3D-Integrated Magnetics using Fe-based Metal Composite Materials for Beyond-10MHz Switching Power Supply

PWRSOC21

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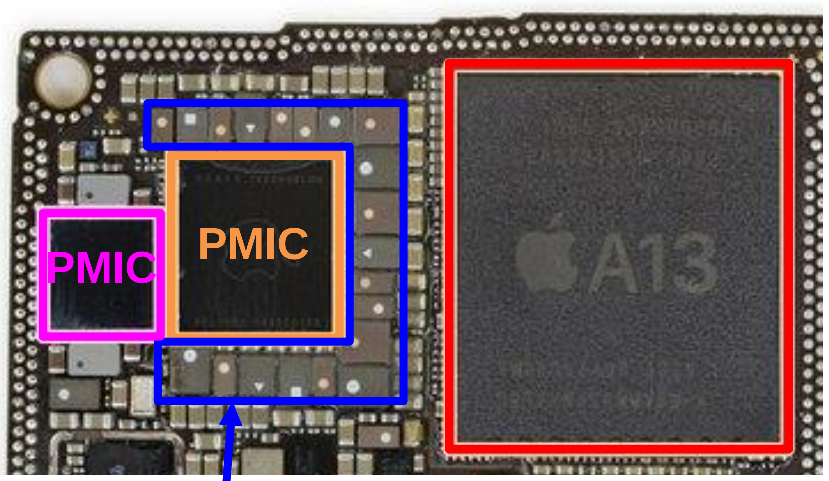
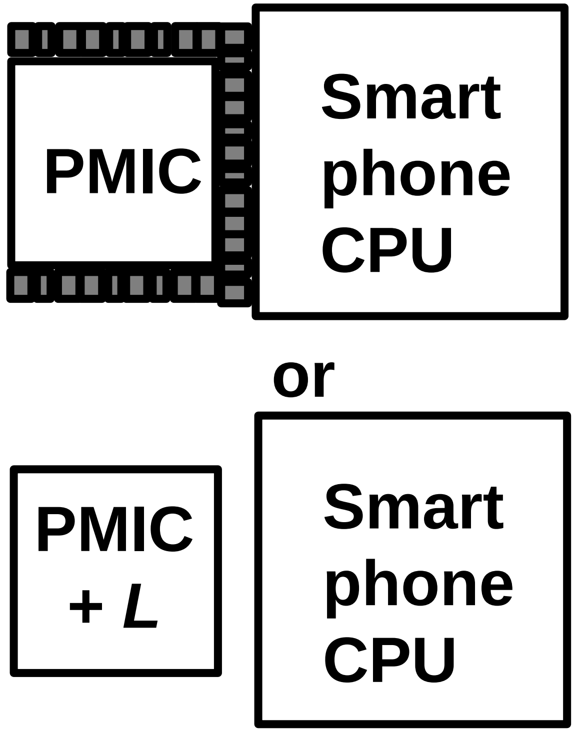
Requirements for Inductor Footprint Reduction



Higher f_{SW}

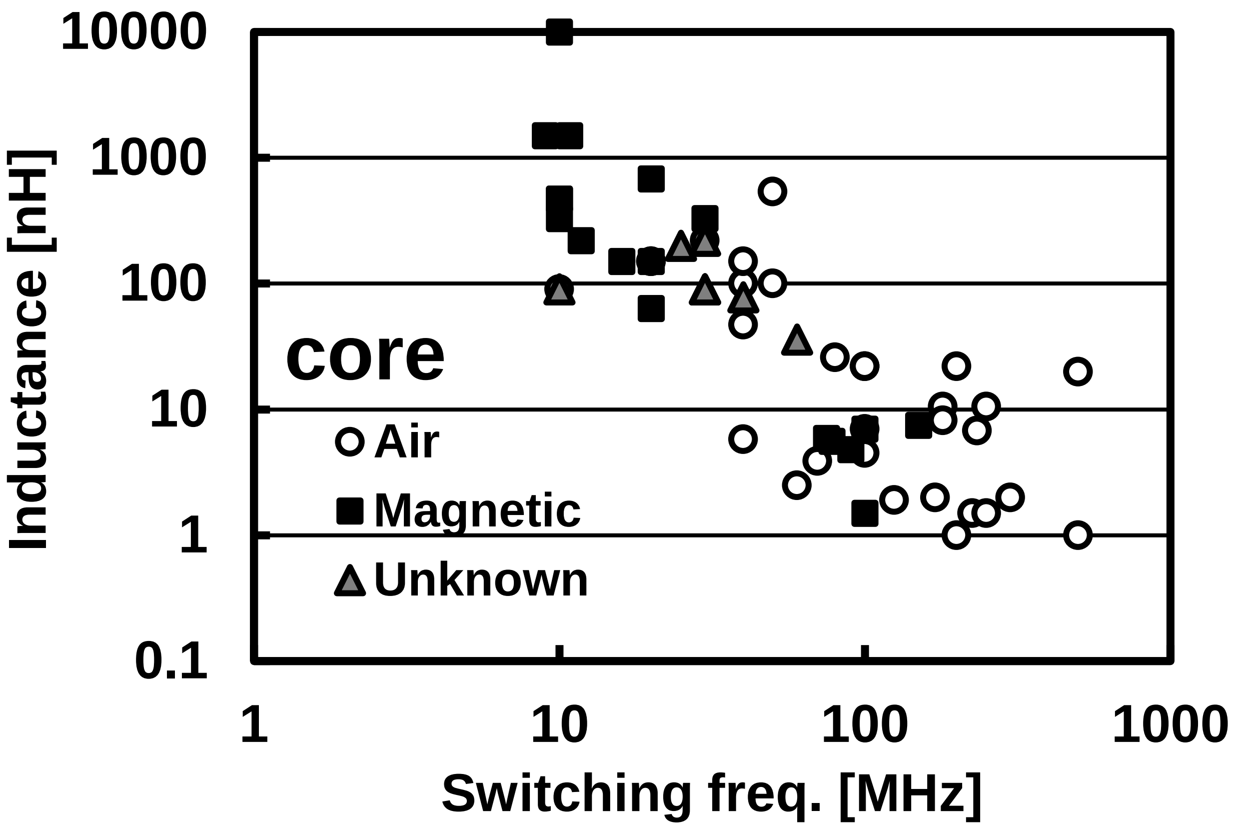
f_{SW}: switching frequency

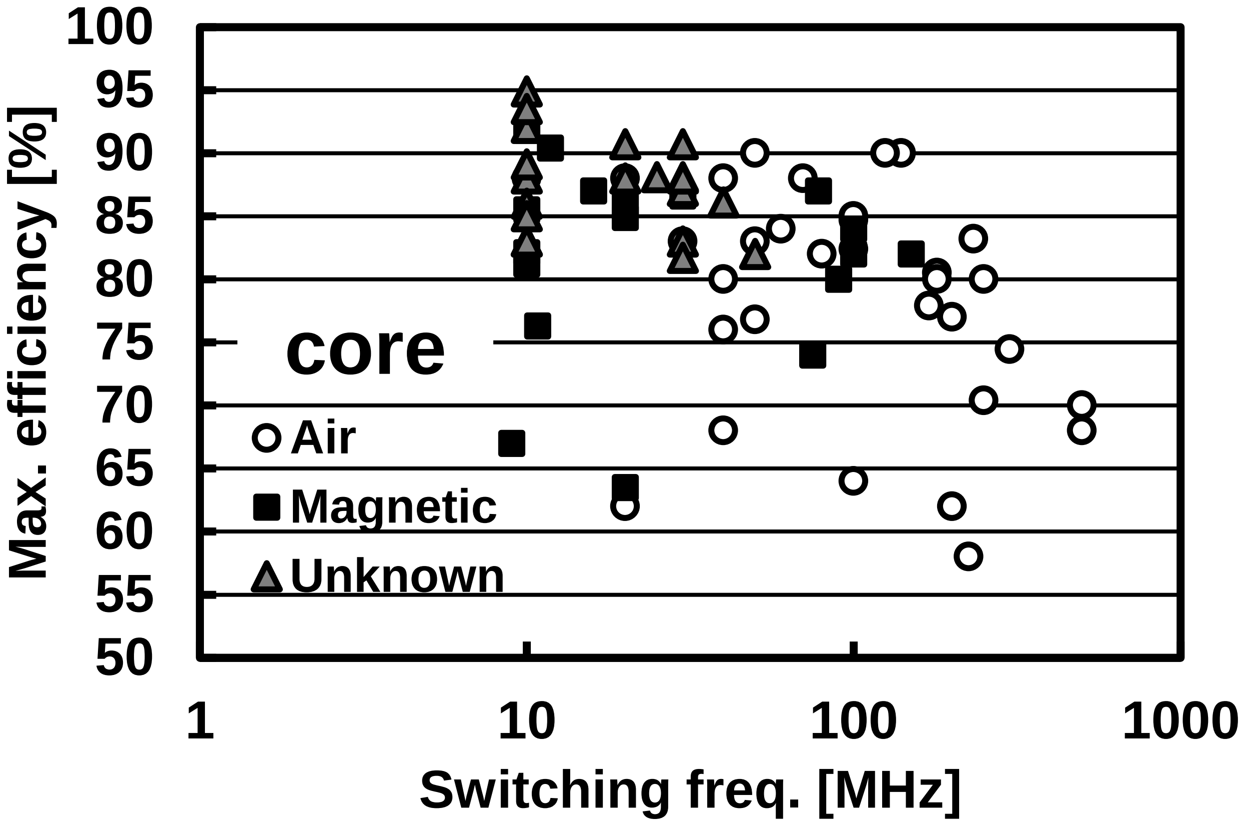


- Smaller passives → Less cost
- Faster load transient response

- Power inductors occupy considerable footprint
- The number of inductors is increasing as many power domain required

Benchmarks for High f_{SW} Converters





- Buck converters, no boost
- Includes HV (>5V) process converters, GaN FET converters
- Does not include resonant converters

- *L* is reduced by increasing switching frequency f_{SW}
- Clear trade-off between loss and efficiency

→ In-package 3D-integration of inductor

Benchmarks for *L*-Integrated Buck Converters

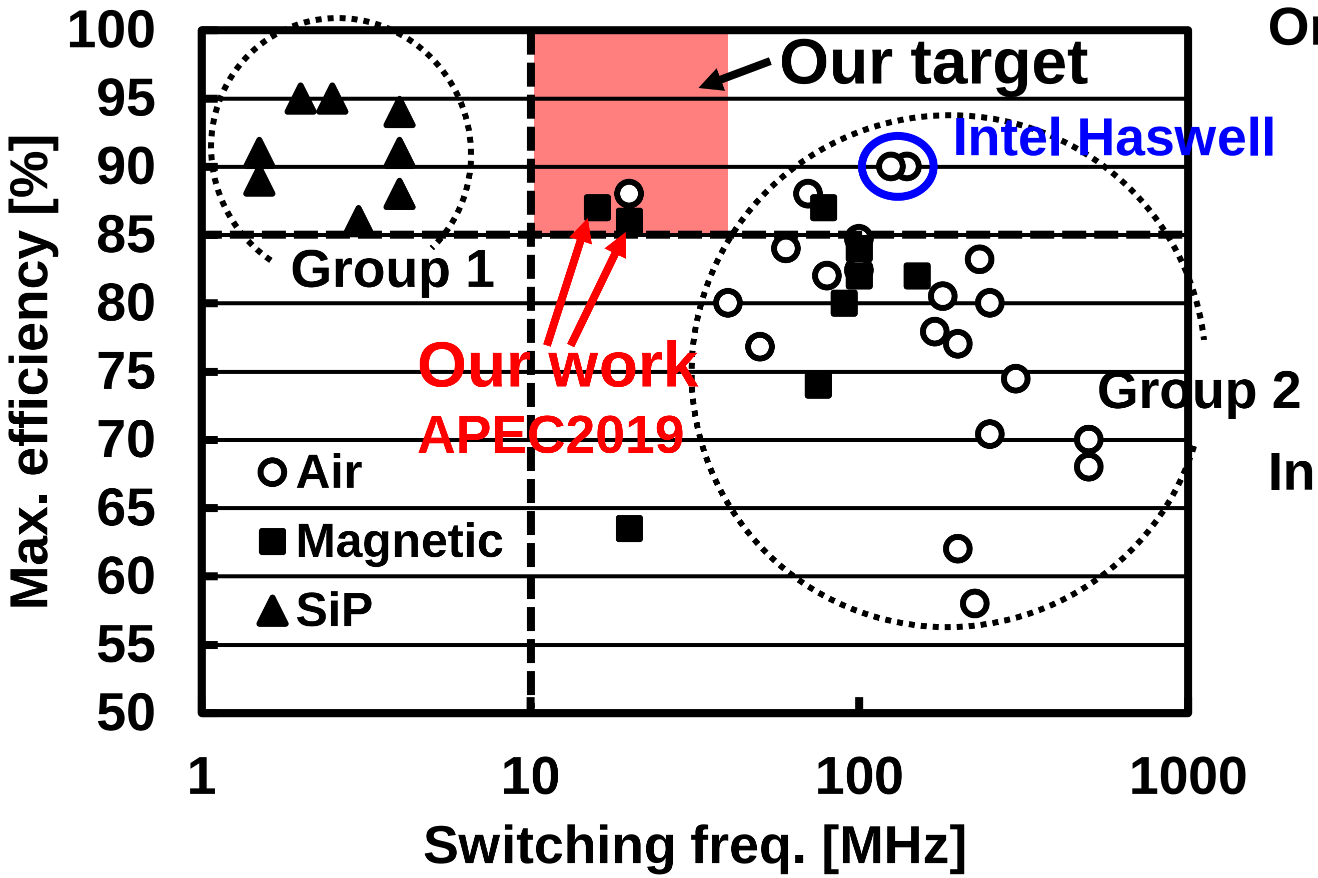
Group 1

180nm~0.5μm CMOS

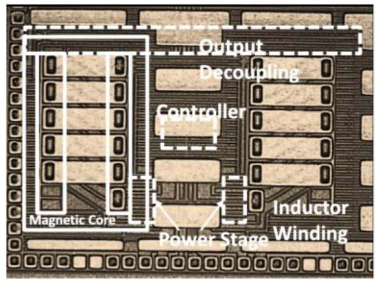
LXDC3EP
Murata, 2014.

FS1404
TDK, 2019.

f_{SW}: <10MHz
L: >1000nH



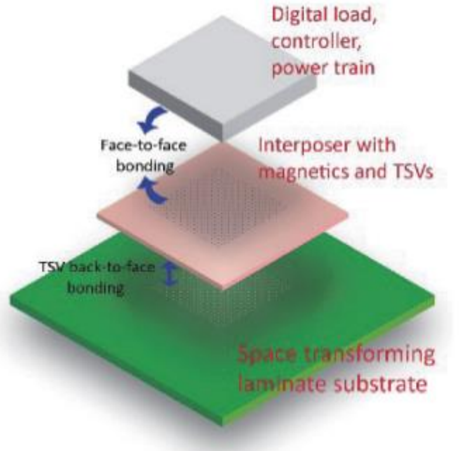
On chip



14nm CMOS

H. Krishnamurthy et al., *JSSC*, pp. 8-19, 2018.

In interposer



45nm
SOI
CMOS

K. Tien et al., *IEEE VLSI*, p. C192, 2015.

Group	Group 1	Group 2
Application	Mobile/Portable	HP CPU (FIVR)
Efficiency	High >90%	Poor < 85%
Cost	Low	High
Footprint	Fair	Small
Transient response	Slow >10μ	Fast

f_{SW}: ≃100MHz
L: ~10nH

FIVR: fully integrated voltage regulator

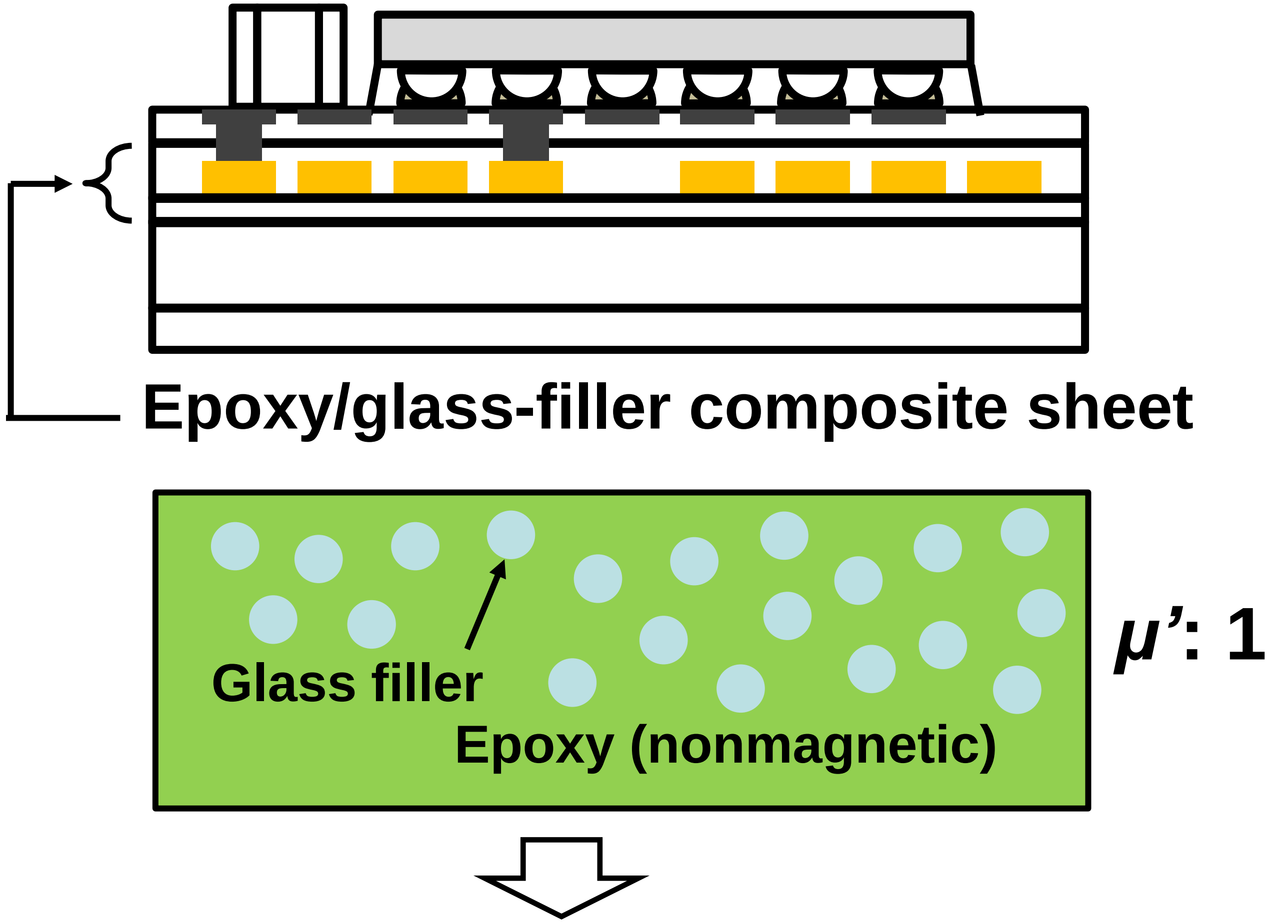
Requirements for 10~40MHz Integrated Inductors

Requirements	Air core	Ni-Zn Ferrite
Tens of nH ~ 100nH	-	-
Small footprint	× Long wiring	OK
Low loss	× Large DCR	× Excessive loss at high f_{SW}
High B_s	OK	× B_s=0.2T, Steep L cutoff
High temp. stability	OK	× High thermal runaway risk
Low fabrication cost (high process compatibility)	OK	× High thermal budget

Fe-based metal composite material core inductor development and its demonstration of 3D-integrated buck converter module

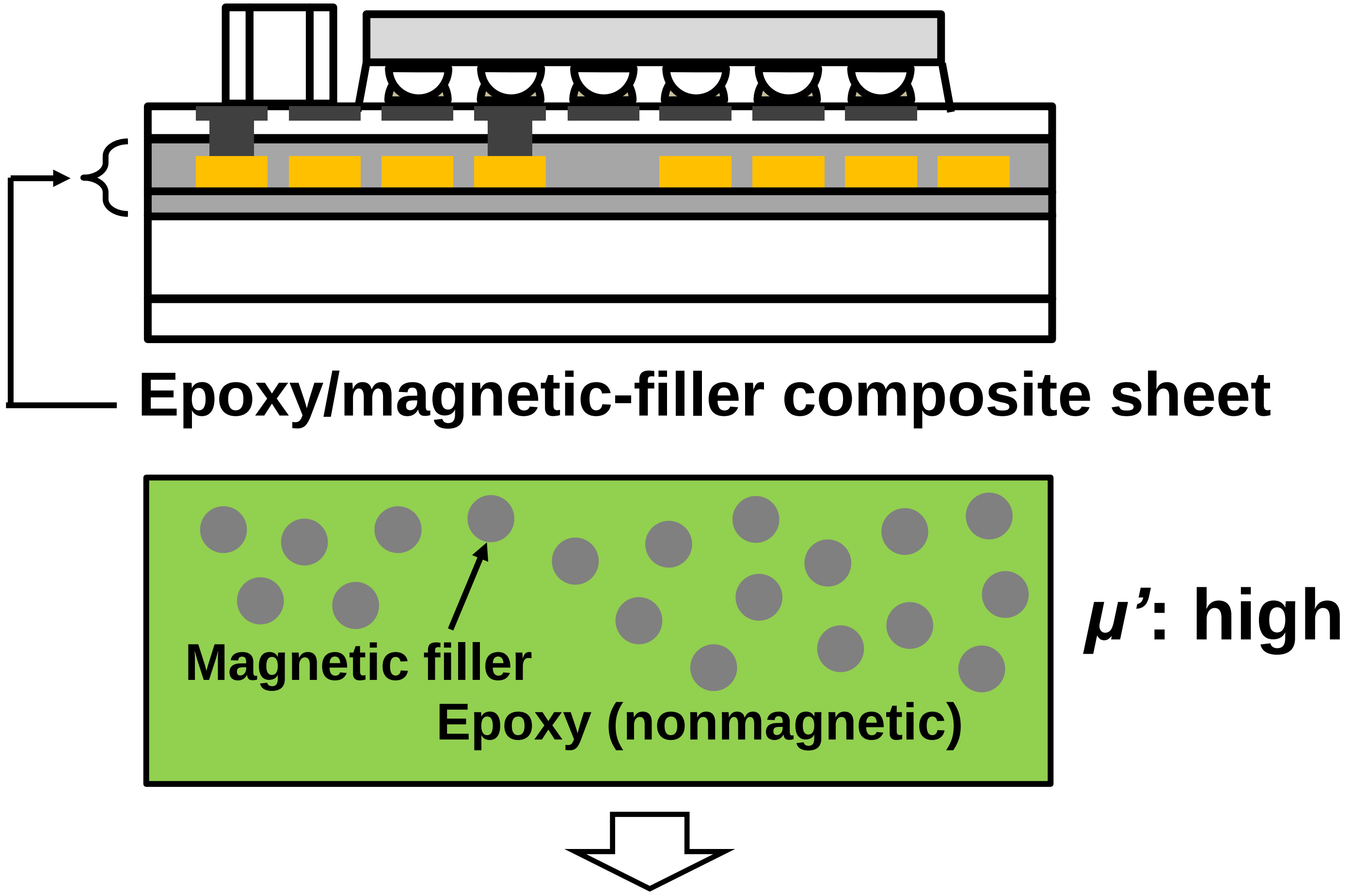
Embedded Magnetic Core Inductor

Conventional: Air core



Small inductance and large size

Proposed: Magnetic core

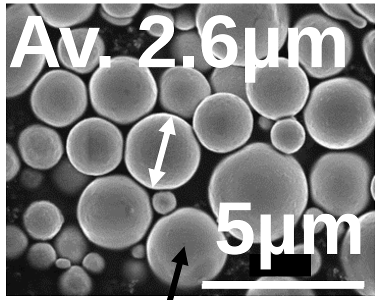


Large inductance and small size

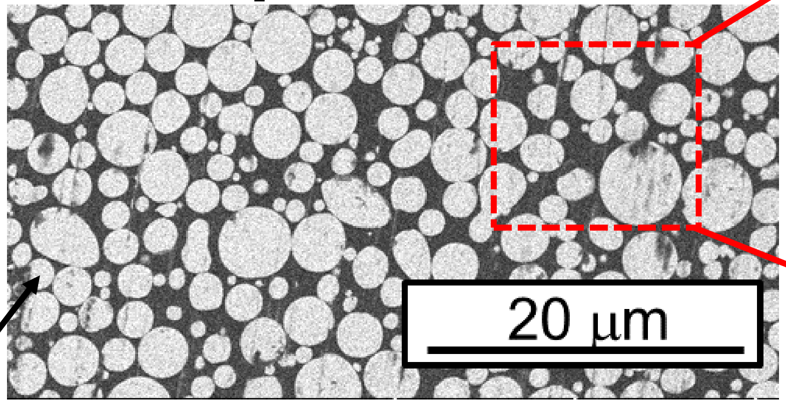
Only filler is replaced to realize closed magnetic circuit inductor
→ Low manufacturing cost (no vacuum thin-film & TSV process)

Proposed Epoxy/magnetic-filler Composite Sheet

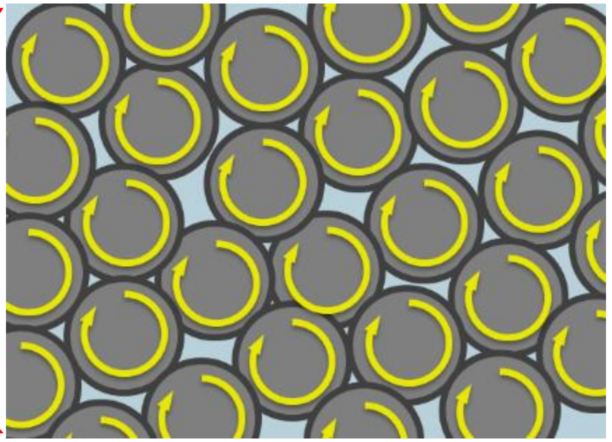
Epoxy
+



Epoxy/magnetic-filler Composite Sheet



Fe-Si-B-C-Cr amorphous powder



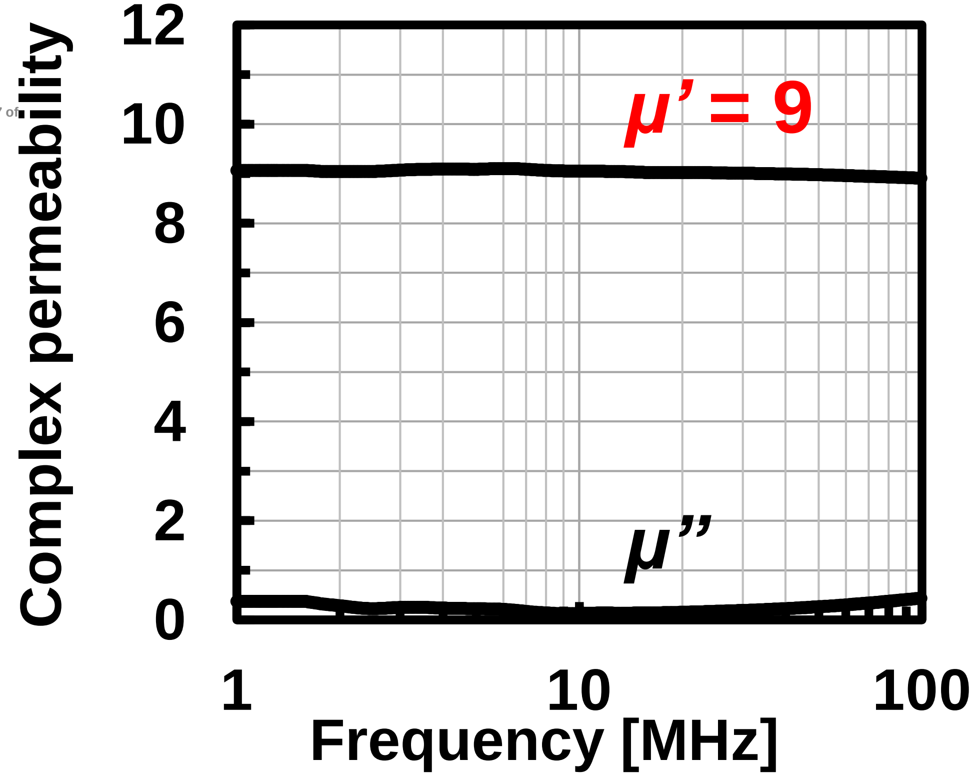
Small grain diameter (average 2.6μm)
+
High resistance coating

High resistivity and low eddy current loss

Epoxy/magnetic-filler Composite Sheet

Relative permeability	9
Resistance coating	0.6 MΩ･m
Max. magnetic flux density	0.8T

Magnetic core inductor:
<u>High inductance</u> and <u>low iron loss</u>



Inductor Fabrication Process

1. Proposed epoxy/magnetic-filler composite sheet

2. Cu seed layer formation for Cu electroplating

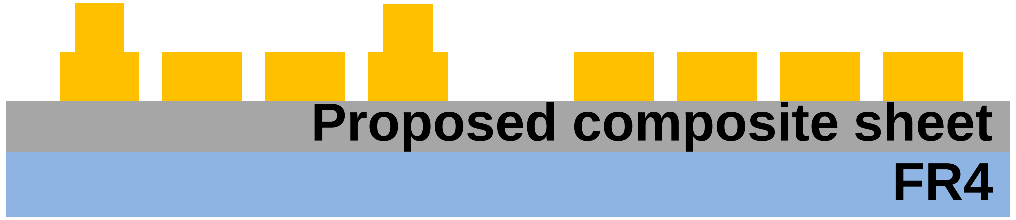
3. Photosensitive dry film

4. Exposure and development

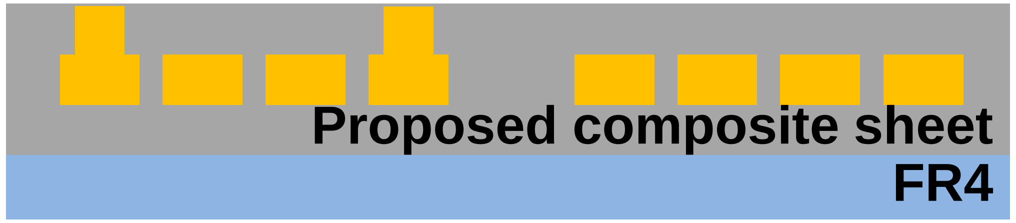
5. Cu electroplating

6. Repeat for via creation (step. 3-5)

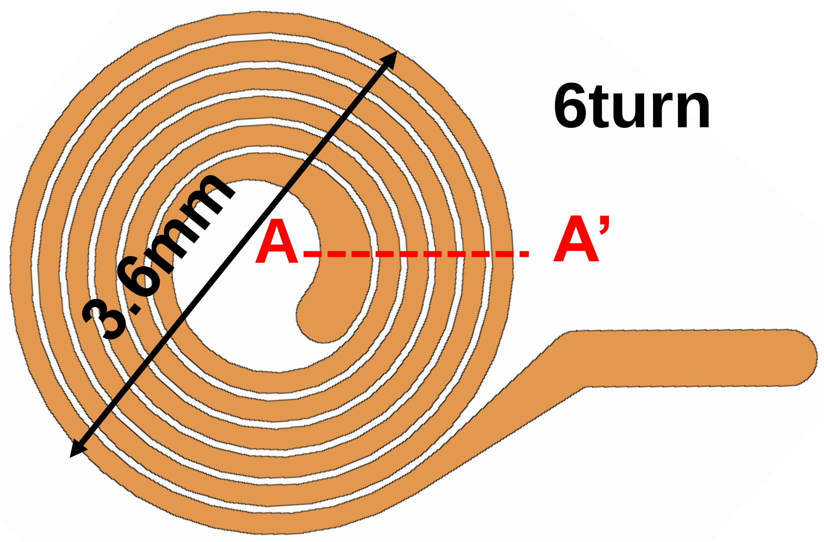
7. Cu seed layer and dry film removal



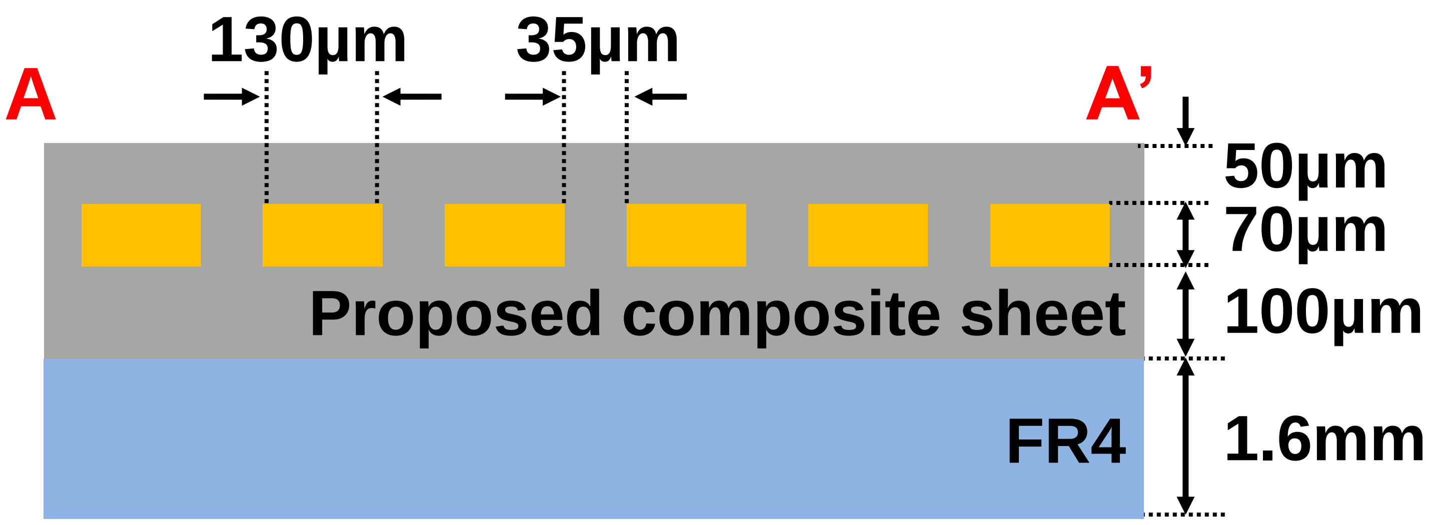
8. Proposed composite sheet lamination and polishing



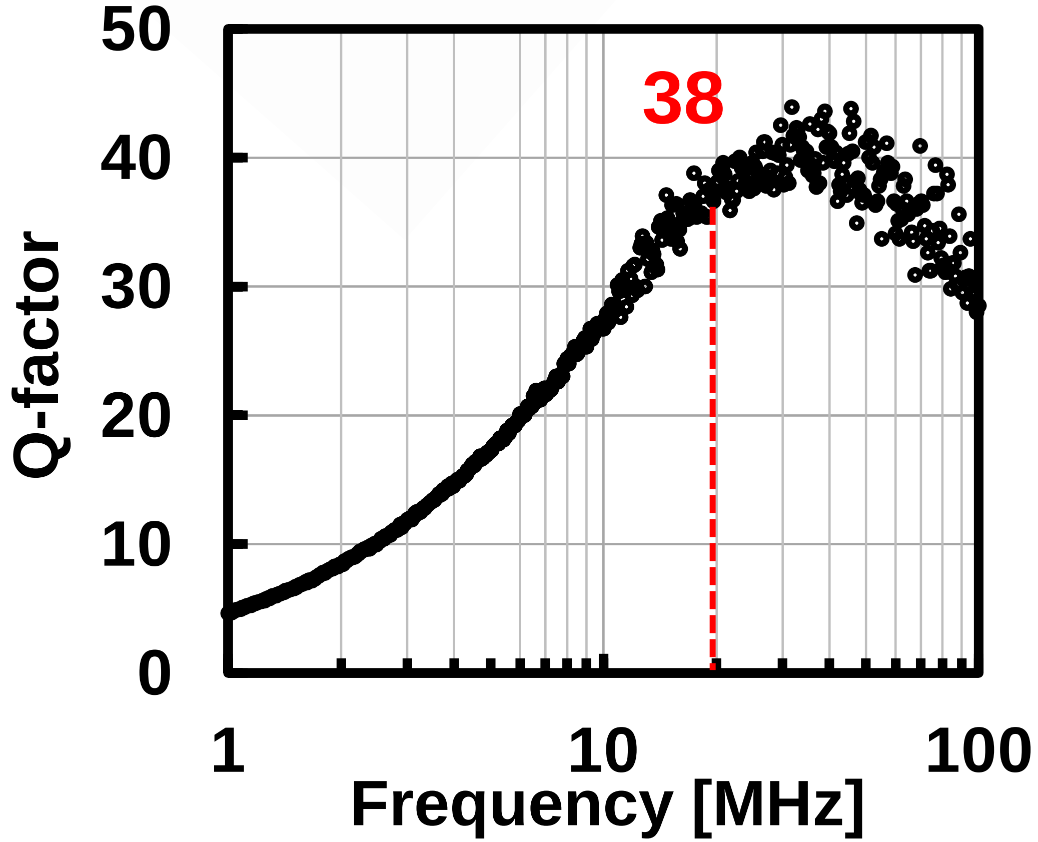
Measurement Results of Individual Inductor

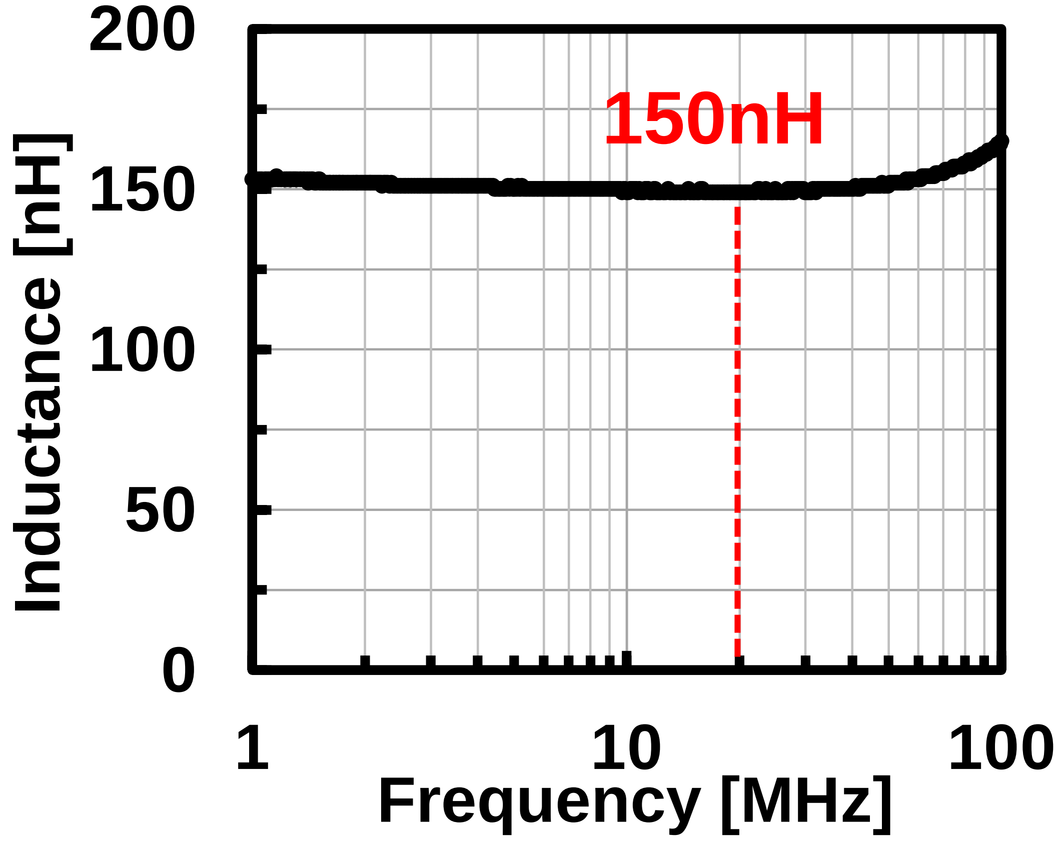


Inductor top view



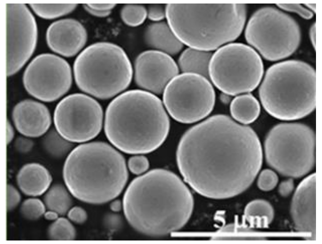
Cross-sectional view at A-A'

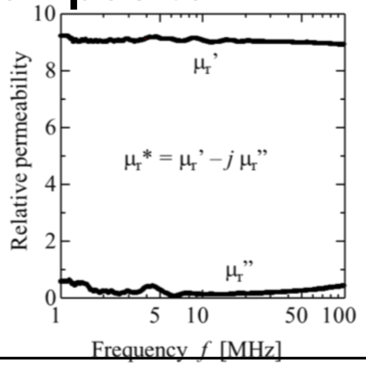


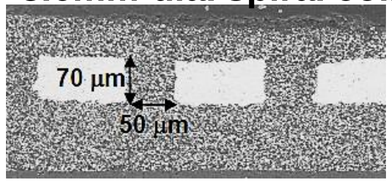


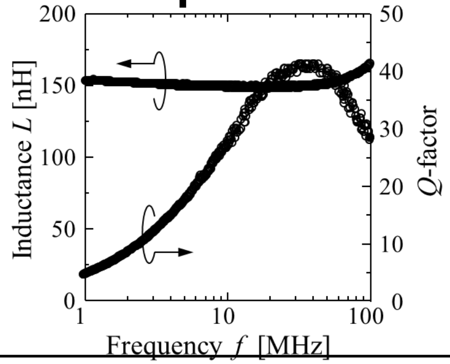
Shinshu Univ.'s High Frequency Magnetic Cores

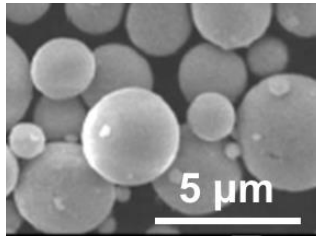
Fe-base sphere powder composite magnetic cores

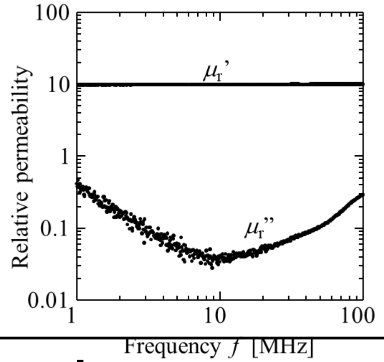
<table>
<tr><th>Starting powder material</th><th>Magnetic properties of composite</th><th>Application to PowerSoC</th></tr>
<tr><td>
Fe-Si-B-C-Cr amorphous
D_{50}: 2.6μm
B_s: 1.3T
H_c: 128A/m
ρ: 1.3μΩ･m
λ_s: >10ppm


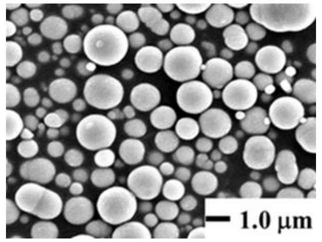
</td><td>
65 vol.%-Fe amo./epoxy composite
B_s: 0.84T
H_c: 160A/m
μ_r': 10@100MHz
μ_r": 0.4@100MHz
P_c: 1W/cc@10MHz, 10mT


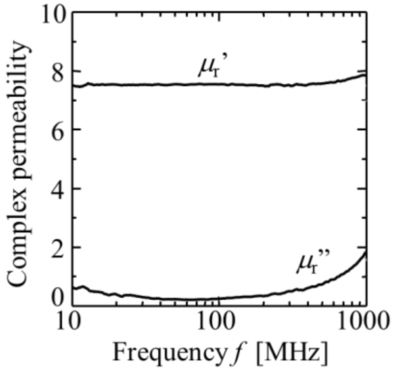
</td><td>
Embedded inductor into interposer for several tens of MHz or beyond
3.6mm-dia. spiral coil




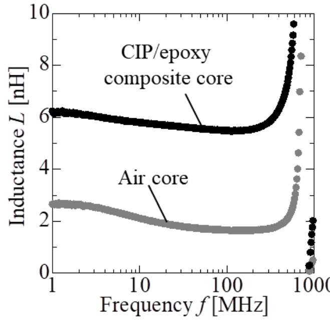
</td></tr>
<tr><td>
Fe-Si-B-Nb-Cu nanocrystalline
D_{50}: 3.5μm
B_s: 1.1T
H_c: 80A/m (Small)
ρ: 1.1μΩ･m
λ_s: <1ppm


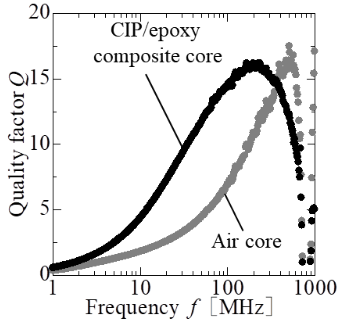
</td><td>
63 vol.%-Fe nano./epoxy composite
B_s: 0.7T
H_c: 80A/m (Small)
μ_r': 10@100 MHz
μ_r": 0.3@100MHz
P_c: ???@10MHz, 10mT


</td><td>
Embedded inductor into interposer for several tens of MHz or beyond
Currently under development.
</td></tr>
<tr><td>
Carbonyl iron (CIP) with nano-crystalline
D_{50}: 1.1μm
B_s: 2.0T
H_c: 1000A/m
ρ: 0.1μΩ･m
λ_s: ???


</td><td>
54 vol.%-CIP/epoxy composite
B_s: 1.08T
H_c: 2000A/m
μ_r': 7.5@100MHz
μ_r": 0.24@100MHz
P_c: ???@10MHz, 10mT


</td><td>
Embedded inductor into interposer for >100MHz
0.88mm-sq. Spiral coil

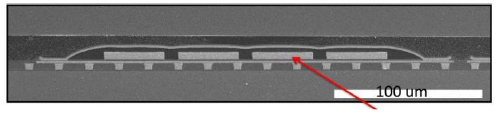



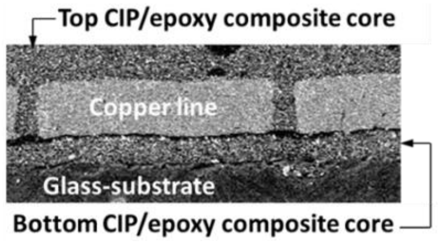


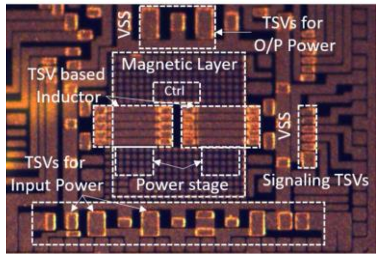
</td></tr>
</table>

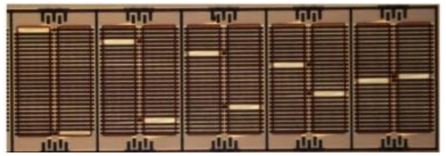
Integrated Magnetic Core Inductor Performance

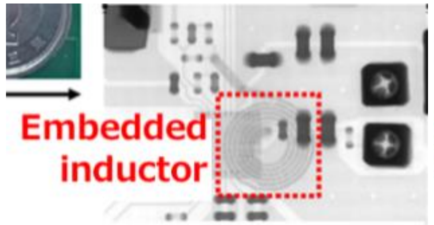
	[N. Sturcken, JSSC 2013]	[Y. Sugawa, TMAG 2013]	[H. K. Krishnamurthy JSSC 2018]	[N. Sturcken PwrSoC 2018]	[T. Fukuoka, APEC 2019]	[M. Sankara-subramanian, ECTC 2020]
	Columbia Univ.	Shinshu Univ.	Intel	Ferric	Shinshu Univ.	Intel
Core material	Thin-film $Ni_{45}Fe_{55}$ permalloy	Carbonyl iron powder/Epoxy composite sheet	Unknown	Thin-film amorphous CoTaZr	Fe-amorphous powder/Epoxy composite sheet	Carbonyl iron powder/Epoxy composite sheet
f_{SW}	75MHz	100MHz	90MHz	>100MHz	16~20MHz	140MHz
Inductor process	Package trace spiral	Package trace spiral	On-chip TSV solenoid	On-chip solenoid	Package trace spiral	Line-pattern SMD
L	5.9nH	5.5nH	4.8nH	7nH@100MHz	150nH	3nH
Q	1.2	15@100MHz		6.3@100MHz	38@20MHz	13
L density	24.1nH/mm^2	7.1nH/mm^2	111nH/mm^2	300nH/mm^2	14.7nH/mm^2	6nH/mm^2
I_{sat} (@L 90%)	NA	6A	<50mA	1A	>2.5A	NA
Chip process	45nm SOI	NA	14nm	NA	0.35µm	NA
Efficiency	71%	NA	80%	NA	86%	NA

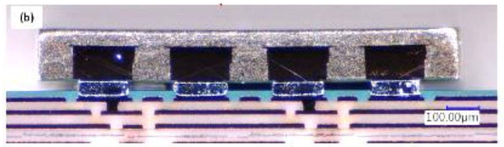








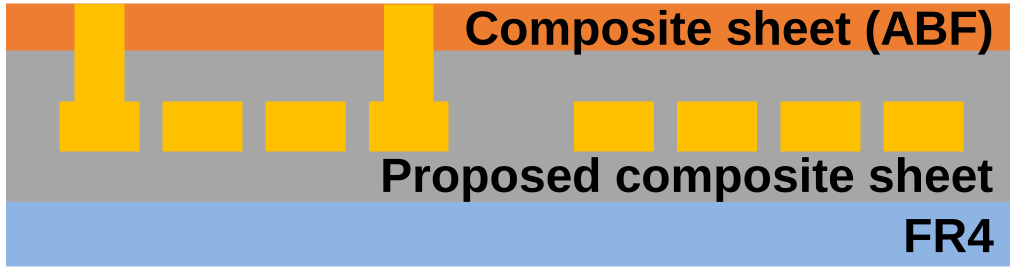




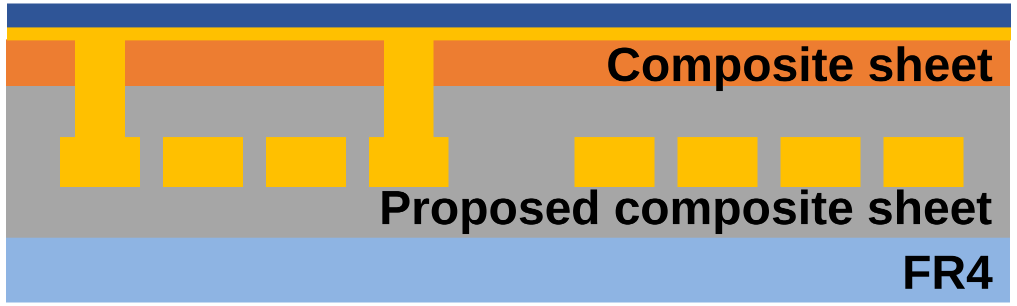
3D-Integrated Buck Converter Fabrication Process

Suppress magnetic flux leakage into the surface interconnect pattern

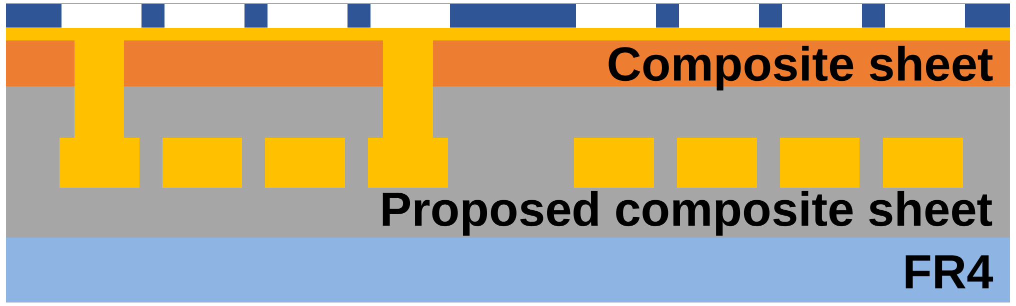
1. Epoxy/glass-filler composite sheet lamination



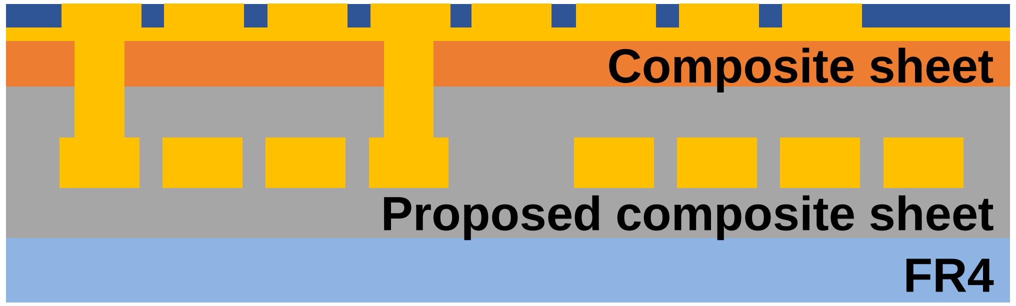
2. Cu seed layer formation and photosensitive dry film lamination



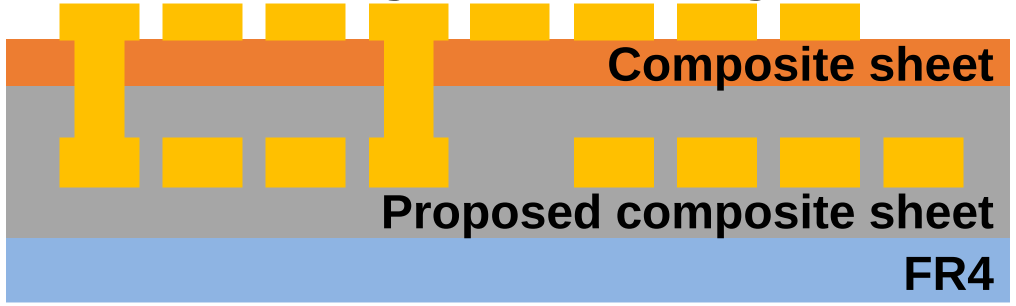
3. Exposure and development



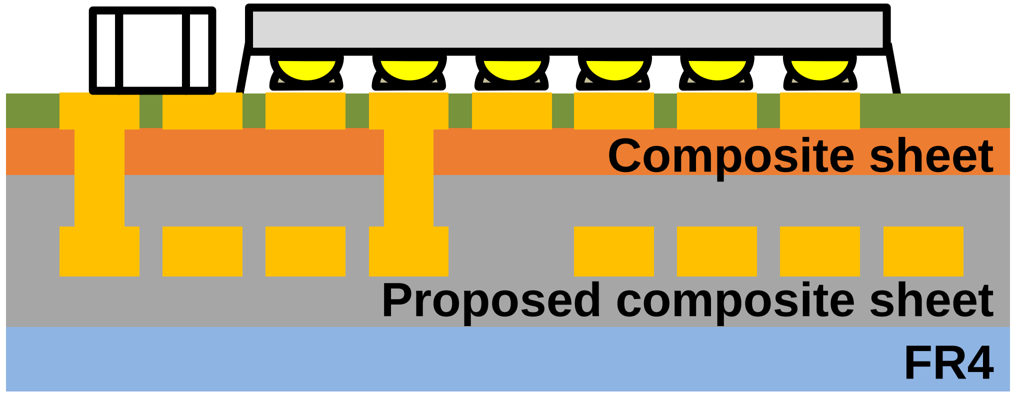
4. Cu electroplating for surface



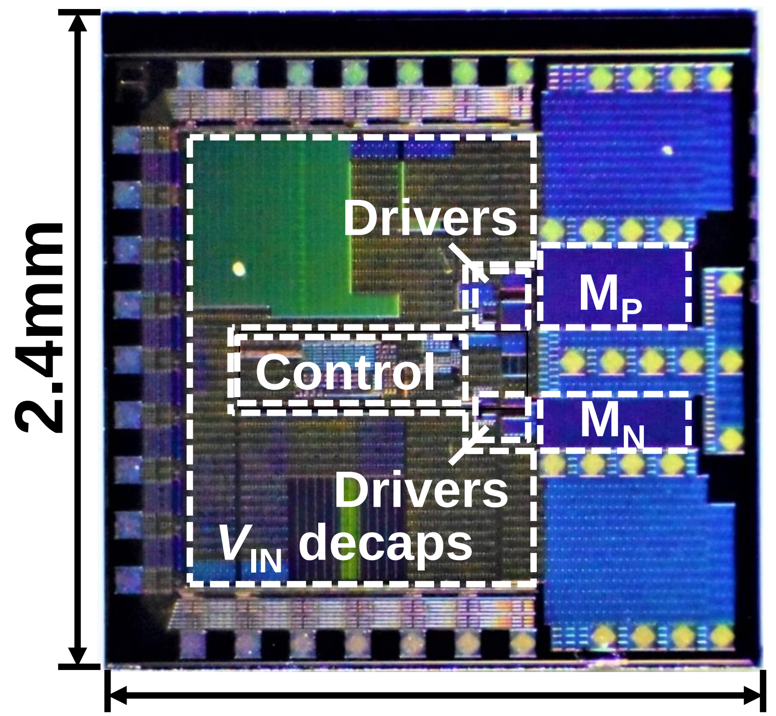
5. Cu seed layer and dry film removal



6. Solder resist layer formation and flip chip mounting and SMT reflow

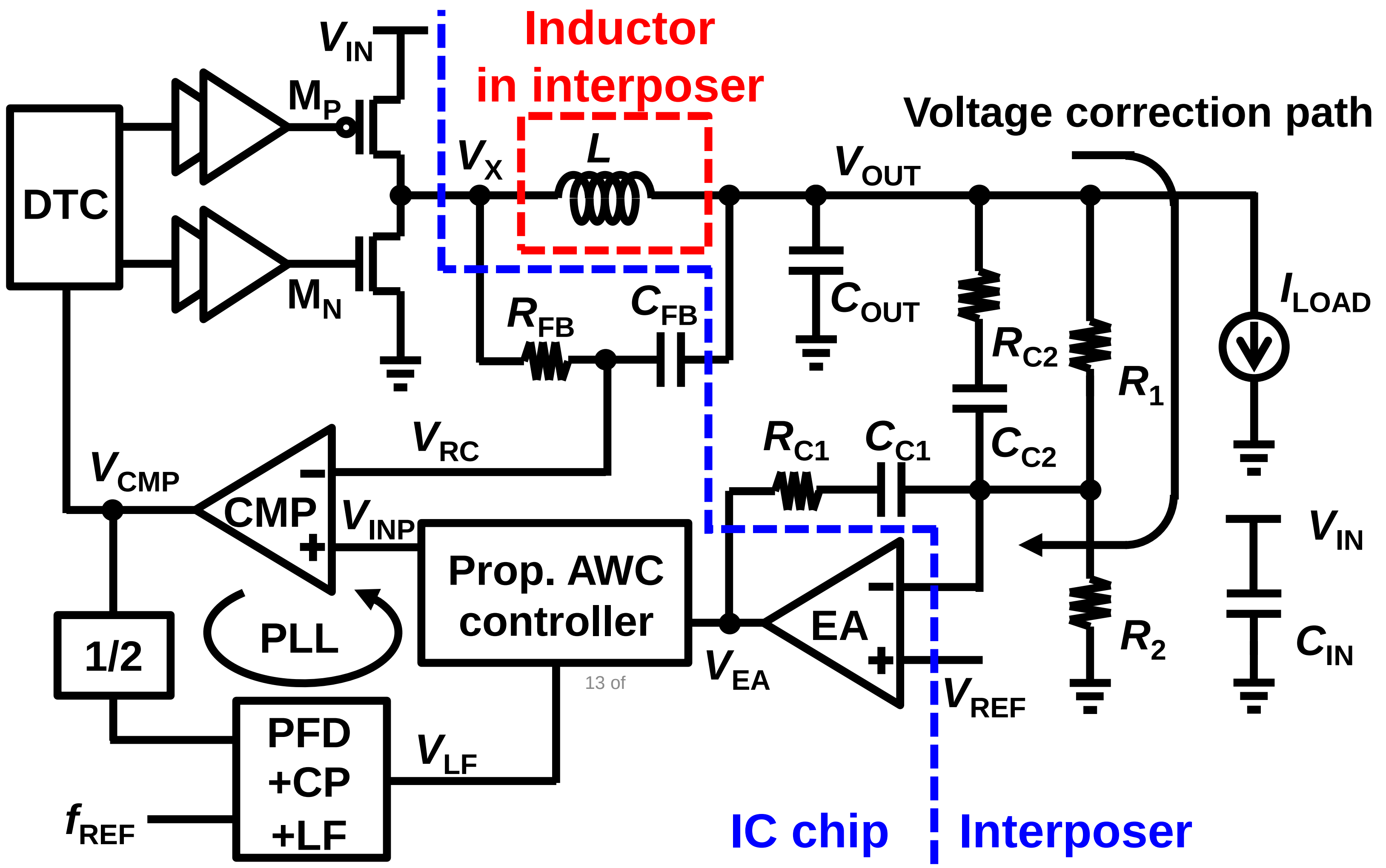


Power FET + Control IC Design



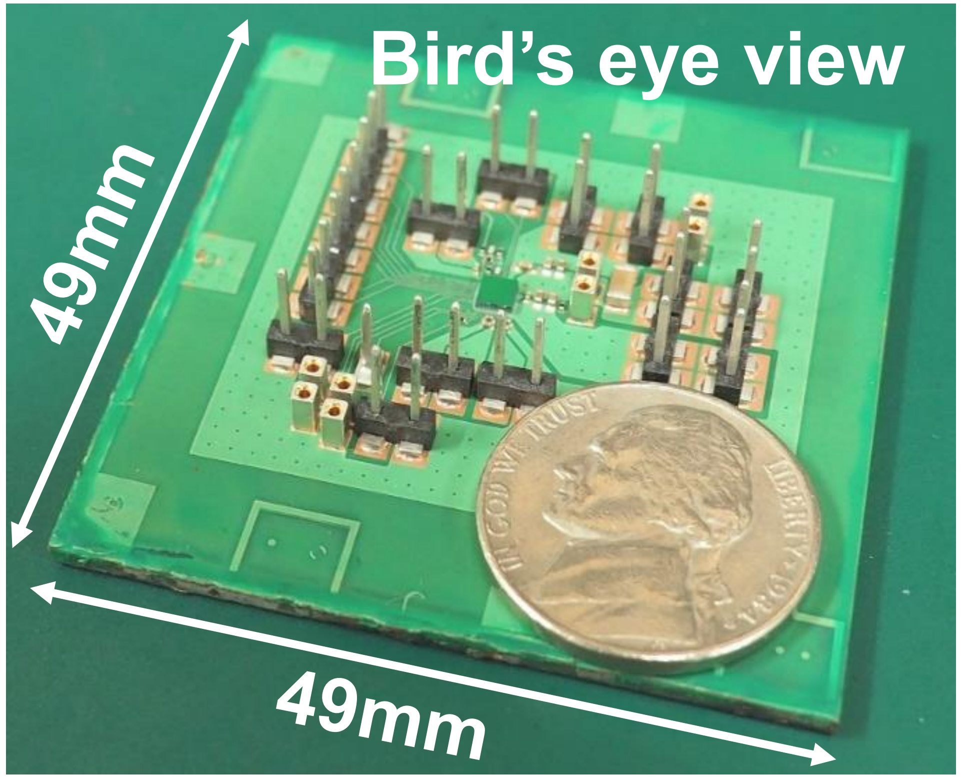
Chip photograph

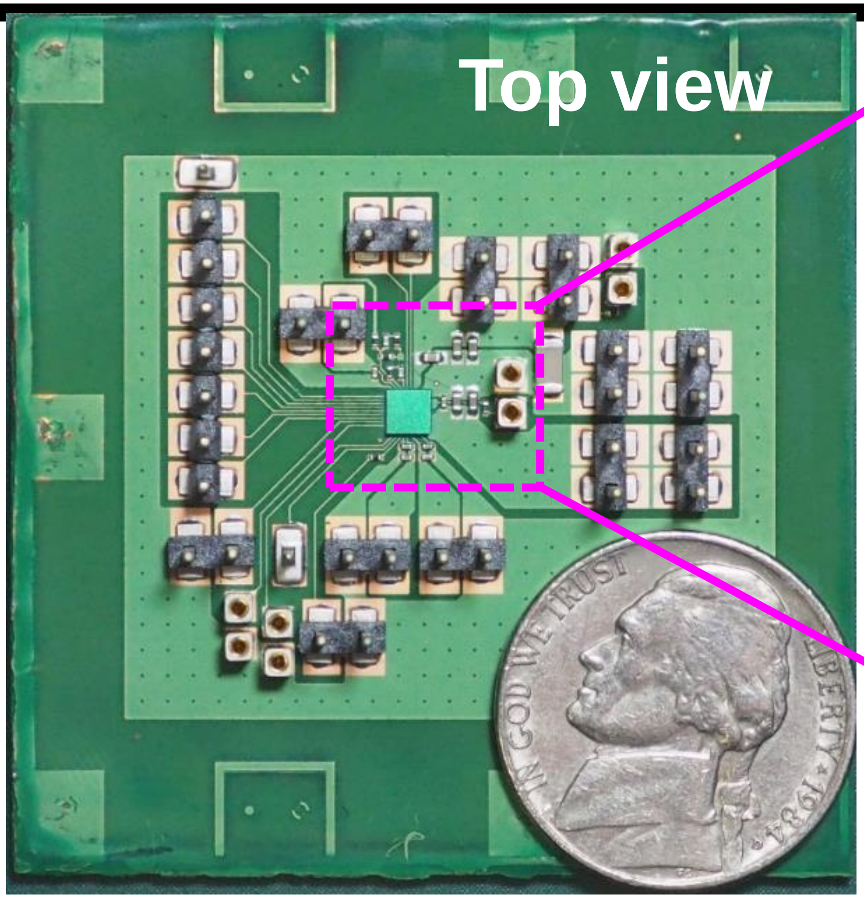
0.35μm standard CMOS process

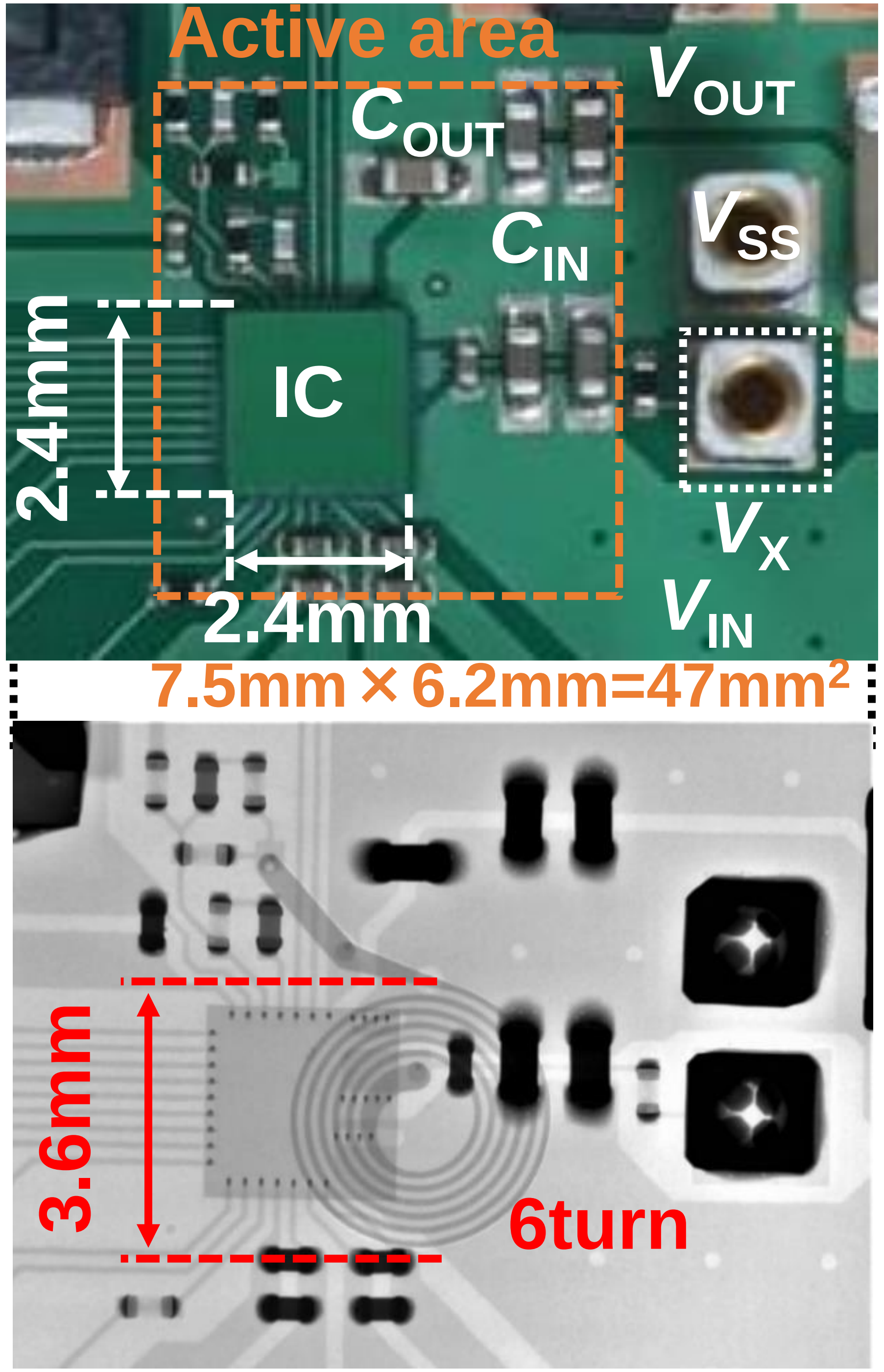


- Adaptive window control quasi-V^2 ripple injection hysteresis control
  → Fast transient response with fixed high f_{SW}(16/20MHz) operation
  - Conventional current mode PWM using high-side PMOS current sensor is not suitable (Op-amp GBW becomes too high to reproduce inductor peak current beyond 10MHz

Fabricated 3D-Integrated Buck Converter







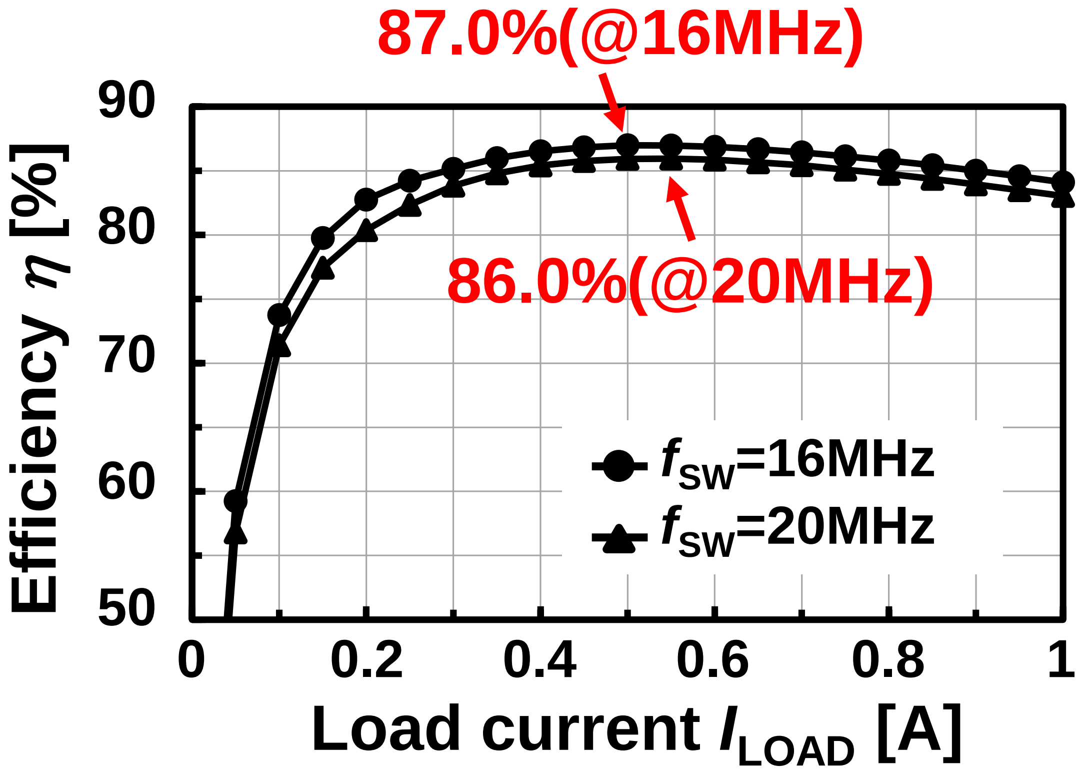
X-ray photograph

- Spiral inductor locates under the IC

⇩

- 3D-integration is successfully achieved
- The footprint is reduced by 34% with the 3D-integration
  - Further footprint reduction is possible
    - Compensation network can be integrated, C_{IN} and C_{OUT} can be reduced

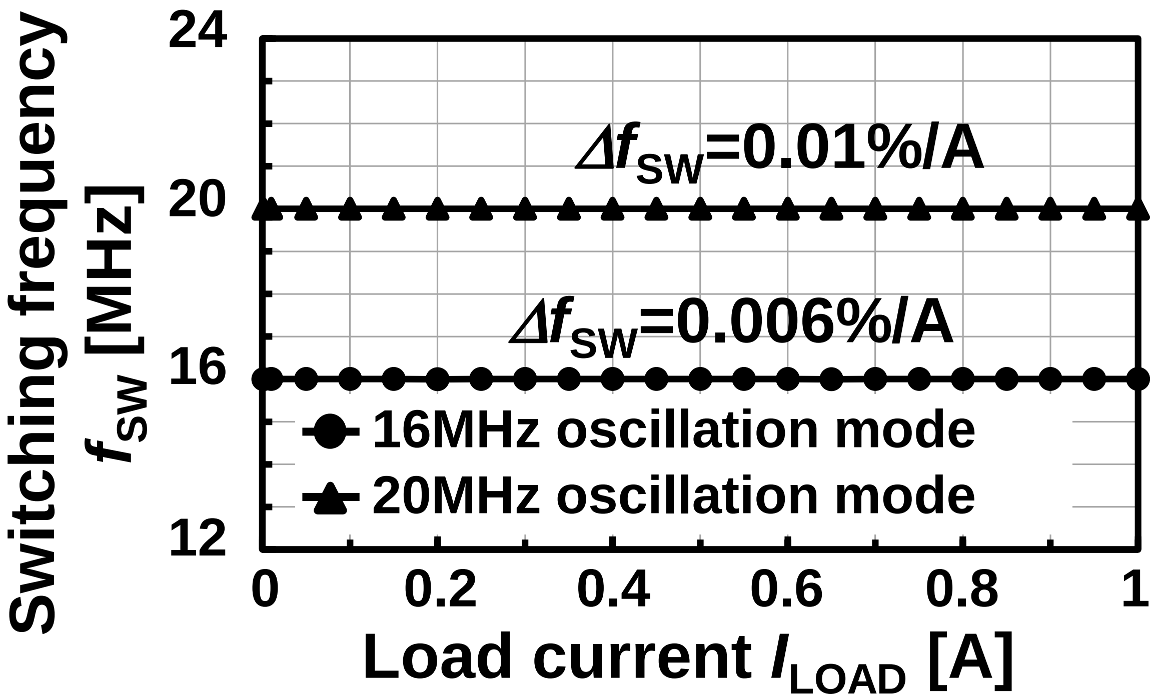
Measurement Results

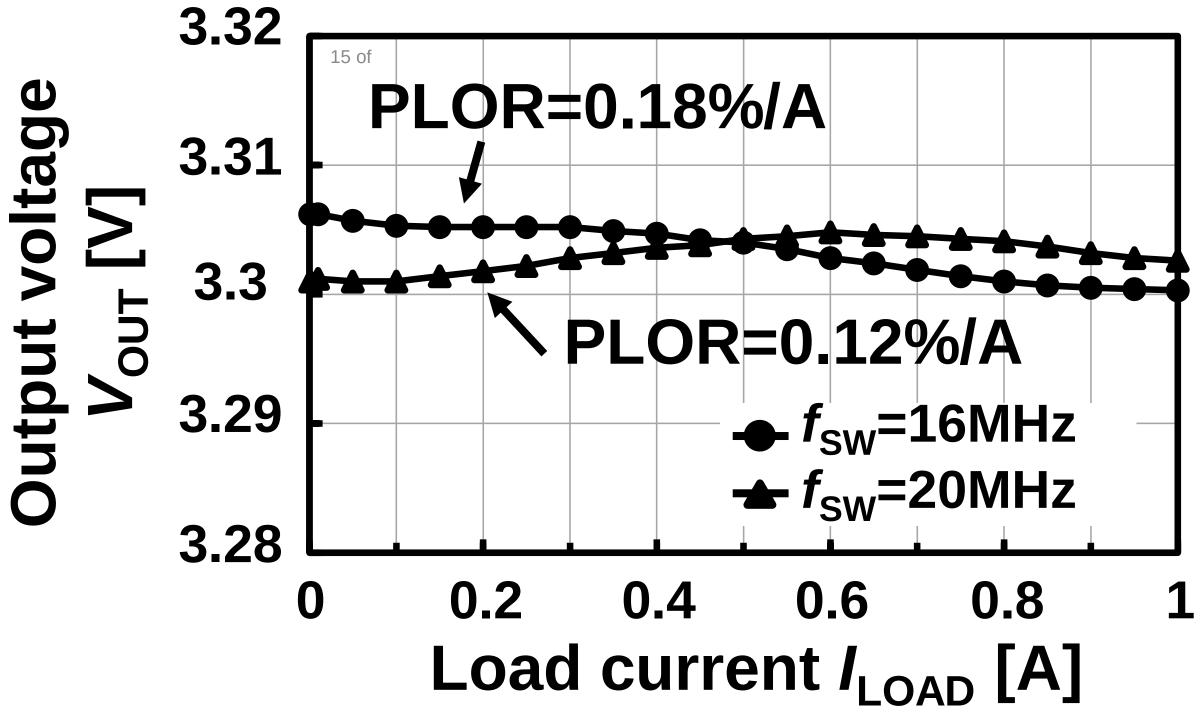


Input voltage V_{IN}: 5V

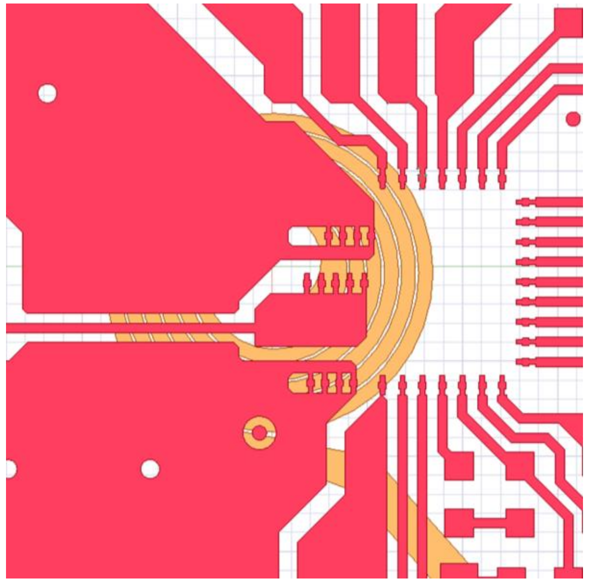
Output voltage V_{OUT}: 3.3V

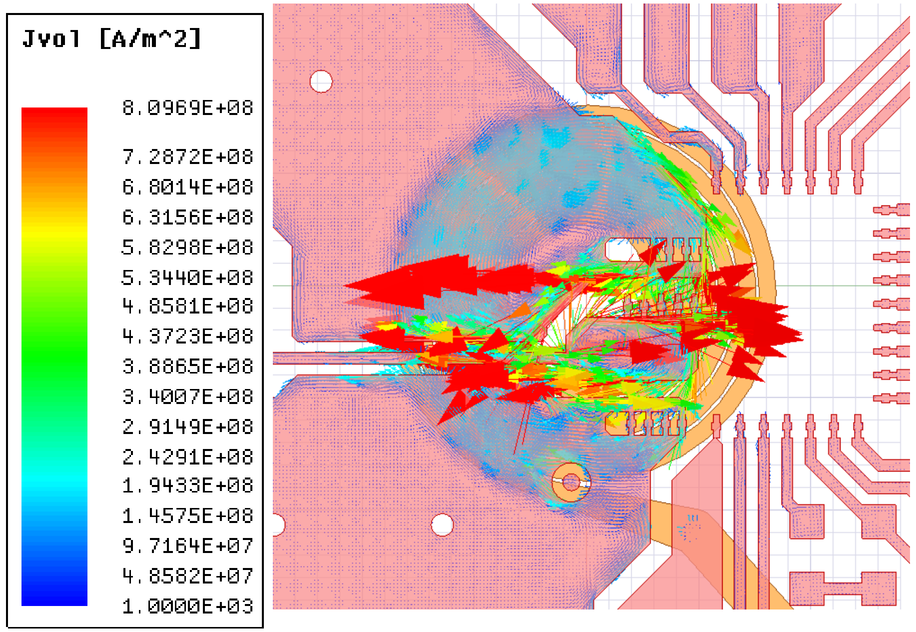
C_G, C_D charge loss dominant

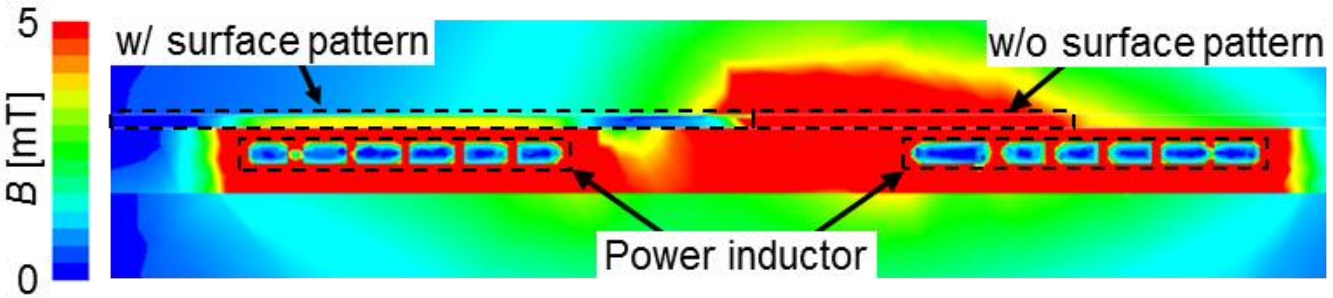




Effect of Magnetic Flux Leakage



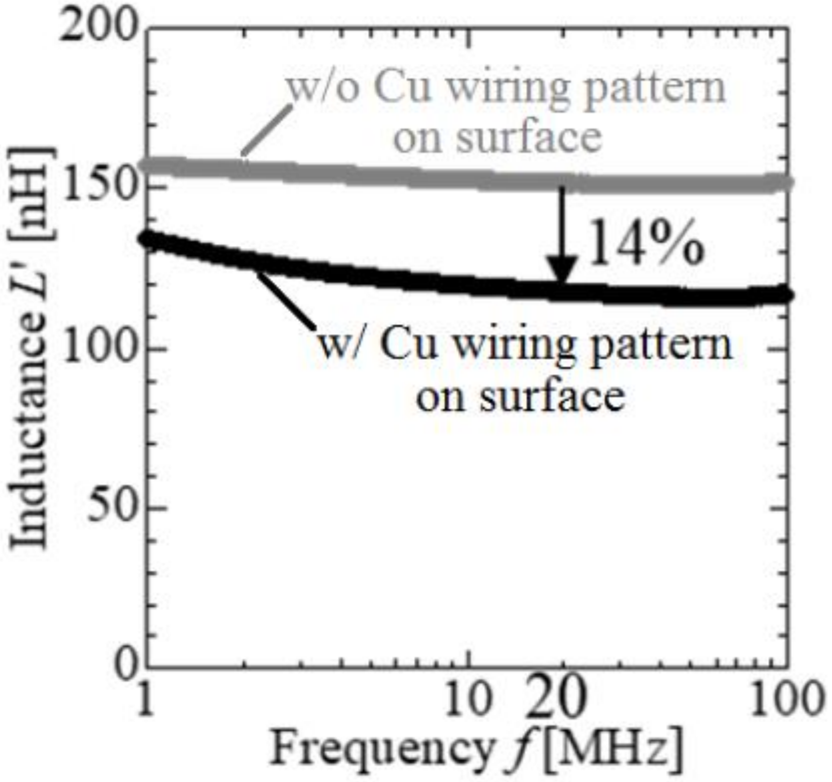


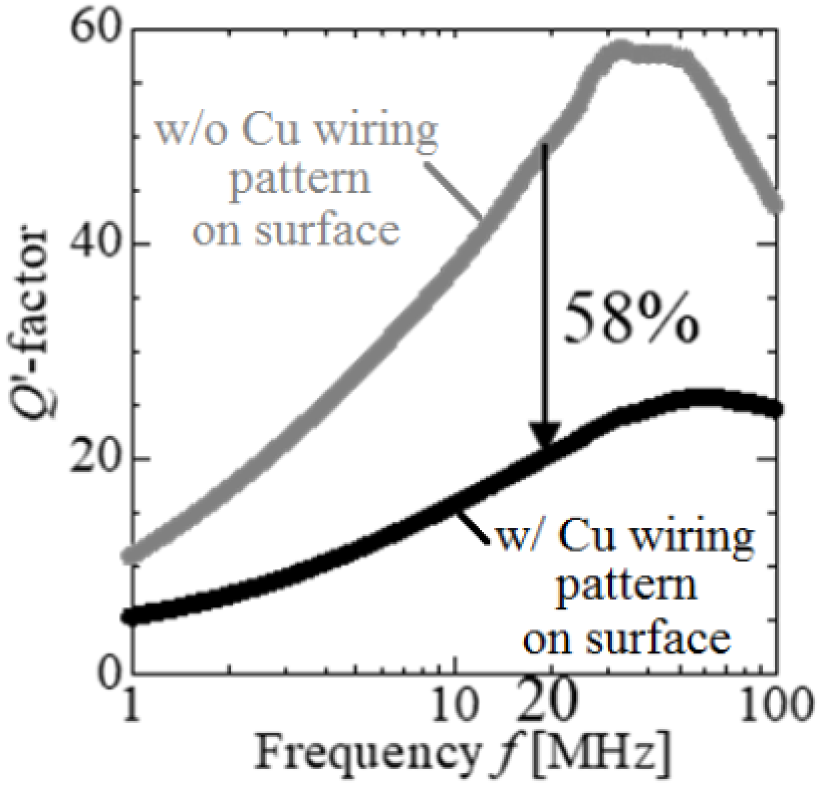


- **Eddy current in the Cu pattern due to flux leakage is confirmed**
  - **Estimated value: *L*~130nH, *Q*=16~20@20MHz**

⇩

- **Higher permeability**
- **Flux shielding**
- **Layout optimization are required**





T. Akiyama et al., *J. Mag. Soc. Jpn*, vol. 43, pp. 64-69 2019.

Fe-Base Flake Powder Composite Magnetic Cores

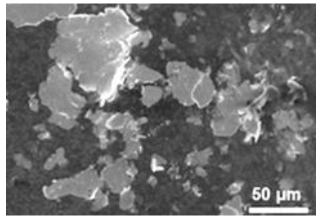
Starting material	Flake powder composite	Application

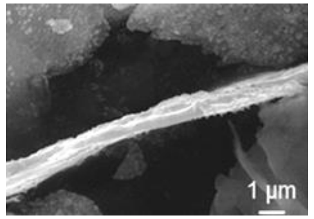
Starting material

Fe-Si-B-Cu-Nb amorphous ribbon

t: 18μm
B_s: 1.1T (Nano)
H_c: 2.4A/m (Nano)
ρ: 1.1μΩ･m

Flake powder fabrication thru vibration milling

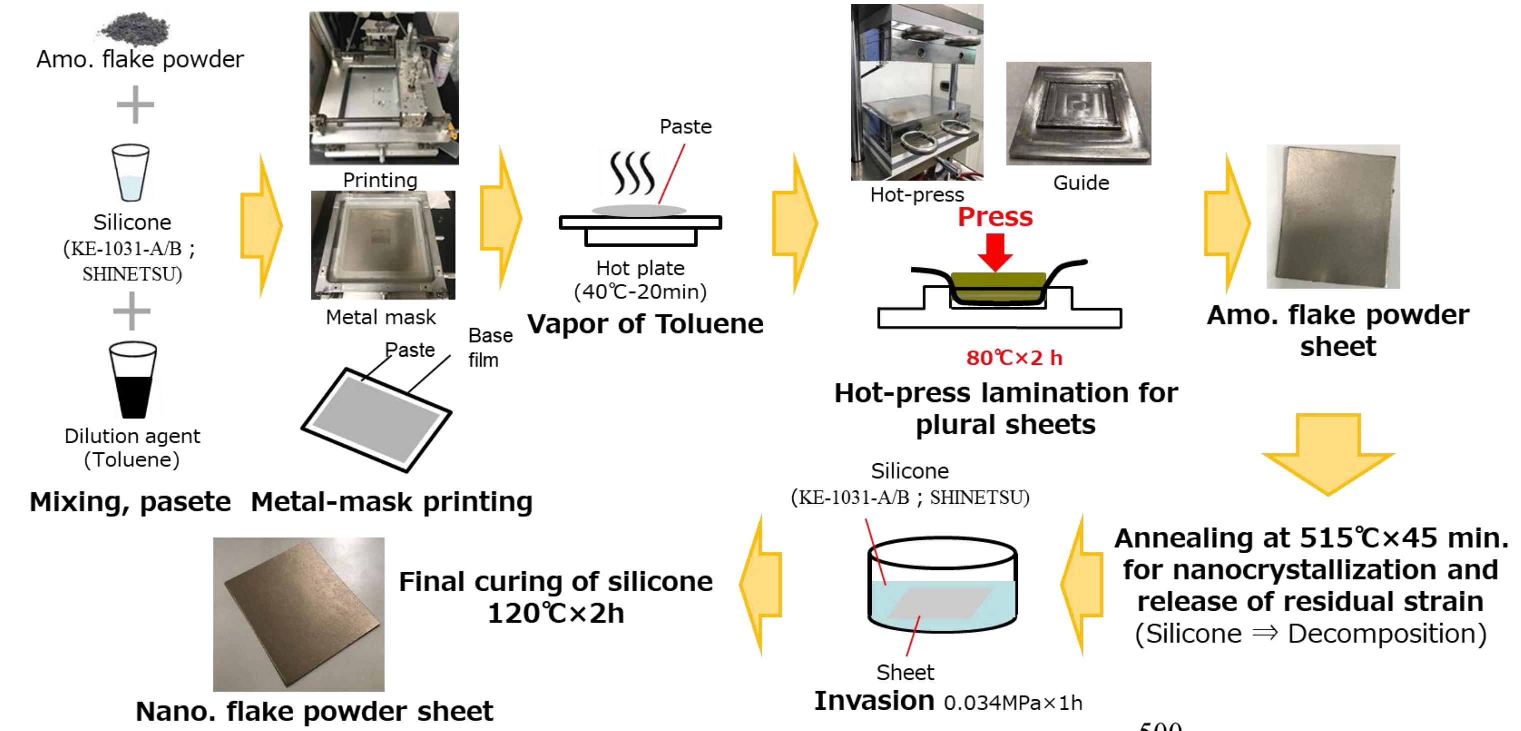




Over 100μm size screening
t: 1～3μm
H_c: 3330A/m (very large due to residual strain thru milling)

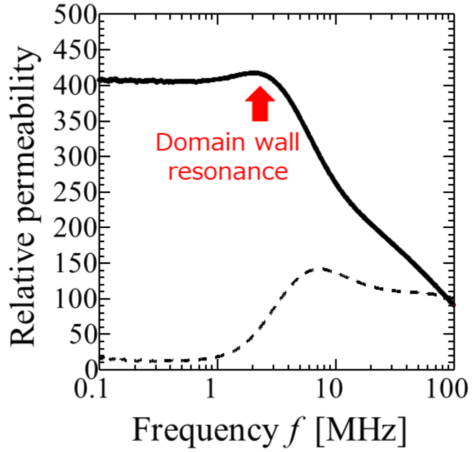
Flake powder composite

Fabrication procedure of Fe-nano flake composite sheet



Isotropic magnetic properties

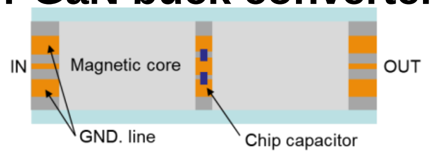
B_s: 0.48T
H_c: 58A/m, cf. 184A/m: Sendust flake sheet
μ_r': 400@1MHz, 260@10MHz
μ_r'': 20@1MHz, 130@10MHz
⇒ Large eddy current due to domain wall motion

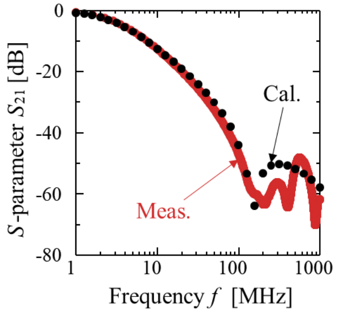


Application

Isotropic sheet

Large loss@high *f*
⇩
LCL noise filter for GaN buck converter





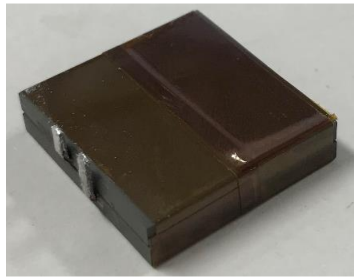
Anisotropic sheet

Introduction of uniaxial anisotropy
⇩
Rotation magnetization small loss@high *f*

Currently under development

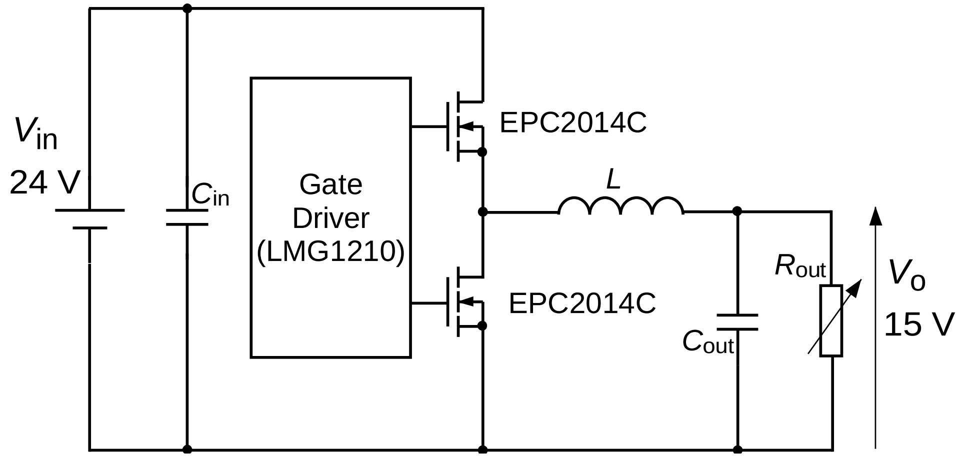
Applications to Planar Bulk Inductor and Transformer

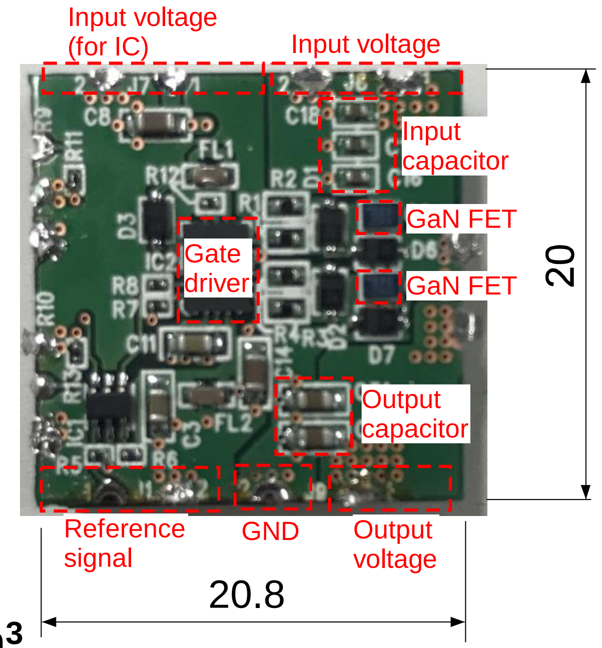
- **Fe-base sphere powder composite materials can be applied to planar bulk magnetic cores**

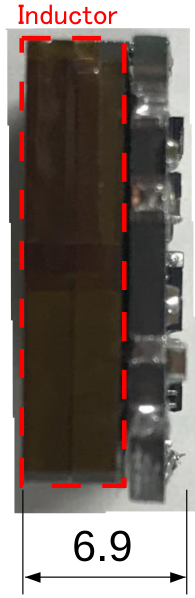


Planar inductor
692nH@15MHz
R_{DC}=5mΩ, R_{AC}=484mΩ@15MHz

24V input 15V output 5~15MHz Buck Converter

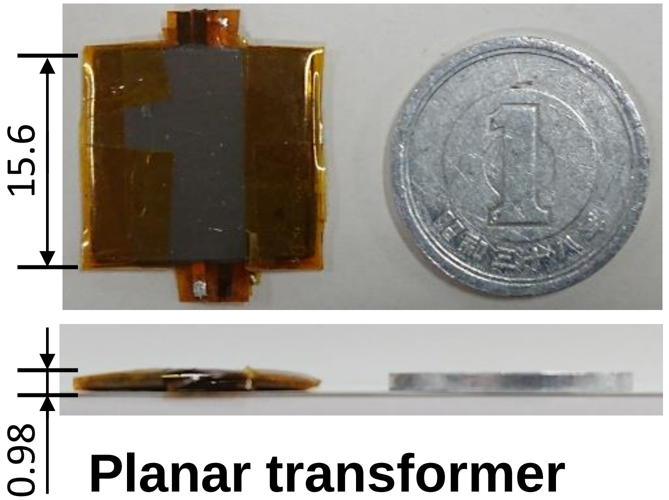






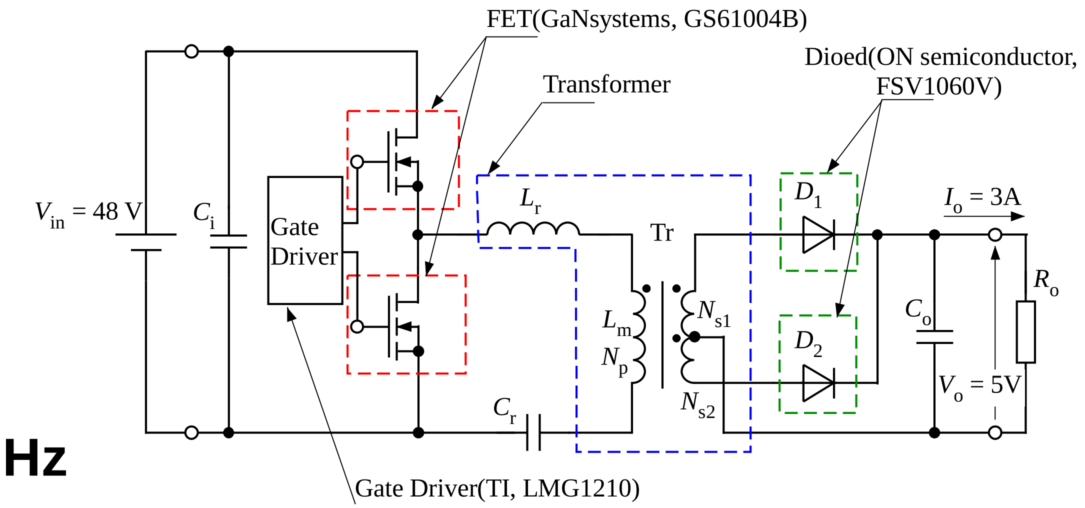
η: 93.3%@60W, 5MHz
Power density: 21W/cm³
Temp. of high-side GaN: 160℃

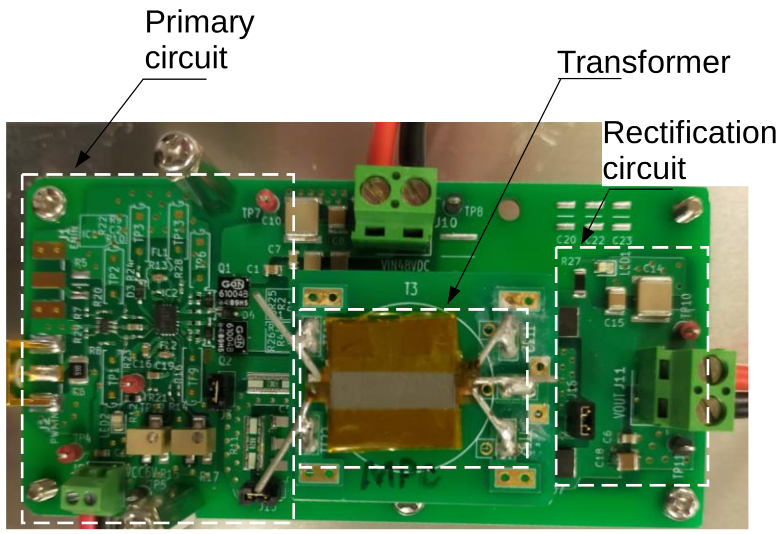
η: 86.0%@30W, 15MHz
Power density: 10W/cm³
Temp. of high-side GaN: 225℃@22.5W



Planar transformer
L=274nH, k=0.63 @15MHz

48V input 5V output 15MHz LLC Converter





η: 66.0%@15W, 15MHz

Conclusions

- **Fe-based metal composite material is suitable for >10MHz f_{SW}**
  - **Sphere powder**
    - **Fe-Si-B-C-Cr amorphous powder composite sheet (μ_r': 10) for 10~40MHz inductor**
    - **Carbonyl iron (CIP) with nano-crystalline powder composite sheet (μ_r': 7.5) for >100MHz inductor**
    - **Low H_c Fe-Si-B-Nb-Cu nanocrystalline powder composite sheet is under development**
  - **Flake powder**
    - **Fe-Si-B-Cu-Nb nanocrystalline powder composite sheet (μ_r': 400@1MHz, 260@10MHz) → Introduction of uniaxial anisotropy is under development**
- **Fe-based metal composite can be applied to both embedded sheet core and bulk core**
  - **State of the art performance is achieved**
- **3D-integrated buck converter module has been successfully demonstrated using sphere powder magnetic core inductor**

Acknowledgements

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Thank you very much for your kind attention.