Atlanta, GA

March 16-20

Georgia World Congress Center

Integrated Magnetics and Heterogenous Integration Enabling Vertical Power Delivery for High Performance Computing

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University College Cork, Ireland

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UCC
University College Cork, Ireland
Coláiste na hOllscoile Corcaigh

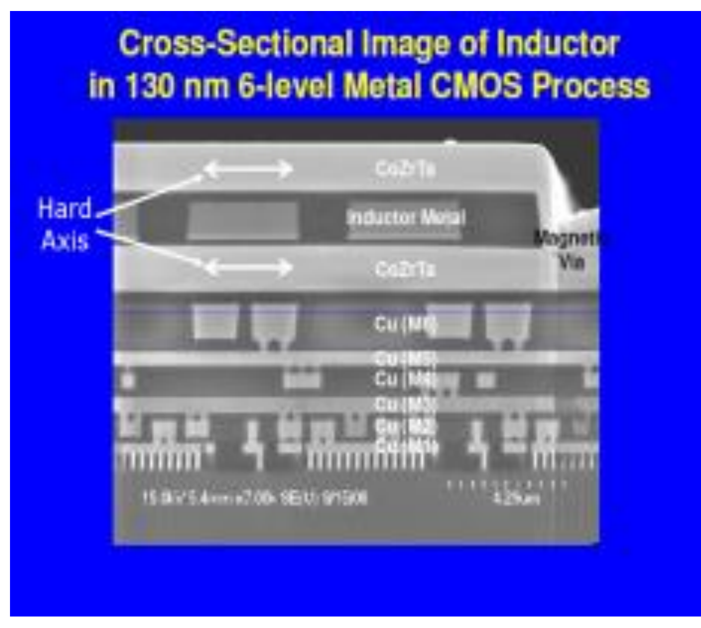
Enterprise Ireland

Summary of Talk

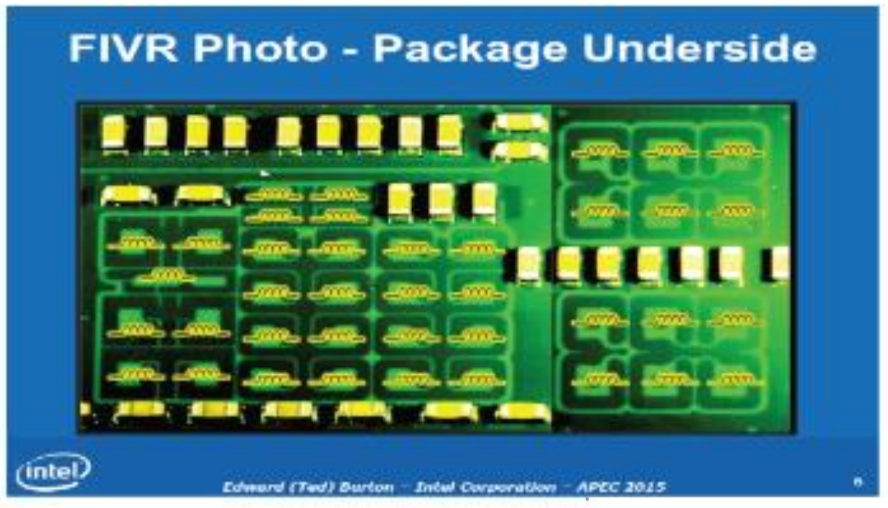
- **Commercial Emergence of Integrated Magnetics for Integrated Power**
- Integrated Magnetics Technologies
- Heterogeneous Integration and Chiplet Platforms for 2.5D and 3D Packaging of Integrated Power
- Key Challenges:
  - Technology
  - Supply Chain
- Conclusions
- Acknowledgements

Intel: Air Core Inductors for iVR

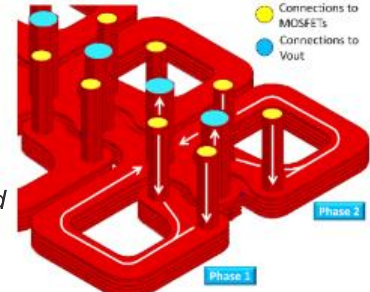
Ted DiBene PwrSoC2010



2014 **Fully Integrated Voltage Regulators (IVR)**



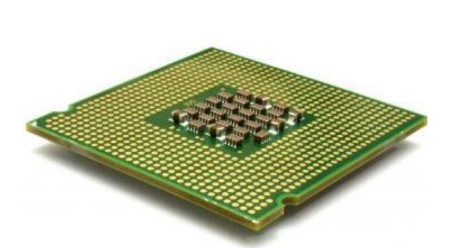
8 to 31 Rails, 49 to 360 Phases, 140 MHz, Air Core

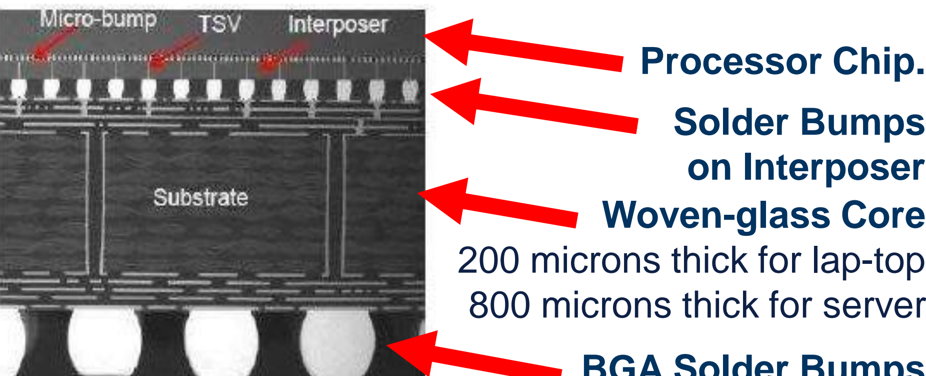


E. A. Burton *et al*., "FIVR — Fully integrated voltage regulators on 4th generation Intel® Core™ SoCs," *2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014*, 2014, pp. 432-439, doi: 10.1109/APEC.2014.6803344.

Intel 2021 - Magnetic Composite Inductor Array Technology

Substrate-embedded vertical co-axial construction





Processor Chip.

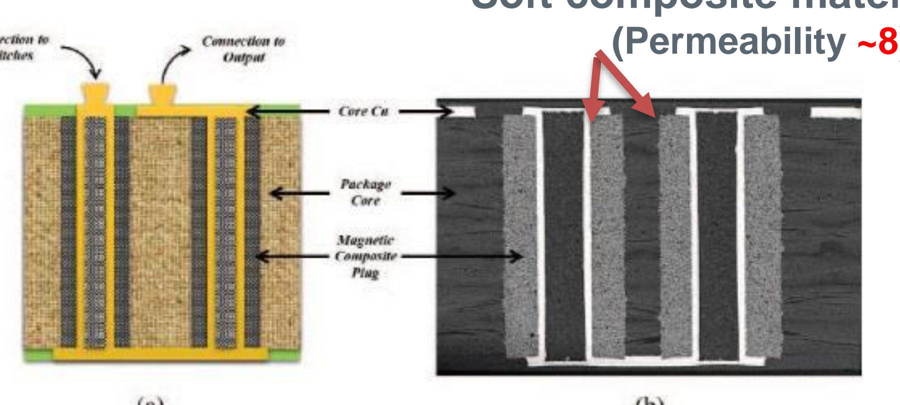
Solder Bumps on Interposer

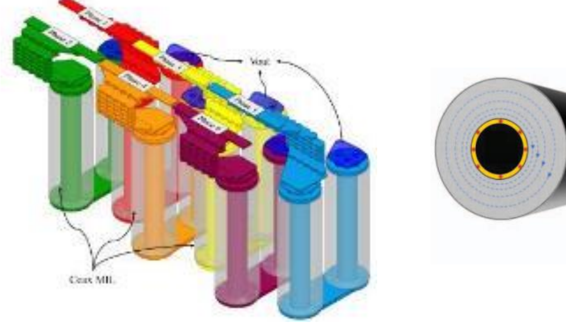
Woven-glass Core

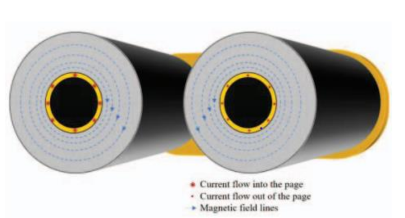
200 microns thick for lap-top
800 microns thick for server

BGA Solder Bumps to Motherboard

Soft composite material
(Permeability ~8)





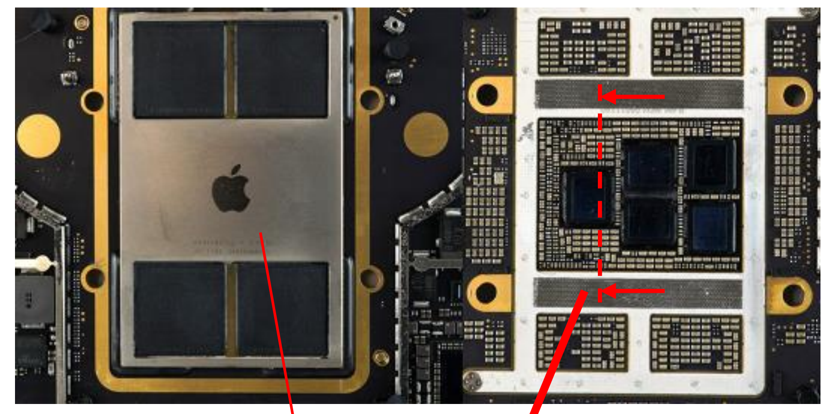


Bharath, K., Radhakrishnan, K., Hill, M. J., Chatterjee, P., Hariri, H., Venkataraman, S., . . . Srinivasan, S. (2021, 1 June-4 July 2021). Integrated Voltage Regulator Efficiency Improvement using Coaxial Magnetic Composite Core Inductors. Paper presented at the 2021 IEEE 71st Electronic Components and Technology Conference (ECTC).

2021 - Magnetic Thin-film Inductor Technology in Commercial Product

On-silicon stripline coupled inductors

October 2021 – Apple Mac M1 Pro / M1 Max



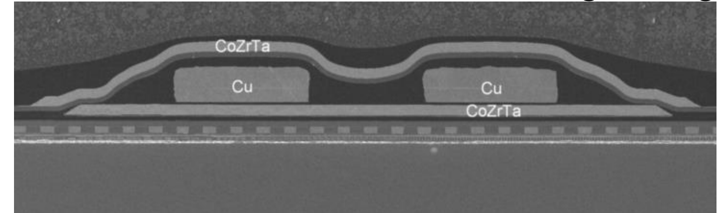
“PwrSoC: Industry Adoption in High-Volume Applications”, Francesco Carobolante, IoTissimo® LLC, IS05.7, APEC2022

[Twitter](#)

[Hector Martin @marcan42](#)

…………custom CLVRs, Coupled Inductor Voltage Regulators. Apple codenames them "MONACO“……means the M1 Max has 140 power converter phases, with 5 of those chips.

TechInsights blog

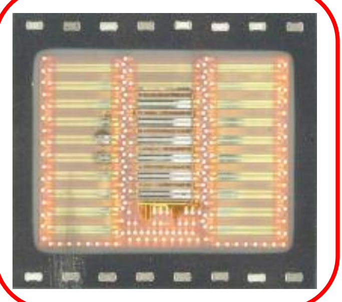


5 X IVRs

28 X 2Φ phase IVR

28 coupled Inductors

(Area: 1.5 mm x 0.3 mm each)



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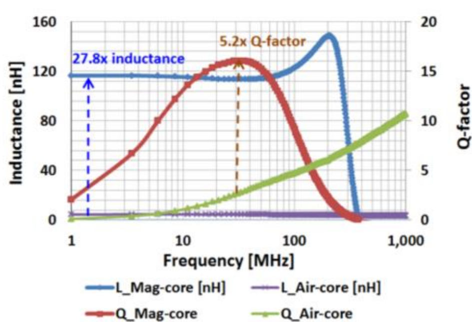
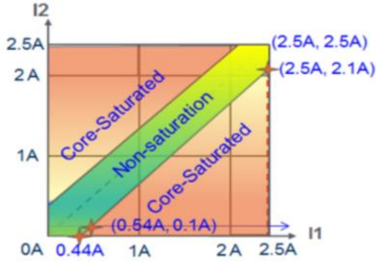
Magnetics on Silicon

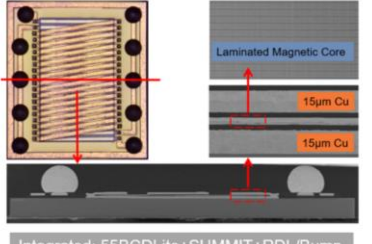
SUMMIT Devices – Single inductor

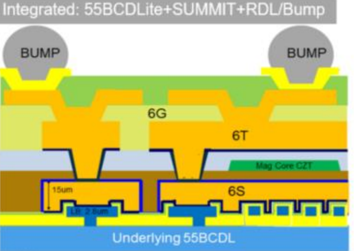
- Q factor > 15 @ 10 - 50MHz
- Inductance density > 100nH/mm²
- L/Rdc > 400nH/Ω
- Saturation Current 0.2A ~2A for single inductors
- Compared with air-core inductor, L increases > 25x and Q-factor increases > 5x.
- Wafer full-map L variation < 2%, Q-factor variation < 5%

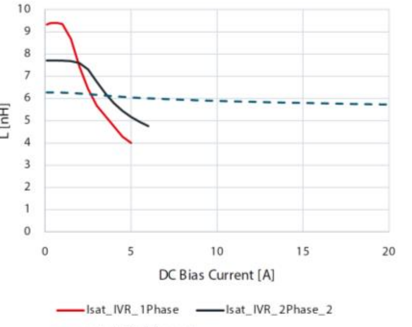


Coupled Inductor



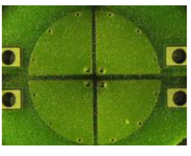




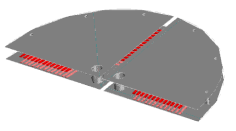


First design from 2011

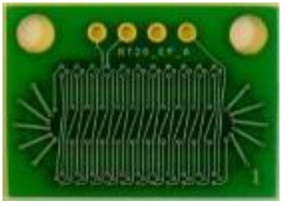
Electroplated thin film magnetic cores

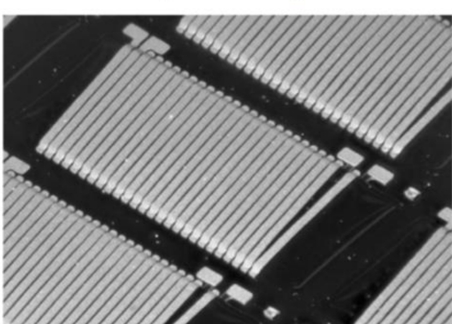


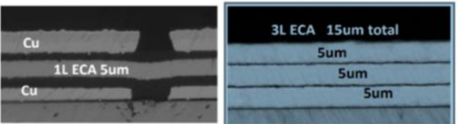
electroplated magnetics



PCB
Integrated Magnetics
US Patent 6150915
(2005)



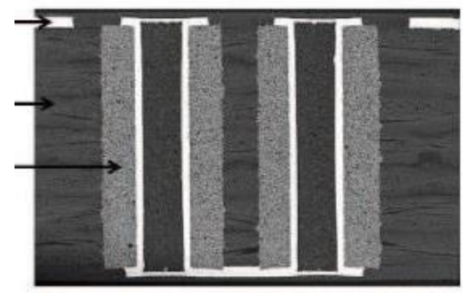


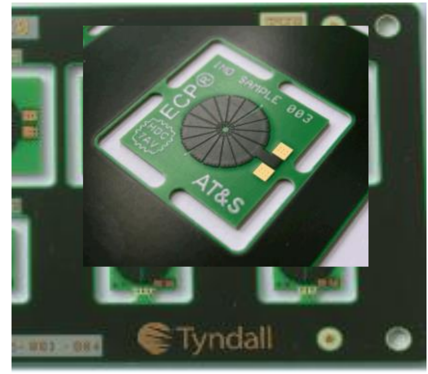


Trifon Liakopoulos, Scalable Integrated Magnetics: A Cost-Effective and Efficient Solution for Vertical Power, PwrSoc 2023, Hanover

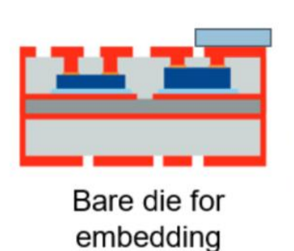
- Suitable for large panel processing
- Novel plating processes to minimise core losses
- Lower cost, faster process than thin film sputtering

PCB Embedded Magnetics

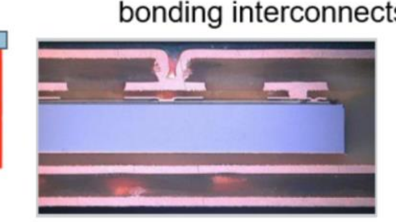




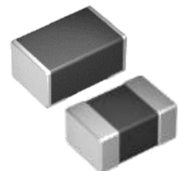
Bare die for wire bonding interconnects



Bare die for embedding



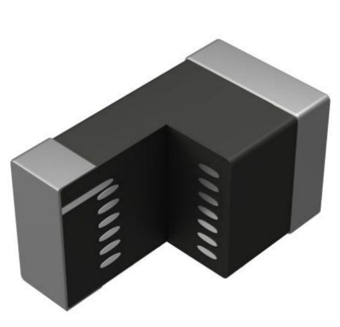
What's LSCN series ? : Metal base multi layer power Inductor

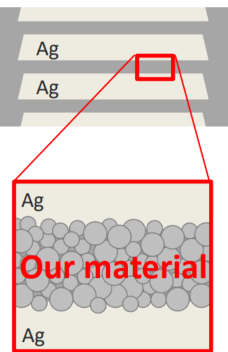


LSCN series use multi layer process & unique **Metal material.**
- High current with small package
- Small case size and low profile
- Customizability (e.g. flexibility in size and array like 2 in 1).

Basic structure of LSCN

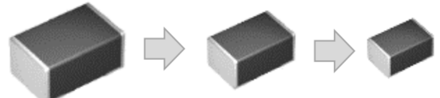
- First in the world -



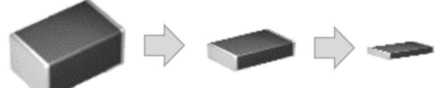


Strong points for LSCN(MC)

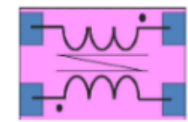
A). Further smaller size (<=1005mm)

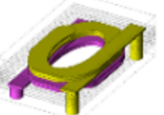


B). Further lower profile (<=0.2-0.3mm)



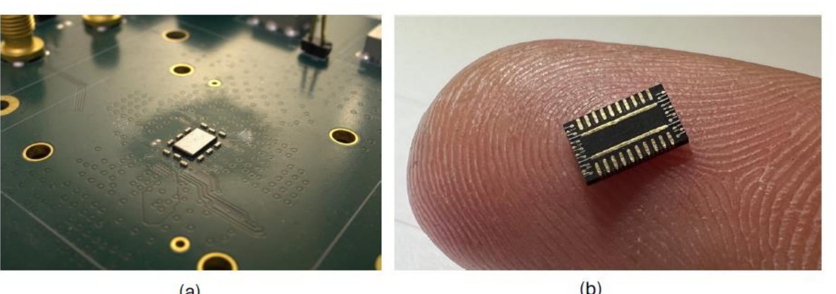
C). Capability of 2 in 1 (Mutually Coupled)



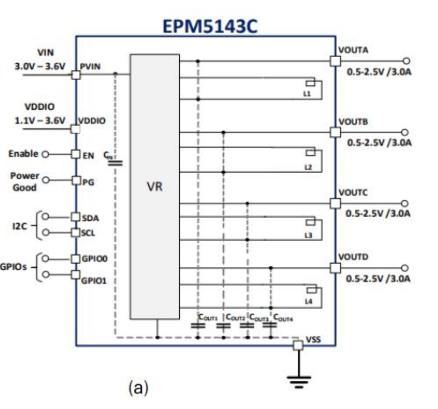


PMIC Modules with Integrated Magnetics

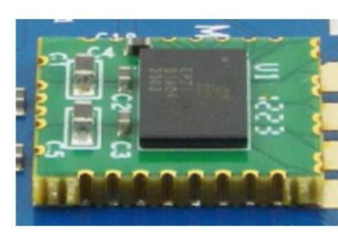
Ferric



(a) (b)



(a)



(b)

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Chiplet level Integration - Possibilities

HBM
SoC
HBM
TIV
RDL
LSI
IPD
LSI
Molding
Substrate

tsmc CoWoS®

Highly integrated VR solutions fit with advanced vertical powering and chiplet strategies for SoC

Top dies
µbump
RDL Interposer
C4
PCB Substrate
BGA
SOC
SOC
HBM
IVR Chiplets

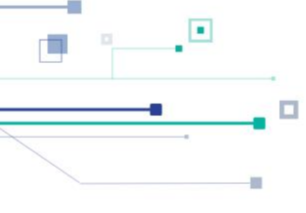
Heterogeneous Integration

Ponte Vecchio
Xe HPC based GPU

Compute	Up to 128 Ray tracing Units	Highest Compute Density socket & node	128 Xe Cores
Memory	Up to 64MB L1 cache in 2 Stacks	Up to 408MB L2 Cache in 2 Stacks	HBM2e
I/O	Up to 8 Fully Connected GPUs	PCIe Gen 5	Xe Link High-Speed Coherent Unified Fabric
Technology	EMIB	Foveros	Intel 7 TSMC N5 TSMC N7

Intel processor

- 47 tiles (chiplets)
- 5 different process nodes
- 100B transistors



FAMES
greener electronics
FD-SOI · NVM · 3D · RF · PMIC

cea leti

Tyndall
National Institute
Institiúid Náisiúnta

SAL
SILICON AUSTRIA LABS

VTT

imec

Fraunhofer
MIKROELEKTRONIK

UCLouvain

Warsaw University of Technology
Centre for Advanced Materials and Technologies
CEZAMAT

GRENOBLE
INP
UGA

UNIVERSIDAD
DE GRANADA

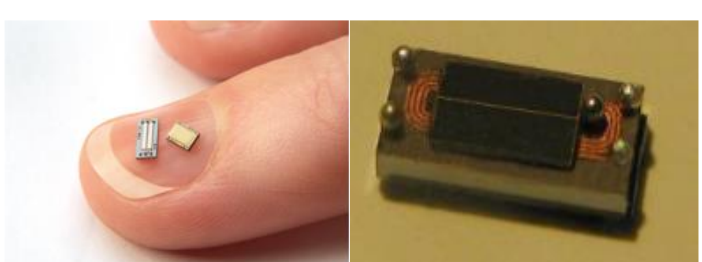
SiNANO
Institute

Chips JU

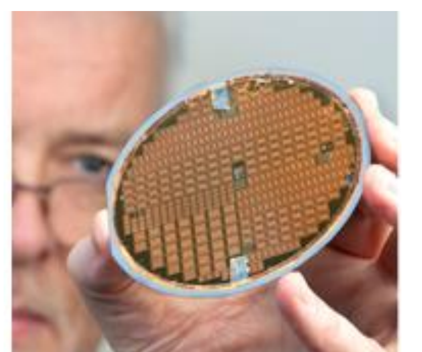
Integrated Power Management

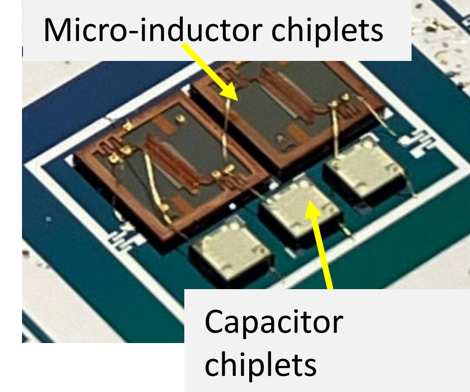
- Deep technological expertise in magnetics and heterogeneous integration

Technology Platform 1
Thin Film
Magnetics on Silicon



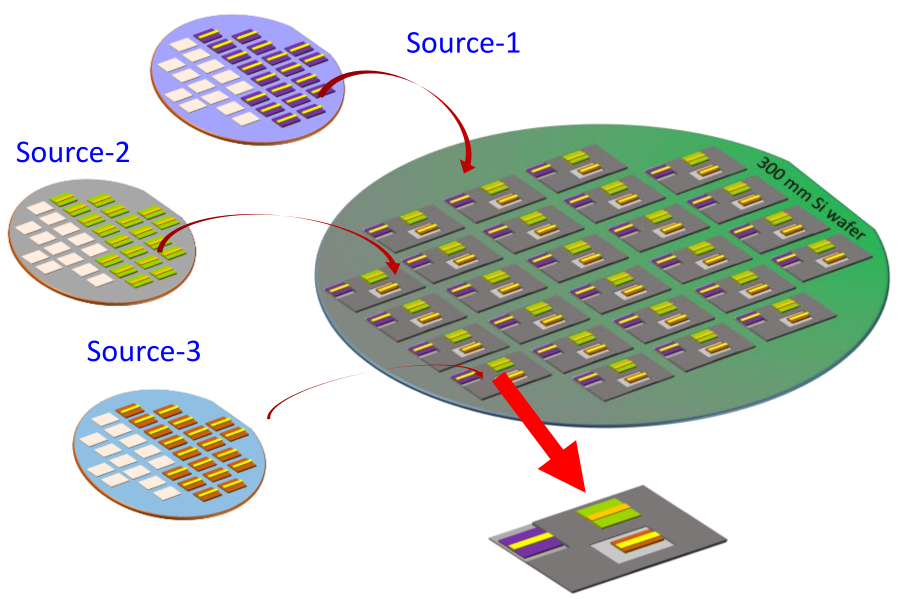
Technology Platform 2
Micro Transfer Printing of Passives
on Functional Silicon Switches & Control

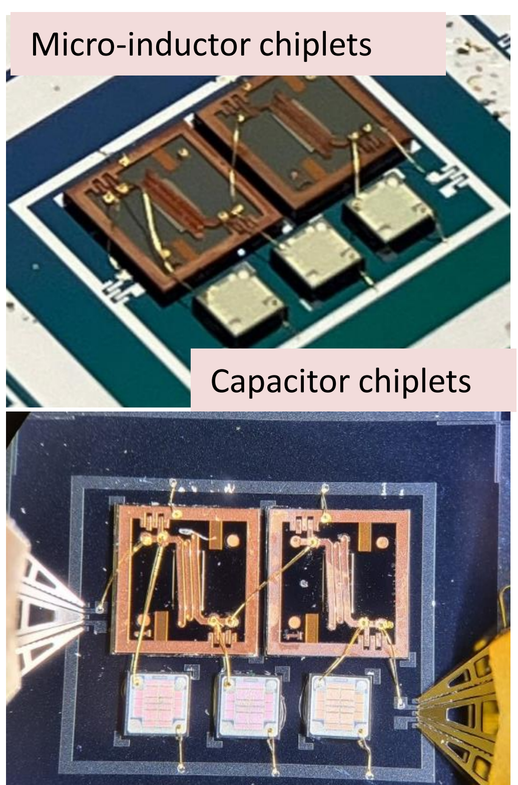




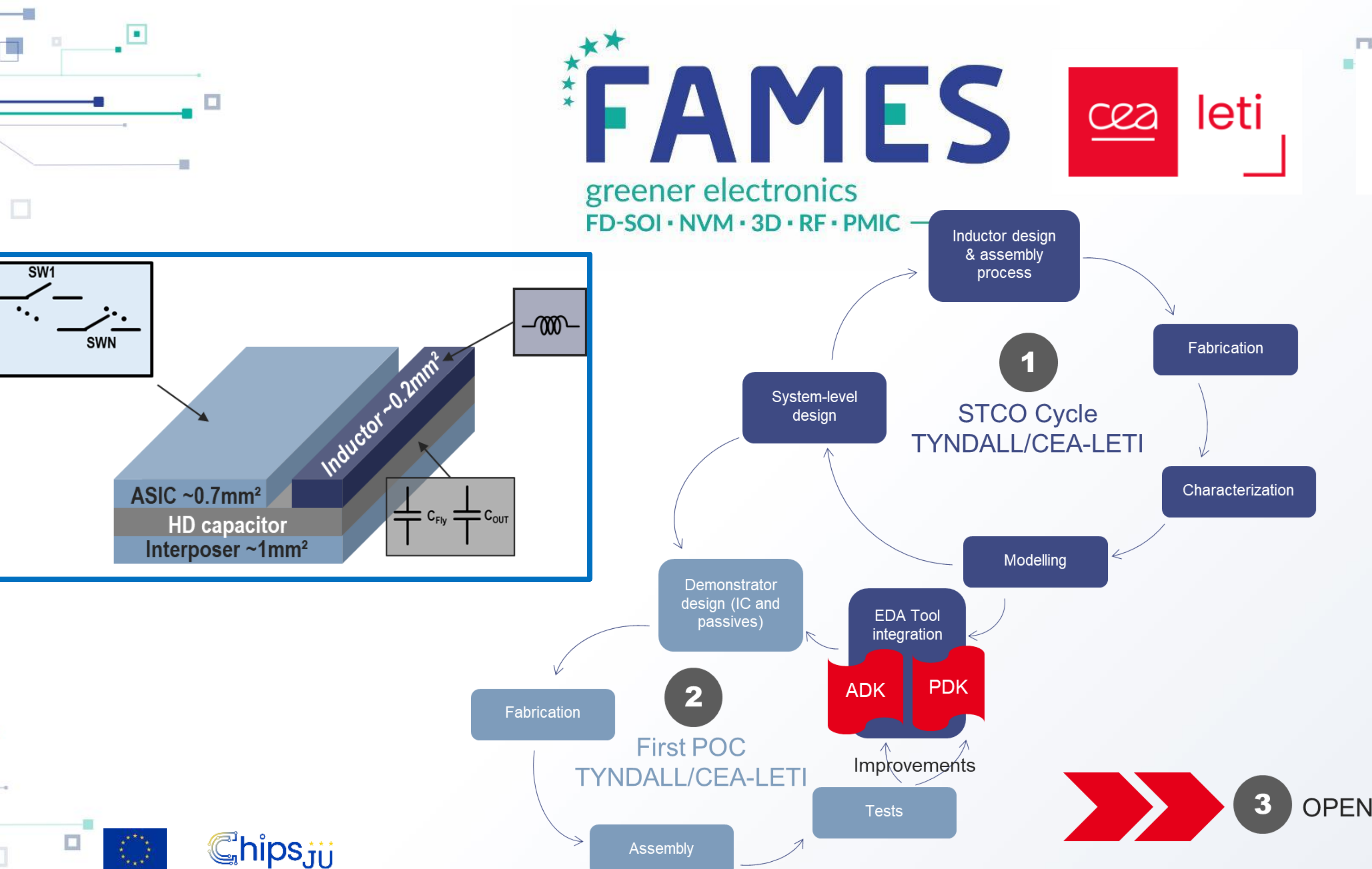
Heterogeneous integration at Tyndall

- Micro Transfer Printing integration:
  Applied at the micron scale
  Demonstrated at the mm scale





Enterprise Ireland I DTIF Tapestry - 2021-2023: (Tyndall, Analog Devices, Limerick; Xceleprint, Cork)



FAMES
greener electronics
FD-SOI · NVM · 3D · RF · PMIC
cea leti
Tyndall
National Institute
Institiúid Náisiúnta
SW1
SWN
Inductor ~0.2mm²
ASIC ~0.7mm²
HD capacitor
Interposer ~1mm²
C_Fly
C_OUT
Inductor design & assembly process
Fabrication
Characterization
Modelling
System-level design
1
STCO Cycle
TYNDALL/CEA-LETI
EDA Tool integration
ADK
PDK
Demonstrator design (IC and passives)
Fabrication
2
First POC
TYNDALL/CEA-LETI
Assembly
Tests
Improvements
3
OPEN ACCESS
Chips JU

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Challenges/Opportunities for Integrated Magnetic Components

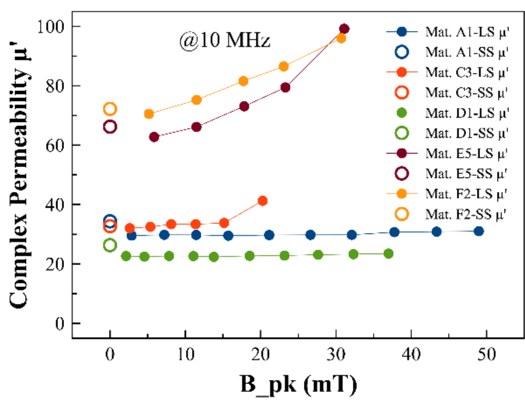
- High Bsat Magnetic Materials
- Higher dc current capability
    - Low resistance windings
        - – Vertical inductors?
- Smaller footprint
- Heterogeneous Integration – Vertical Power
    - – reduce parasitics, increase transient performance
    - – With Load
    - – With power switches, drivers, control, capacitors
- Trade-off - Energy Storage – Magnetics Vs Capacitors
- Dynamic operation of power delivery – save system energy

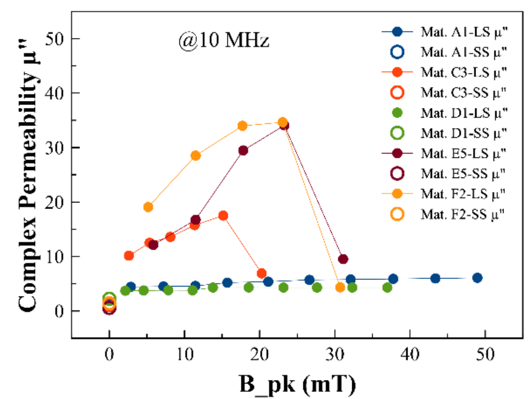
Large-signal Test – 10–100Mhz, 5-10Amps

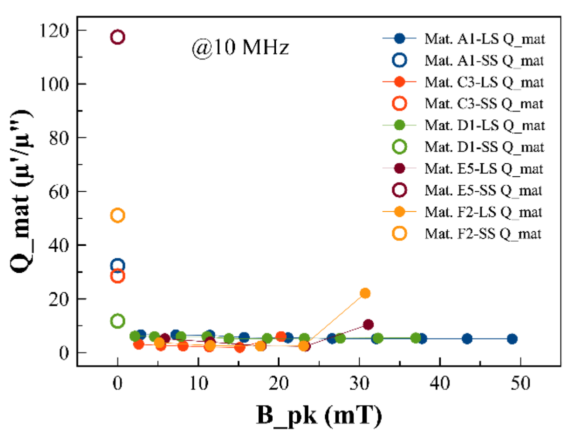
Essential for accurate characterization/modelling of magnetic materials and devices

5 different soft-magnetic materials (*shown in five different colors*) are tested and compared

○ small-signal (SS) measurement data | --●-- large-signal (LS) data measured at different B_pk







- **No correlation** observed between small-signal (SS) and large-signal (LS) measurement of magnetic materials
- Material performance [Q_mat (μ'/μ")] under small-signal differs significantly from large-signal

A. J. Hanson, J. A. Belk, S. Lim, C. R. Sullivan and D. J. Perreault, "Measurements and Performance Factor Comparisons of Magnetic Materials at High Frequency," in IEEE Transactions on Power Electronics, vol. 31, no. 11, pp. 7909-7925, Nov. 2016, doi: 10.1109/TPEL.2015.2514084.

High Frequency Magnetic Material Database

Current status

Input :

Circuit Parameters
+
Available magnetic core information:
small signal core date sheet

Error > 100 %

ANSYS Maxwell | COMSOL MULTIPHYSICS | MICROMETALS IRON POWDER CORES | PowereSIM

Future

Input

Circuit Parameters
+
Available magnetic core information:
small signal core date sheet

Large signal inductor core emulator

Output :

Digital Twins of Large-signal magnetic core:
Large signal Inductor core data sheet (1-50 MHz)

Error < 5 %

ANSYS Maxwell | COMSOL MULTIPHYSICS | MICROMETALS IRON POWDER CORES | PowereSIM

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International Workshop on
Power Supply On Chip

2008-2023

Integrated Power Conversion and Power Management

PwrSoC / PSiP
Driving
New Global Supply Chains

Electronics Systems

TEXAS INSTRUMENTS

AT&S

Passives

System on Chip (SoC)

AMD

RENESAS

ANALOG DEVICES

TEXAS INSTRUMENTS

Infineon

ON

Integrated Magnetic Supply Chains

- **Magnetics on Silicon**
  - Relatively simple process
  - Magnetics close to Load - in interposer or on PMIC
  - Needs development of heterogeneous integration processes
  - Limited foundries with capability

- **PCB Embedded Magnetics**
  - Range of options: magnetic composite, magnetic core, thin film inductor, discrete chip inductor
  - Technology proven for embedded silicon – pathway for magnetic embedding
  - Limited number of companies in PCB embedding space

- **PMIC/Magnetics Modules**
  - As per Empower, Ferric
  - Low profile (0.6mm) surface mount module with multiple converters
  - Uses existing assembly capabilities

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Power Supply System Specifications

Take Up No Space

Cost Nothing

Last Forever

Zero Power Loss

Magnetic Components – A Pain Point

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Low Voltage Integrated Power Management Research

Tyndall National Institute
Institiúid Náisiúnta

Hugh Smiddy
Head of Business Development

Dr. Make Hayes
Head of Group
ICT 4 Energy Efficiency

Willie Lawton
Program Manager

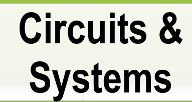
Prof. Cian O'Mathuna
Research Programme Director
Integrated Power & Energy Systems

Materials
- Design & Simulation
- Synthesis/ Deposition
- Test

Magnetic Composite | Anisotropic Thin film | Isotropic Thin film

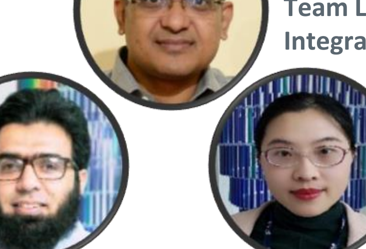
Devices
- Design
- Fabrication
- Test
- Heterogeneous Integration

Vertical | Solenoid | Stripline | Toroidal



Circuits & Systems
- Design
- Test

Power Management ICs
- Design
- Tape-out/ Validation



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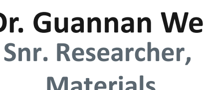

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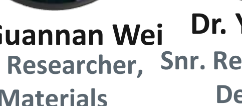

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THANK YOU

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