UNIVERSITY of DELAWARE

Magnetic Substrates for Power Supply on a Chip

Yang Zhou, Xiaoming Kou, Paul Parsons, Asif Warsi Muhammad, Hao Zhu[1], Stoyan Stoyanov[1], and John Q. Xiao

jqx@udel.edu, 302-831-6547
Department of Physics & Astronomy
University of Delaware
Newark, DE 19716

[1]Spectrum Magnetics, LLC
Wilmington, DE 19804
http://www.spectrum-magnetics.com

Outline

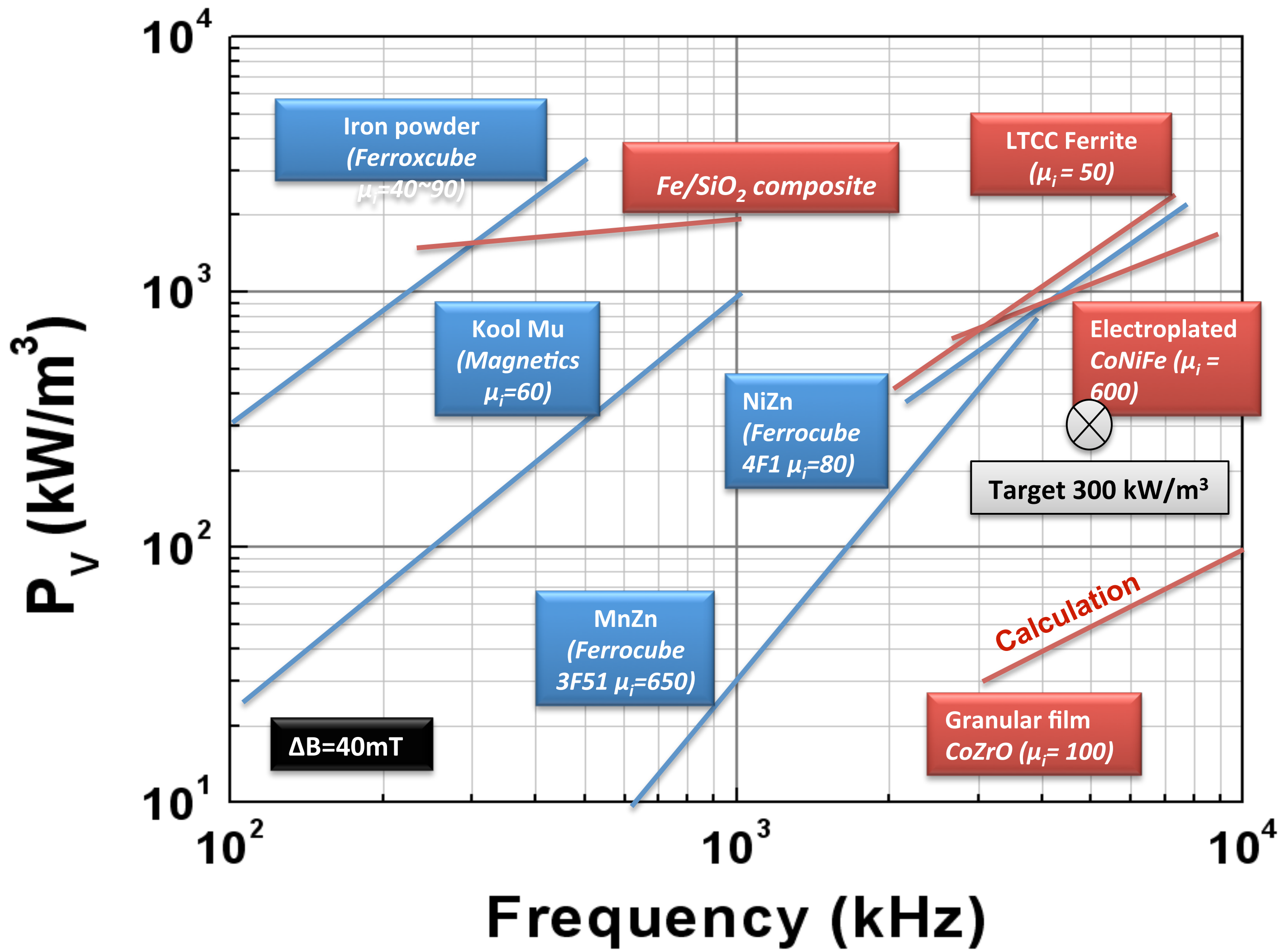
I. Introduction

II. Physics Principals and Our Strategy

III. Material Platforms

IV. Summary

Overview of Soft Magnetic Materials



1. Powder cores
   f_{op} < 200 kHz.
2. Amorphous/nano-crystalline cores
   f_{op} < 200 kHz.
3. Ferrites
   low power.
4. Granular films
   thin film applications
5. Fe Nanocomposites
   high loss

Objective

- Magnetic substrates with following specs:

Operation freq. f_{op} (MHz)	Induction swing ΔB (mT)	Core loss P (kW/m^3)	Saturation Induction B_{sat} (T)
5	40	< 300	≥ 0.5

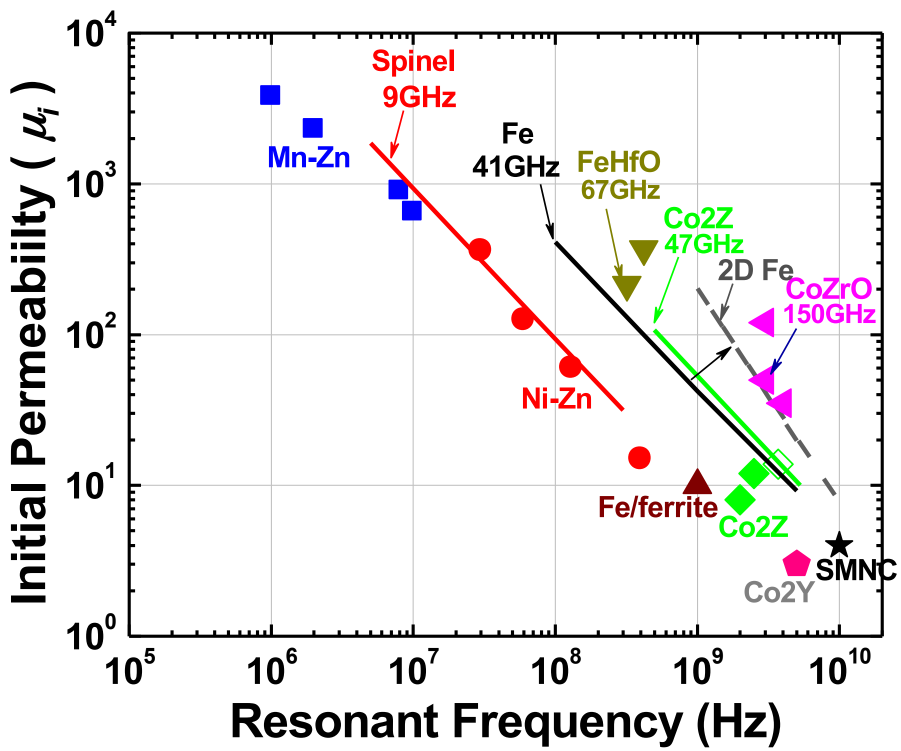
- Compatible with semiconductor integration process

Physics Principals — Snoek's Law

$$(\mu - 1)\omega_{res} = \frac{2\gamma}{3} \times (4\pi M_s)$$

γ: gyromagnetic ratio (*28 GHz/T*)
M_s: saturation magnetization

- f_{op} needs to be 2-3 orders lower than f_{res} for small losses
- 3d transitional metal and alloy (CoFe, Fe, and FeNi) has high M_s



Snoek's limit can be enhanced in 2D system!

$$(\mu - 1)\omega_{res} = \frac{2\gamma}{3}(4\pi M_s)[\frac{3}{4}\sqrt{\mu - 1}]$$

Physics Principals — Magnetic Losses

$$P_{Total} = P_{hys} + P_{eddy} + P_{anom} = k_1 f + \frac{k_2 B^2 t^2}{\rho} f^2 + P_{anom}(f)$$

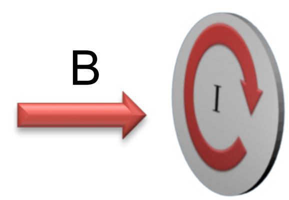
Small P_{hys} requires small k_1

Small P_{eddy} requires large ρ and/or small t

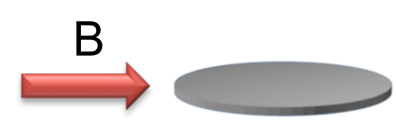
1. FeCo, FeNi, Fe
2. Amorphous Materials
3. Exchanged coupled systems (nanocrystalline materials)

$$K_{eff} = \frac{K}{\sqrt{N}} = K\sqrt{\frac{D^3}{L_{ex}^3}}$$

- Insulating coating of particles: 3D
- Insulation // B: 2D or 1D



Strong Eddy Current

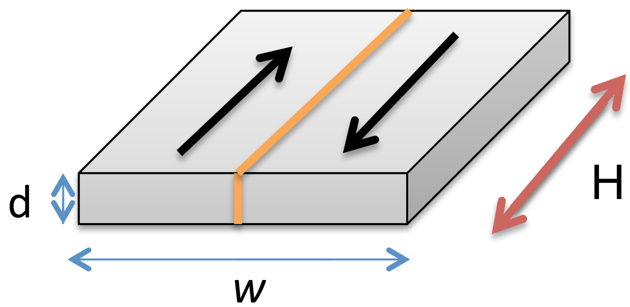


Weak Eddy Current

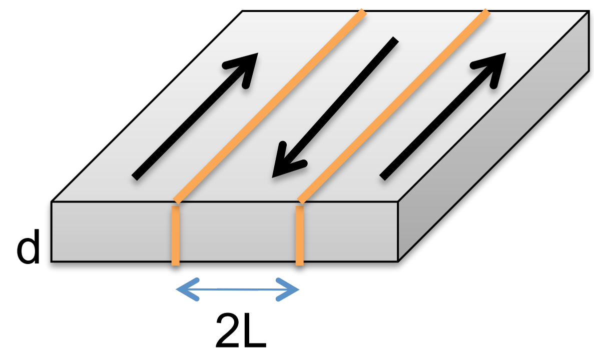
Preferred

Physics Principals — Anomalous Loss

- If domain wall exists and moves during excitation, eddy current can concentrate in and near domain wall, causing large excessive eddy current loss



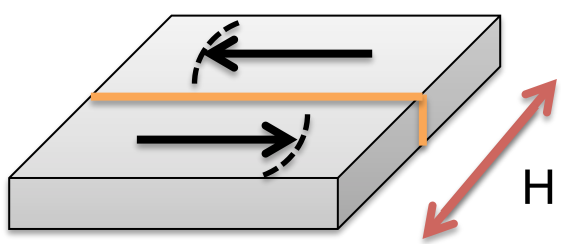
$W_{dyn}/W_{cl} \cong 1.63w/d$



d.w. spacing $2L$ $\quad W_{dyn} \cong 1.63(2L/d-1)W_{cl}$ if $2L \gg d$

$W_{dyn} \cong W_{cl}$ if $2L \ll d$

A uniaxial easy axis

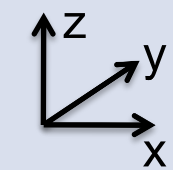
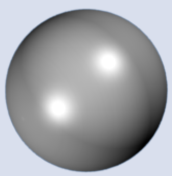


Now only magnetization rotation is involved

- Magnetic field annealing can be performed to introduce an easy axis in the materials, perpendicular to the magnetic induction direction. Anomalous eddy current loss can be largely eliminated.

Physics Principals — Demagnetizing Effect

$$H = H_{ext} - NM$$

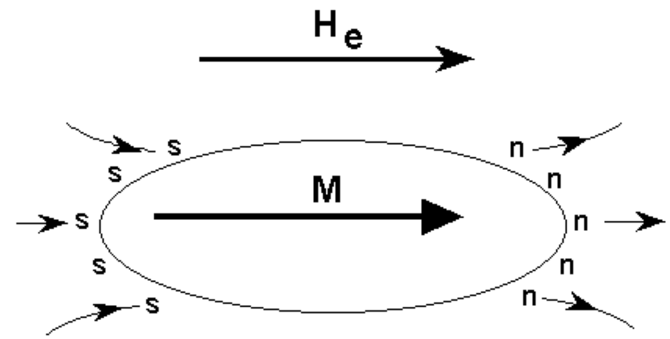
	Sphere	Long rod/wire	Thin film/ flake
			
N_x	4π/3	0	0
N_y	4π/3	2π	0
N_z	4π/3	2π	4π

N

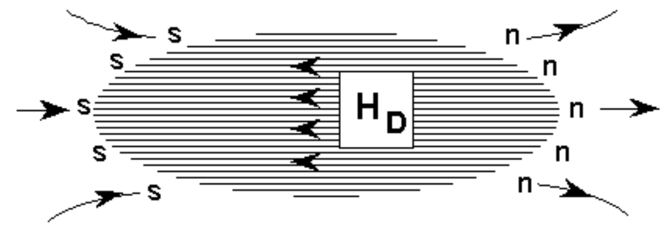
N

N :

Random, non-interacting particle assembly



Magnetization Produces Apparent Suface Pole Distribution



Demagnetizing Field Due to Apparent Surface Pole Distribution

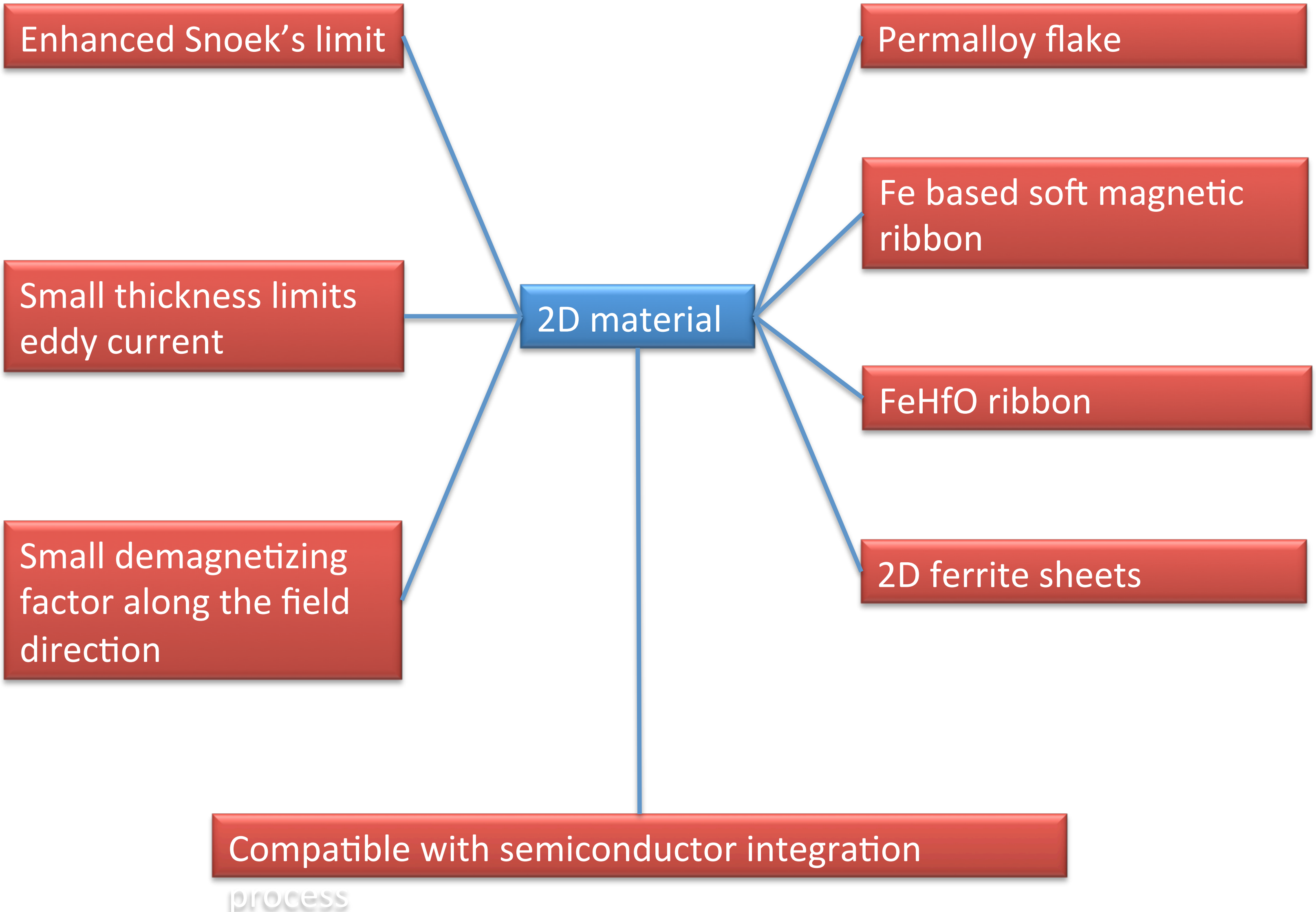
> 1

$H_i = H_e - H_D$

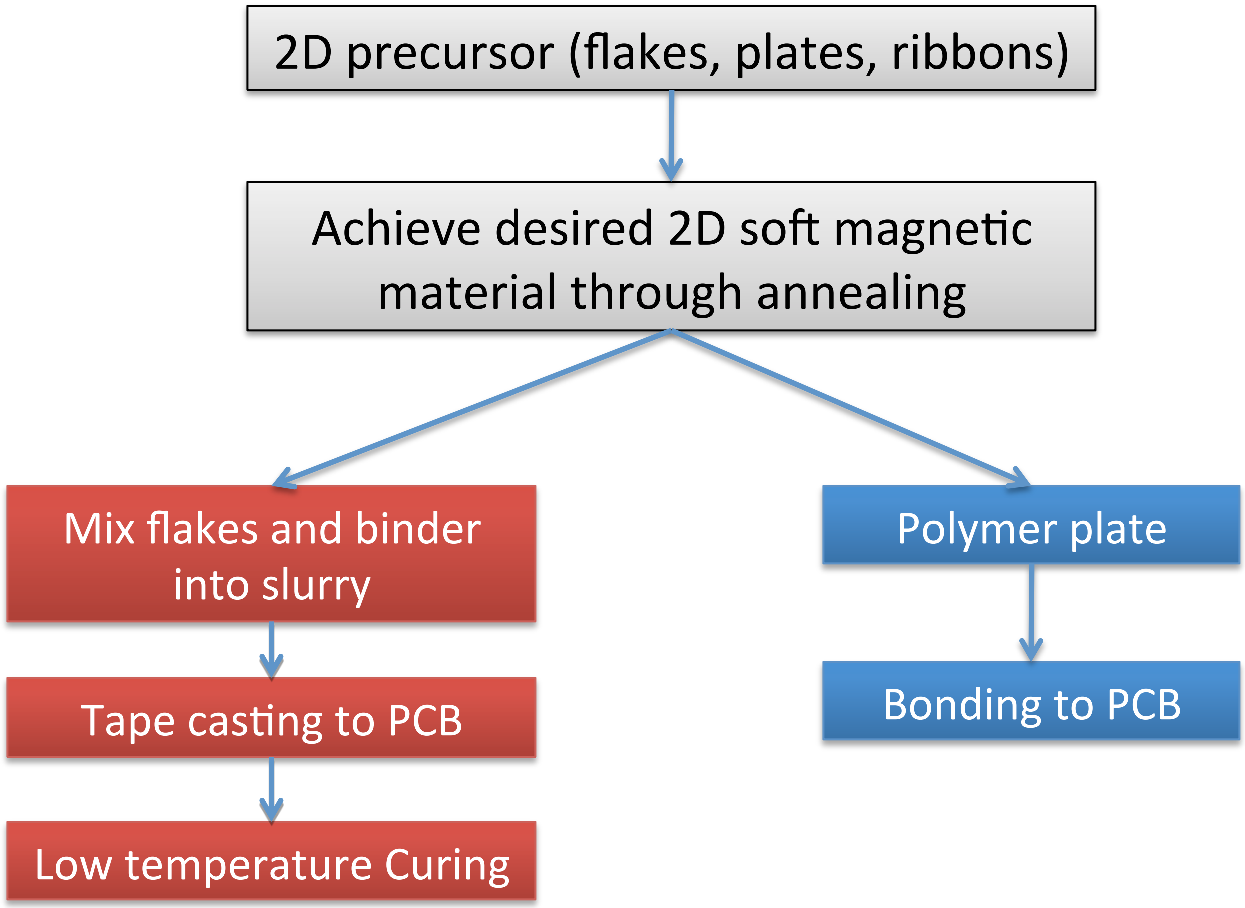
$H_D = NM$

N= demagnetizing factor

Our Strategy



Our Strategy—Compatibility



Material platforms

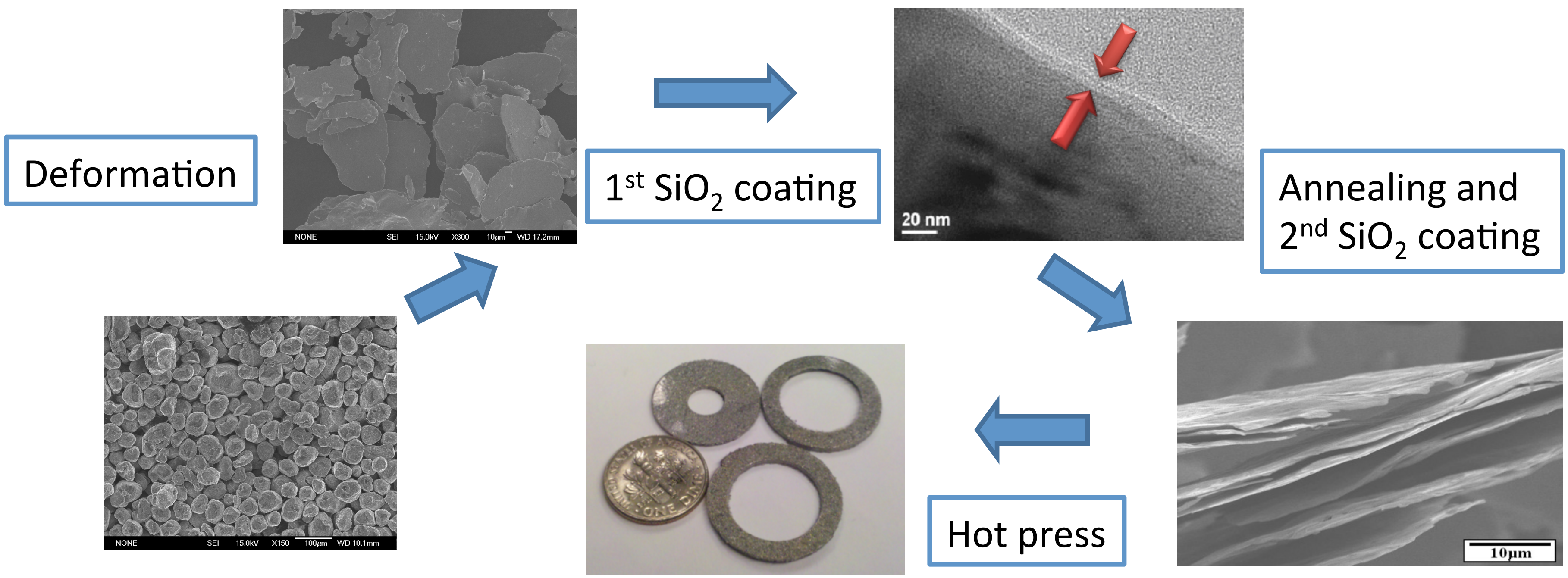
a) Permalloy Flake

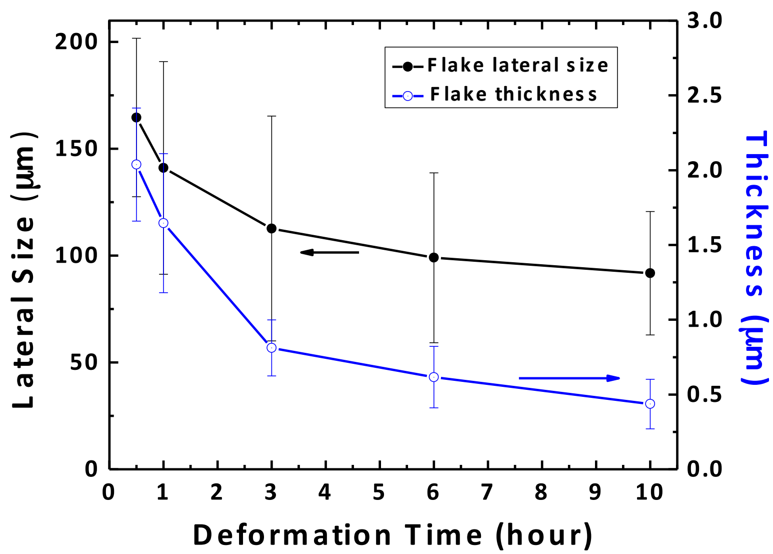
b) Nanocrystalline Ribbon by Melt-spinning

c) FeHfO Ribbon

d) 2D NiZn Ferrite

Permalloy Flake

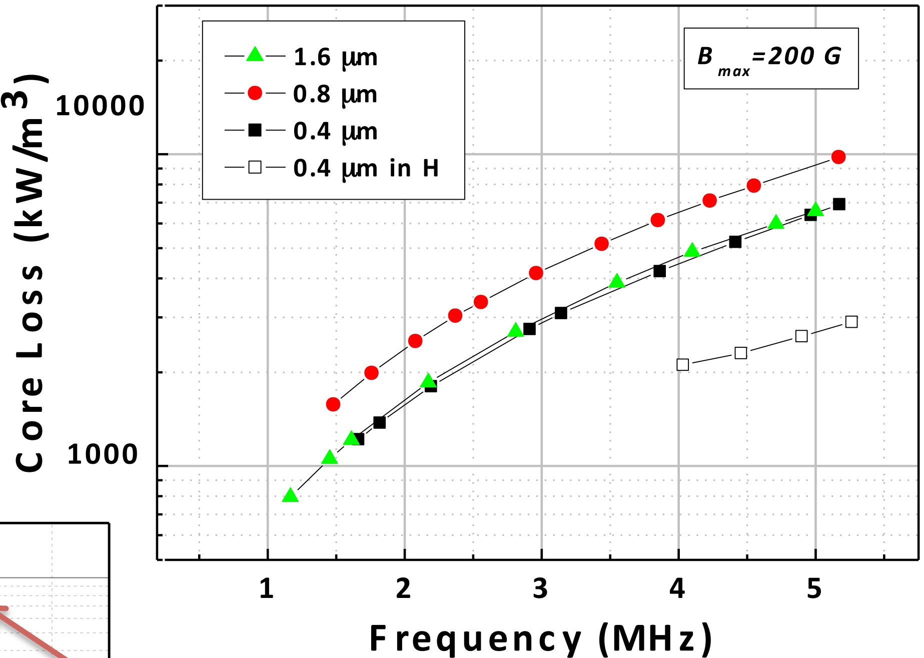


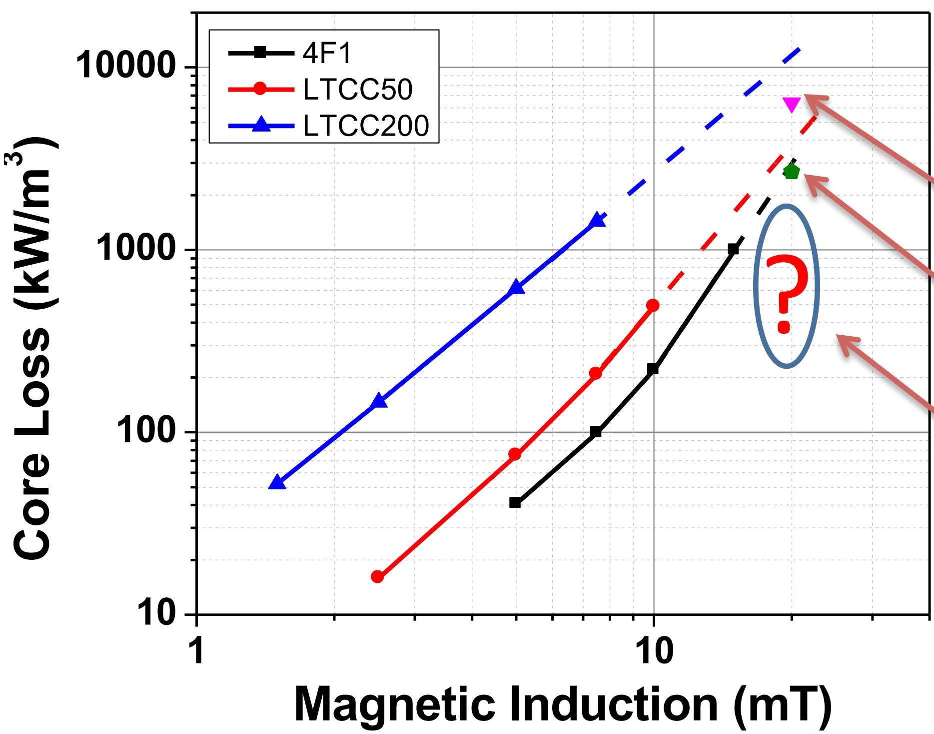


Milling Time	Thickness	Lateral size	H_c before annealing	H_c after annealing	H_c of hot pressed ring
(h)	(μm)	(μm)	(Oe)	(Oe)	(Oe)
1	1.6	141	5.4	2.4	3
3	0.8	113	5.4	2.9	2.9
6			6.1	1.8	3.4
10	0.4	92	6.8	1.8	3.5

Permalloy Flake-Core Loss

Thickness (μm)	Core loss @ 5 MHz (kW/m³)	Permeability @ 5 MHz
1.6	6570	100
0.8	9280	61
0.4	6380	74
0.4 in H	2680	40





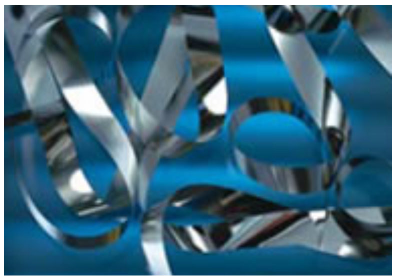
0.4 um thick flake

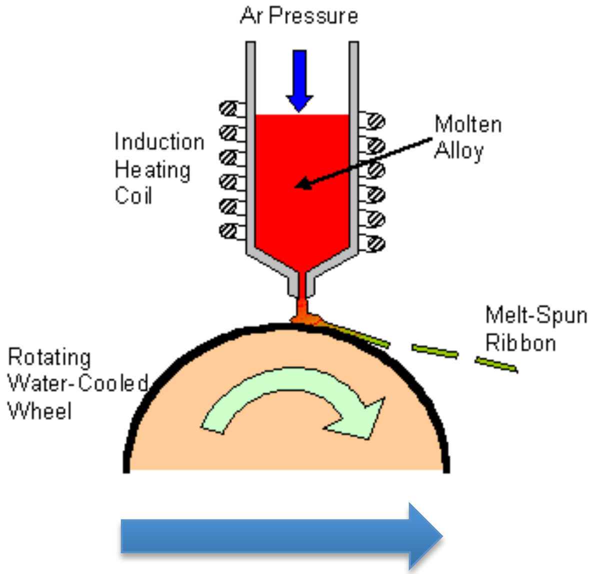
0.4 um thick flake in H field

With better alignment and softer starting particles

Nanocrystalline Ribbon by Melt-spinning

Commercial Finemet Ribbon 18 µm





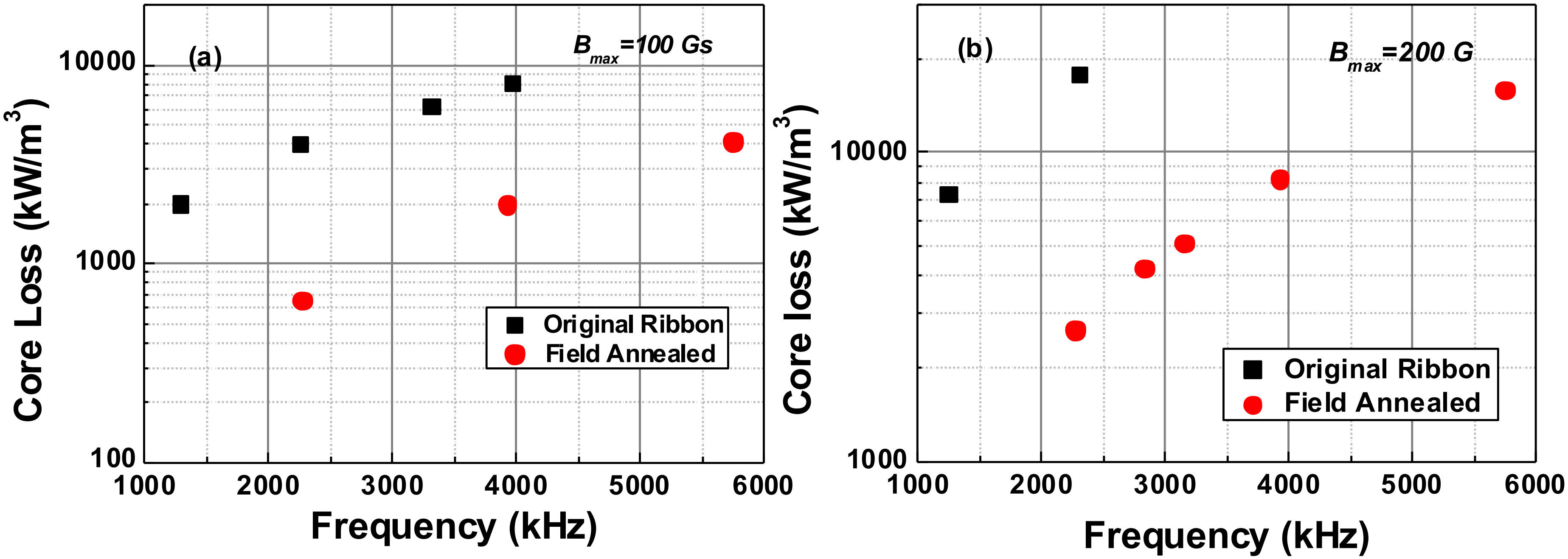
Homemade Ribbon

$$Width \times Thickness = \frac{\pi \Phi^2 P^{1/2}}{2^{3/2} V_S \rho^{1/2}}$$

ρ: density
Φ: orifice diameter
P: ejecting pressure
V_s: surface velocity of the wheel

- Small orifice diameter, small ejecting pressure, large surface velocity of the wheel are preferred.
- Formation of nanocrystallites also requires high cooling rate, thus high temperature is favored.

Nanocrystalline Ribbon-Field Annealing



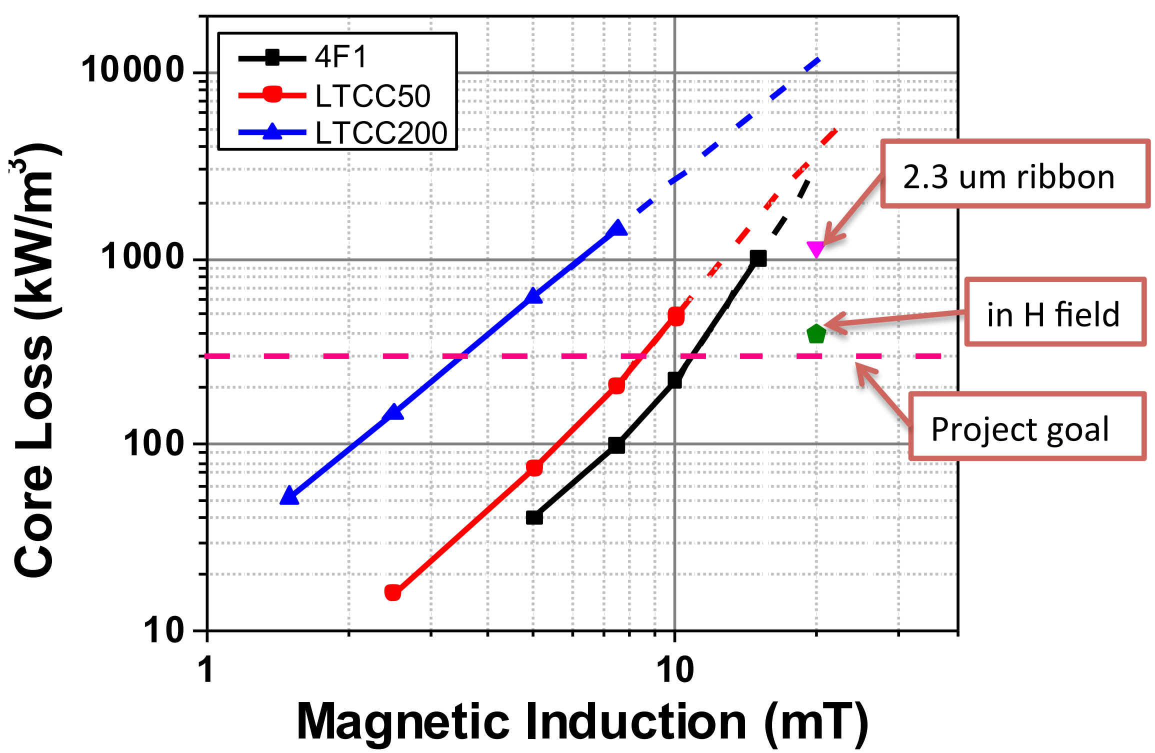
- Core losses were reduced in both cases.
- At B_{max}=*100 G*, core loss decreases from 8140 to 2064 kW/m^3 at 4 MHz.
- At B_{max}=*200 G* and 5 MHz, the core loss is about 12000 kW/m^3

Mo-doped Permalloy Ribbon-Thinning

Chemical etching

Taping, cutting and winding

Ribbon thickness (mm)	Core loss (kW/m^3)	Permeability at 5 MHz	In DC field
2.3	**1160**	1070	No
2.3	**390**	317	Yes



FeHfO Ribbon

$$P_{Total} = P_{hys} + P_{eddy} + P_{anom} = k_1 f + \frac{k_2 B^2 t^2}{\rho} f^2 + P_{anom}(f)$$

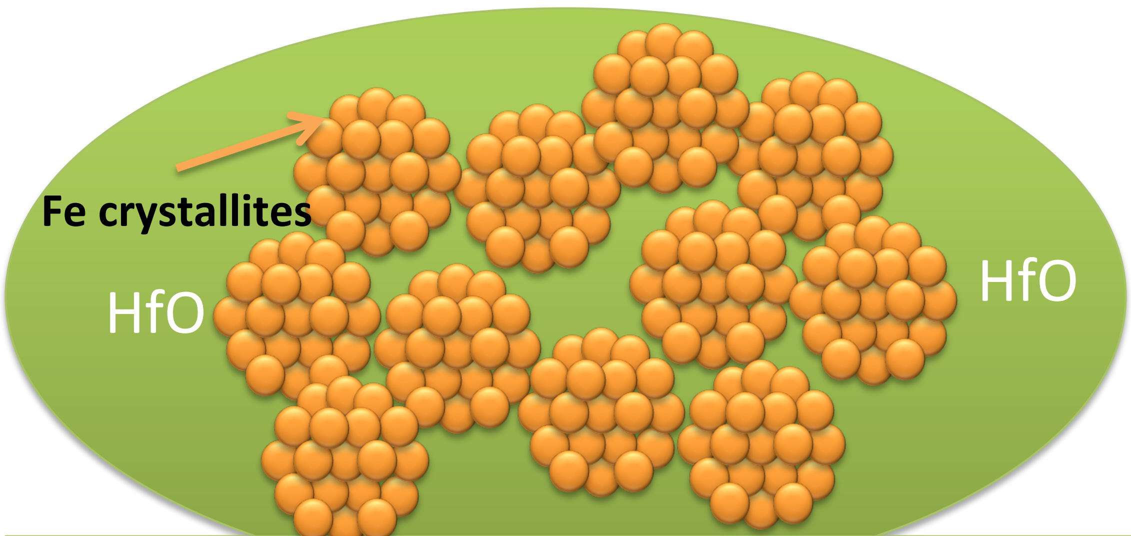
Small P_{hys} requires small k_1

Small P_{eddy} requires large ρ and/or small t

1. Small k_1 can be achieved through exchange coupled Fe nanocrystallites

2. Thin ribbon limits eddy currents

3. HfO provides large resistivity

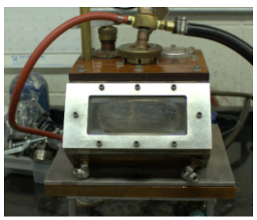


Exchanged coupled Fe crystallites embedded in HfO matrix

FeHf based Ribbon

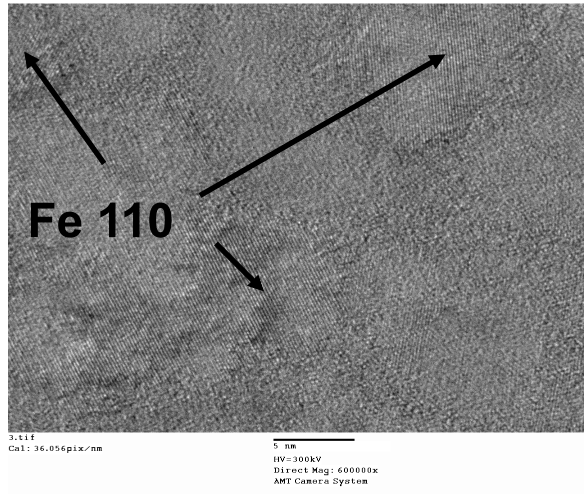
Select materials

Make ingot by arc melting

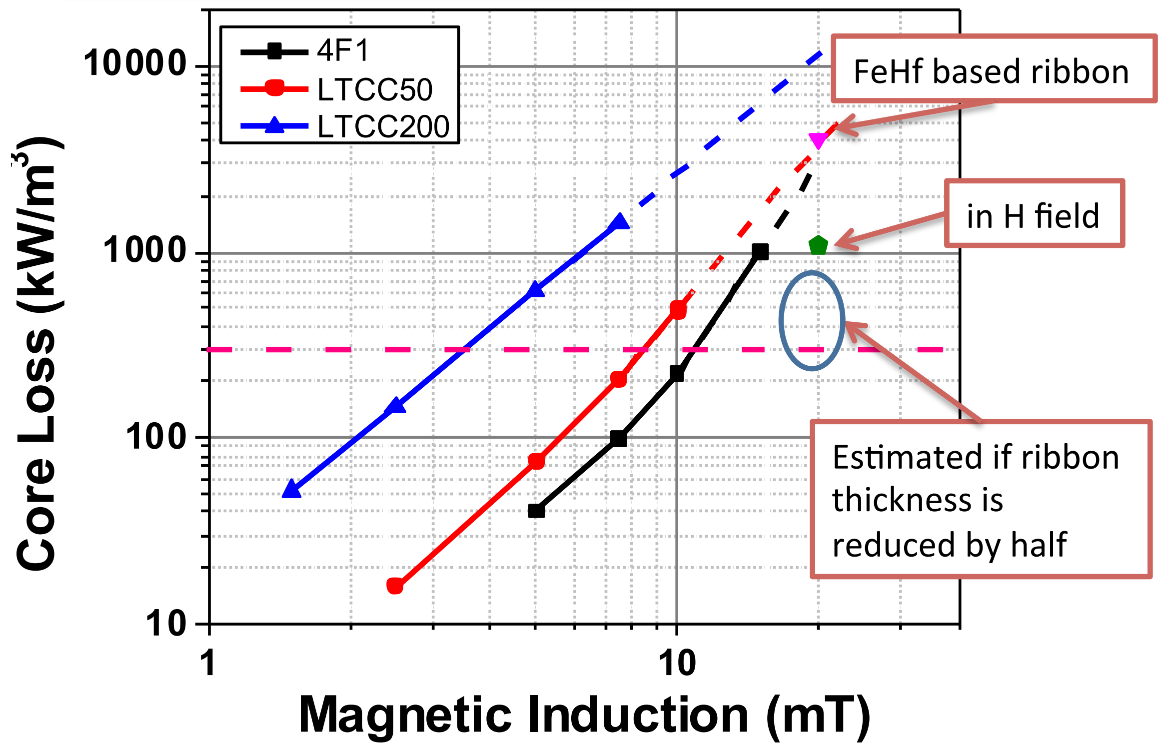


Make ribbon by melt spinning

Post treatment



H_c < 0.4 Oe
Fe particle size ~ 15 nm
M_s ~ 150 emu/g
μ > 140 @ 5 MHz



2D NiZn Ferrite

Strategy

- 2D NiZn ferrite
  - Bulk property optimization
    - Composition tuning
    - Grain size optimization
  - 2D sheet

Snoek's limit is enhanced in 2D system:

- Material can have higher FMR without sacrificing permeability
- Higher FMR helps to reduce loss

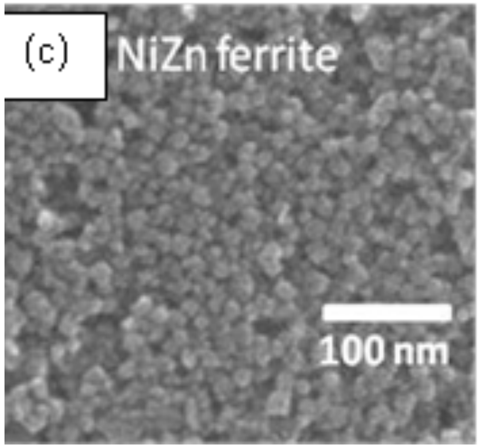
Fabrication

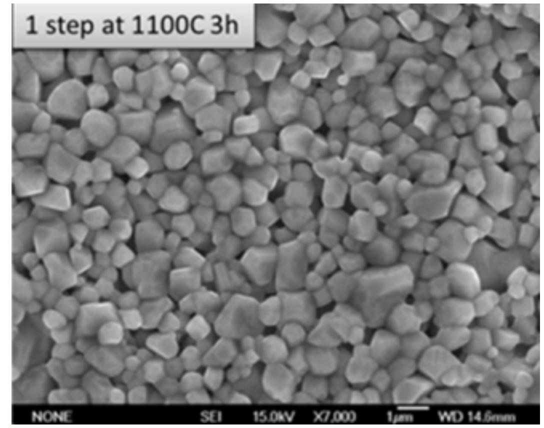
Co-precipitation → Milling Pressing → Sintering → Bulk material

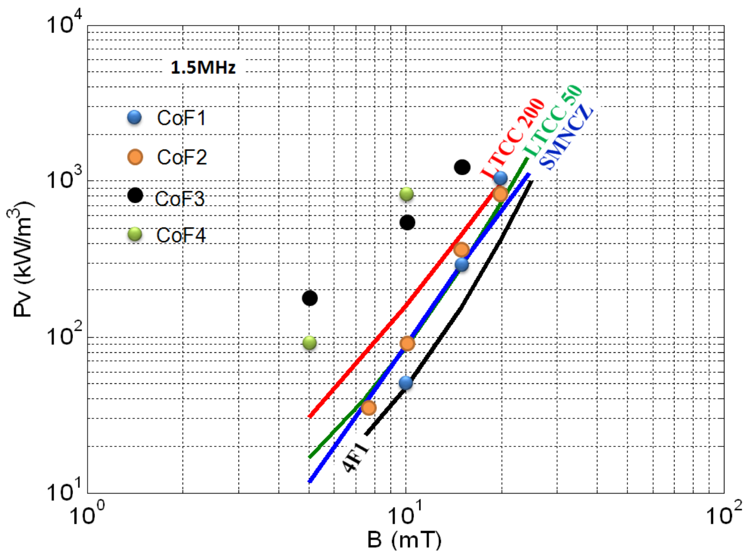
Co-precipitation → Slurry → Casting →

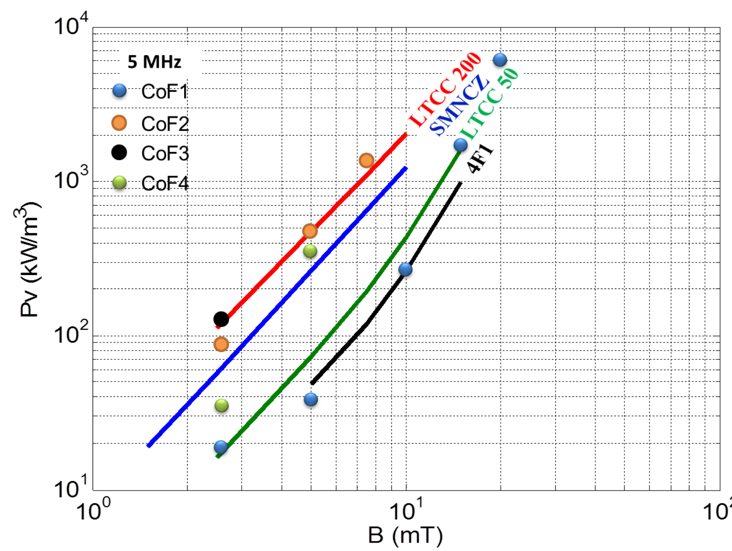
→ Sintering

2D NiZn Ferrite—Bulk





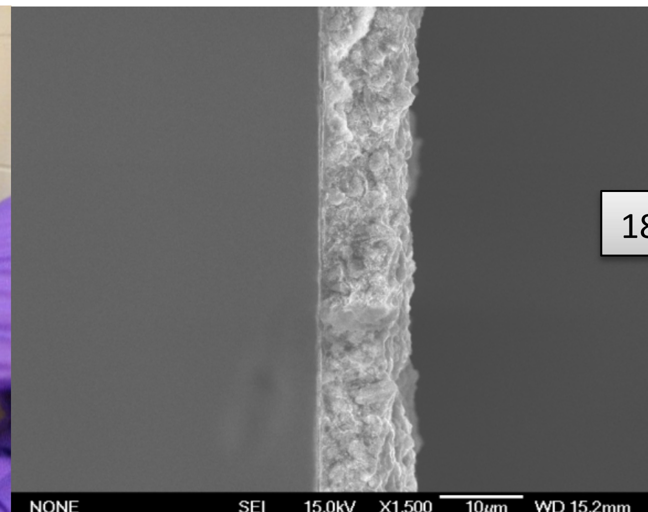


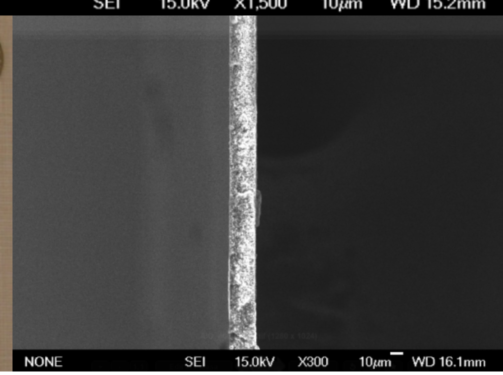


- At 5 MHz, *B<10 mT,* CoF1 is similar to 4F1,
- At 5 MHz, *B>10 mT,* CoF1 is similar to LTCC 50.
- CoF1 has μ= 80~90, higher than both 4F1 and LTCC 50.
- At 1.5 MHz, CoF2 has similar loss as LTCC 50, but *μ* of CoF2 is exceptionally high (*μ=643*)

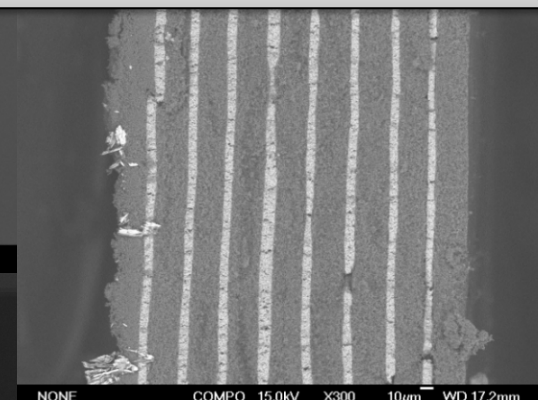
2D NiZn Ferrite—Tape Casting

Ferrite NP powders made by co-precipitation → Milling with binder → Tape casting





18 layers of CoF1 + 18 layers of Al_2O_3



Summary

- Physics principles for high frequency soft magnetic materials
- Submicron permalloy flakes, thin ribbons, and thin ferrite sheets have been successfully fabricated
- Thin Mo-doped Permalloy ribbon and FeHf-based ribbon are most promising to achieve low loss and high permeability and satisfy the needs for DC/DC converter applications

Thank you