Thursday, October 18th
Session 4: Integrated Magnetics

Fe-based Metal Composite Magnetic Core and Its Application to High-frequency Switching DC-DC Converter

Toshiro Sato[1]*,
Tsutomu Mizuno[1], Makoto Sonehara[1], Kousuke Miyaji[1],
Tsuyoshi Funaki[2], Takaaki Ibuchi[2]

[1]Shinshu University, Nagano, Japan
[2]Osaka University, Osaka, Japan

Outline

◆ **Background**

Magnetic materials issue for beyond MHz power conversion

◆ **Fe-based metal composite bulk core**

(1) Casting method for making bulk magnetic core

(2) Leakage transformer and its application to MHz switching LLC resonant converter

◆ **Fe-based metal composite sheet core**

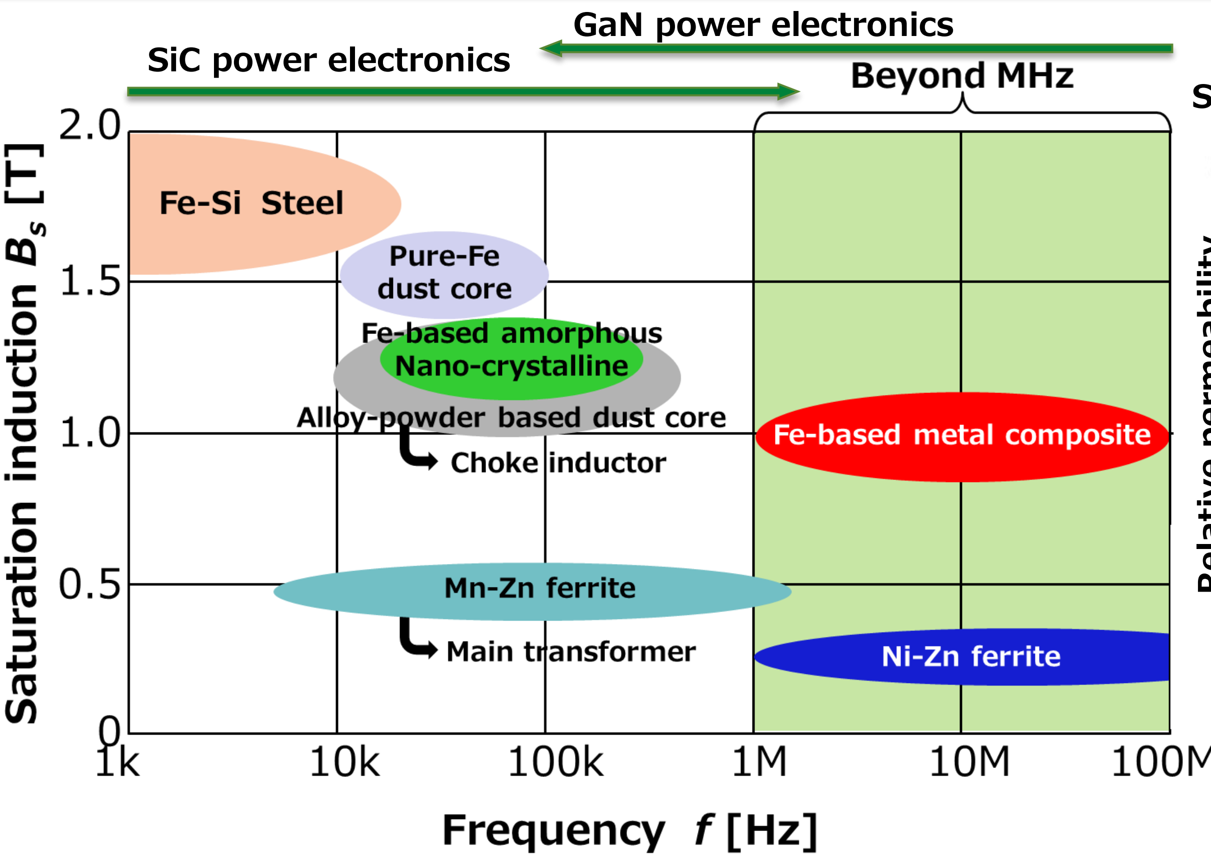
(1) Sheet core fabrication for making embedded inductor and transformer in organic interposer

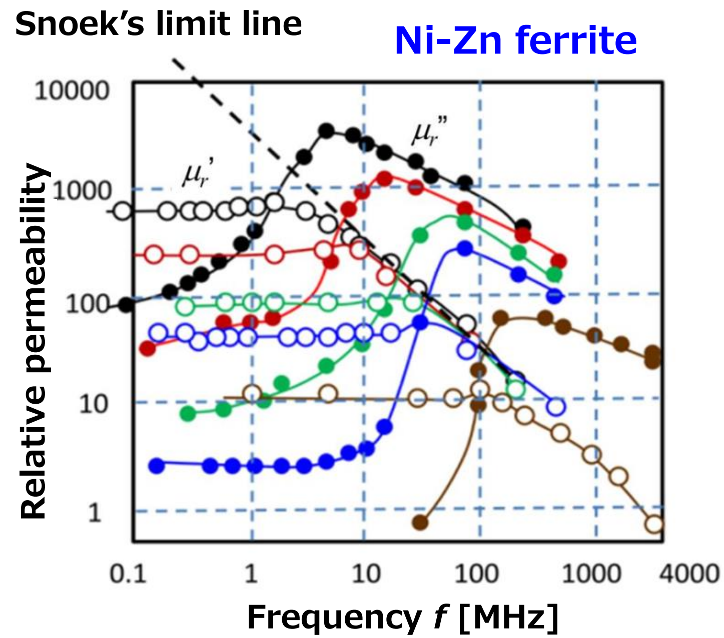
(2) Embedded spiral inductor and its application to 20MHz switching back converter fabricated in organic interposer

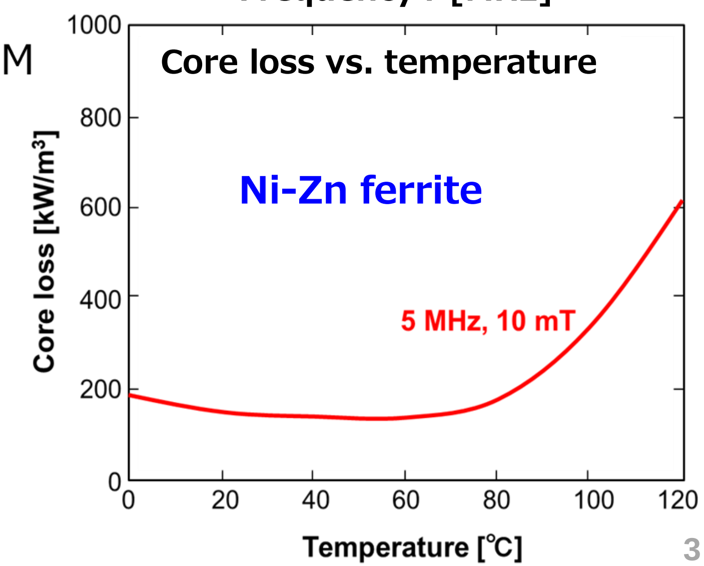
◆ **Conclusion and future work**

◆Background

Magnetic materials issue for beyond MHz power conversion







Ni-Zn ferrite core

- Low B_s of 0.2～0.3 T
- Snoek's limit at beyond MHz
- Core loss $W_c \propto B_m^{a}$, $a \fallingdotseq 3$
- T_c ≒< 300℃, Thermal runaway@beyond 100℃

Metal-based composite with small eddy current

◆Why Fe-based metal composite core ?

PWR SoC 18

Why metal-based ?

Two times higher Currie temperature than that of Ni-Zn ferrite

⇒ typically T_c ≒ 600℃

Core loss per cycle $W_{co} = W_{ho}(H_c) + W_{eo}(\rho)$

W_{ho}; Hysteresis loss per cycle, H_c ; Coercivity
W_{eo}; Eddy current loss per cycle, ρ ; Resistivity

Decrease of coecivity with increasing temperature due to de-pinning effect at high temperature

⇒ Decrease of hysteresis loss with increasing temperature

Increase of volume resistivity with increasing temperature

⇒ Decrease of eddy current loss with increasing temperature

⬇

If the mechanism of the magnetization reversal is thermally stable, temperature coefficient of the core loss is negative (no risk of thermal runaway)

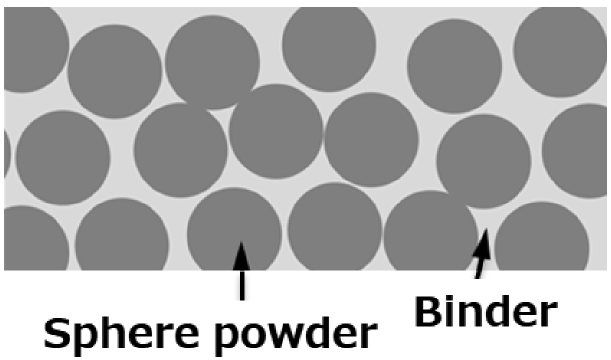
◆Why Fe-based metal composite core ?

Why sphere metal powder used for composite ?

Each sphere powder; Demagnetizing field effect still quite remains.

⬇

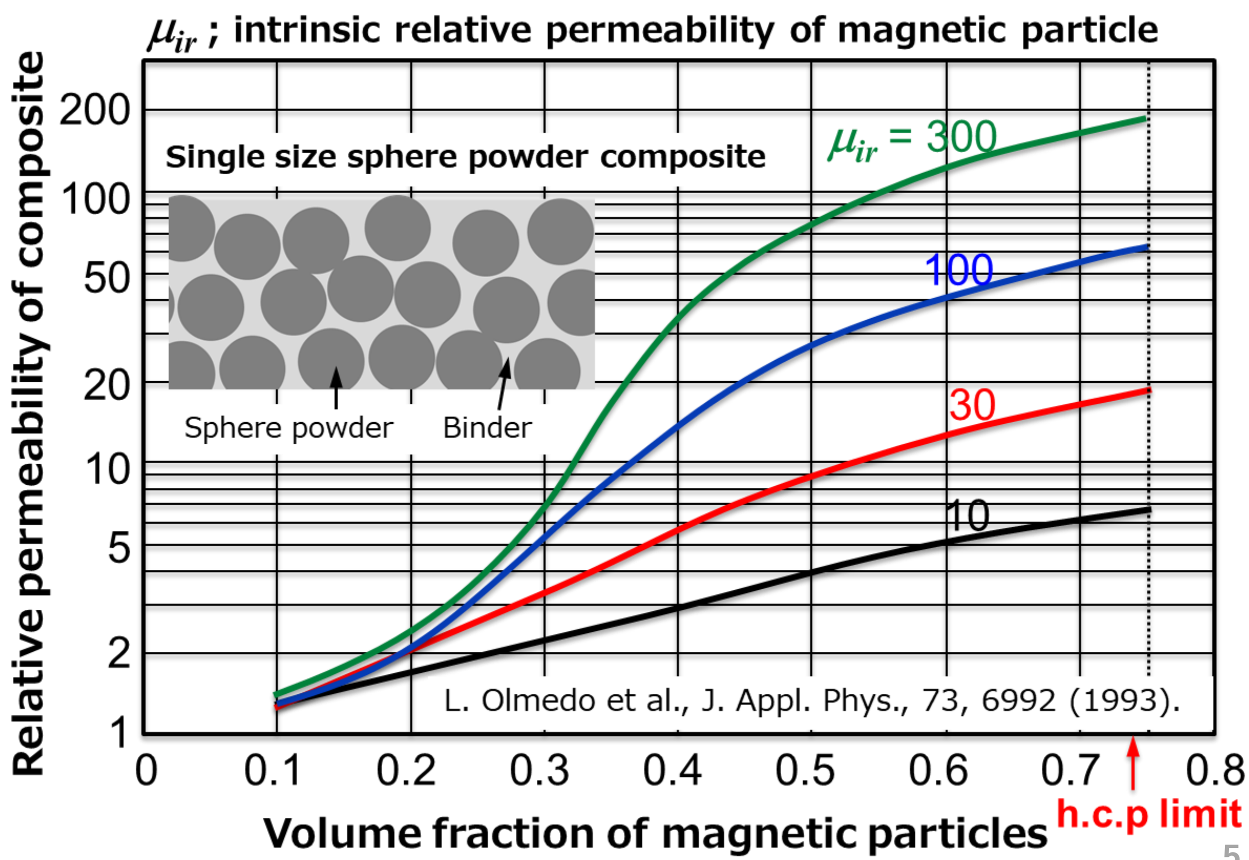
Magnetization reversal; Thermally stable demagnetizing field effect
⇒ Temperature dependence of magnetization (T_c)



Fine metal powder composite

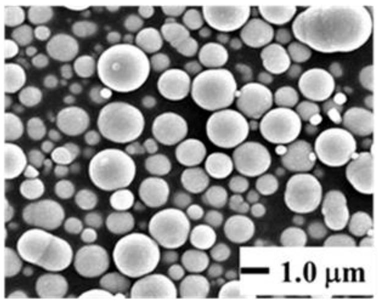
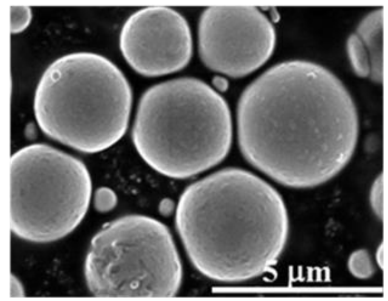
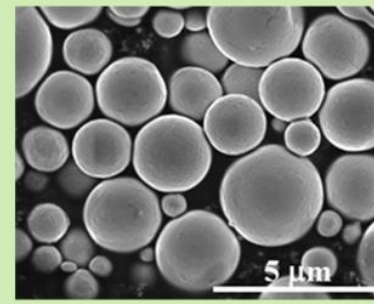
⬇

Moderate permeability, Low loss and thermal stability for high-frequency power conversion



◆Fe-based metal composite magnetic core

A few μm size Fe-based fine metal powders under study

	Carbonyl-iron Powder (CIP)	Fe-Si polycrystalline powder	Fe-based amorphous powder (Fe-AMO)
			
Finest D_{50}	1.6 μm	3.5 μm	2.6 μm
M_s	2.0 T	1.8 T	1.3 T
ρ	0.1 μΩ・m	0.7 μΩ・m	1.3 μΩ・m
H_c	720 A/m (9 Oe)	720 A/m (9 Oe)	128 A/m (1.6 Oe)

from $Fe(CO)_5$

Atomized powder

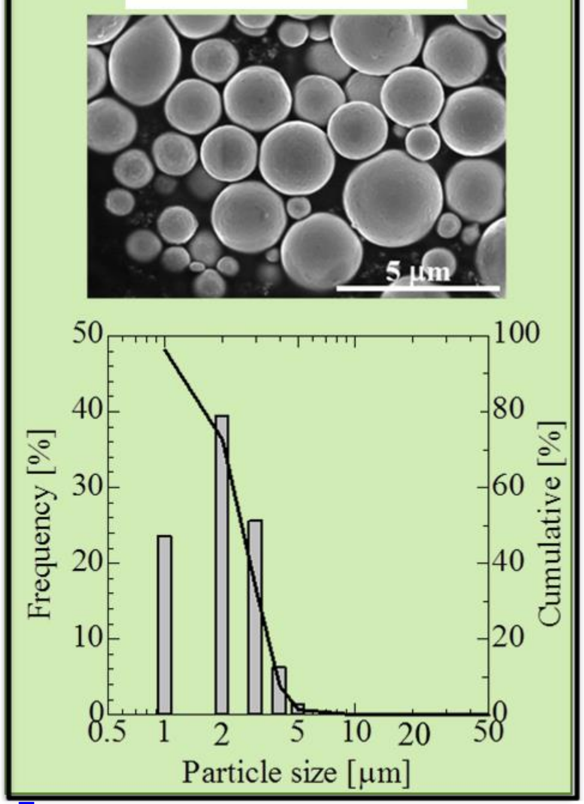
➡ **Fe-based amorphous powder (Fe-Si-B-Cr-C) was selected.**

◆Fe-based metal composite magnetic core

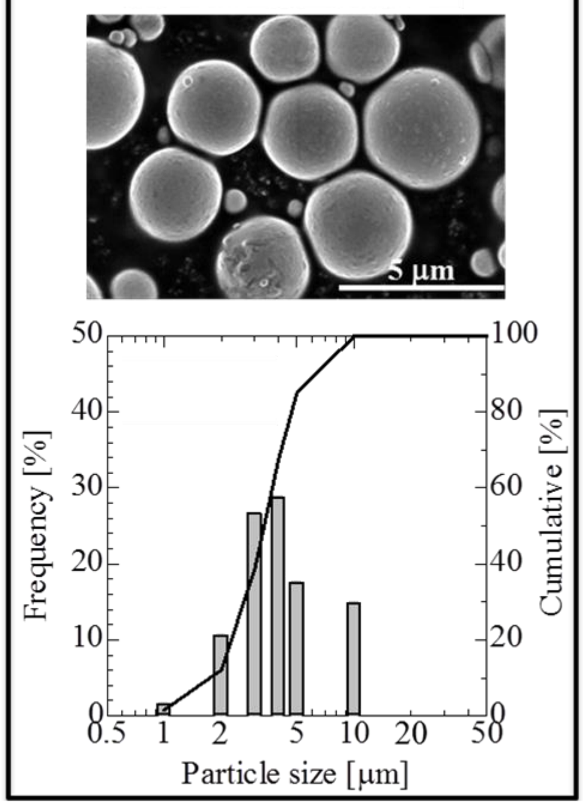
Fe-based amorphous powder (EPSON Atmix, Co., Japan)

SWAP powder ; Spinning Water Atomization Process*
Composition ; $Fe_{73.7}$ $Si_{11.0}$ $B_{11.0}$ $Cr_{2.3}$ $C_{2.0}$ (at.%), $Fe_{87.8}$ $Si_{6.6}$ $B_{2.6}$ $Cr_{2.5}$ $C_{0.5}$ (wt.%)
Saturation magnetization Ms ; 12.6 kG, 1.26 T , Magnetostriction λ_s; Unknown

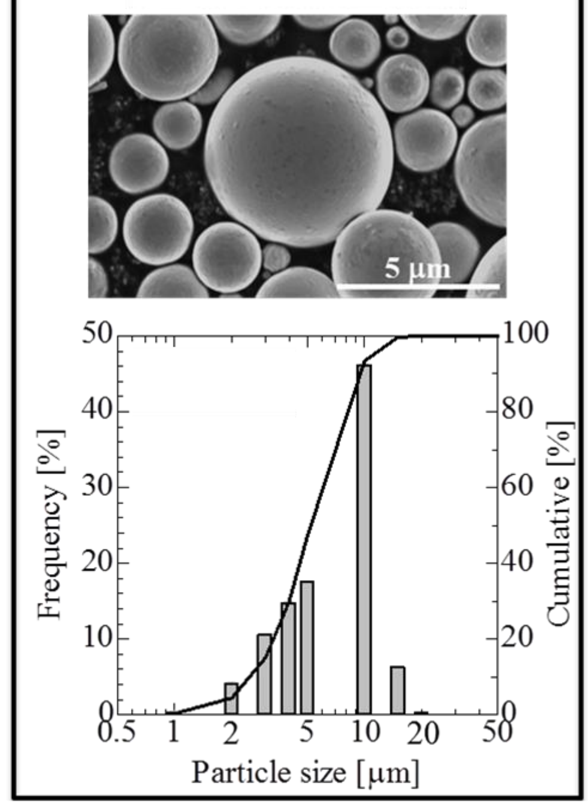
D_{50} = 2.6 μm



D_{50} = 3.4 μm



D_{50} = 5.2 μm



Finest SWAP powder

* I. Otsuka et al., *IEEE Trans. Magn.*, Vol.44, No.11, pp.3891-3894 (2008).

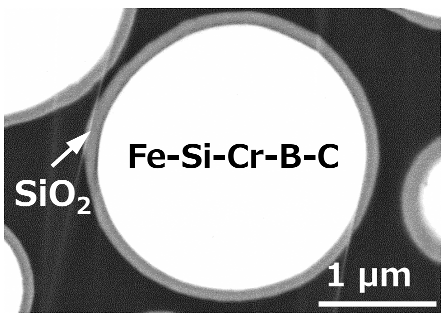
◆Fe-based metal composite magnetic core

Formation of insulating surface layer on Fe-based amorphous powder

Silica coating*

Stöber method using TEOS

$$Si(OC_2H_5)_4 + 2H_2O + NH_3 \Rightarrow SiO_2 + NH_3 + 4C_2H_5OH$$



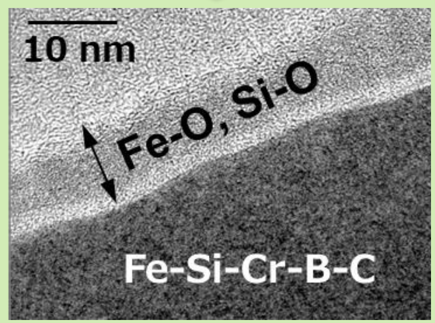
Silica single phase surface layer

Uniform thin silica layer possible
Very thin 8 nm layer possible
Slight increase of powder coercivity due to compressive stress

Thermal oxidation in dry air**

Fe-Si-Cr-B-C in dry air

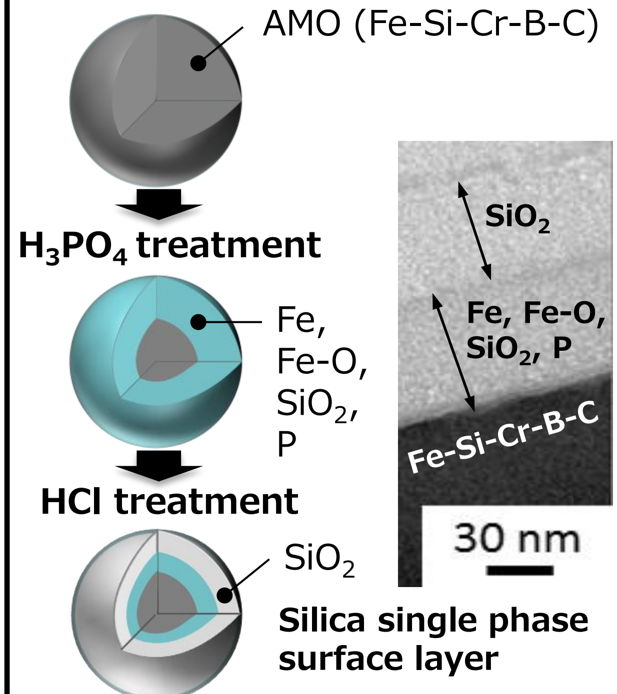
300℃×3h



Glass-like thin surface layer (Fe-O, Si-O)

Uniform glass-like layer possible
Decrease of coercivity via 300℃×3h

Two-Step acid solution processing***



Silica single phase surface layer

Thermal oxidation was selected for making insulating surface layer.

* K. Sugimura *et al*, *AIP Advances*, Vol.6, 055932 (May 2016).
** Kanako Sugimura *et al*., *IEEE Trans. Magn.*, Vol.53, No.11, #2801406 (Nov. 2017)
*** Kanako Sugimura *et al*., *IEEE Tran. Magn.*, Vol.54, No.11, (Nov. 2018), to be published.

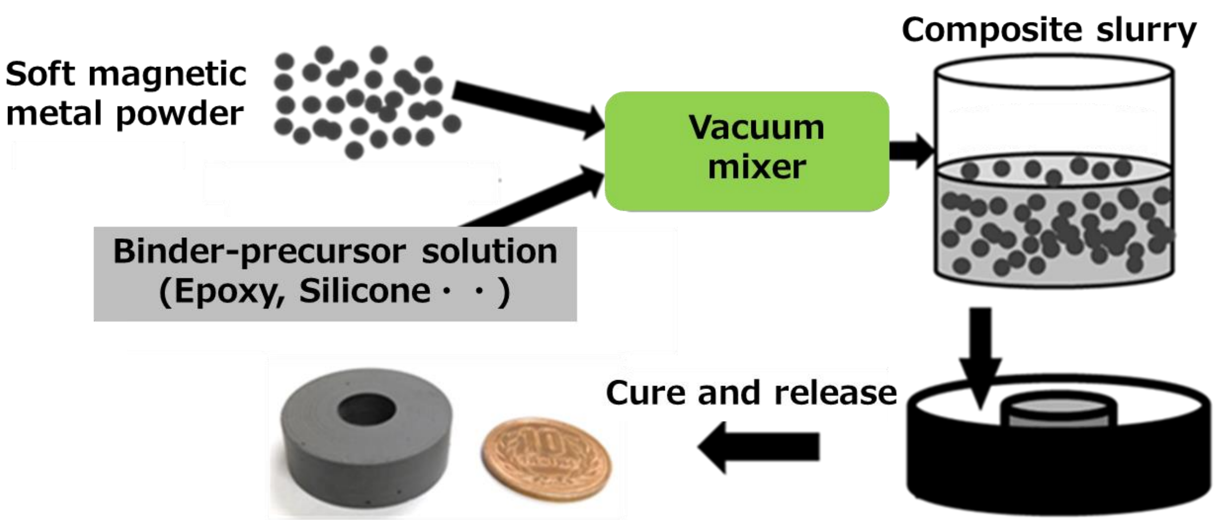
◆ Fe-based metal composite bulk core

Casting method for making bulk magnetic core using a few μm size fine powder

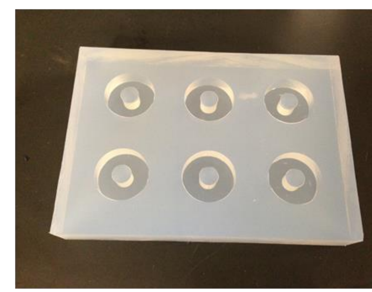
Why casting method ?

⇒ Difficult to make fine powder composite by conventional press method

⇒ Lower process cost of casting method than that of press method



Vacuum mixer



Silicone rubber template

Muffle furnace

To obtain dense core by casting,

Binder content as small as possible,
Slurry viscosity as low as possible

⬇

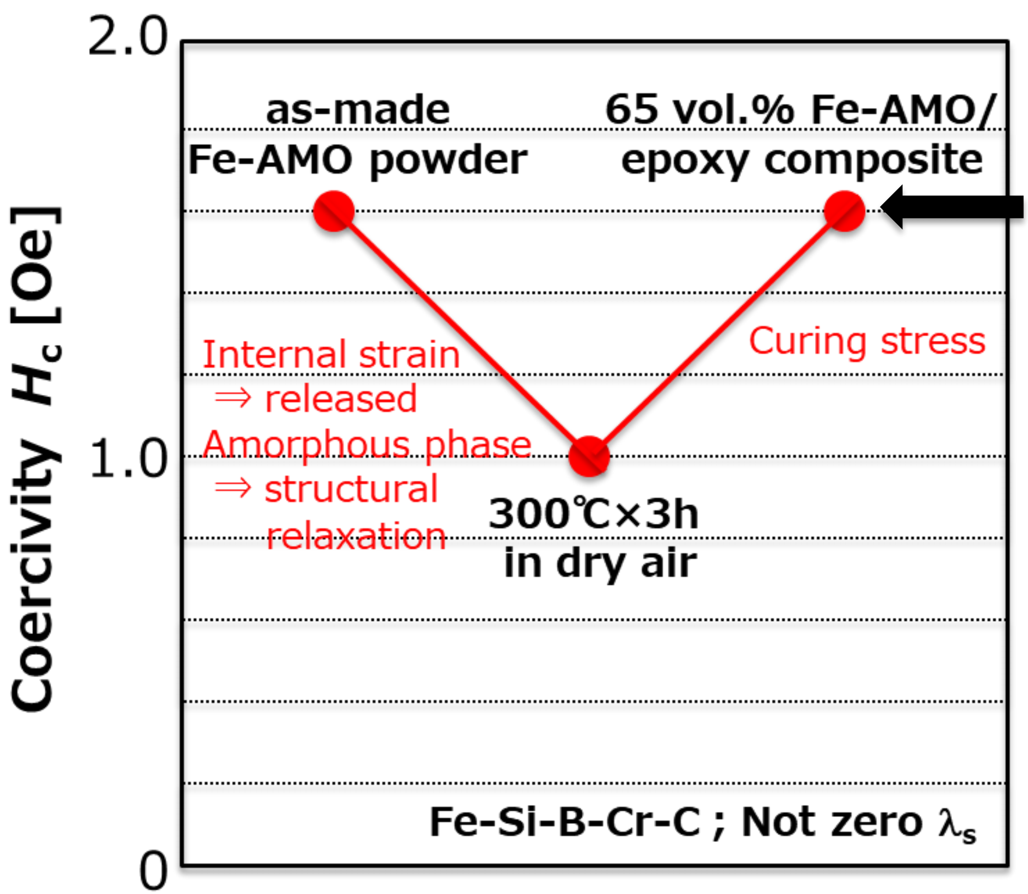
By using appropriate dilution agent,
Composite core as dense as possible

◆ Fe-based metal composite bulk core

Composite bulk core consisting of 2.6 μm size fine Fe-AMO powder and epoxy resin

Magnetic properties

Coercivity change from as-made Fe-AMO powder to Fe-AMO/epoxy composite core



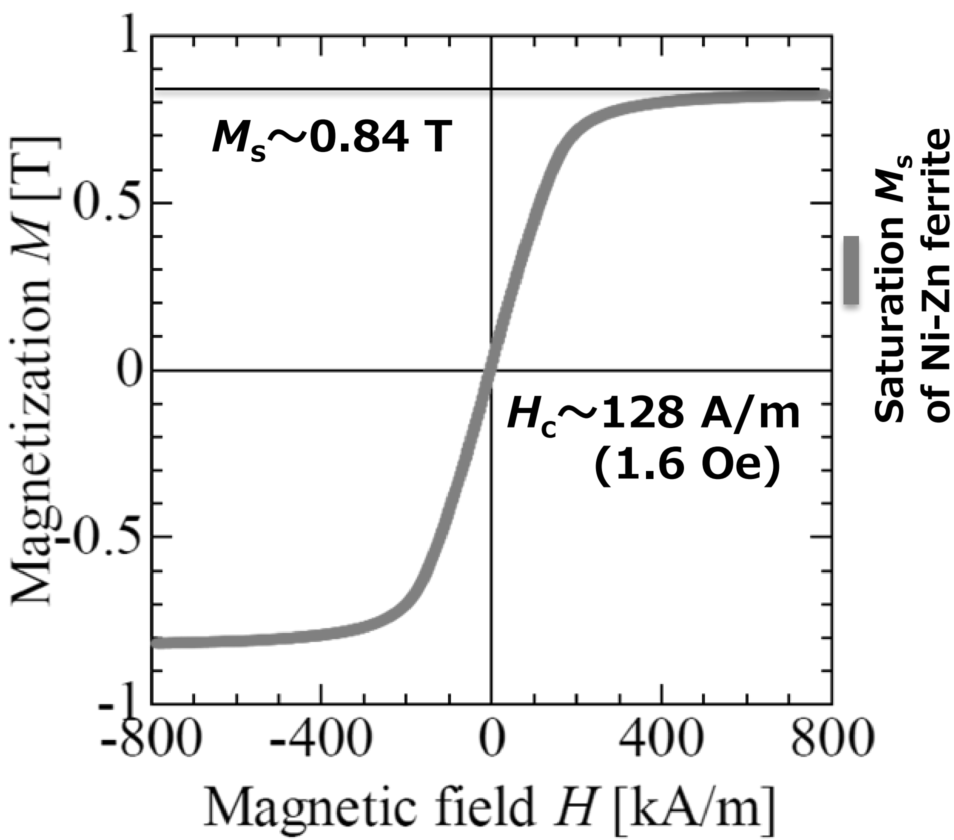
Nearly closed package when using 2.6 μm size fine Fe-AMO powder and epoxy resin

◆ Fe-based metal composite bulk core

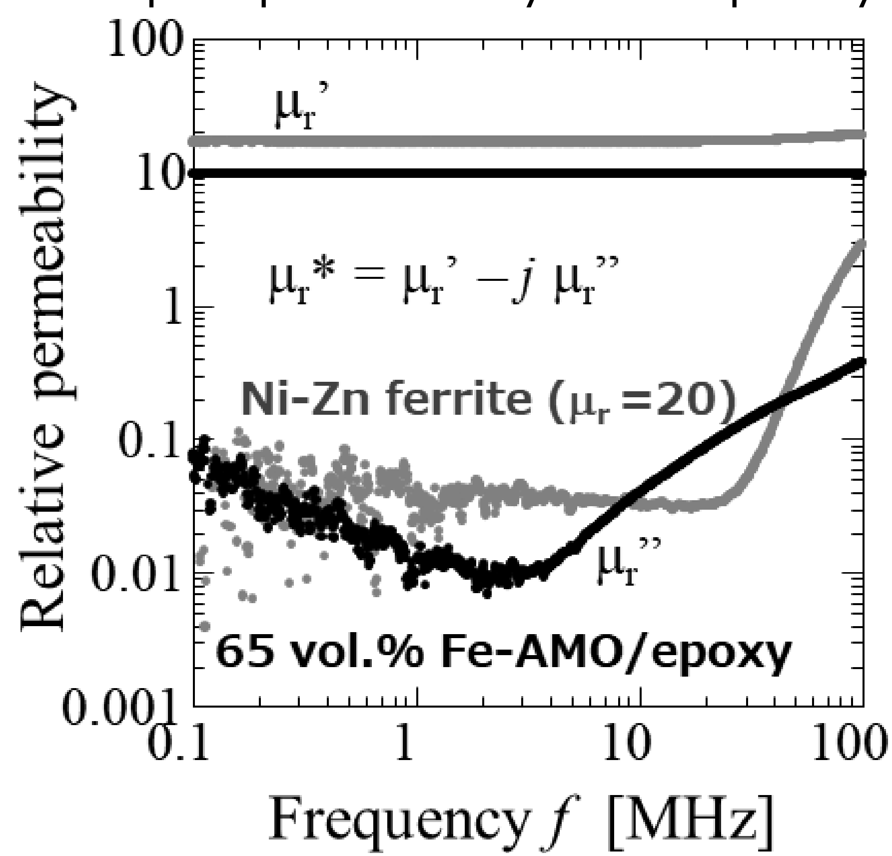
Composite bulk core consisting of 2.6 μm size fine Fe-AMO powder and epoxy resin

Magnetic properties ; 65 vol.% Fe-AMO composite core

Static *M-H* curve



Complex permeability vs. frequency

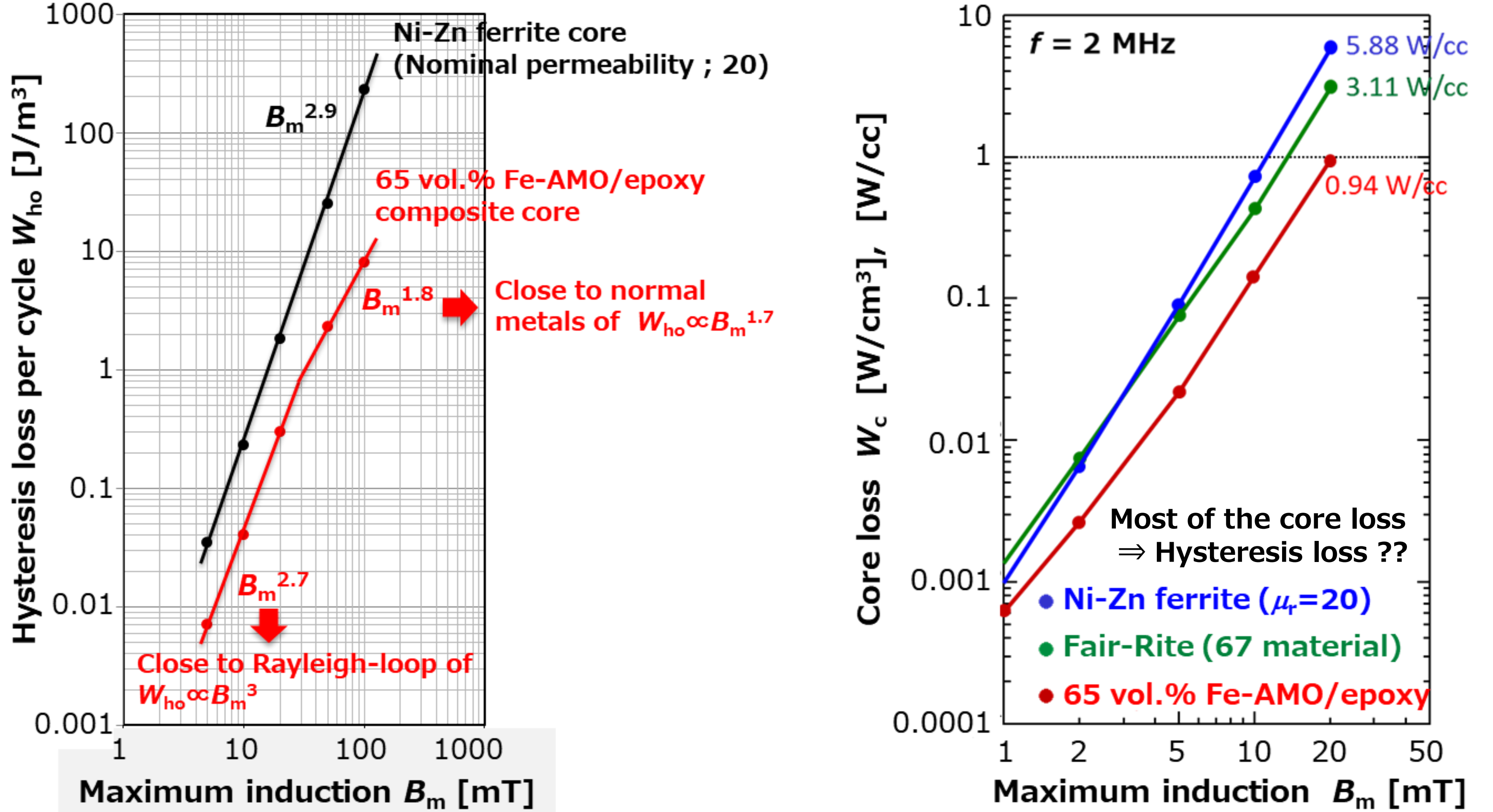


Kanako Sugimura *et al.*, *IEEE Trans. Magn.*, Vol.53, No.11, #2801406 (Nov. 2017)

◆ Fe-based metal composite bulk core

Composite bulk core consisting of 2.6 μm size fine Fe-AMO powder and epoxy resin

Magnetic properties ; 65 vol.% Fe-AMO composite core



Kanako Sugimura *et al.*, *IEEE Trans. Magn.*, Vol.53, No.11, #2801406 (Nov. 2017)

◆LLC resonant DC-DC converter application

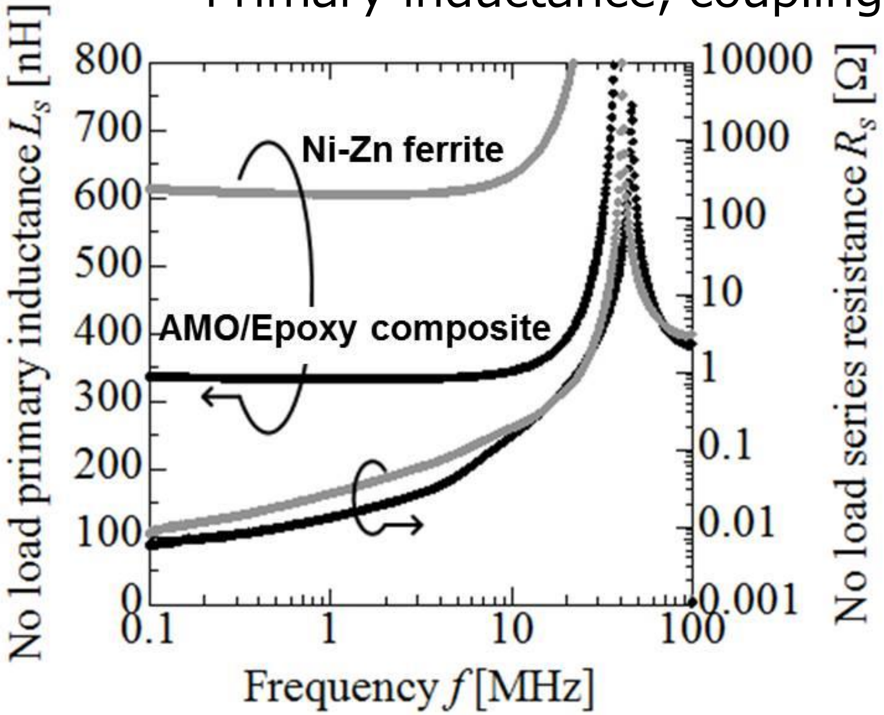
Fe-based amorphous composite bulk core

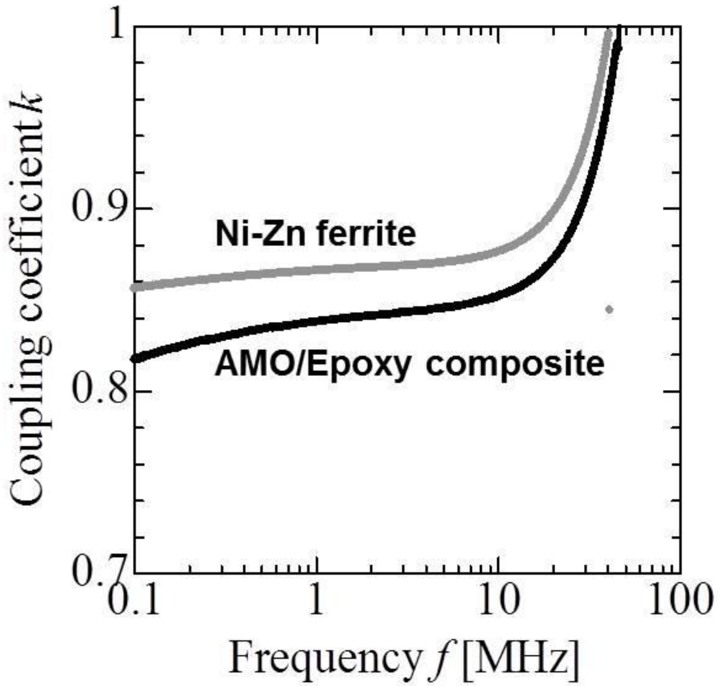
Leakage transformer for MHz power conversion

Core dimension;
Φ_o15.5mm × Φ_i9.0mm × h11.1mm
Volume ; 1.39 cm^3

Windings ; $N_1 : N_2 : N_3 = 5 : 4 : 4$

Primary inductance, coupling coefficient *vs*. frequency





Kanako Sugimura *et al*., *IEEE Trans. Magn.*, Vol.53, No.11, #2801406 (Nov. 2017)

◆LLC resonant DC-DC converter application

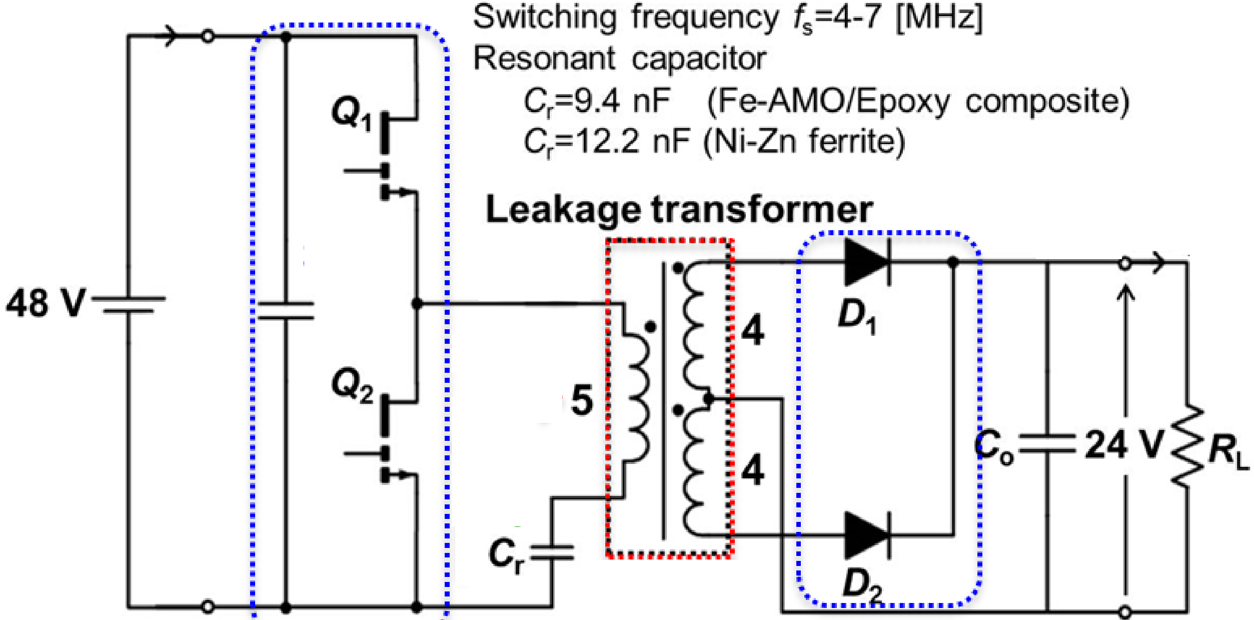
Fe-based amorphous composite bulk core

Leakage transformer for MHz power conversion

MHz switching LLC resonant converter

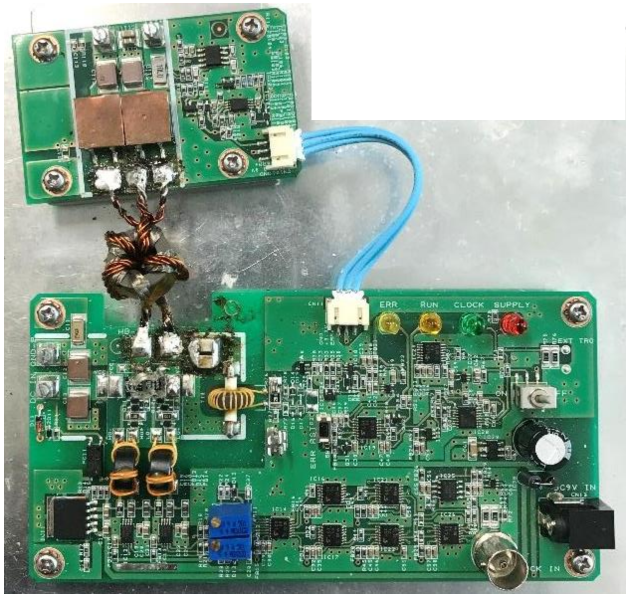
MHz switching LLC resonant converter using a leakage transformer

Switching frequency f_s=4-7 [MHz]
Resonant capacitor
C_r=9.4 nF (Fe-AMO/Epoxy composite)
C_r=12.2 nF (Ni-Zn ferrite)



GS61004 ; GaN Systems
($V_{DX\ MAX}$=100 V, $I_{DS\ MAX}$=45 A, R_{DS}=15 mΩ, Q_G=6.2 nC)

SCS220AJ ; ROHM
(V_R=650 V, I_F=20 A, $V_{F\ max}$=1.6 V)

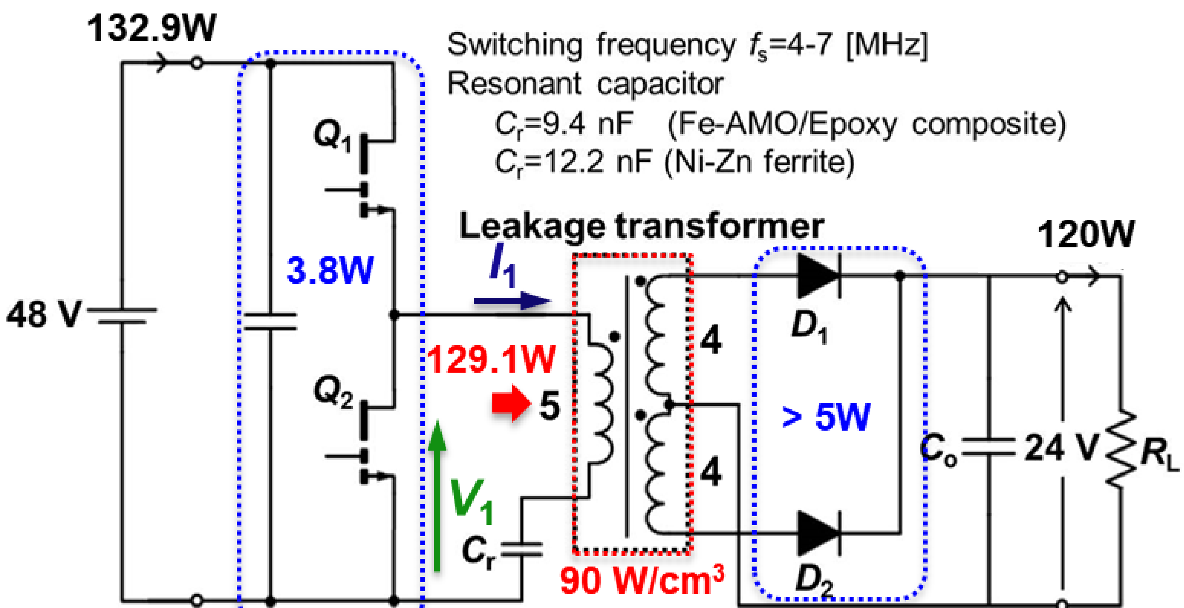


Kanako Sugimura *et al.*, *IEEE Trans. Magn.*, Vol.53, No.11, #2801406 (Nov. 2017)

◆LLC resonant DC-DC converter application

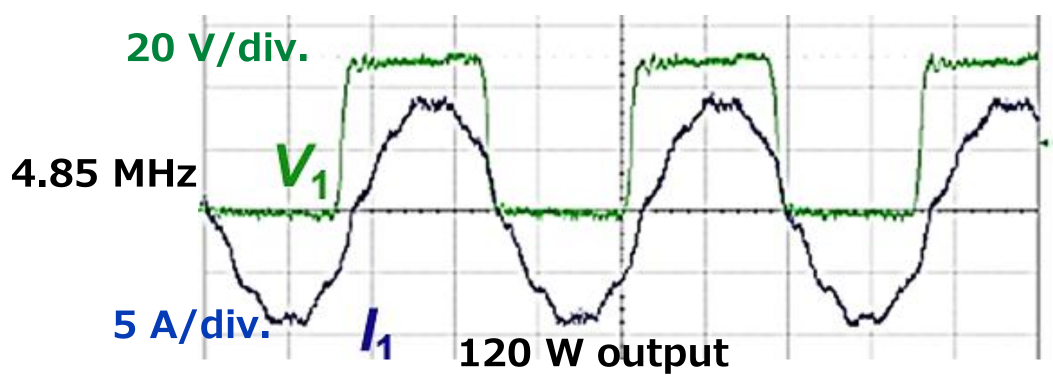
MHz switching LLC resonant converter

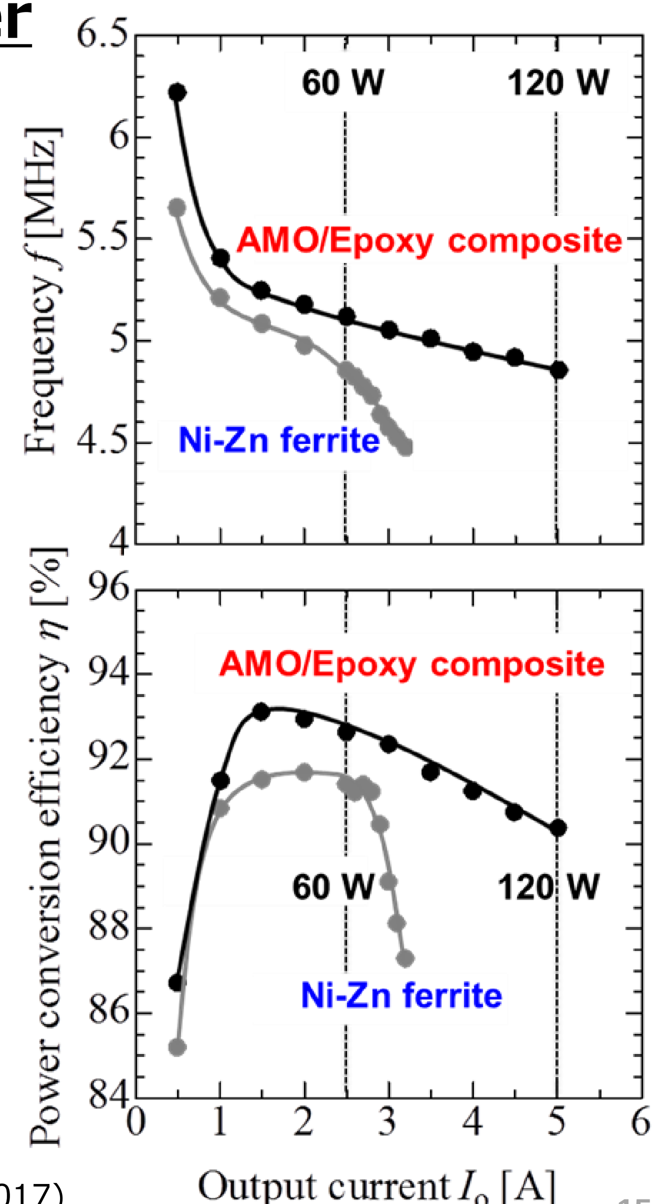
Switching frequency f_s=4-7 [MHz]
Resonant capacitor
C_r=9.4 nF (Fe-AMO/Epoxy composite)
C_r=12.2 nF (Ni-Zn ferrite)



GS61004 ; GaN Systems
($V_{DX\ MAX}$=100 V, $I_{DS\ MAX}$=45 A, R_{DS}=15 mΩ, Q_G=6.2 nC)

SCS220AJ ; ROHM
(V_R=650 V, I_F=20 A, $V_{F\ max}$=1.6 V)





Kanako Sugimura *et al.*, *IEEE Trans. Magn.*, Vol.53, No.11, #2801406 (Nov. 2017)

◆Fe-based metal composite sheet core

Sheet core fabrication and lamination process for embedded inductor and transformer

Composite sheet fabrication

Composite slurry with metal-powder and binder-precursor solution

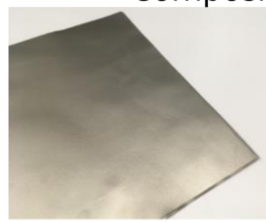
↓

Doctor blade coater

↓

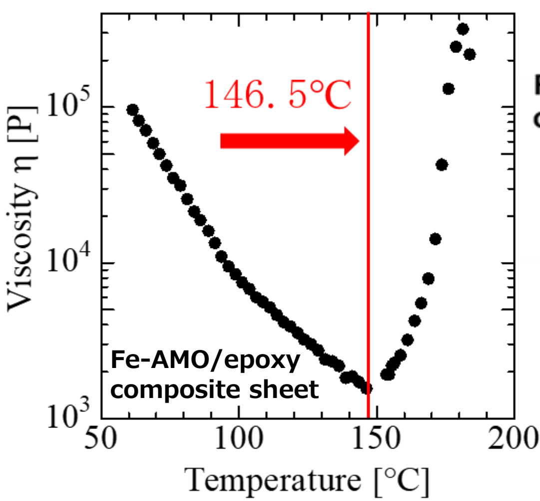
50～120μm thick composite sheet

Composite sheet

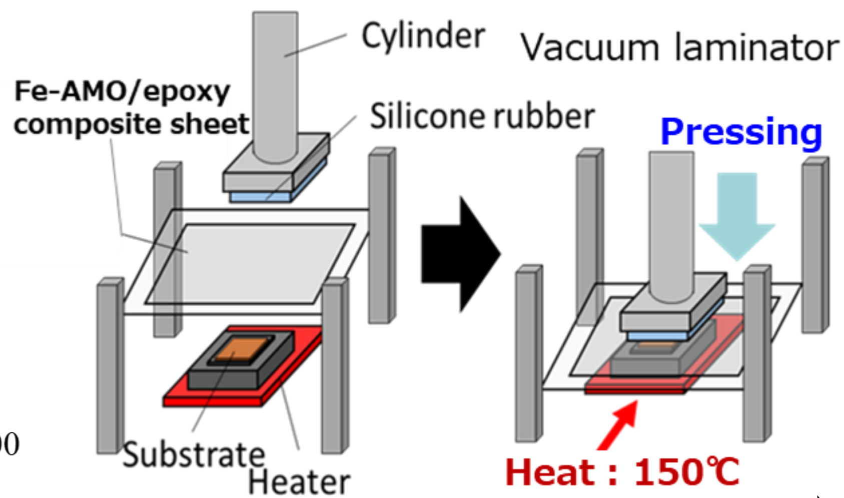


Doctor blade coater

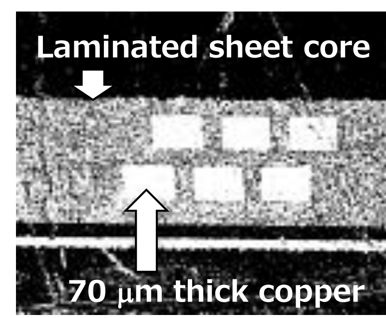
Hot press lamination in vacuum



Sheet viscosity vs. temperature



Hot press lamination in vacuum



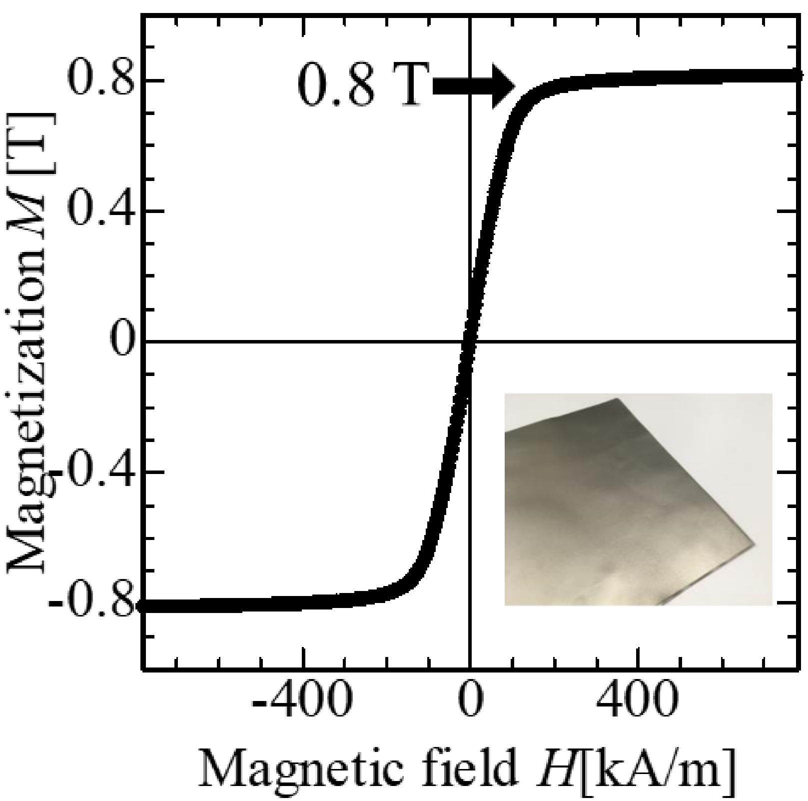
Embedded inductor

◆Fe-based metal composite sheet core

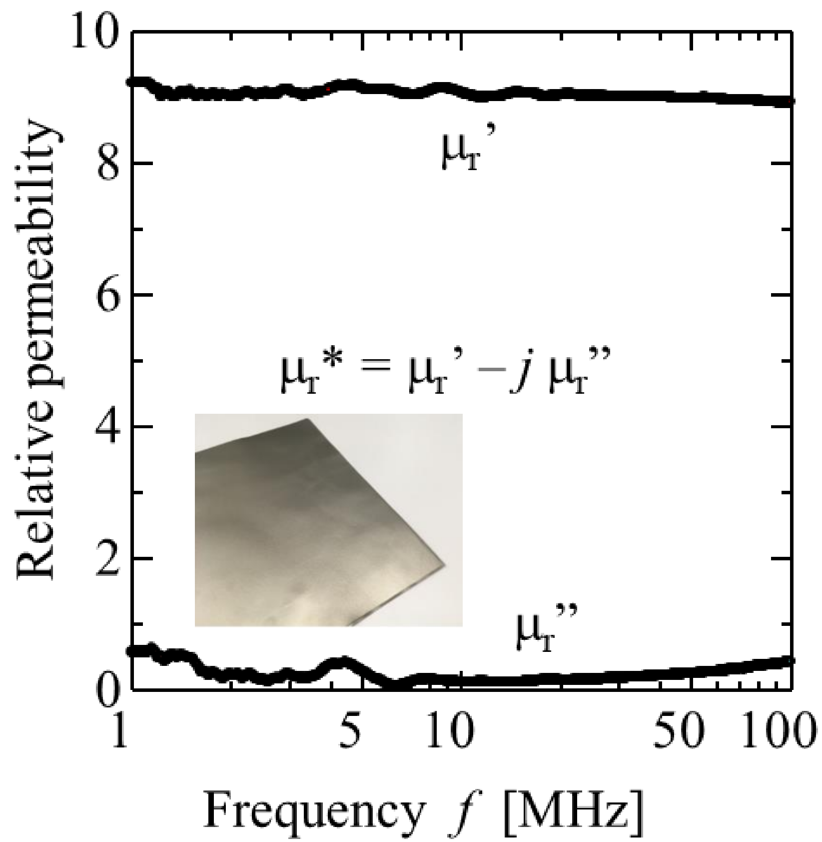
Laminated Fe-based amorphous composite sheet core

Magnetic properties

Static *M-H* curve



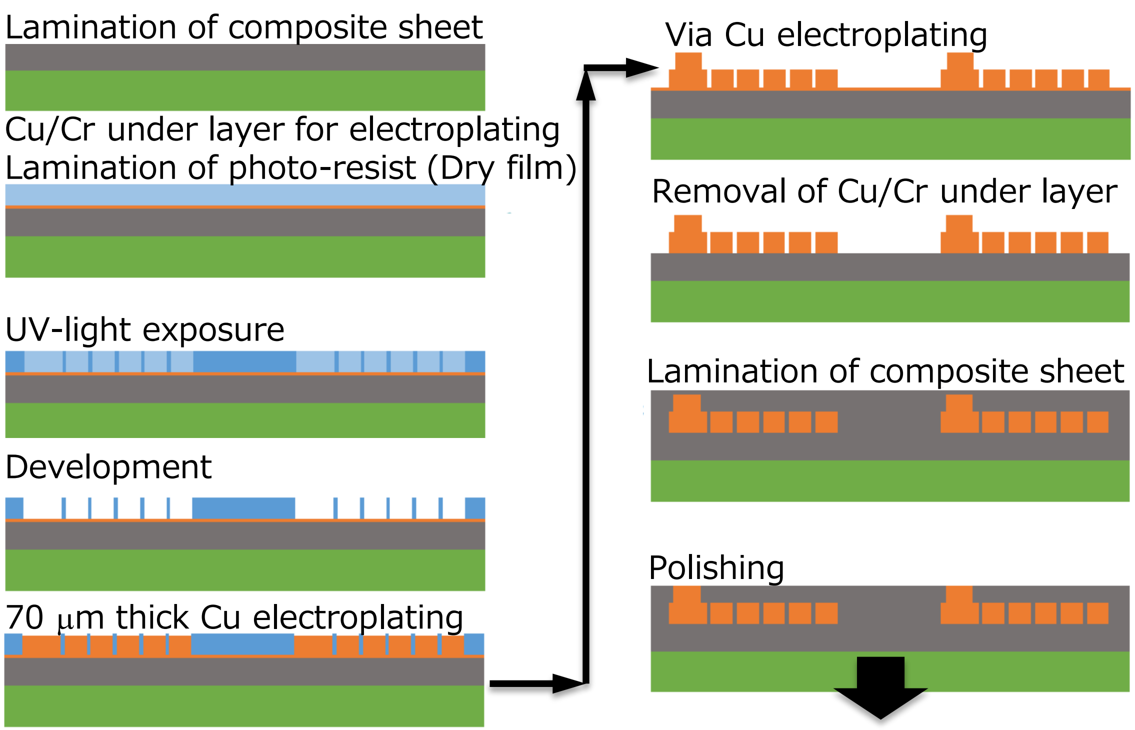
Complex permeability

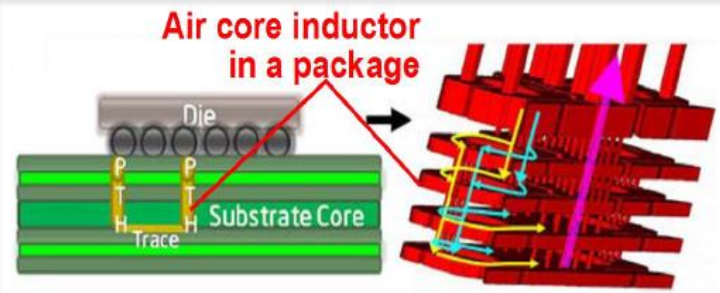


◆Fe-based metal composite sheet core

Laminated Fe-based amorphous composite sheet core

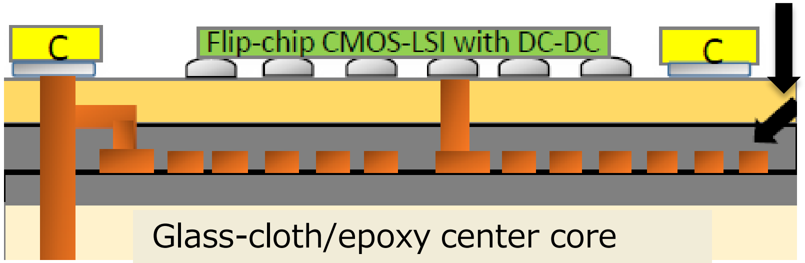
↳ Spiral inductor embedded in organic interposer

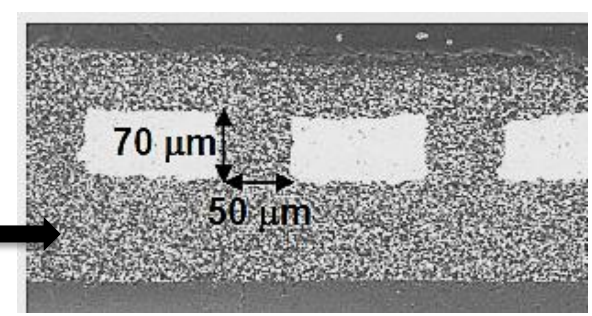




140MHz switching buck converter with air-core inductor

Nasser kurd et al. : "Haswell: A Family of IA 22 nm Processors", *IEEE Journal of Solid-State Circuits*, Vol. 50, No. 1, pp. 49-58 (2015)





Partial cross-section of spiral inductor

20MHz switching buck converter with embedded magnetic core inductor

◆20 MHz buck DC-DC converter application

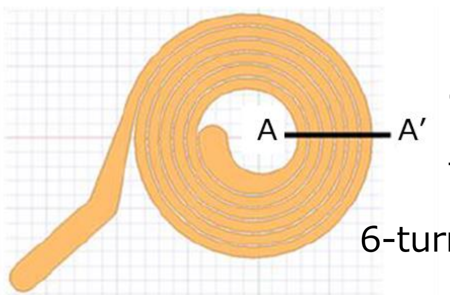
Laminated Fe-based amorphous composite sheet core

Spiral inductor embedded in organic interposer

20MHz switching buck converter

Design parameters of 20MHz switching hysteresis-controlled buck converter

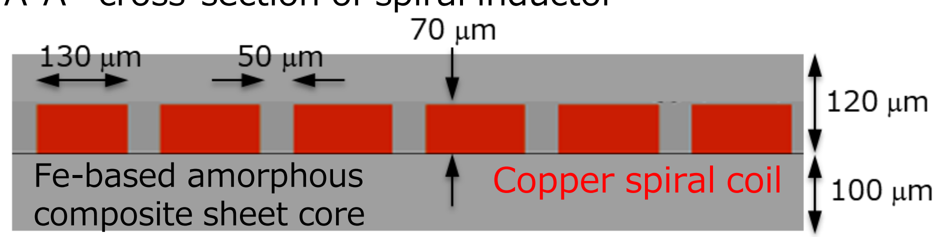
Input ; 5 V, Output ; 3.3 V · 0.8 A, Main switch and control circuit ; 0.35 μm-CMOS
Inductor ; L > 100 nH, DCR < 100 mΩ, Q > 20@20 MHz



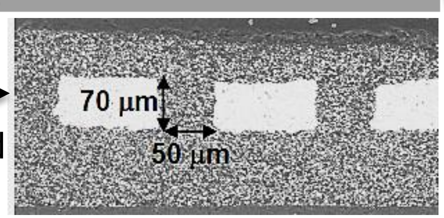
Inner dia. ; 1.4 mm
Outer dia.; 3.6 mm
Line/space ; 130/50 μm
Thickness ; 70 μm

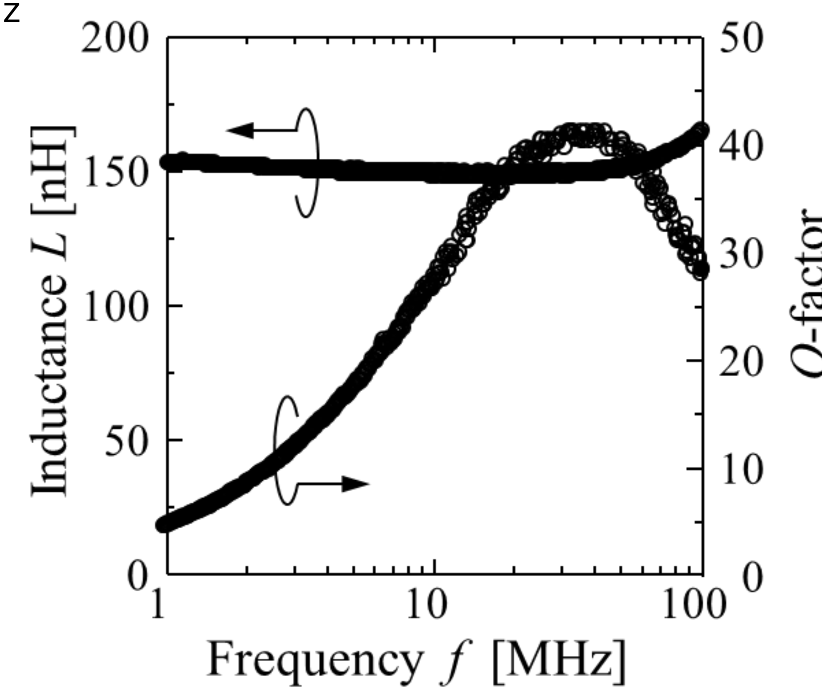
6-turns copper spiral coil

A-A′ cross-section of spiral inductor



Fabricated





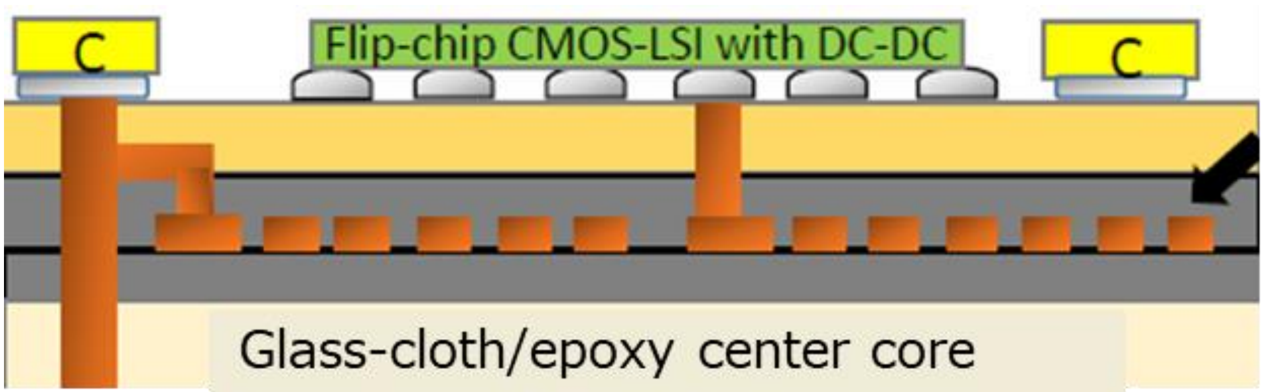
DCR designed ; 70 mΩ
⇒ 170 mΩ including thru-via contact resistance

◆20 MHz buck DC-DC converter application

Laminated Fe-based amorphous composite sheet core

→ **Spiral inductor embedded in organic interposer**

→ **20MHz CMOS switch buck converter fabricated in organic interposer**



Fe-based amorphous composite sheet core

The detailed information will be presented in APEC2019, Anaheim CA, USA, March 2019

◆Conclusion and future work

Atomized Fe-based amorphous fine sphere powder has been used for composite core and applied to high frequency switching converter.

Current issue ; Difficult to increase permeability

Flake composite core will be effective for increasing permeability beyond MHz frequency.

◆**Sphere and flake hybrid**

・**Virginia Tech.** ; Yi Yan *et al*., *IEEE Trans. Magn*., Vol.54, No.1, #2800106, 2018.

◆**Fabrication of flake composite**

・**Dartmouth College**; B.A. Reese *et al*., INTERMAG2018, CG-041, Singapore, Apr. 2018.

・**Tokin A Kemet Co.** ; Kenichi Chatani, *International Symposium on 3D Power Electronics Integration and Manufacturing*, S3-1, College Park, MD USA, June 2018.

◆**Fabrication of Fe-based amorphous flakes**

・**Northeastern Univ.** ; Kun Qian *et al*., arXiv.org > physics > arXiv:1806.02486, 4 pages, June 2018.