oscillator based Low Voltage Cold Start

ONE of TWO types of coupled inductors: Thin-film Magnetics-on-Silicon

Meissner Oscillator

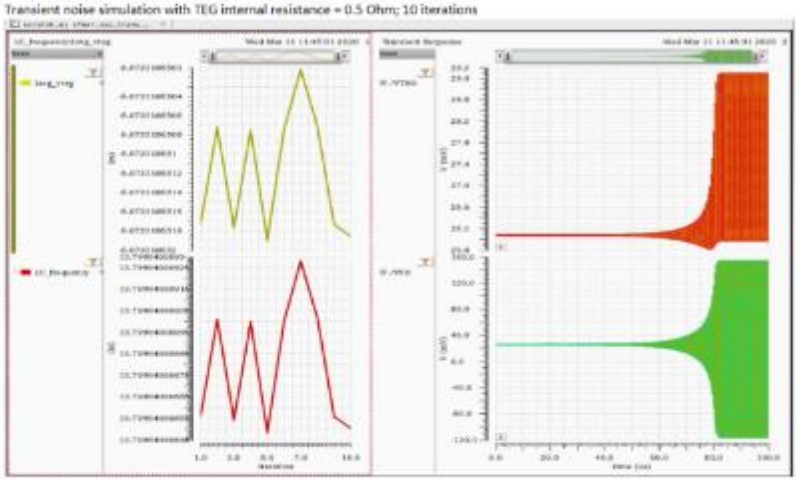


	100 Hz	15 MHz	20 MHz
Lm [nH]	4	16.4	18.7
L1_leak [nH]	4	19.2	19.1
L2_leak [nH]	100	90	80
Rm [Ohm]	0.001	0.261	0.972
R1_leak [Ohm]	0.049	0.53	0.568
R2_leak [Ohm]	0.8	6.7	7.8

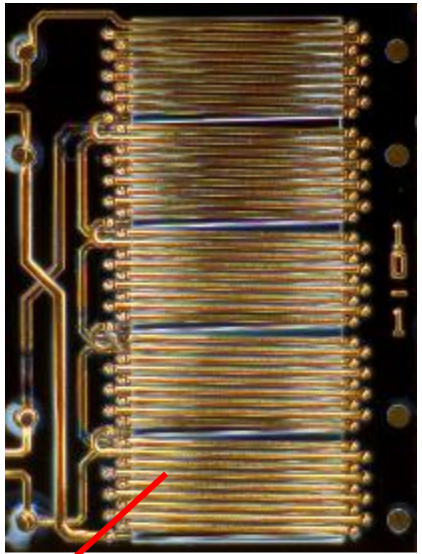


180 nm CMOS simulation using measured S Parameter Model:

- 14 MHz = f0
- 4.2 mA Iin @ 30 mV (SCH)
- 200 X 100 um Dep.
- Device k ~ 0.65



Feature	Dimension
Cu trace width	80 um
Cu trace thickness	16 um
Via diameter	100 um
Bond-pad diameter	160 um
Die size after dicing	4×5.2 mm^2
Die size before dicing	4.6×5.9 mm^2



Magnetics-on-Silicon coupled inductor

EU H2020 Grant No. 730957

Tyndall Cold–Start Coupled Inductors

Thin-film Magnetics-on-Silicon

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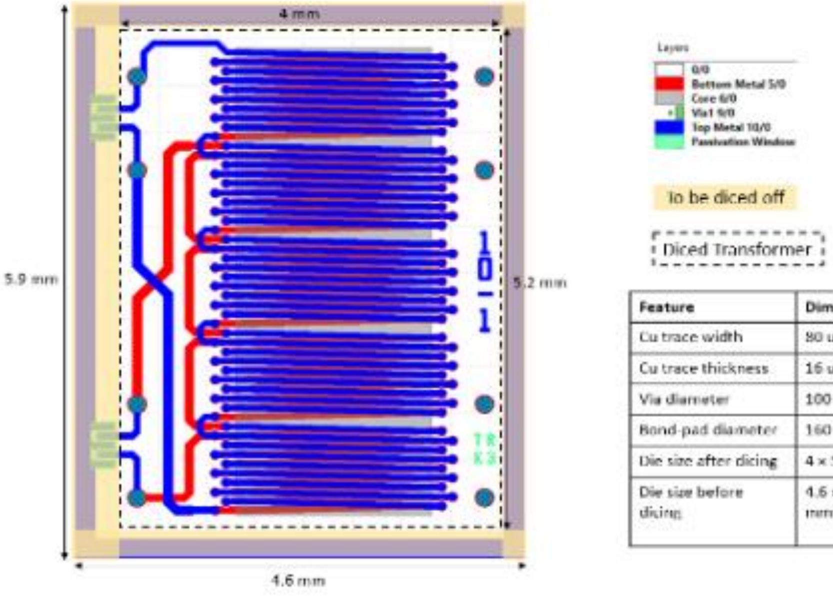
Planar solenoidal thin film Magnetics-on-Si

- 4” Wafers fabricated in Tyndall
- Core = 16 laminations of Co-Zr-Ta-B = ~4 µm
- Magnetising Inductance, (Lmp) ~ 20 nH (4:40 turns)

Structure of the Fabricated Core



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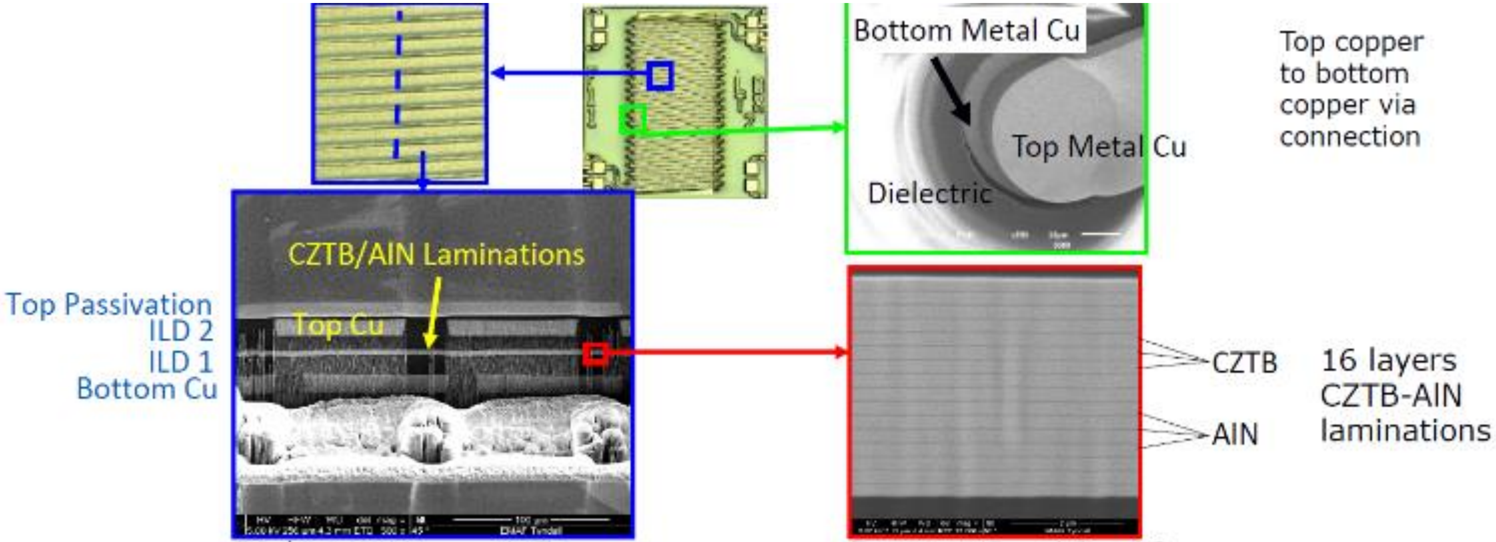


Dielectric 1 1.5um
Adhesion Layer 20nm
Laminated Core 4.8 um

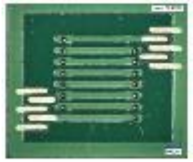
Bottom Cu 16 - 18um
Top Copper 14 - 16um
Cu Via interconnect 14um

Tyndall Cold–Start Coupled Inductors

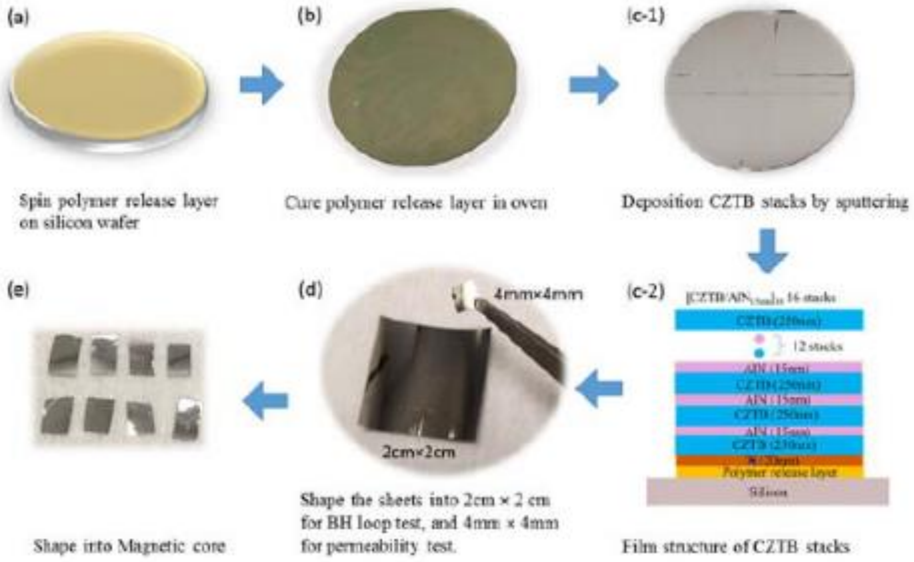
PCB-embedded coupled Inductors

Multi-Layer CZTB in Flip Chip PCB

- Solenoidal inductor device design
- Enables 70+ um Cu thickness
- Retains high Q at 40 MHz (Q= 23)
- Cost effective Flip Chip approach
- Good DCR



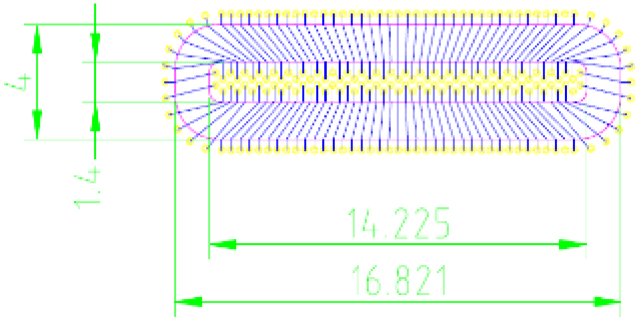
2 X 2.8 mm CZTB film



D. Jordan et al, "High Q-Factor PCB Embedded Flip-Chip Inductors with Multi-Layer CZTB Magnetic Sheet for Power Supply in Package (PwrSiP)", DOI 10.1109/JESTPE.2020.2983125

PCB Embeddable Planar Toroidal Inductor

- 1:100 shown, 4 mm X 17 mm, (1:40 is half size)
- Commercial magnetic material (3M EM15TF grade ferrite sheet)
- I_{MAG} = 2 mA, I_{in} = 6.6 mA, 7.5 MHz, Vin= 20 mV (SCH SIM)



PCB Embedded Magnetic Sheet Material based magnetic devices enable "disappearing" the coupled inductor into the system PCB core.

Summary of CMOS SCHEMATIC Simulated Performances

Various Cold Start Block Designs

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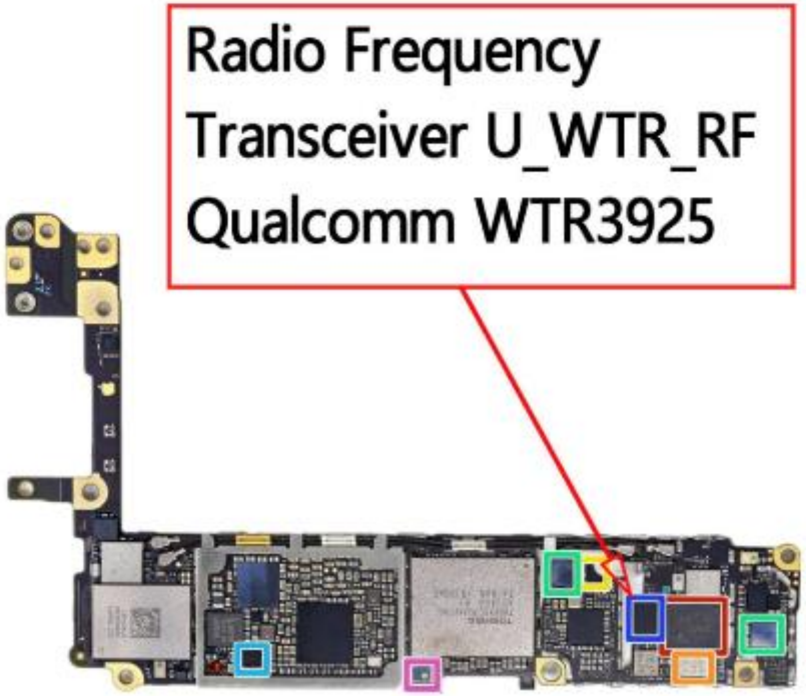
Architecture	Vsu	Psu	I_load	Estimated On-chip area	Estimated Off-chip area PCB Embedded (ECP) Magnetic Device technology
RO LVCS only	175 mV	5.3 uW	60 nA	3mm x 1mm	None
Meissner Oscillator LVCS with thin-film magnetics-on-silicon (MoS) Tx	80 mV	500 uW	60 nA	2mm x 1mm CMOS 6mm x 4.5mm MoS 1:10 turns	CMOS BEOL Compatible – over PMIC top metal layer
Meissner Oscillator LVCS with ECP Tx	40 mV	240 uW	60 nA	2mm x 1mm CMOS	16mm x 4mm 1:100 turns PCB ECP
LC LVCS	150 mV	15 uW	36 nA	200u x 200u	16mm x 4mm PCB ECP 50:50 turns

- Commercial 180 nm PMICs achieve RO (ring oscillator) LVCS at ~ 400 mV.
- Using larger devices and operating in sub-threshold region, RO LVCS start-up at ~ 200 mV can be achieved
- The thin film sputtered inductor in planar solenoidal format poses difficulty in achieving high turns ratio and coupling factor. But, start-up voltage capability of 80 mV can be achieved

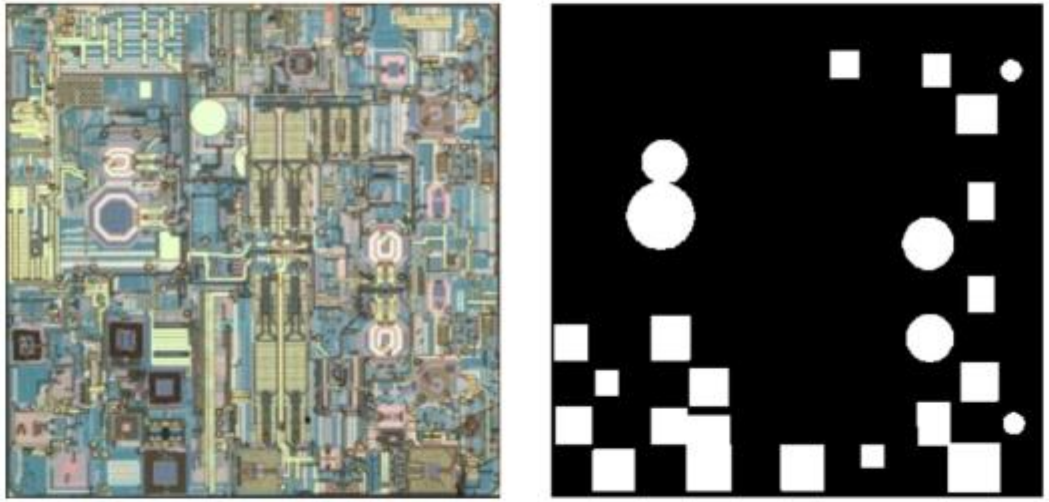
Case study #2:

An on-chip planar inductor with a ferrite film core

Inductors Consuming a Lot of Space in Modern Electronics

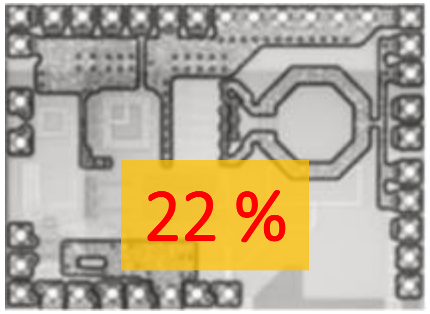


iPhone 8 teardown

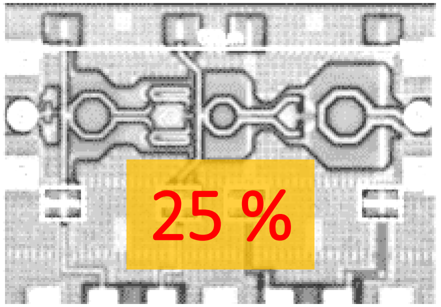


QUALCOM WTR 3925: Multimode RF transceiver for LTE; Fabricated with 28 nm CMOS technology node

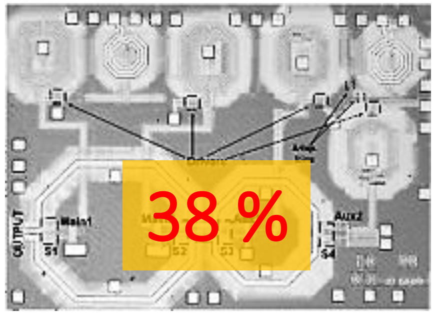
15% of chip area - consumed by just 24 inductors



4G CMOS power amplifier



28 GHz 5G phase array

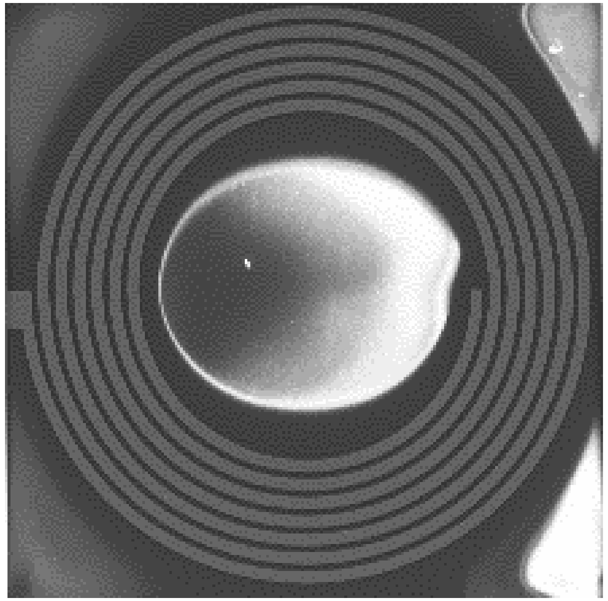


Doherty LTE power amplifier

All commercial on-chip GHz inductors today are 'air core'… why??

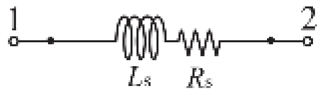
Understanding On-chip Inductor … operating at 10s of GHz

On-chip Inductor

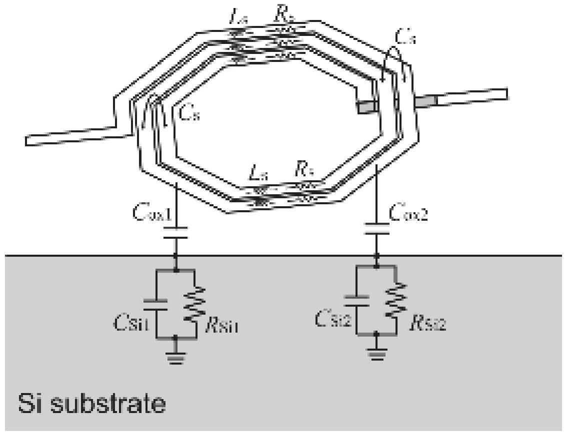


$$L = K_1 \mu_0 \mu_r \frac{N^2 D_{avg.}}{(1 + K_2 \rho)}$$

L = Inductance
K_1, K_2= Layout dependent coefficient
N = Number of turns
$D_{avg.}$= $(D_{in}+D_{out})/2$
ρ = Fill factor: $(D_{in}-D_{out})/(D_{in}+D_{out})$



Here comes "The Magnetic Material"
The search for a suitable magnetic material and a suitable process to integrate it on-chip



Physical model

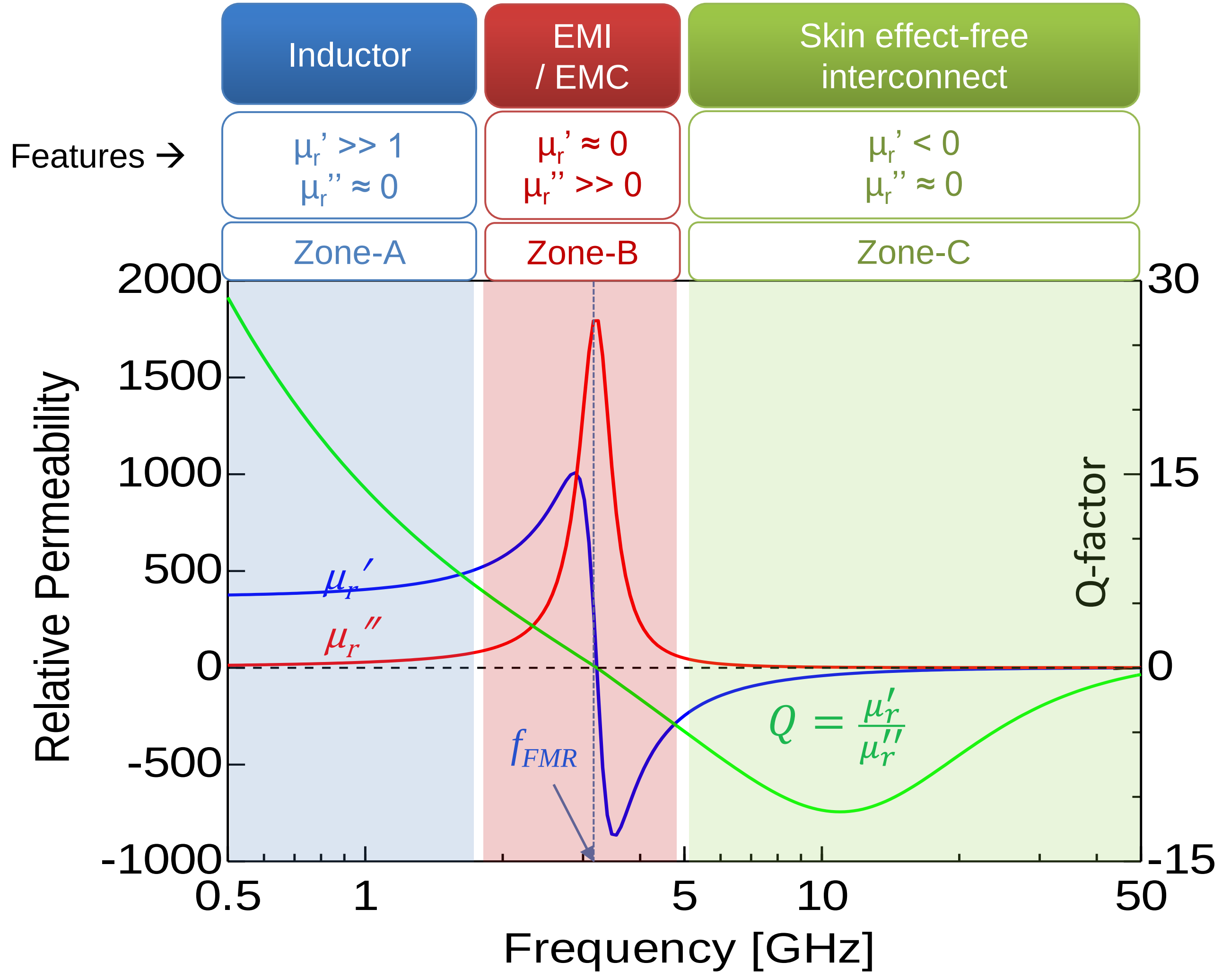
Special Process Requirements:

- Need a thin (~1-5 μm) and continuous film on the coil and core
- The film should be smooth and uniform
- The film should be strongly adherent
- The process temperature **<400 °C** (to be compatible for BEOL)

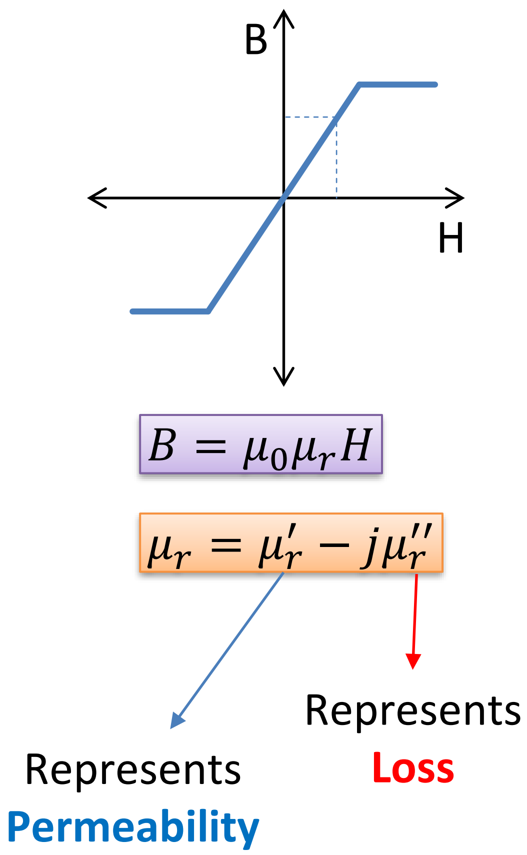
Let's search for a material and a process

High-frequency Magnetic Characteristics

The frequency dependent **complex permeability** of the magnetic body



FeCoBN film, Kim et al. J. Appl. Phys, 2006



Find a magnetic material that suits – or MAKE one if unavailable

Choosing an Appropriate Magnetic Material

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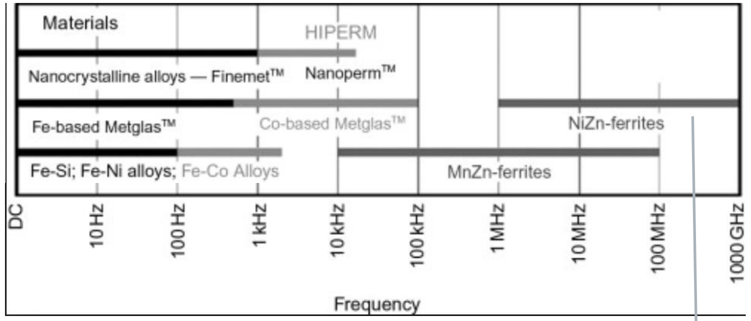
For high (>10 GHz) FMR frequency

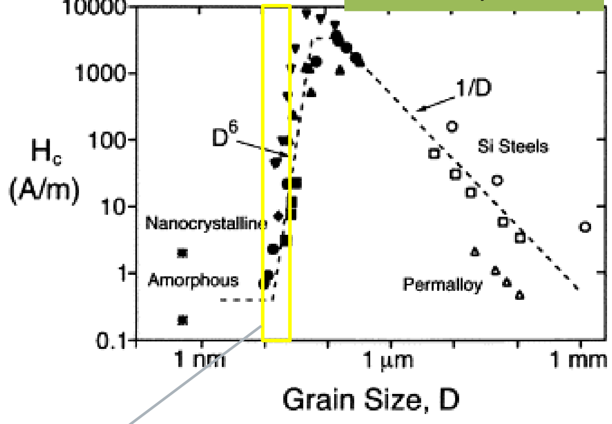
Ferromagnetic resonance frequency of various materials



Willard et al., Handbook of Magnetic materials, Vol. 21, pp. 173, 2013

For low-loss (no H_c)

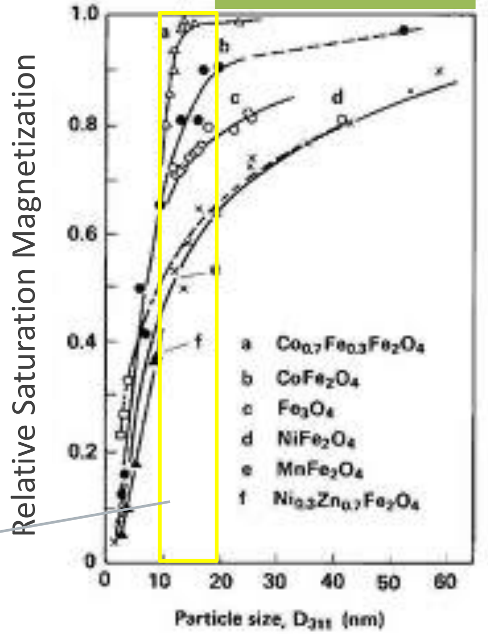
Coercivity vs. size



G. Herzer, IEEE Trans. On Magneics, 25, 5, 1990, Pages 1397-1402 ▲
M.E. McHenry et. Al., Acta Materialia, 48, 1, 2000, Pages 223-238 ▶

For high μ_r'

Moment vs. size



Ferrites are the best hope for FMR >1 GHz

- But can they be useful >10 GHz (the upcoming 5G bands)?

Particle size ~10-20 nm is the best to stem loss while retaining meaningful permeability

- Therefore, we need **nanoferrites**

How resonance in spinel ferrites can exceed their natural FMR?

Spinel Ferrite Structure and Its Magnetism

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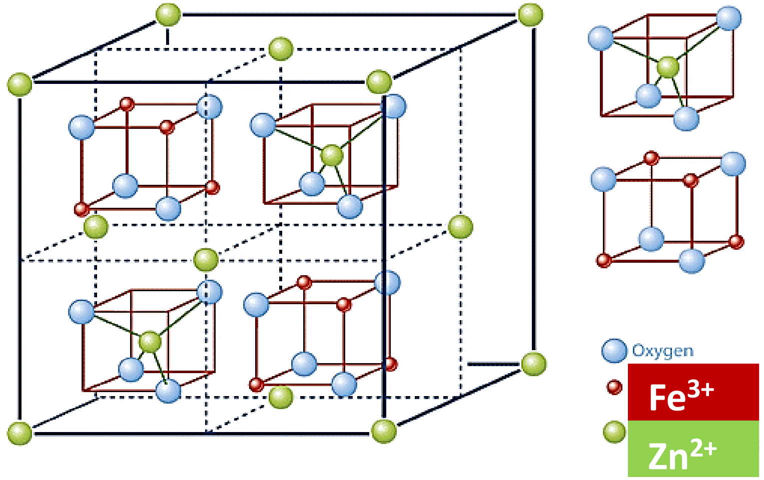
Zinc ferrite (ZF) structure: Normal Spinel



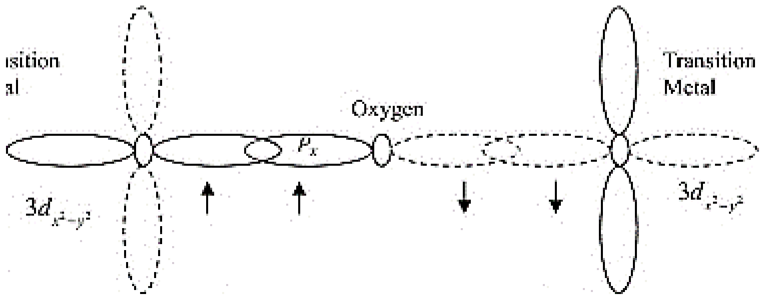
Tetrahedrally coordinated **A-sites**: 64 available; 8 occupied

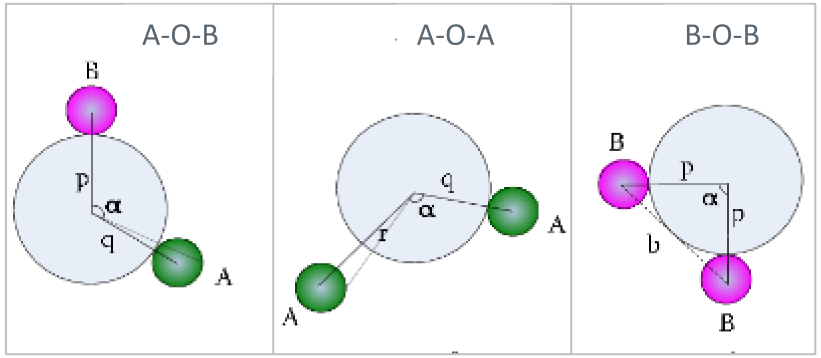
Octahedrally coordinated **B-sites**: 32 available; 16 occupied

Normal Spinel: $(Zn^{2+})[Fe^{3+}_{2}]\,O_4$
Partially Inverted Spinel: $(Zn^{2+}_{1-x}\,Fe^{3+}_{x})[Zn^{2+}_{x}\,Fe^{3+}_{2-x}]O_4$
Inverted Spinel: $(Fe^{3+})[Ni^{2+}\,Fe^{3+}]O_4$

'x' is inversion; $0 \leq x \leq 1$

Origin of Magnetism in Spinel Ferrites: Superexchange





Bond lengths matter → smaller is better

Bond angles also matter → Co-linear is the best

$$\mu_{B(Net)} = \mu_{B(A\text{-}site)} - \mu_{B(B\text{-}site)}$$

f_{FMR}>10 GHz in Spinel Ferrite: Our Way

Inversion-induced up-shift of ferromagnetic resonance (FMR) frequency

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Generally, bulk spinel ferrites exhibit FMR ≤100 MHz

Nanostructured spinel ferrites exhibit FMR ≤1 GHz

Now, change of cation distribution other than that in the bulk is against the thermodynamically equilibrium condition, BUT can lead to unusual characteristics

We needed a 'far-from-equilibrium' condition to achieve extreme inversion, and thus, f_{FMR} >10 GHz

Normal Zinc Ferrite: $(Zn^{2+})[Fe^{3+}_{2}]O_4$ ⟶ Antiferromagnetic

Partially inverted zinc ferrite (piZF): $(Zn^{2+}_{1-x}Fe^{3+}_{x})[Zn^{2+}_{x}Fe^{3+}_{2-x}]O_4$ ⟶ Ferrimagnetic

Can we expand the range of applicability of spinel ferrite family

Zn-ferrite, MnZn-ferrite, Ni-ferrite, NiZn-ferrite, etc.

Microwave-Assisted Solvothermal Deposition (MAS-D) Process Design

A typical recipe – developed for piZF film deposition

Precursor A
Zinc(II)-acac

Reaction Mixture

Precursor B
Iron(III)-acac

Solvent
Ethanol + 1-decanol
(3 : 5 vol. ratio)

Substrate loading

Microwave
Irradiation

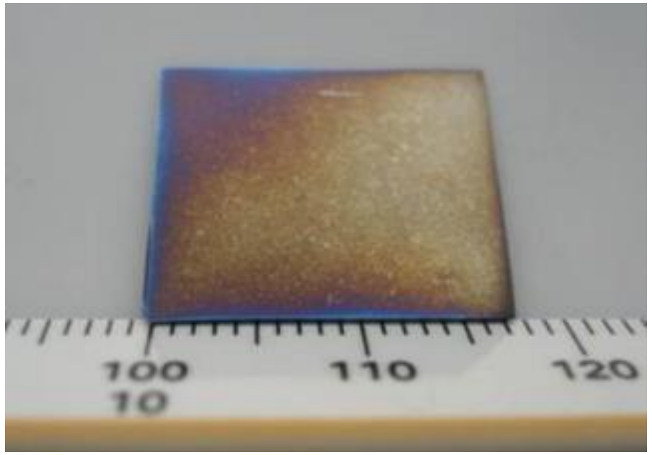
CEM-Discover (FMW)
300 W; 5 min
190 ° C, 200 psi

Thin Film of piZF on the substrate
($ZnFe_2O_4$)

Further readings on recipe development:

R. Sai et al., J. Mat. Chem., 22, 5, p2149 (2012)
R. Sai et al., MRS Proc., 1400, s-06 (2012)
R. Sai et al., MRC Proc., 1386, d-07(2011)
R. Sai et al., J. App. Phys., 117, 17, p17E511 (2015)
R. Sai et al., RSC Advances., 5, 14, p10267 [2015]

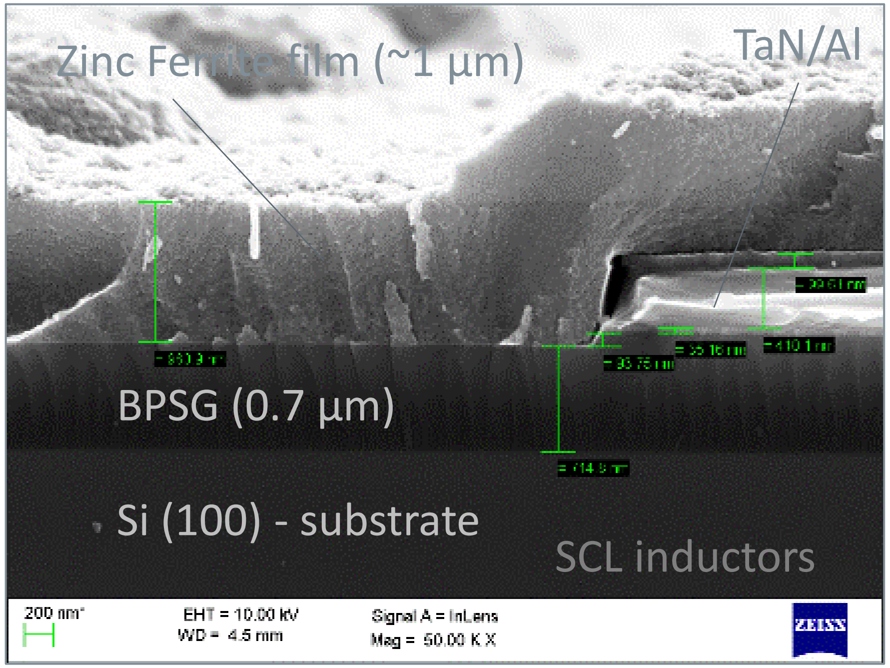
Deposition system

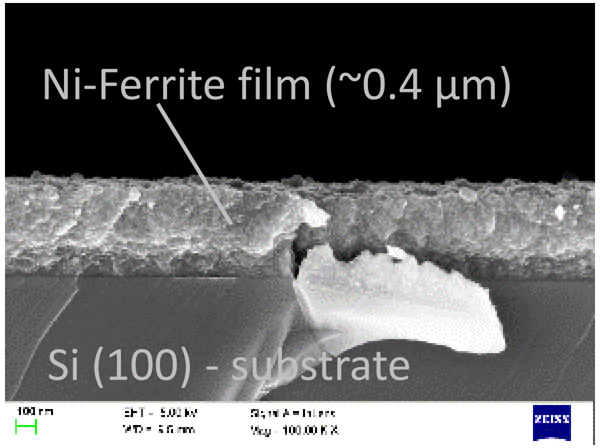


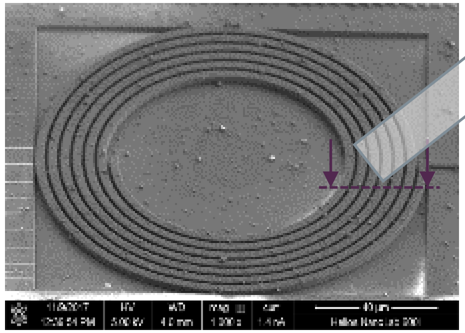
piZF deposited on Si (100) substrate

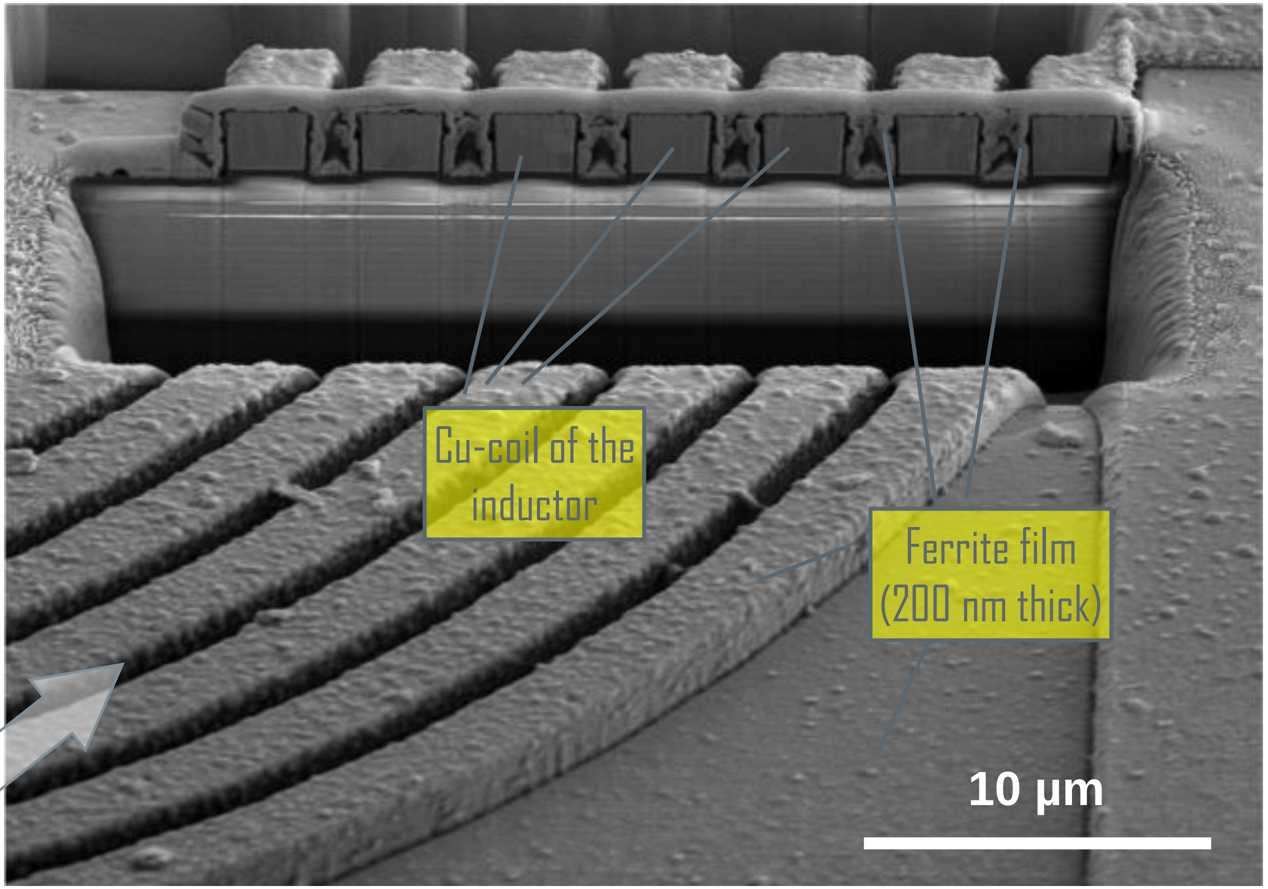
Our Ferrite-film Technology (MAS-D)

For On-Chip Applications









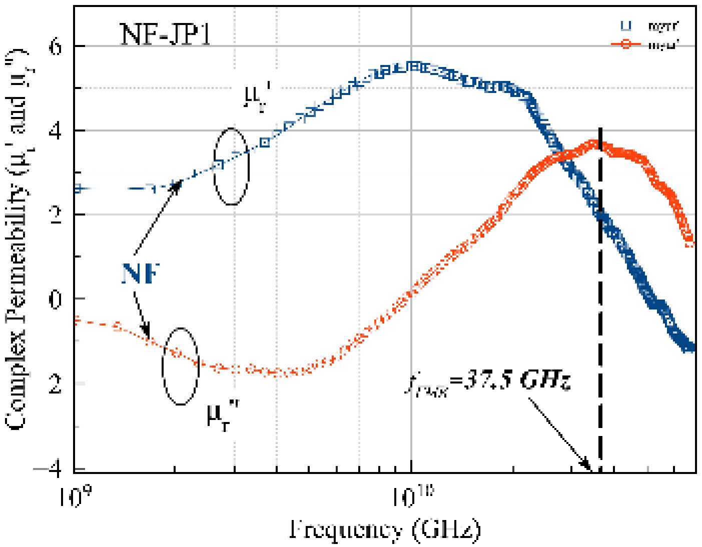
Ferrite film on M6 of Si-CMOS chip (UMC, Taiwan)

Deposited by Microwave-Assisted Solvothermal Deposition (MAS-D)

Excellent High Frequency Properties

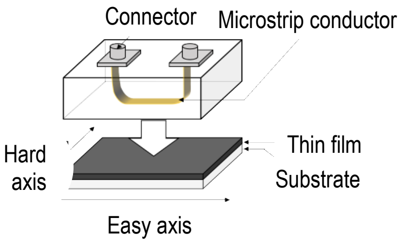
Crystal-engineered ferrite films exhibiting FMR >10 GHz

Ni-ferrite (37.5 GHz)

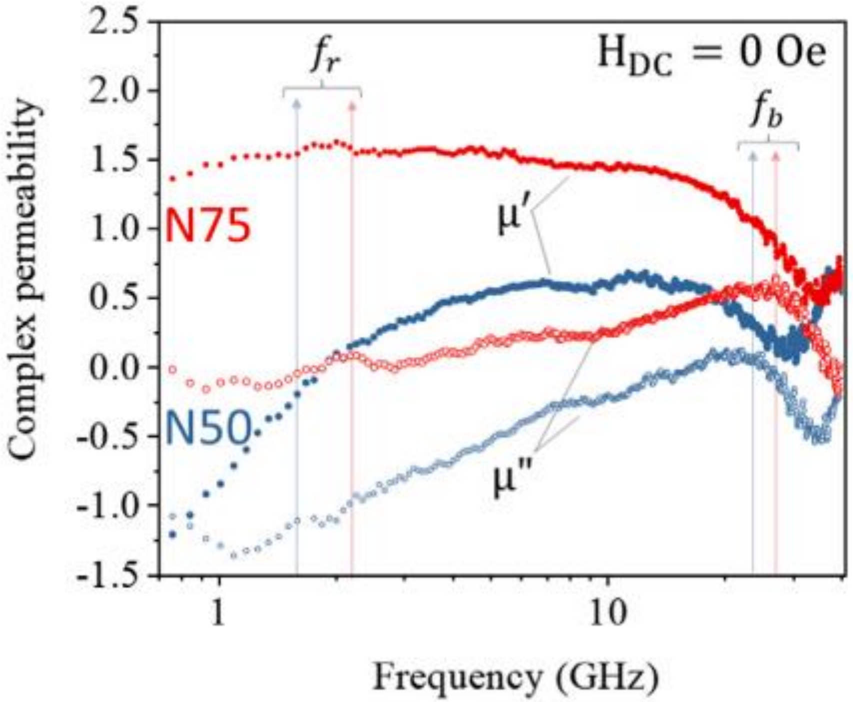


S. Yabukami, … R. Sai et al., 10.1109/TMAG.2020.3011971, (2020)

μ-f measured by microstrip probe (43 GHz)



T. Kimura *et* al., J. Mag. Soc. of Japan, 38, 3, 2014, pp. 87.



S. Arackal, R. Sai et al., Appl. Phys. Lett. 121, 062402 (2022)

f_r: ferromagnetic resonance freq.
f_r: Superparamagnetic resonance freq.

N75: $Ni_{0.75}Zn_{0.25}Fe_2O_4$
N50: $Ni_{0.50}Zn_{0.50}Fe_2O_4$

Presence of superparamagnetic resonance that exceeds ferromagnetic resonance keeps the permeability high at a very high frequency

Results – Enhanced Inductance and Q-factor

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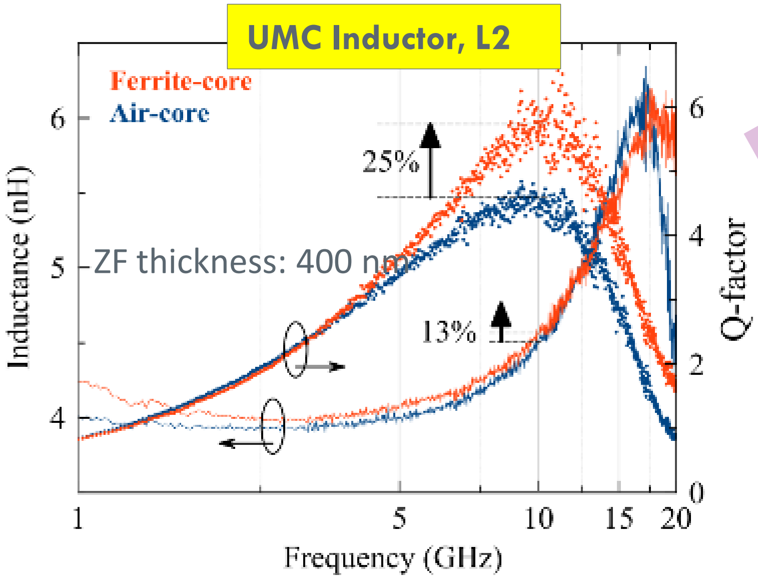
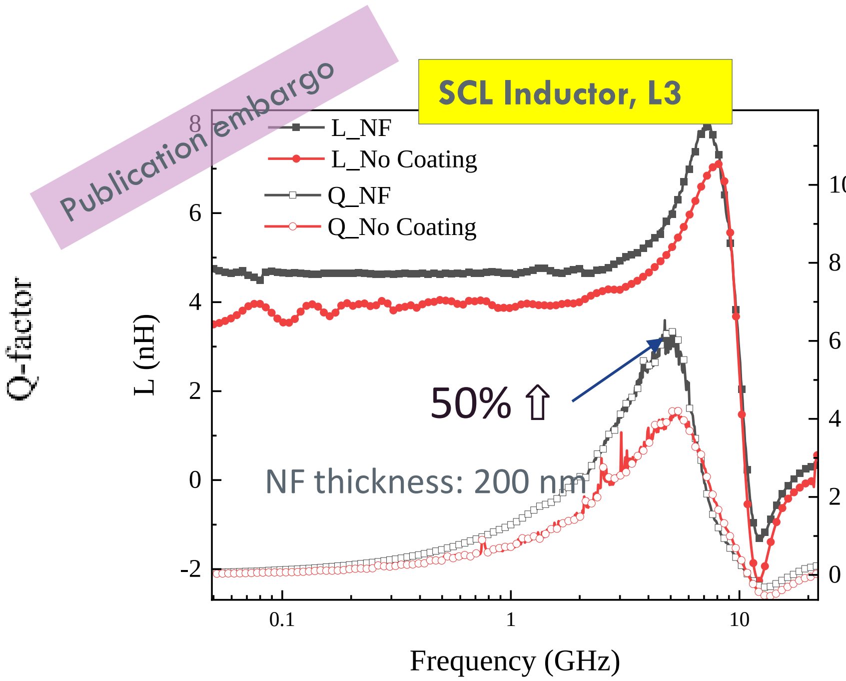
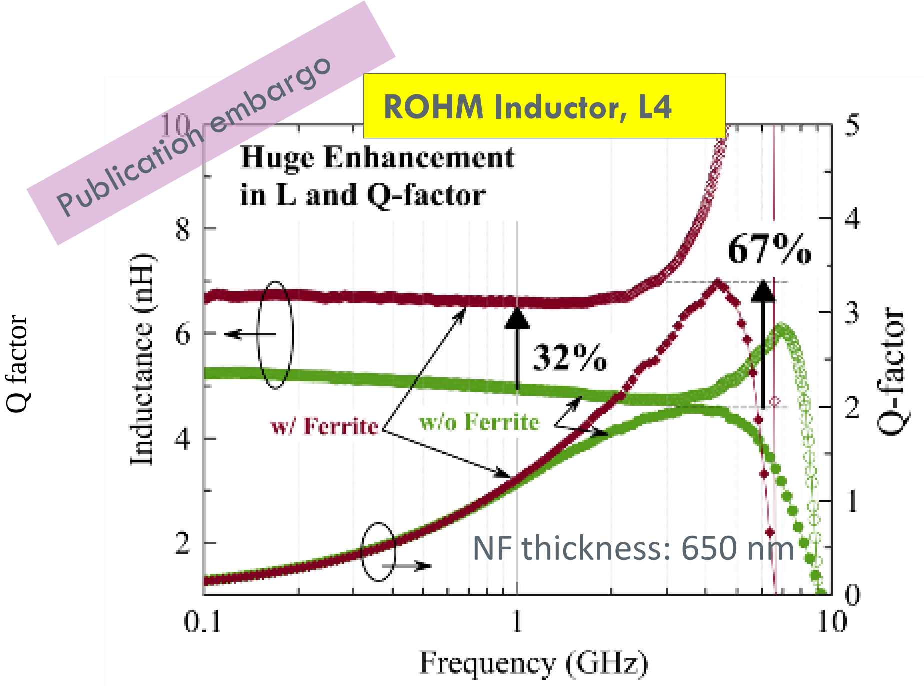


R. Sai et al, IEEE Mag. Lett., 8, p1, (2017)





	L2	L3	L4
Inductance:	13% ⇧	16% ⇧	32% ⇧
Q-factor:	25% ⇧	50% ⇧	67% ⇧

Significant enhancement in both inductance and Q-factor
Obtained above 5 GHz

Outlook:

What are the key requirements for ultra-low power integrated magnetics?

Key Design Parameters…

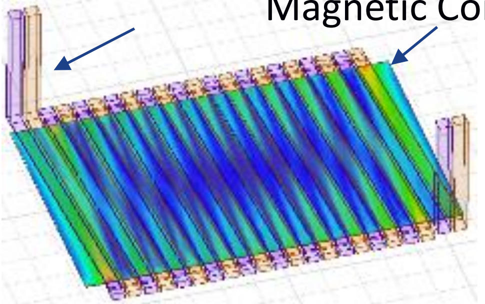
- **For Ultra low power IoT applications:**
  - Solenoid inductor vs. Stripline inductors
  - Why High permeability material needed?
  - Why high-resistive materials preferred?

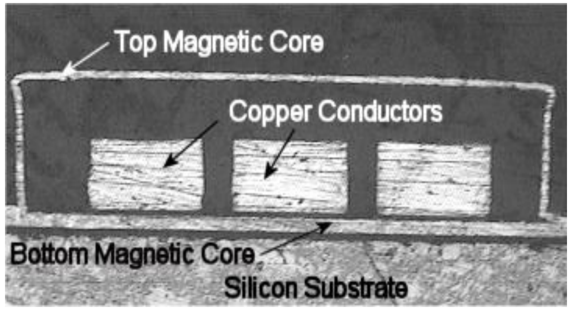
Key Design Parameters…

Solenoid vs. Stripline

Interleaved plated copper windings

Sputtered Magnetic Core





NiFe Racetrack shows core top and bottom

Solenoid:

- Lower cost single laminated core
- No multi-lamination magnetic vias
  - Higher Device Q but there will be near-field EMI/Loss (Lower System Q)

Strip-Line:

- Closed core construction
- Lower Device Q, higher System-Q
  - Greater material & out-of-plane eddy loss
- Low DCR, High I_{SAT}, Lower L/mm^2

Parameter	CZTB Planar Solenoid – Fabricated Example	CZTB Strip Line – FEM Design Example
Cu thickness	2 X 15 µm	1 X 30 µm
Core thickness	1 X 4 µm	2 X 5 µm
nH/mΩ	0.6	~ 1.2
nH/mm^2	10	~ 2.0
Qss	24 @ 30 MHz	21 @ 100 MHz
I_{SAT}	0.9 A	5 A

Key Design Parameters…

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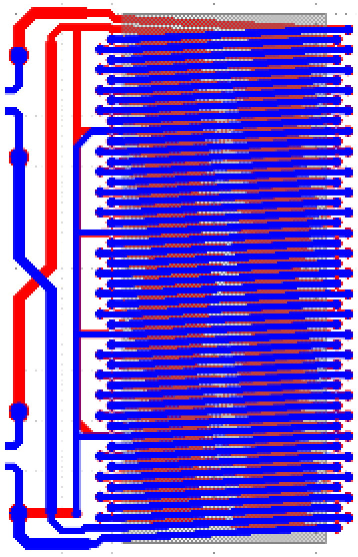
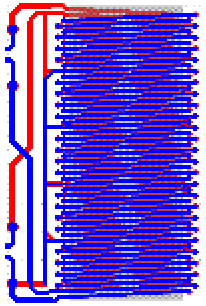
Why high-permeability needed?

Higher relative permeability allows high turns ratio transformer within small footprint for energy harvester power conversion in IoT applications.

Core permeability
µr = 500



Core permeability
µr = 1500



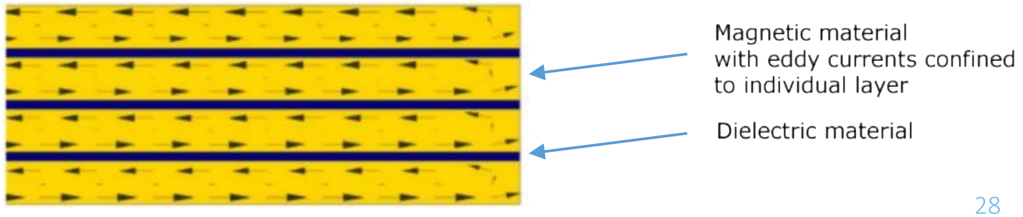
- ➢ 70 - 80% reduction in footprint
- ➢ Reduced size
- ➢ Lower cost
- ➢ Higher turns ratio (1:20 or higher) i.e. less turns required on primary and hence more room for secondary

Why high-resistivity needed?

- Present state-of-the-art materials (CZT, CZTB) are used in laminated stacks with layer thicknesses ~200 nm.
- This thickness is well below material skin depth at current frequencies
  → Very effective in suppressing eddy current loss.
- High resistivity (> 200 µOhm-cm) of material offers:
  - Further reduced high frequency eddy current loss
  - Thicker magnetic layers in laminated stack
    → Reduced processing cost
  - Higher relative permeability with same skin depth

Skin depth $= \sqrt{\dfrac{\quad}{\quad 0 \quad r}}$

Where, ρ = Resistivity
f = frequency
$\mu_0 = 4\pi \times 10^{-7}$ H/m
μ_r = Relative permeability



Conclusions

- **For low-voltage cold start circuit designated for integrated energy harvesting smart sensor node:**
  - The thin film integrated magnetics in planar solenoidal format offer **THREE times lower** voltage cold start than the best commercial ring oscillator
  - Both **thin film magnetics** and **PCB embedded magnetics** simply disappear inside the chip or circuit board with minimal profile (~75 µm)
- **For on-chip ferrite-core inductor:**
  - Defect-engineered partially inverted nanocrystalline ferrite thin film offers some **permeability up to 20 GHz with insignificant loss.**
  - Up to **65% enhancement in Q-factor above 1 GHz achieved** in the ferrite-core on-chip inductors
- **Outlook:**
  - Need magnetic materials with higher permeability and higher resistivity.
  - A stripline inductor design is beneficial for handling larger current density

New Power Magnetics Ecosystem

Most of them are/were our collaborators…

Systems ▶

Silicon Foundries, OSATs, Heterogeneous Integration ▶

Discrete Passives ▶

System on Chip (SoC) ▶

PMIC ▶

Power Semiconductor ▶

Semiconductor Equipment ▶

Multi-€m licenses of advanced power technology to

- **2015: 2 of world's Top 5 consumer device companies**
- **2018: License to global semiconductor**

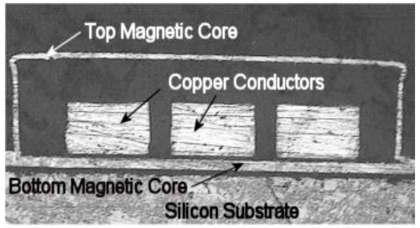
Integrated Magnetics @ Tyndall – in a nutshell

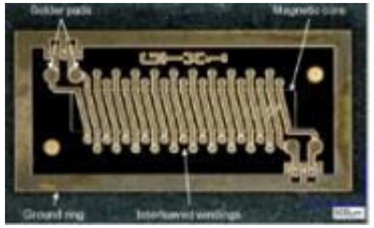
Achievements • Acknowledgements

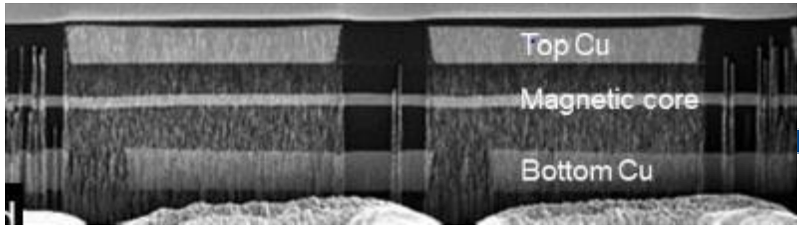
- 150+ Person years of effort | €30M+ Investment over 20 years
- Highest efficiency demonstrated for micro-inductors (93%) & micro-transformers (78%)
- First embedded inductor using electroplated magnetic core
- Founded International Workshop on Power Supply on Chip (PwrSoC)

Magicians and "Pain Killers" at Tyndall – past and present!

- Integrated Magnetics and Integrated Power Systems Teams
- Silicon Fabrication; Packaging & Integration
- Business Development; Finance; OCLA, Tyndall/UCC; UCC TTO







EARTO

European Association of Research and Technology Organisations

2021 Awards

Winner:

Tyndall National Institute

For:

Integrated Magnetics for Power Supply-on-Chip & Power Supply-in-Package (MagIC).

Award presented to

Cian Ó Mathúna,

October 27th, 2021

Top Awards

for Tyndall – Integrated Magnetics

Inaugural IEEE PELS Technical Achievement Award for Integration and Miniaturization of Switching Power Converters

Thank you for your kind attention…

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