Geometries and Fabrication Processes for High-Performance Nano-Granular Magnetics on Silicon

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Required for magnetics success

- Good materials: copper and ?
- Geometry selection
- Good models: faster than 3D FEA
- Design optimization: target system efficiency and power density not arbitrary inductor specs
- Fabrication process
- Measurements
- Reliability
- Low cost

All are important but only items in red discussed in this talk

- Good materials: copper and **?**
- Geometry selection
- Good models: faster than 3D FEA
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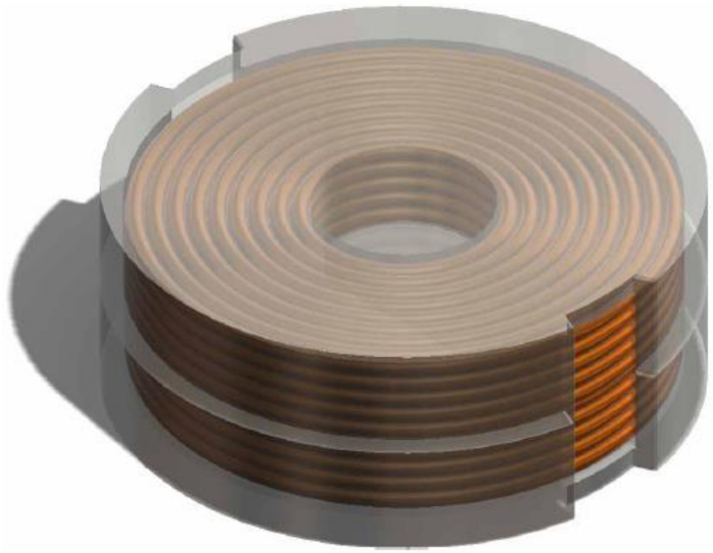
- Measurements
- Reliability
- Low cost

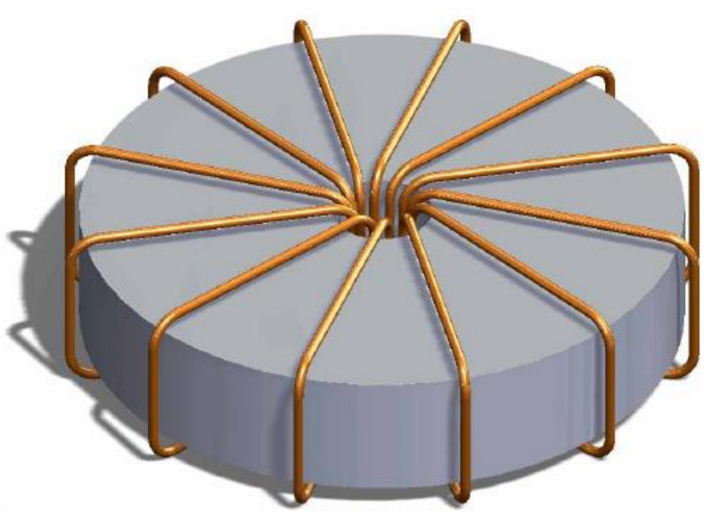
Two types of inductors

Pot-core



- Core wraps winding

Toroidal



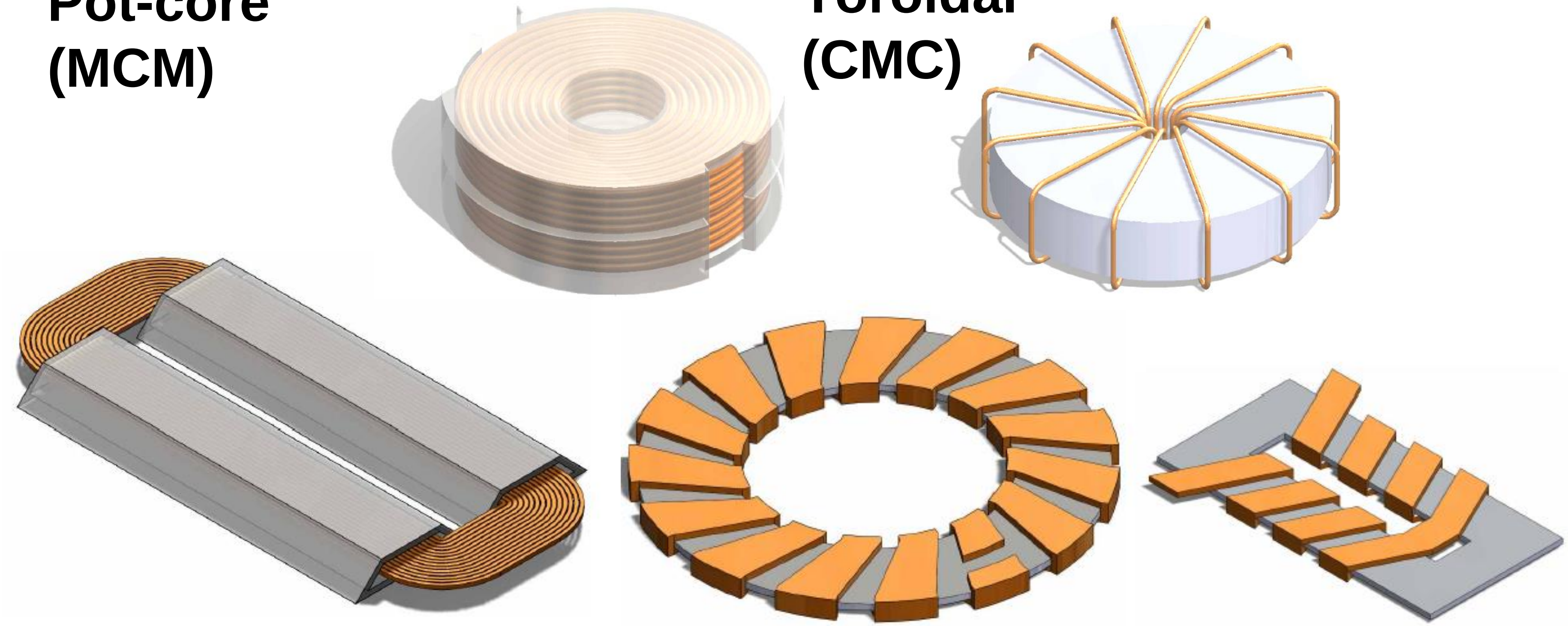
- Winding wraps core

- Many intermediate geometries are also possible

Inductors on Si

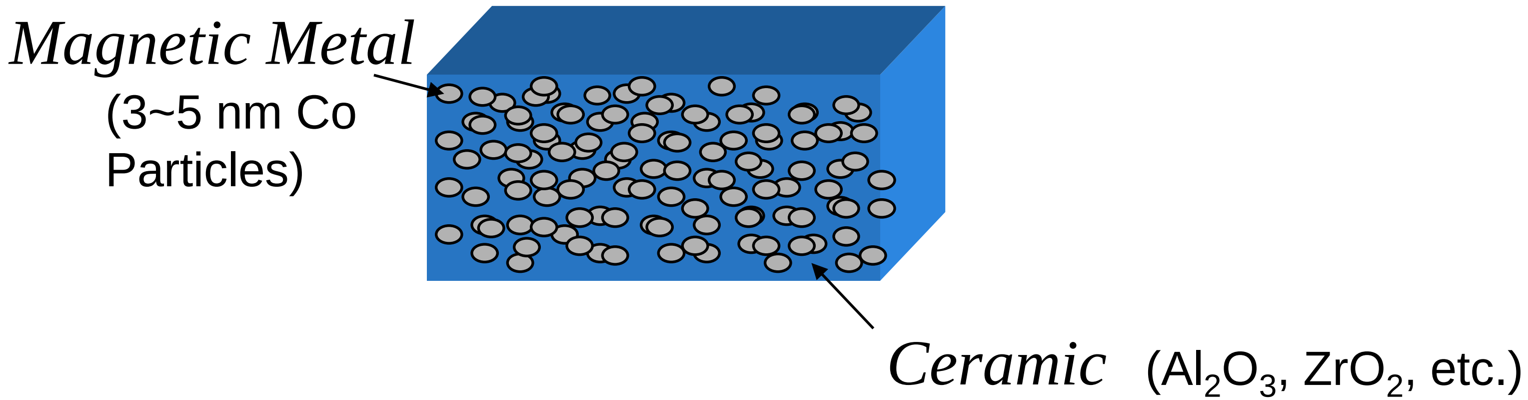
Pot-core (MCM)

Toroidal (CMC)



- Two magnetic depositions
- One magnetic deposition.

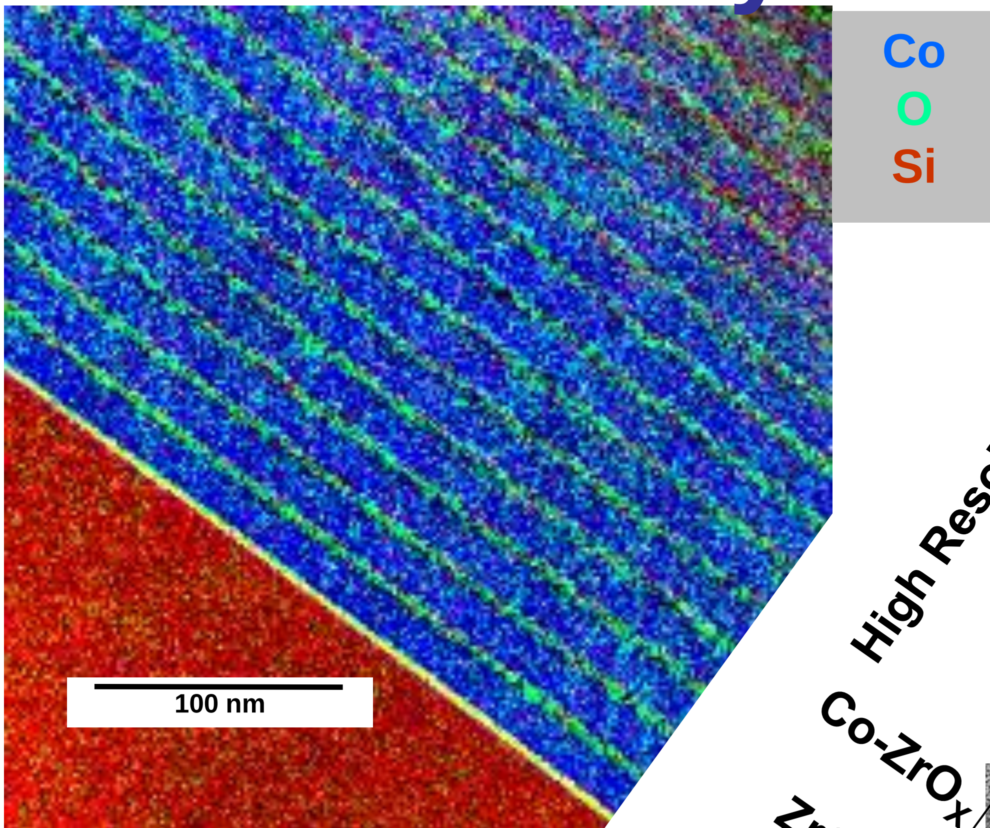
Nano-composite magnetic materials

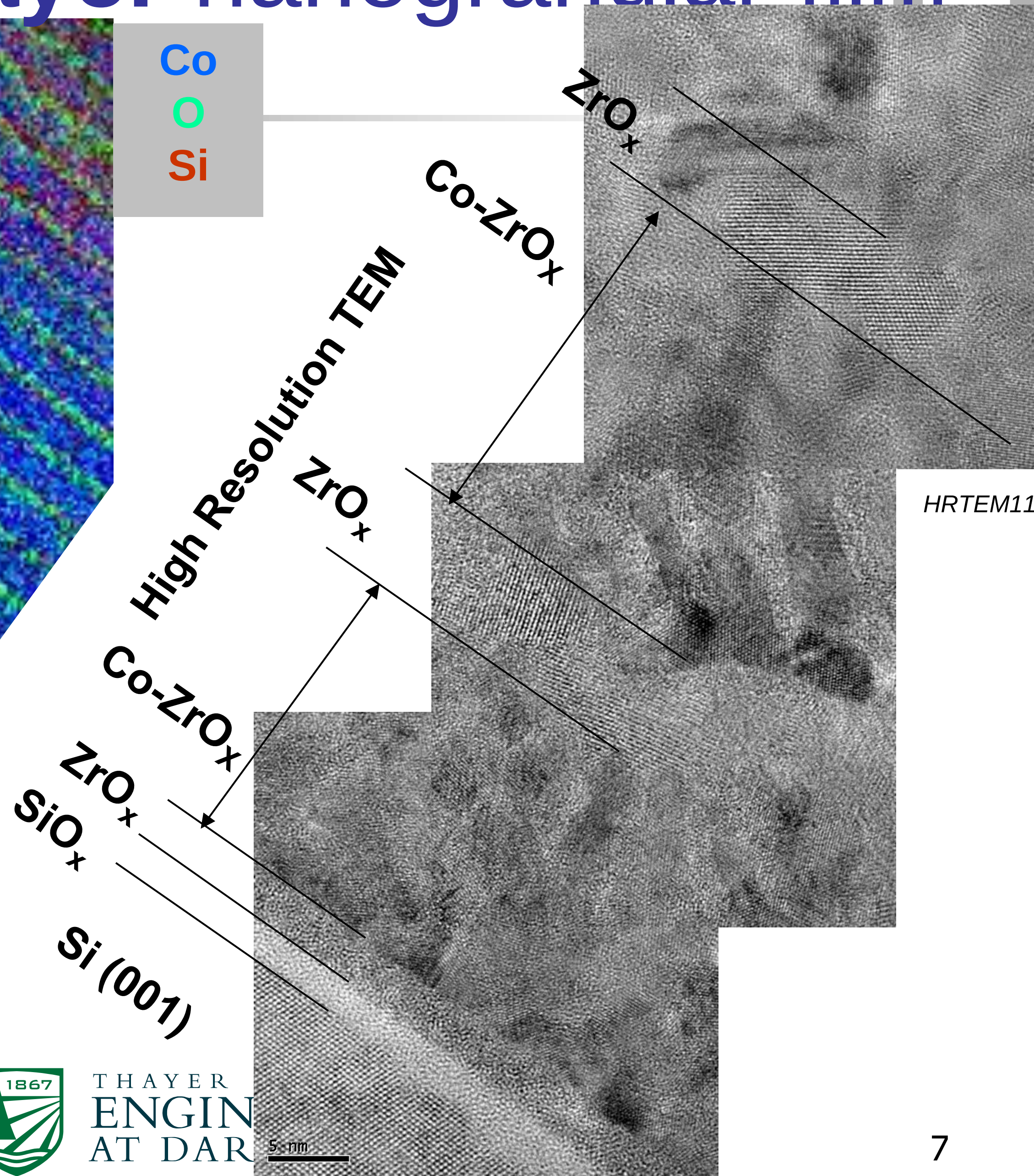


Advantages:

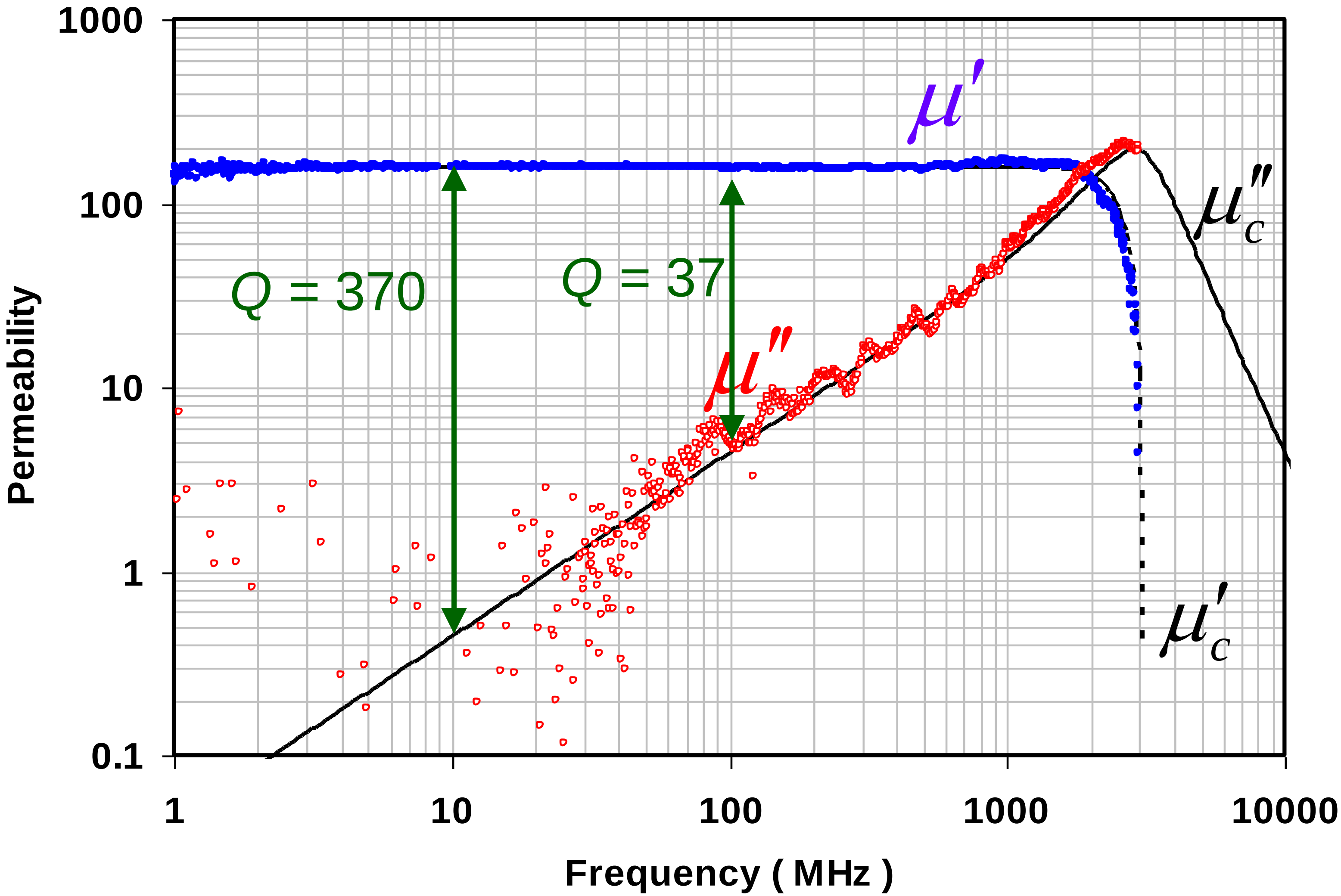
- Ferromagnetic (coupled particles)
- High resistivity (300 ~ 600 μΩ·cm) controls eddy-current loss independent of flux direction.
- Some have strong anisotropy for low permeability and low hysteresis loss.

TEM of **multilayer** nanogranular film



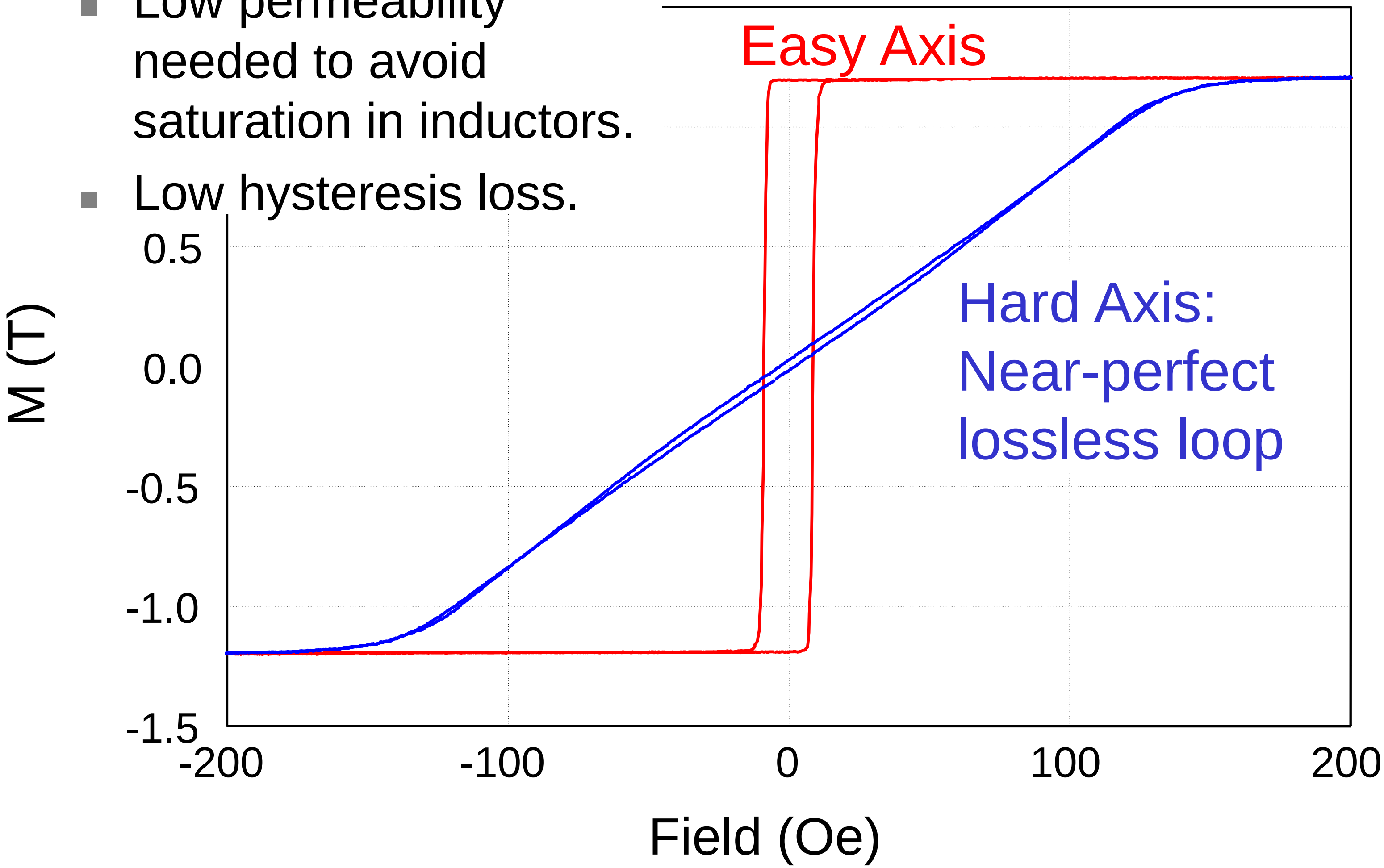


Permeabilty vs. frequency



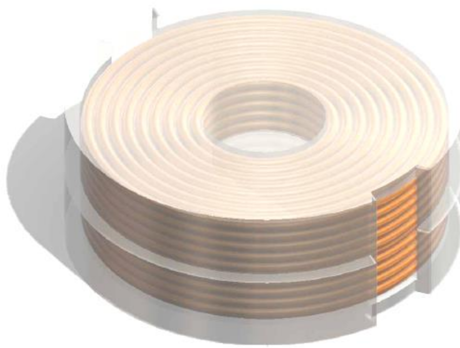
Magnetic anisotropy: common in thin-film magnetic materials

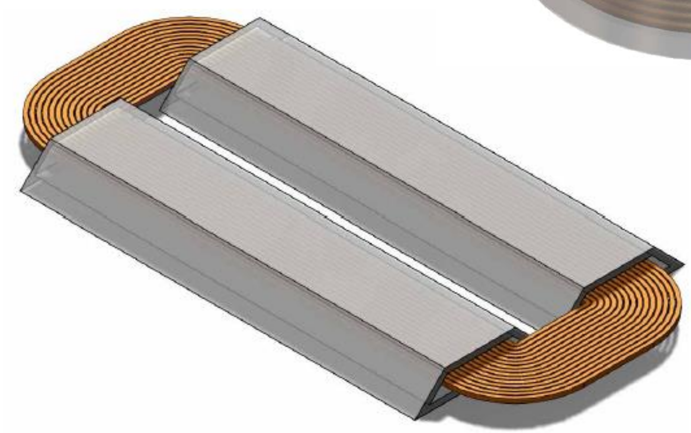
- Hard axis loop provides:
  - Low permeability needed to avoid saturation in inductors.
  - Low hysteresis loss.



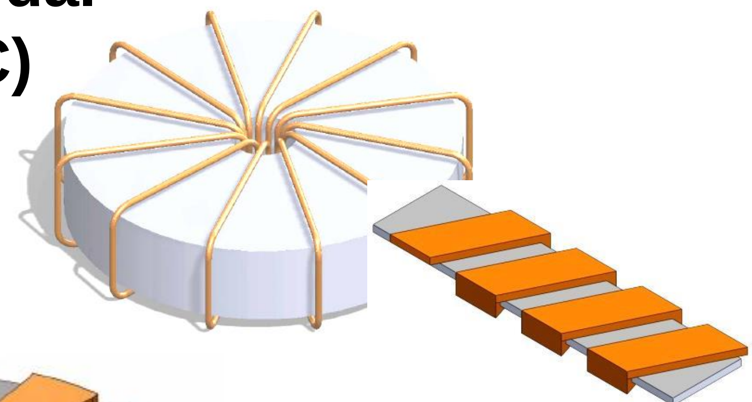
Microfabricated inductors

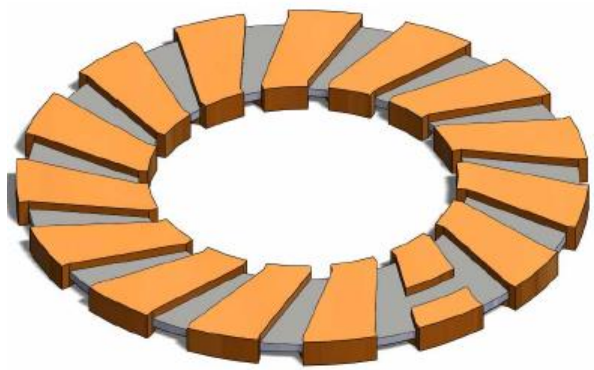
Pot-core (MCM)

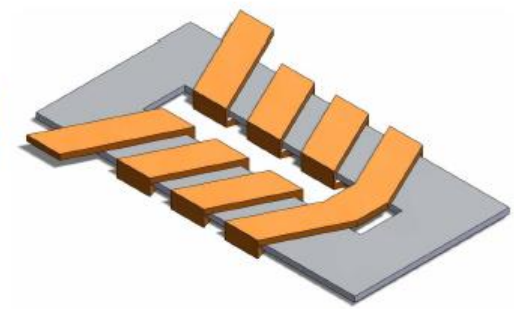




Toroidal (CMC)



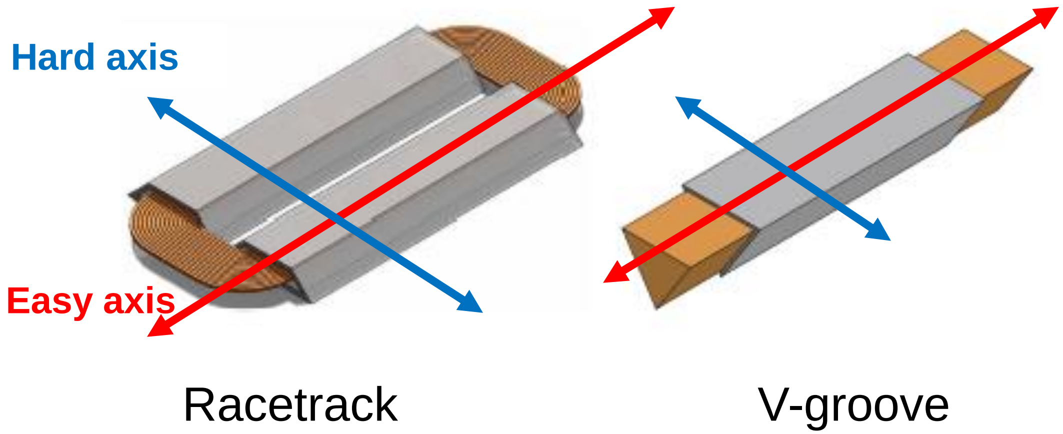


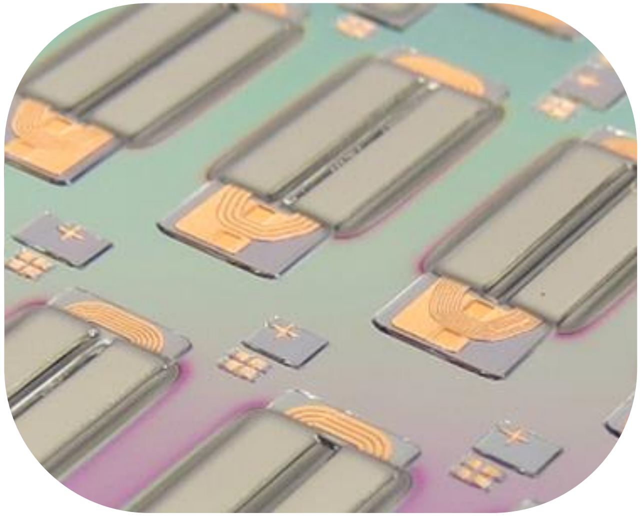


- Two magnetic depositions
- **Uses magnetic material only in hard axis**

- **Does not work with uniaxial anisotropy**

Applying anisotropic materials in microfabricated magnetics

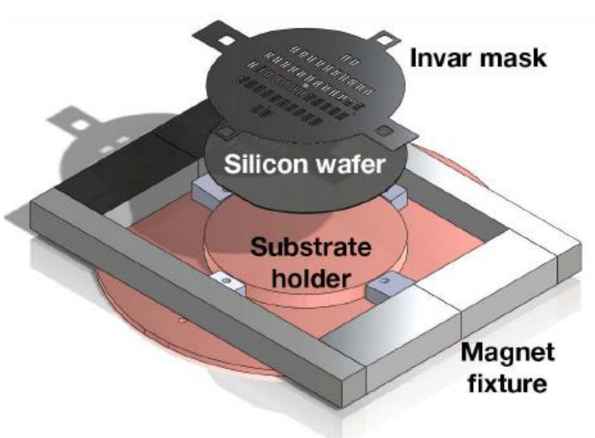


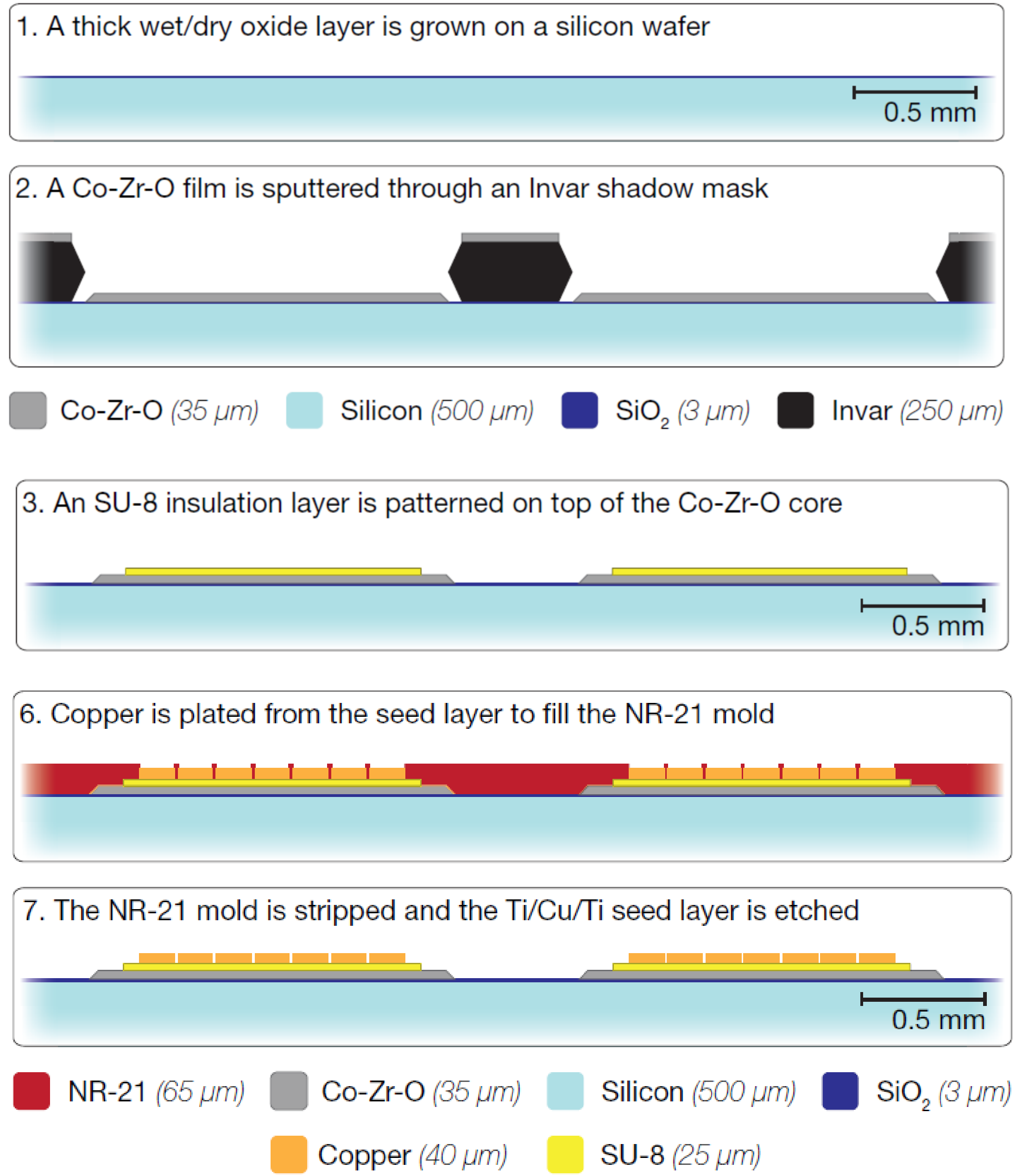


- Racetrack for multi-turn high-Z;
- V-groove for single-turn low-Z.
- Material oriented by field applied during deposition

Fabrication Steps 1-7 of 11

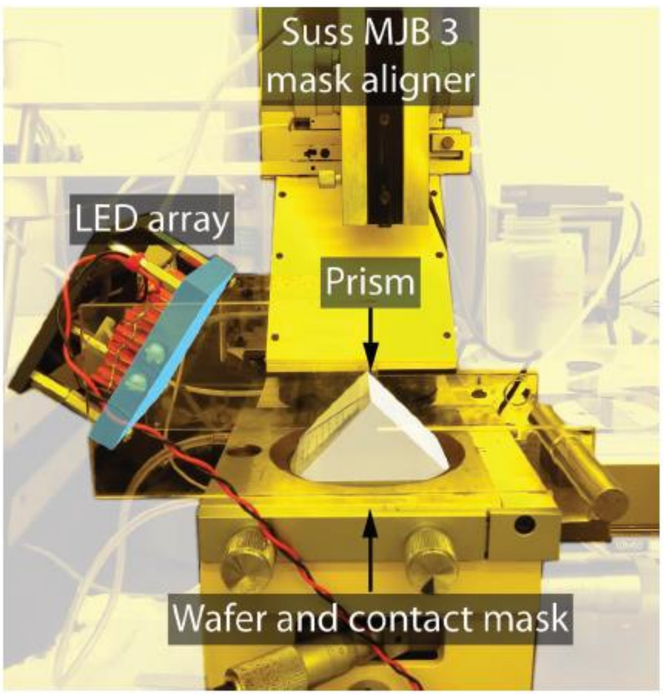
- Mostly standard processes.
- Reactive sputtering of Co-Zr-O magnetic material.
  - Shadow mask or wet etching

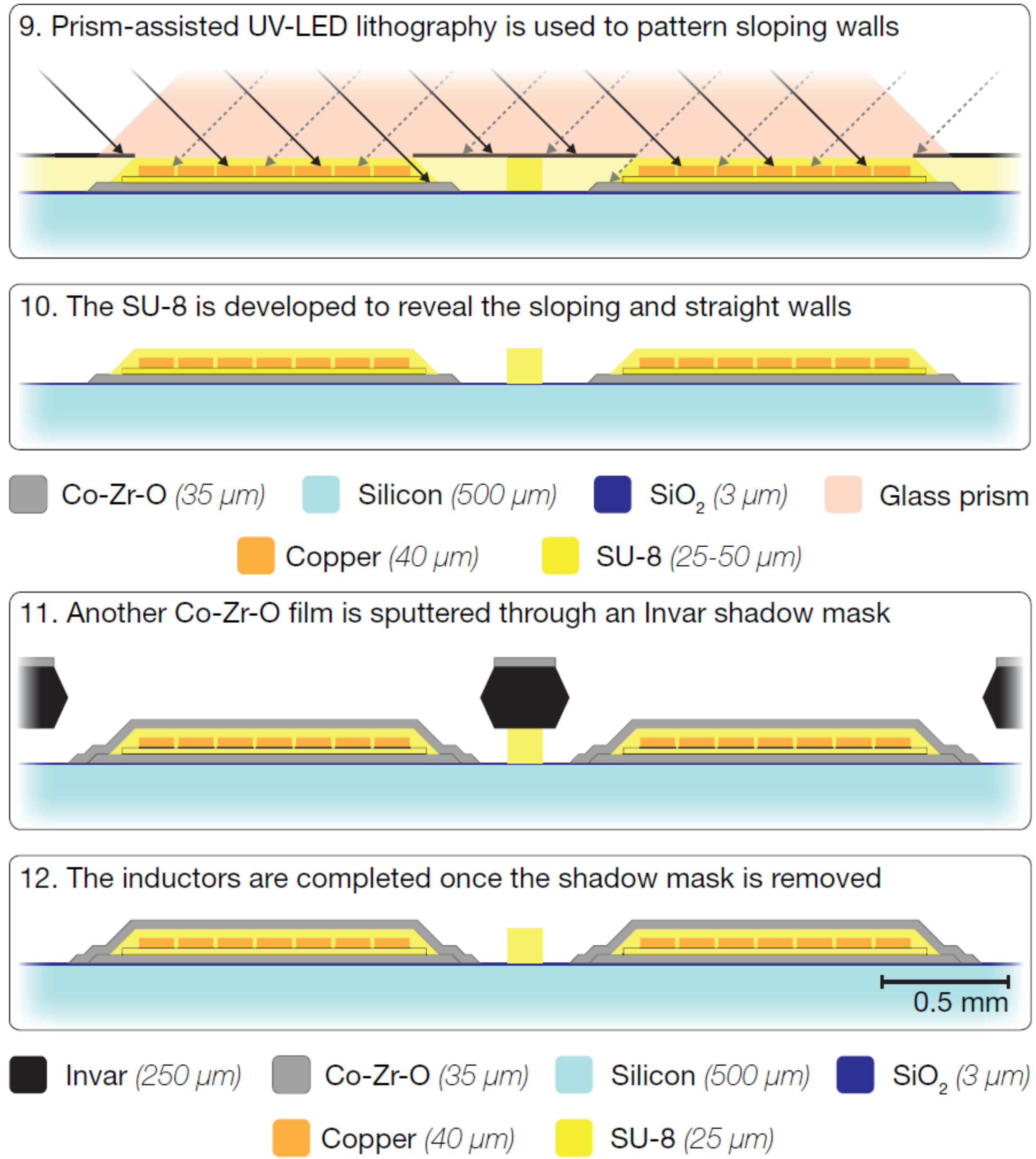




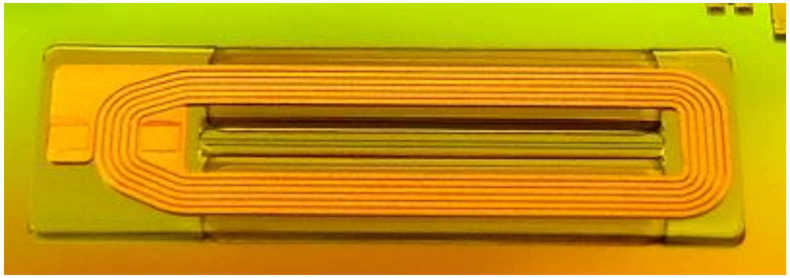
Fabrication
Last 3 steps

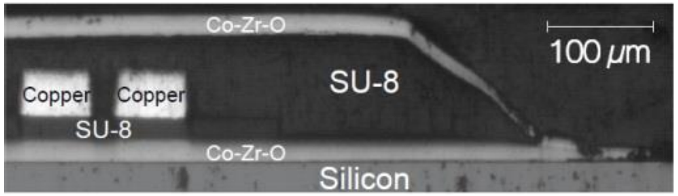
Sloping sidewalls on top insulator achieved with prism-assisted UV-LED lithography.

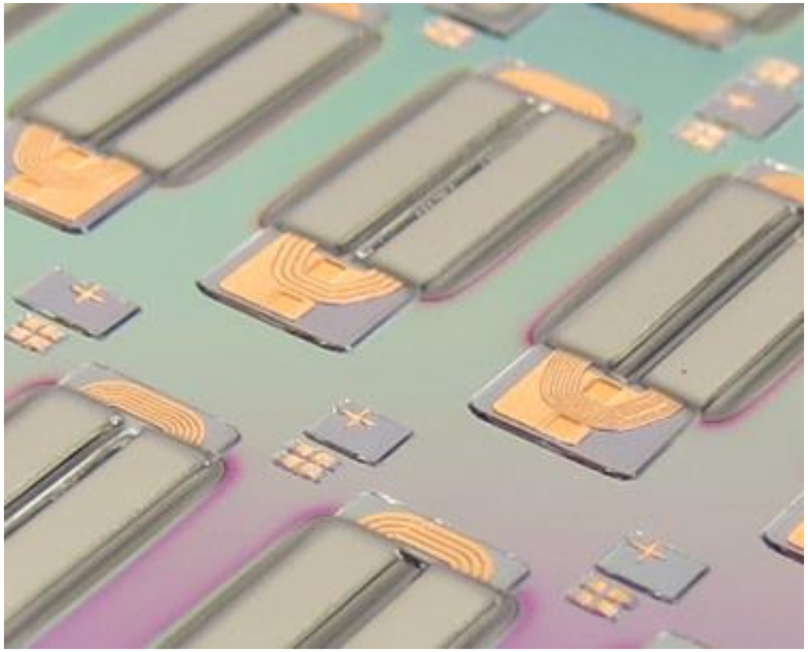


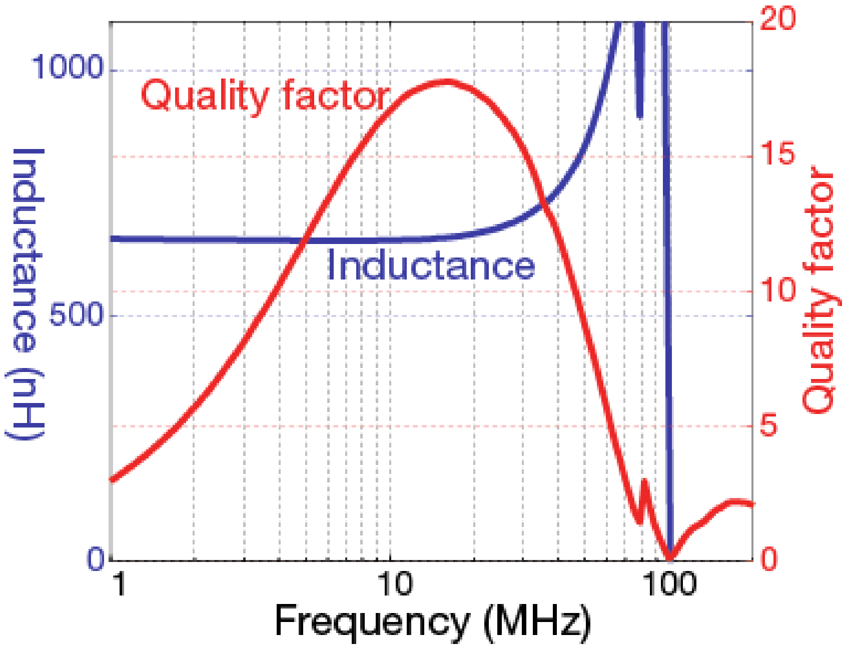


Racetrack inductors fabricated at Dartmouth

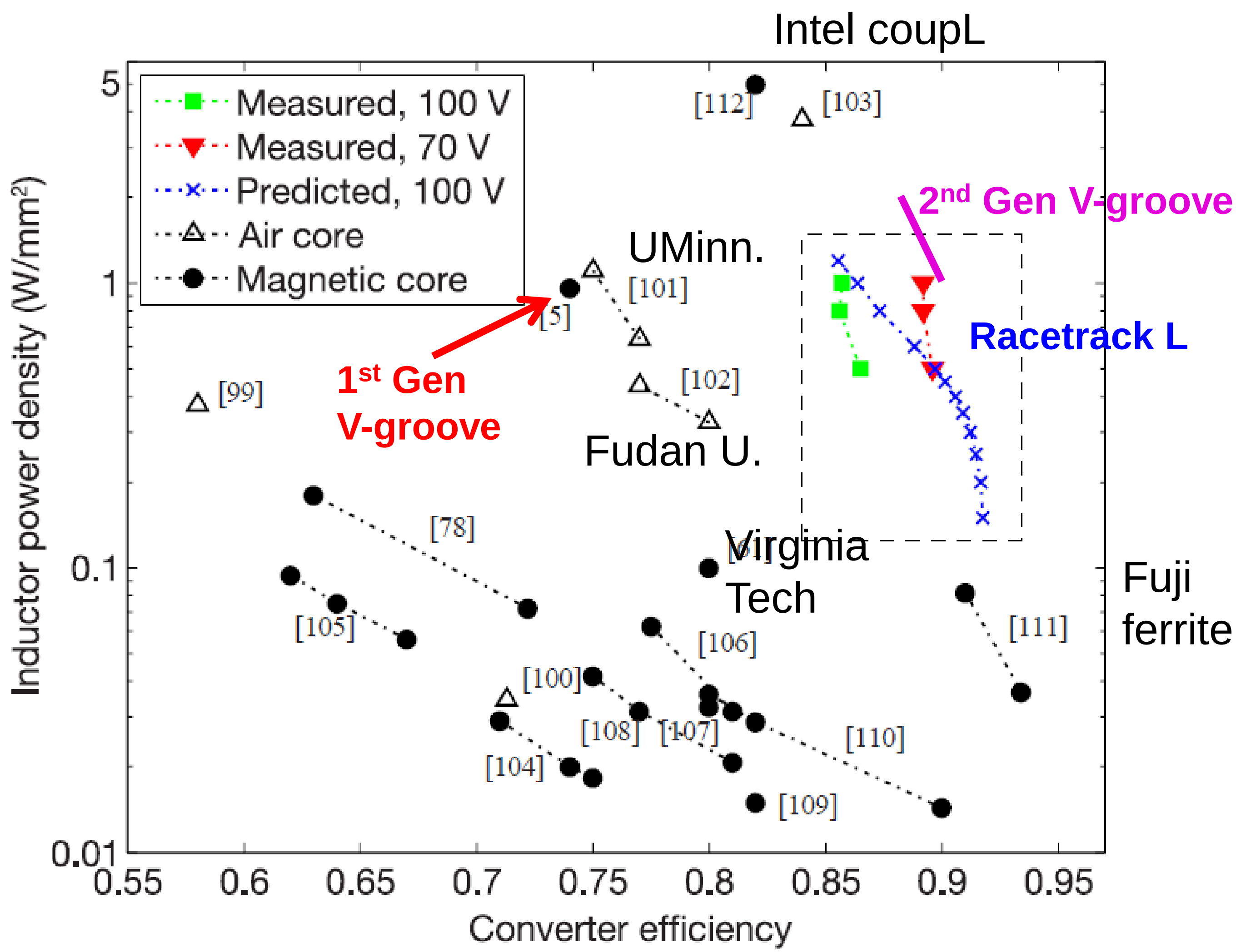






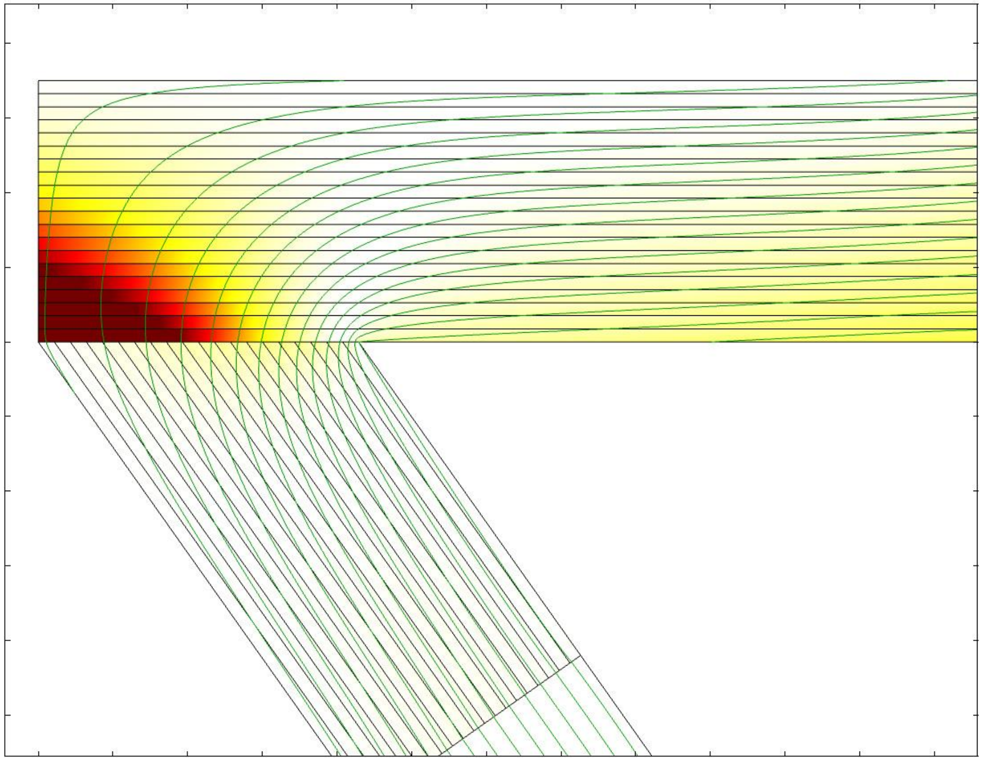


Performance in 100 V to 35 V converter and comparison to other some other work:

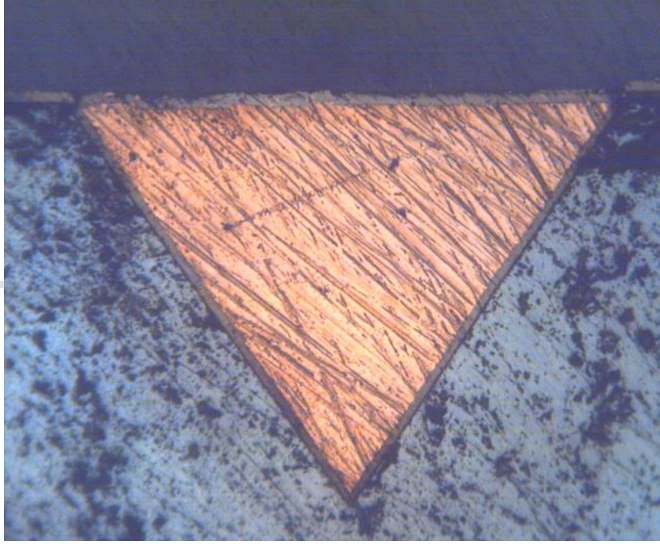


Flux crossing magnetic laminations

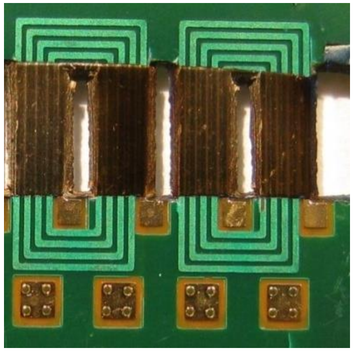
- Problem in corners where top and bottom magnetic core halves join.
- Excess eddy currents limit efficiency and Q.
- Power loss, due to **o**ut-**o**f-**p**lane **f**lux (OOPF): P_{OOPF}.



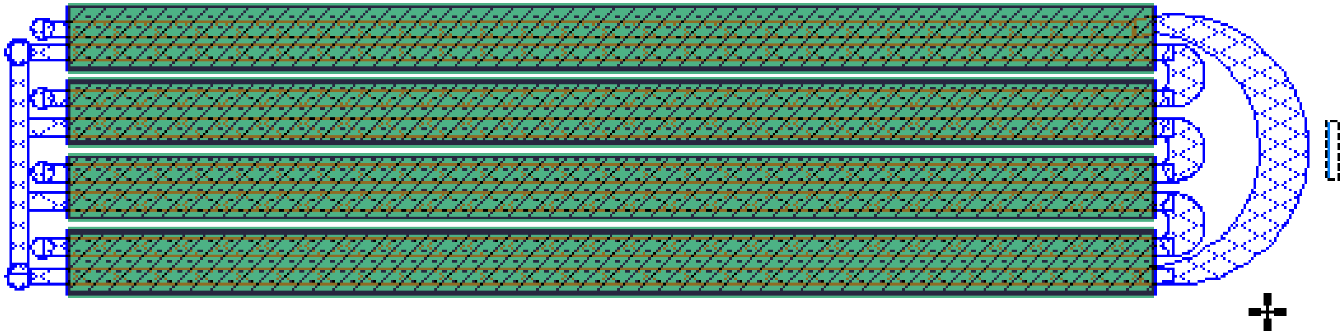
Variations on the theme: Other designs with the same problem.

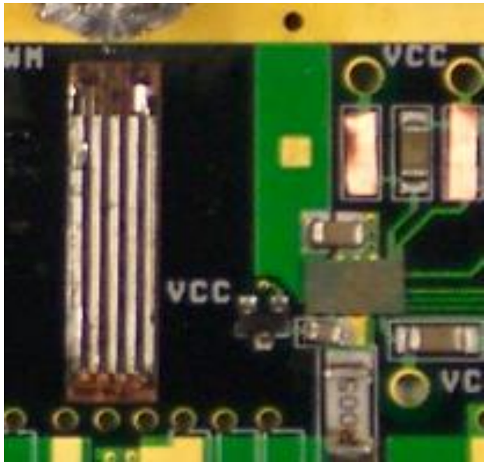


- V-groove 1-turn inductor for high current (up to 12 A)



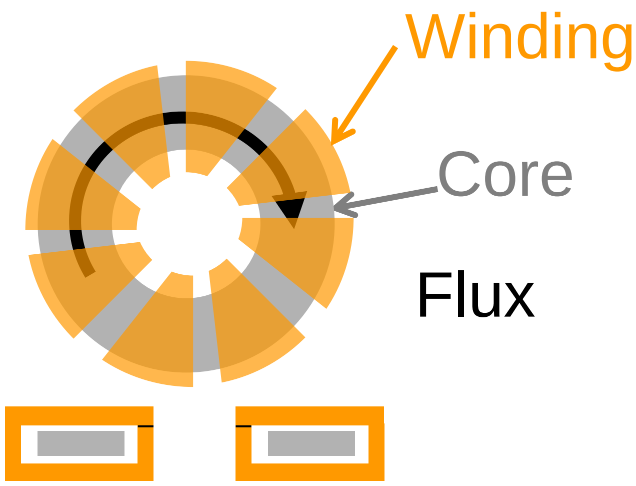
- Polyimide substrate with sputtered material on both sides
- Microfabricated coupled inductors (2004, with Tyndall)





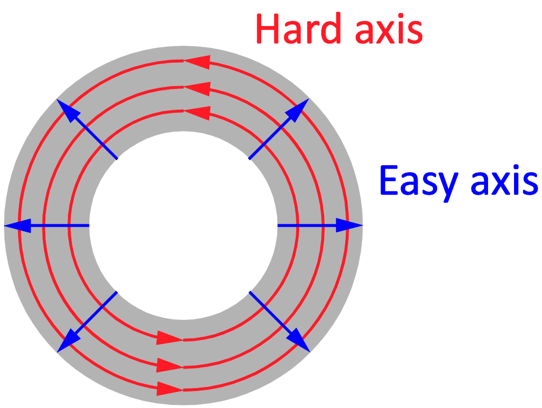
Toroidal Inductors:
No out-of-plane flux! No P_{OOPF}!

- **Advantage:**
  - Flux stays in plane, minimizing eddy-current losses.
- **Challenge:**
  - Flux direction varies; sometimes oriented incorrectly for the magnetic material anisotropy.
- **Solution:**
  - Induced radial anisotropy, such that flux travel is always in the low-loss hard-axis direction.

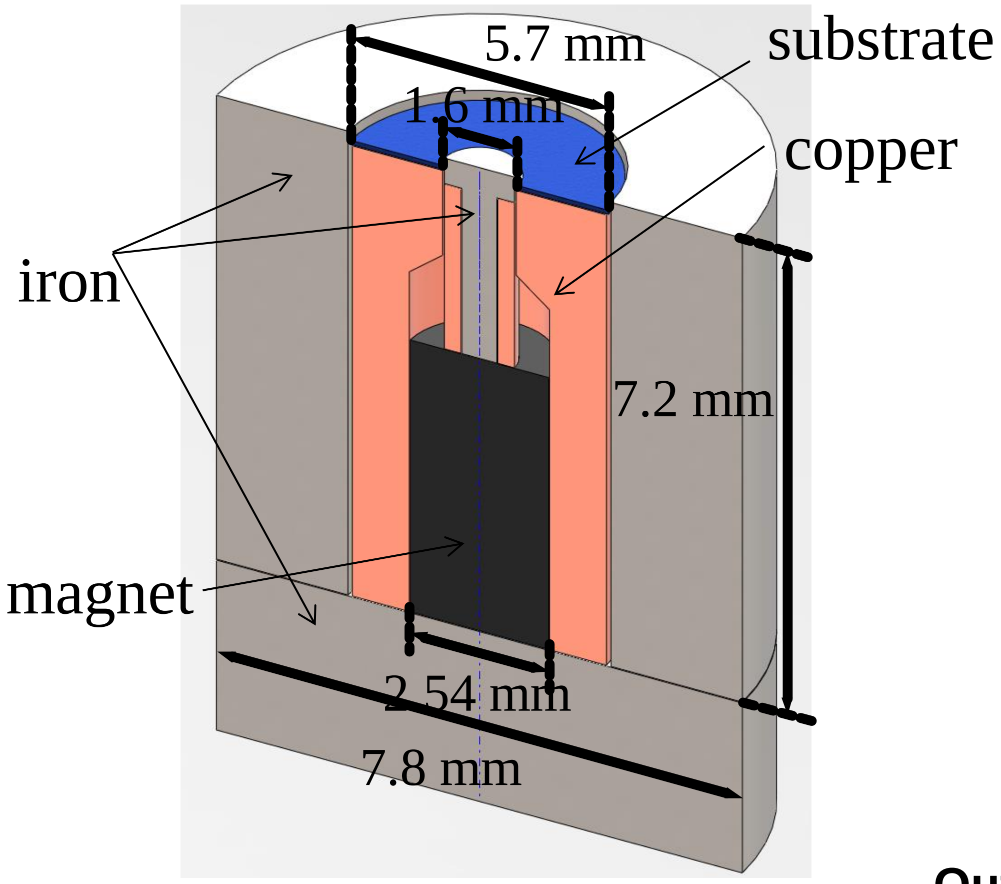


Radial anisotropy

Qiu and Sullivan. APEC, 2012

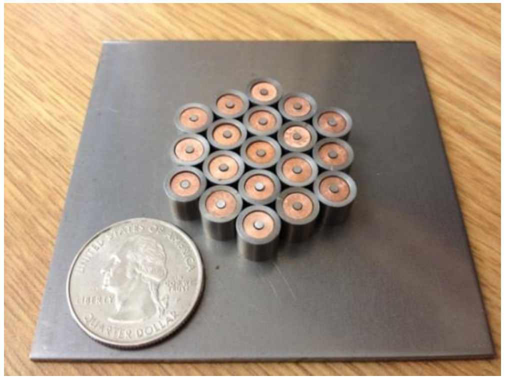


Fixture to deposit toroidal cores with radial anisotropy

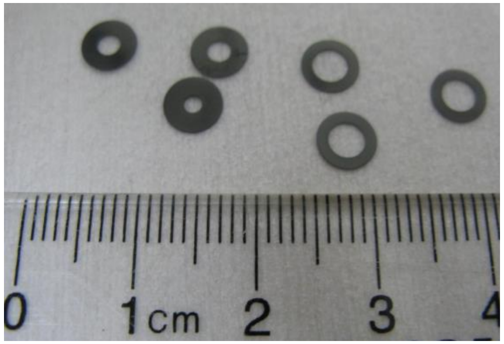


Qiu and Sullivan , CIPS, 2012

Fabricated array of fixtures



Co-Zr-O radial-anisotropy cores

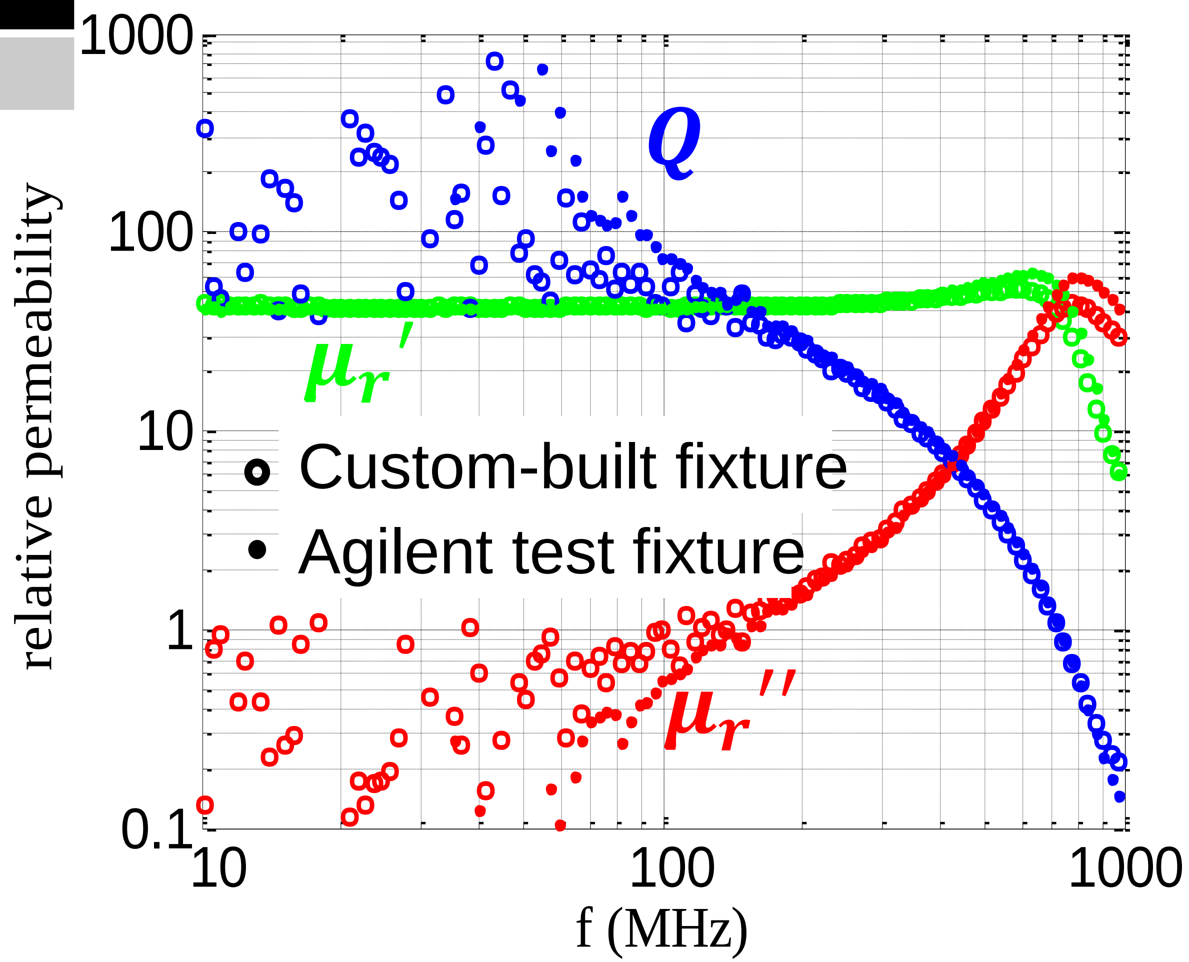


Outer diameters: 5.5 mm
Inner diameters: 1.7 mm, 2.3 mm, 3.4 mm
Thickness: 6 μm, 40 μm

Permeability of radial-anisotropy cores

Outer diameter	Inner diameter	thickness
5.5 mm	3.4 mm	40 μm

- High Q: ~ 100 at about 60 MHz.
- Resonance at about 800 MHz.
- Two test fixtures agree.

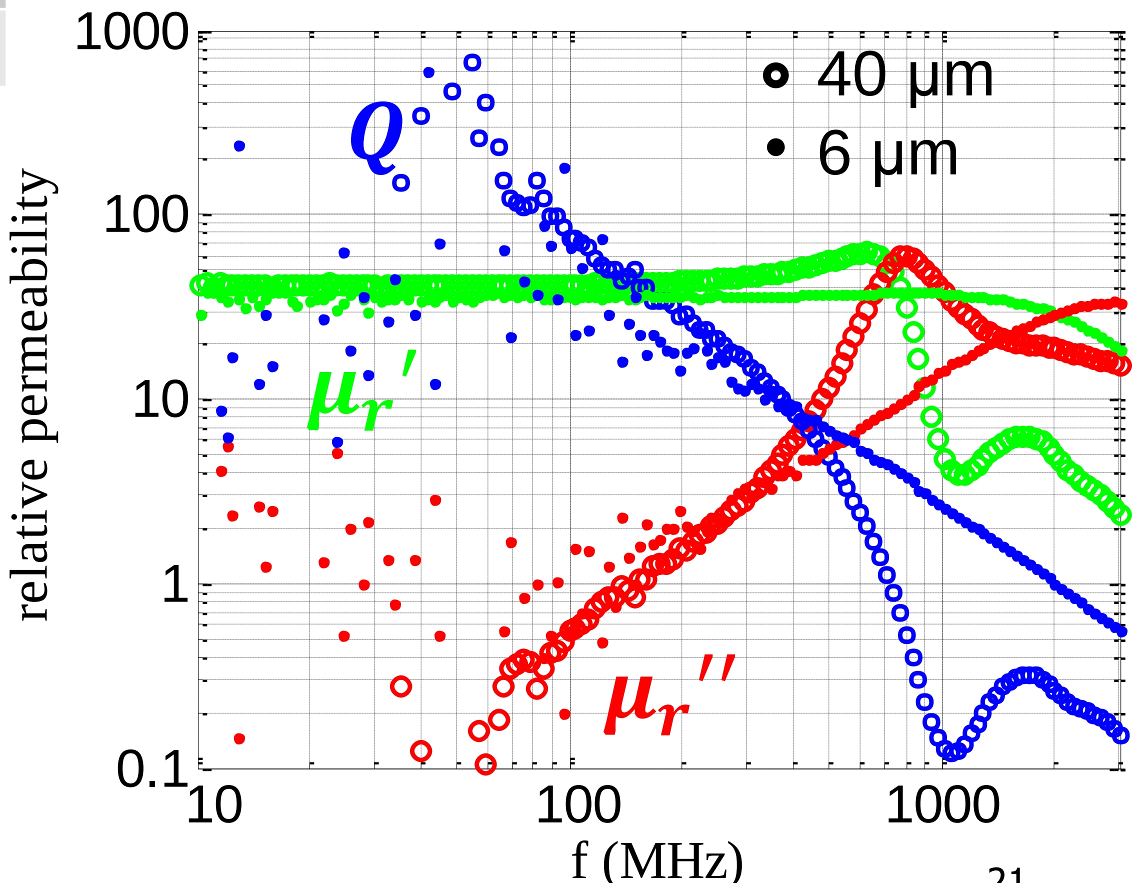


Permeability of radial-anisotropy cores with different thicknesses

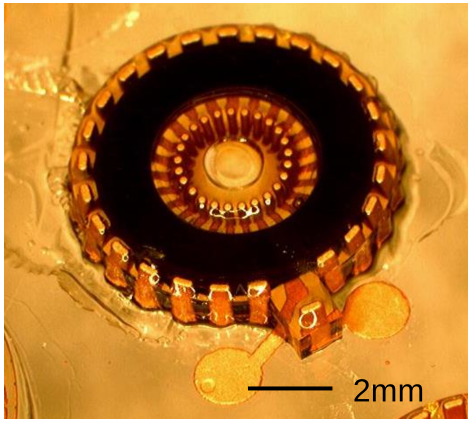
Outer diameter	Inner diameter	thickness
5.5 mm	3.4 mm	40 μm
5.5 mm	3.4 mm	6 μm

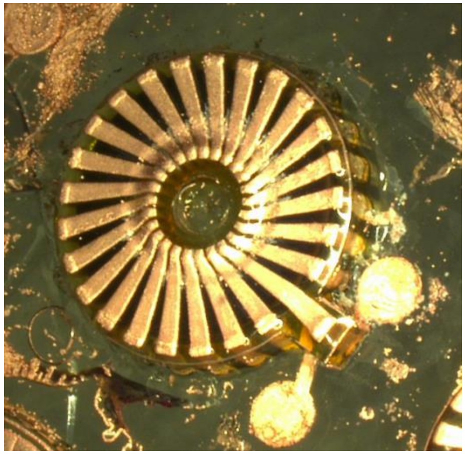
- Both cores show a real part of relative permeability of about 40.
- Both cores show Q~100 at f < 100 MHz.
- Characteristics differ at f > 500 MHz:
  - The thicker core has a lower resonant frequency, presumably a self-resonance of the multi-layer structure.

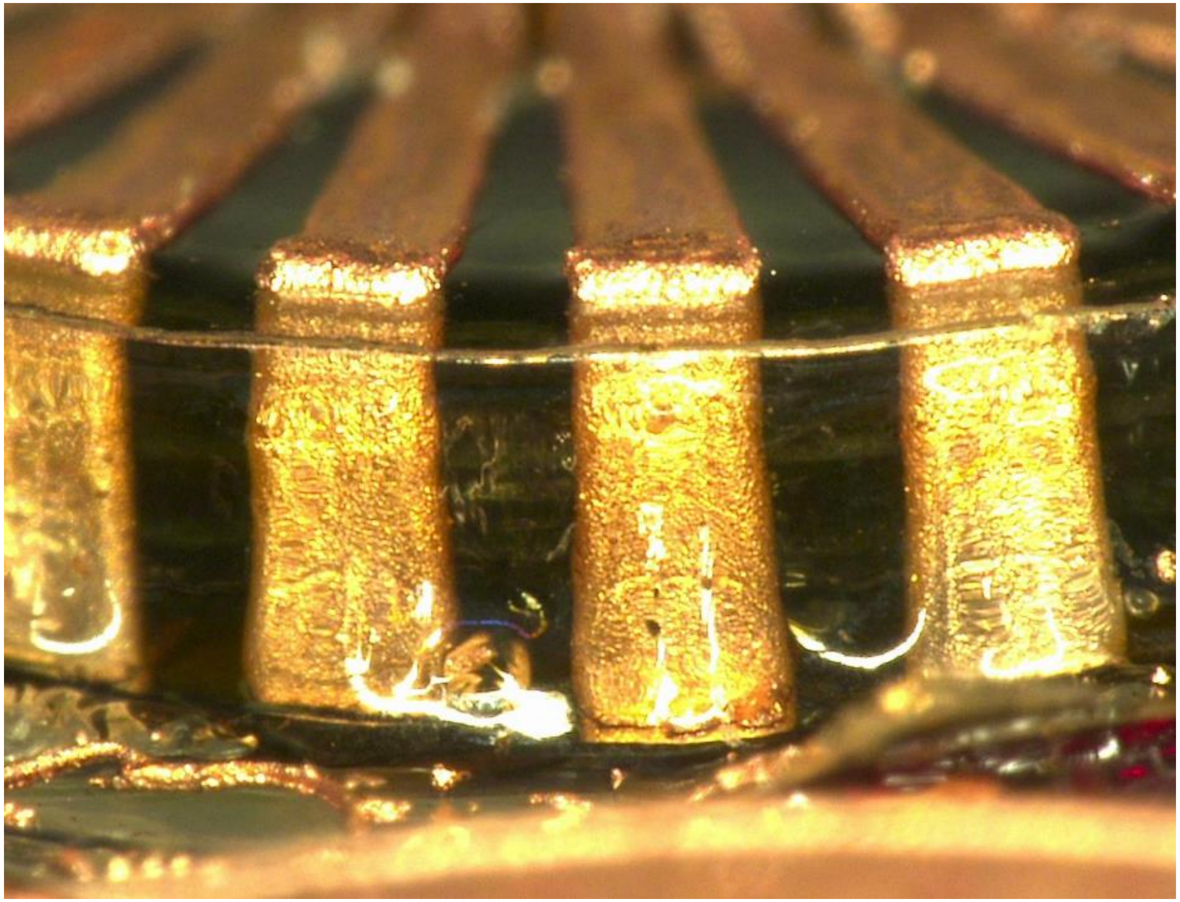
Measured by Agilent test fixture



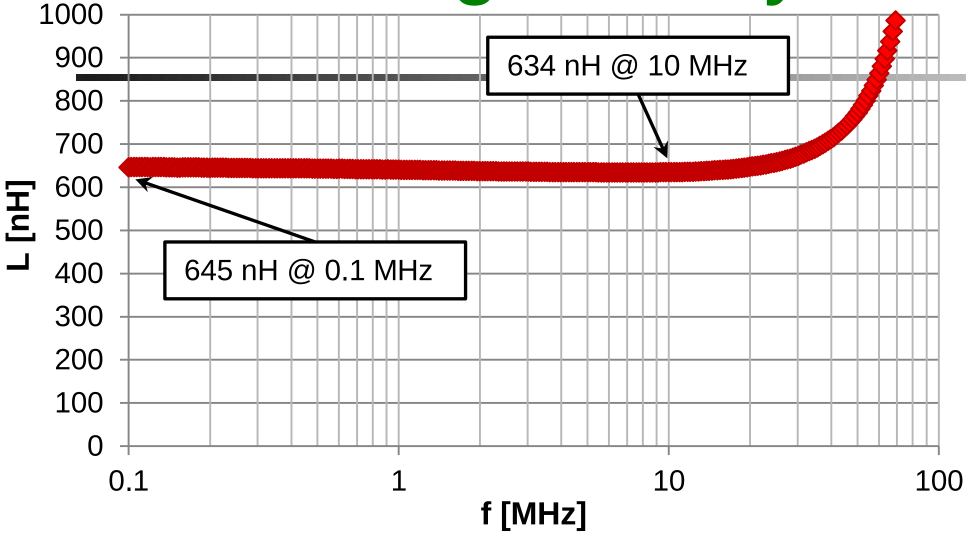
CoZrO core integrated inductor: Dartmouth cores integrated by Georgia Tech

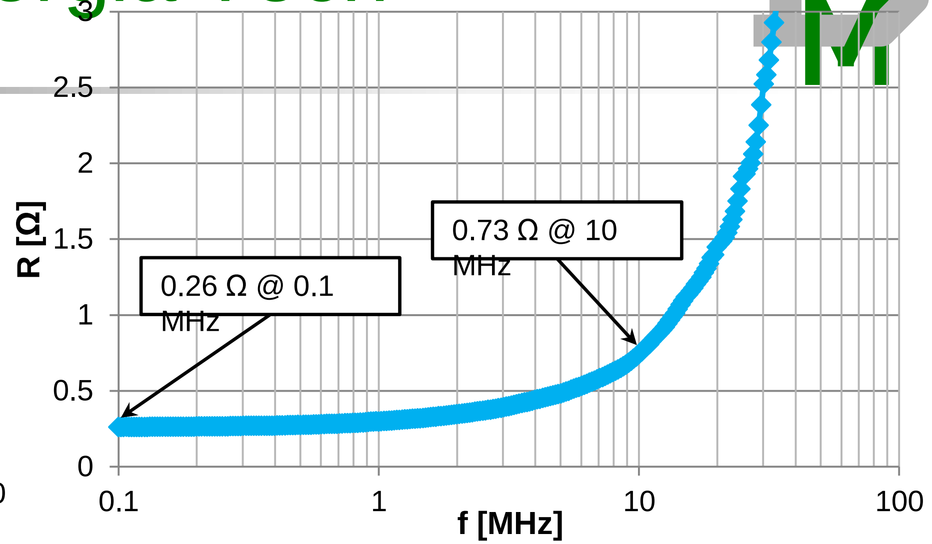


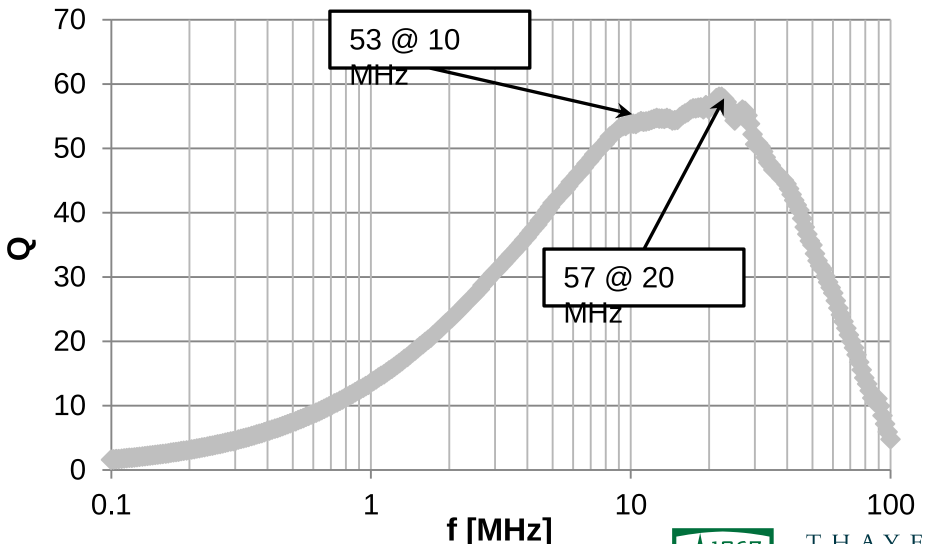


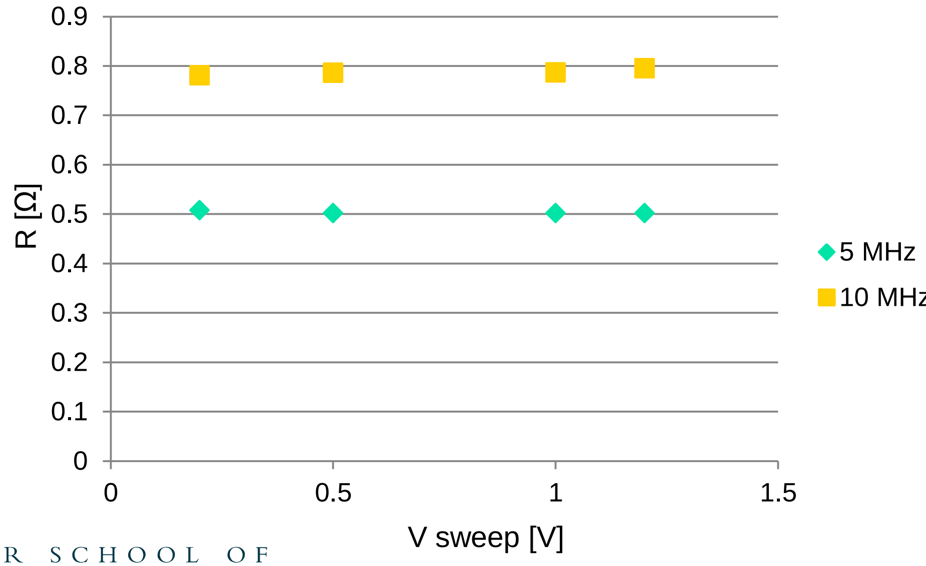


CoZrO core integrated inductor: Dartmouth cores integrated by Georgia Tech









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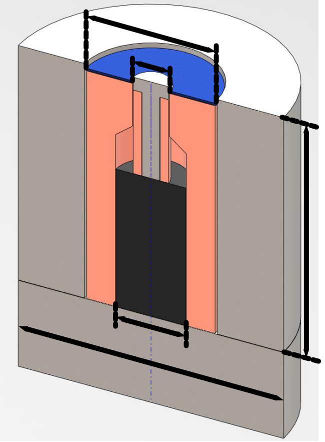
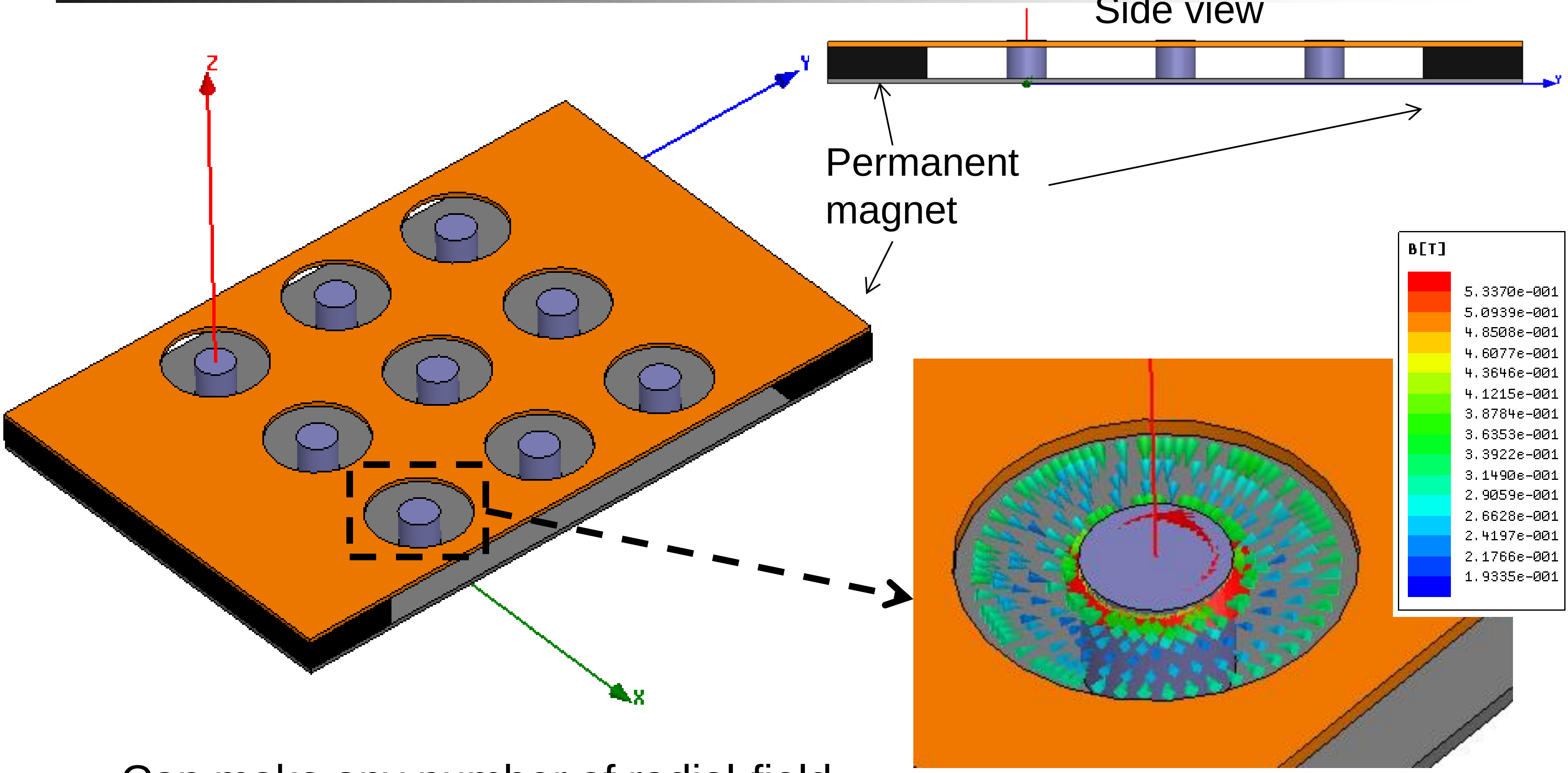
Batch fabrication

- Cores were deposited on individual substrates, and manually dropped in windings at process mid-point.
- OK for a demonstration project, but can we do true batch fabrication?
  - Many on one substrate.
  - All processes on one substrate.
  - Avoid the need for a tiny magnet for each.

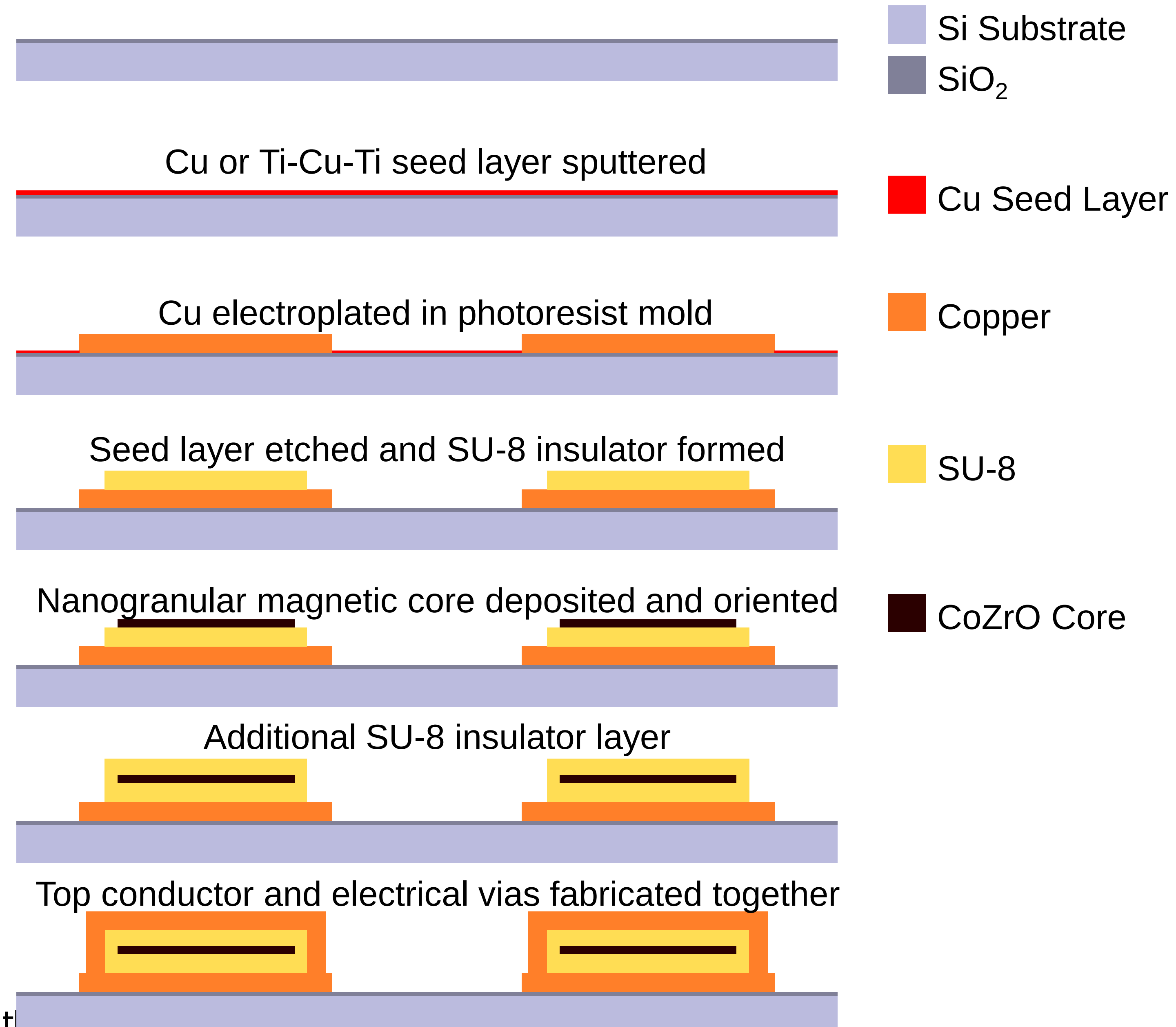


Shared-magnet radial-field fixture

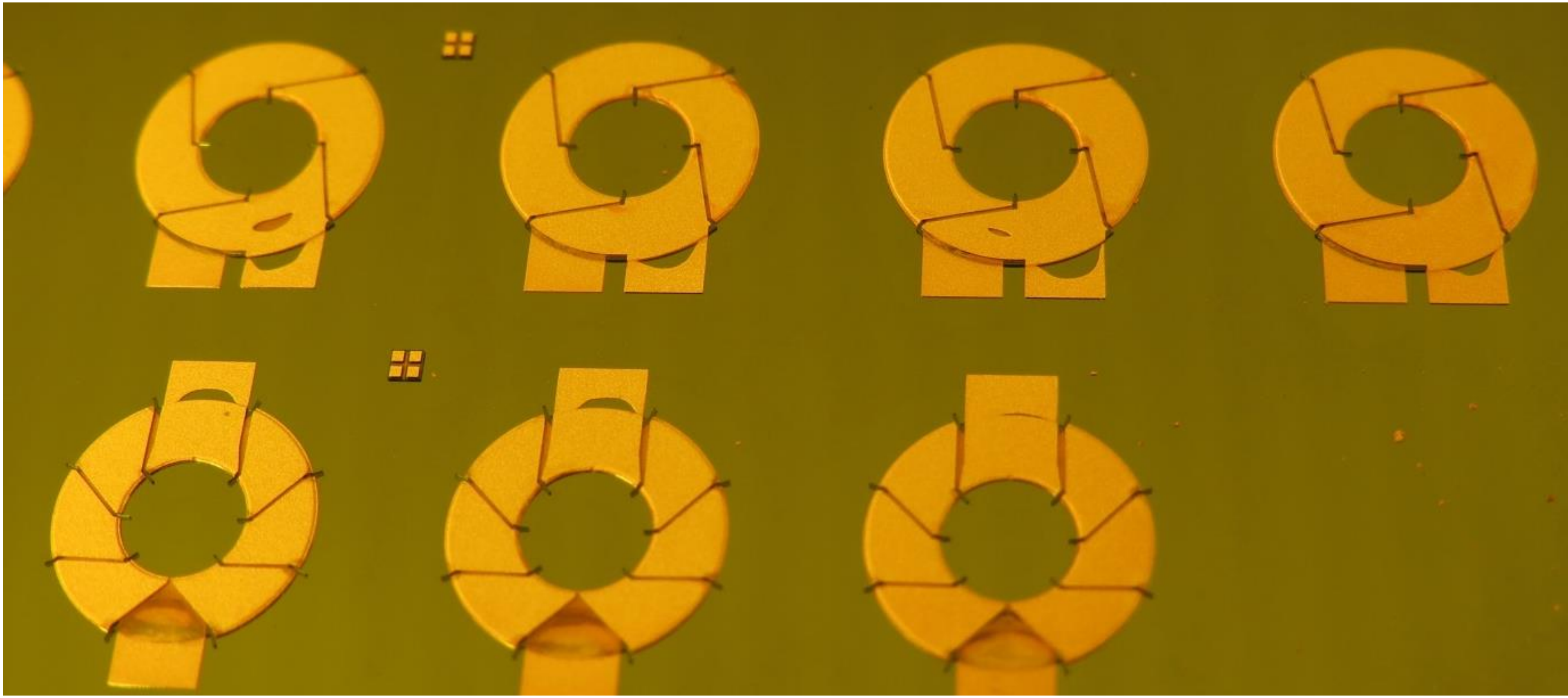


- Can make any number of radial-field regions with only two magnets.
- Can photo etch new top plate for a new design.

Process flow



Samples with dummy core



All four-turn inductors—lower winding design minimizes capacitance.

See Jizheng Qiu, A.J. Hanson, C.R. Sullivan, "Design of toroidal inductors with multiple parallel foil windings“ Control and Modeling for Power Electronics COMPEL 2013.

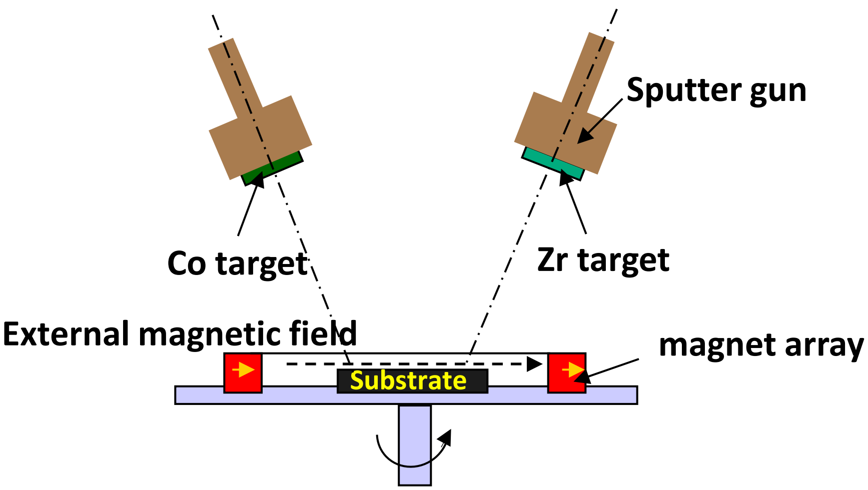
Summary

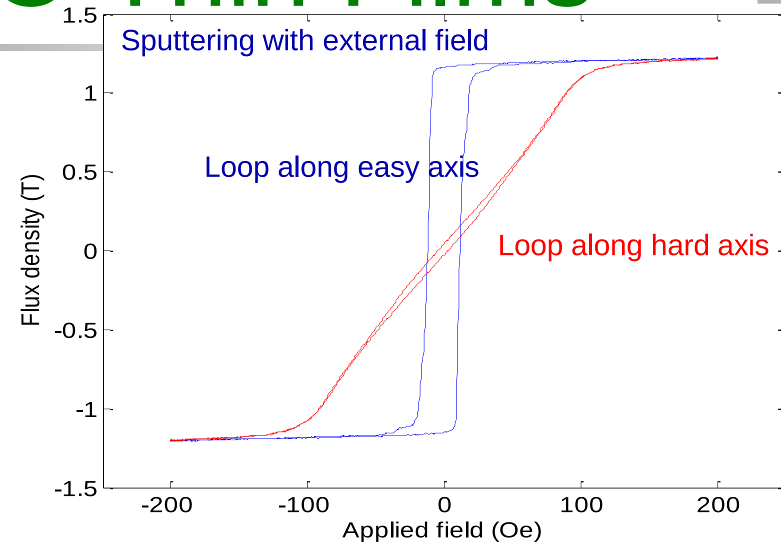
- Anisotropic nanocomposite magnetic materials can provide high performance at MHz frequencies.
- Design options for anisotropic materials include
  - Racetrack and similar geometries.
  - Toroids with radial anisotropy.
- Racetrack inductor performance proven in high-voltage dc-dc converters.
- Radial anisotropy proven in individual cores.
- Process proposed for batch fabrication of toroidal inductors.
- Other important topics not addressed here include modeling, design optimization, and measurement techniques.

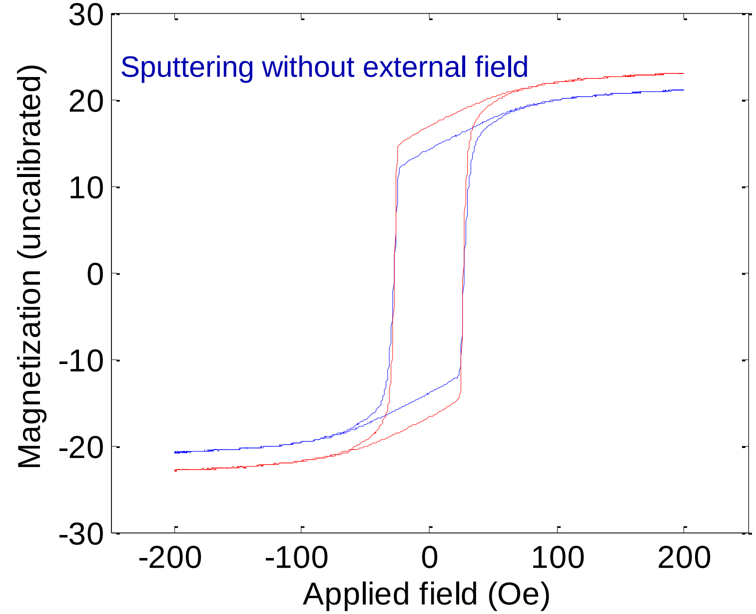
Key references

- A. J. Hanson, J. Belk, S. Lim, C. R. Sullivan and D. J. Perreault, "Measurements and Performance Factor Comparisons of Magnetic Materials at High Frequency," *IEEE Transactions on Power Electronics*, 2016 DOI:10.1109/TPEL.2015.2514084
- M. Araghchini, Jun Chen, V. Doan-Nguyen, D. V. Harburg, F. Herrault, et al "A Technology Overview of the ARPA-E PowerChip Development Program," *IEEE Transactions on Power Electronics,* 28(9) Sept. 2013 doi: 10.1109/TPEL.2013.2237791.
- C.R. Sullivan, D. V. Harburg, Jizheng Qiu, C. G. Levey and Di Yao, "Integrating Magnetics for on-Chip Power: A Perspective," *IEEE Transactions on Power Electronics,* 28(9), pp.4342,4353, Sept. 2013, doi: 10.1109/TPEL.2013.2240465.
- Charles R. Sullivan, Bradley A. Reese, Aaron L. F. Stein and Phyo Aung Kyaw, "On Size and Magnetics: Why Small Efficient Power Inductors Are Rare," International Symposium on 3D Power Electronics Integration and Packaging, June 2016.
- Charles R. Sullivan, Jizheng Qiu, Daniel V. Harburg, and Christopher G. Levey, "Batch Fabrication of Radial Anisotropy Toroidal Inductors," International Symposium on 3D Power Electronics Integration and Packaging, June 2016.
- C. R. Sullivan, "Prospects for Advances in Power Magnetics," VDE International Conference on Integrated Power Electronics Systems (CIPS), March 2016.
- Jizheng Qiu, H. Syed, and C. R. Sullivan, "Complex Permeability Measurements of Radial-Anisotropy Thin-Film Magnetic Toroidal Cores," IEEE Energy Conversion Conference and Exposition (ECCE), Sept. 2013.
- D.V. Harburg, Jizheng Qiu, Rui Tian, G.R. Khan, D. Otten, C.G. Levey and C.R. Sullivan "Measured Performance and Micro-Fabrication of Racetrack Power Inductors," IEEE Energy Conversion Conference and Exposition (ECCE), Sept. 2013.

Anisotropic Co-Zr-O Thin Films







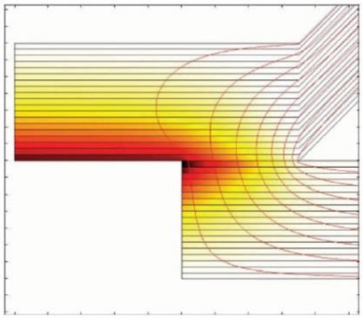
Magnetic material properties:

- High Resistivity: 300~600 μΩcm
- Relative permeability: 80~100
- High saturation flux density: 1.2 T
- Low coercivity: 4 Oe
- High in-plane anisotropy

Sun et al., 2005, 2007

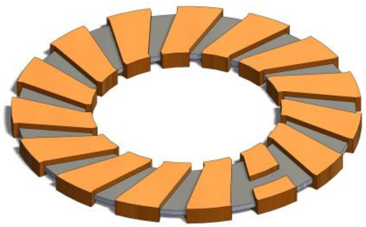
Thin-film inductor geometries

Via loss in racetrack

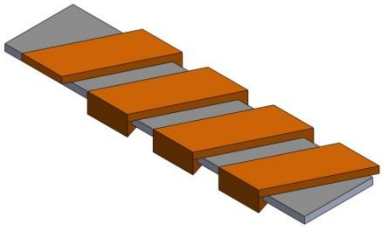


Racetrack

Toroid



Solenoid



	Racetrack	Toroid	Solenoid
Closed core	Yes	Yes	No
Core deposition steps	2	1	1
Magnetic vias	Yes	No	No
Compatible with uniaxial anisotropy	Yes	No	Yes

Pictures from "Integrating Magnetics for on-Chip Power: A Perspective", C. R. Sullivan et al., IEEE trans on power electronics, 2013.