PWR SoC '12
Palace Hotel, San Francisco, CA
Nov. 16-18, 2012

Low-Profile Toroidal Power Inductors Using Radial-Anisotropy Thin-Film Magnetic Materials

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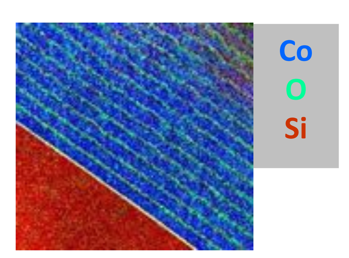
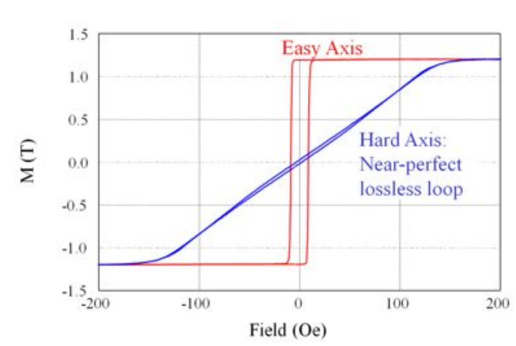
Introduction

- Low-profile toroidal power inductors for power supply on chip and/or in package to improve integration.
- Nanogranular magnetic material Co-Zr-O with radial-anisotropy developed for toroidal inductors
  - Deposited in the presence of radial magnetic field.
  - Radial easy axis and circumferential hard axis (aligned with flux direction).
- Two winding fabrication approaches:
  - Printed circuit board (PCB)-based
  - Microfabricated (CMOS-compatible)
- Toroidal inductors fabricated and tested at small-signal levels.

Co-Zr-O Nanogranular Material

- High saturation flux density: 1.1~1.2 T (3X ferrite)
- High resistivity: 300~600 μΩ·cm (>10 X NiFe)
- Moderate permeability: 40~80 μ_0 (ideal for inductors)
- Anisotropy provides low hysteresis loss.
- Operation to several GHz

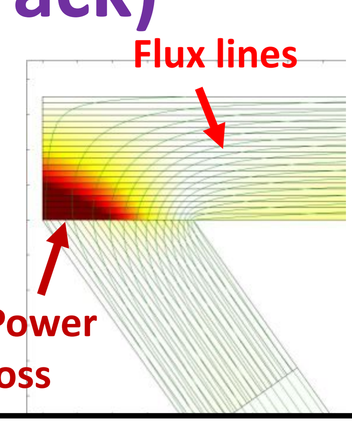




Hysteresis loops

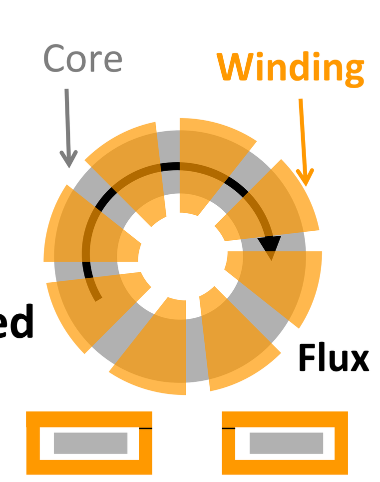
Loss in magnetic vias in some inductor geometries (e.g. racetrack)

- Significant eddy-current losses where top and bottom magnetic cores meet.
- The magnetic-via loss constitutes a big proportion of the total loss.
- Limits maximum quality factor.



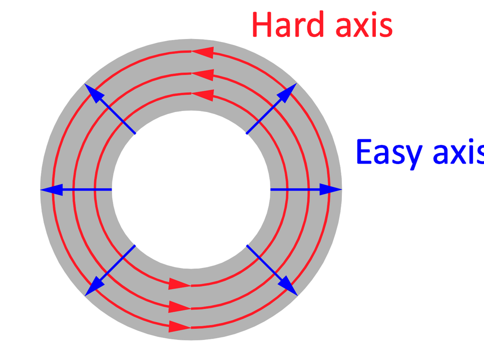
Magnetic-Core Toroidal Inductors

- Advantage:
  - Flux stays in plane, minimizing eddy-current losses.
- Challenge:
  - Flux direction is circumferential, can't be aligned with uniaxial anisotropy
- Our solution
  - Induce radial anisotropy to align flux direction in the low-loss hard axis.

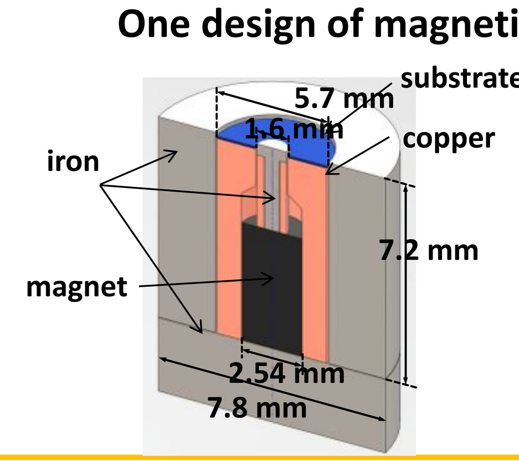


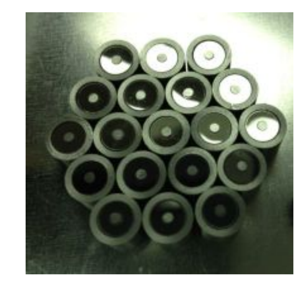
Radial-Anisotropy Toroidal Cores

- Depositing magnetic material in the presence of a radial magnetic field creates
  - radial easy axis
  - circumferential hard axis.
- Fixtures are built to create in-plane radial field.



One design of magnetic field fixture

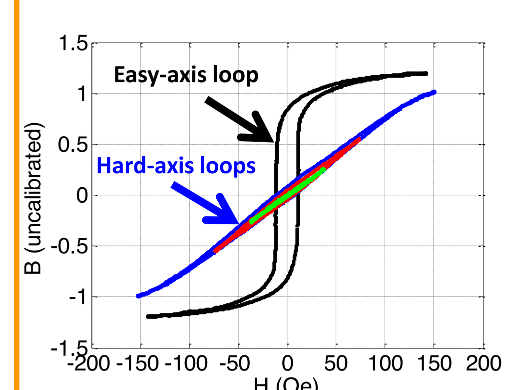




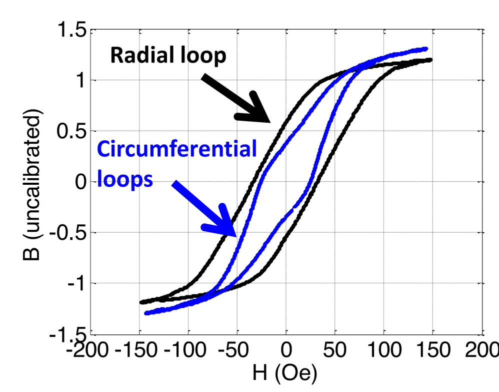
Outer radius: 2.8 mm
Inner radius: 1.7 mm
Magnetic film thickness: 40 μ m

Toroidal Core Measurements

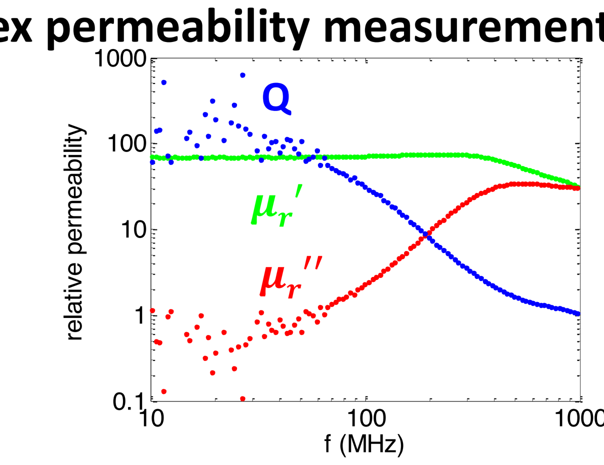
- Hysteresis measurements
- Complex permeability measurements



B-H loops of cores deposited w/ a radial field

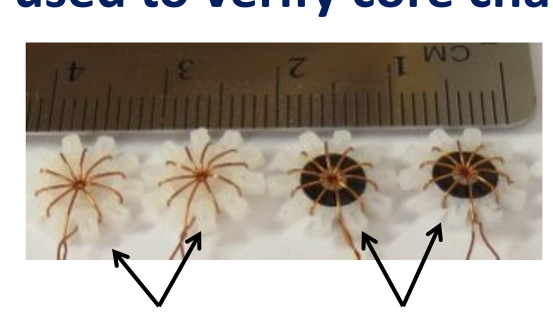


B-H loops of cores deposited w/o a radial field



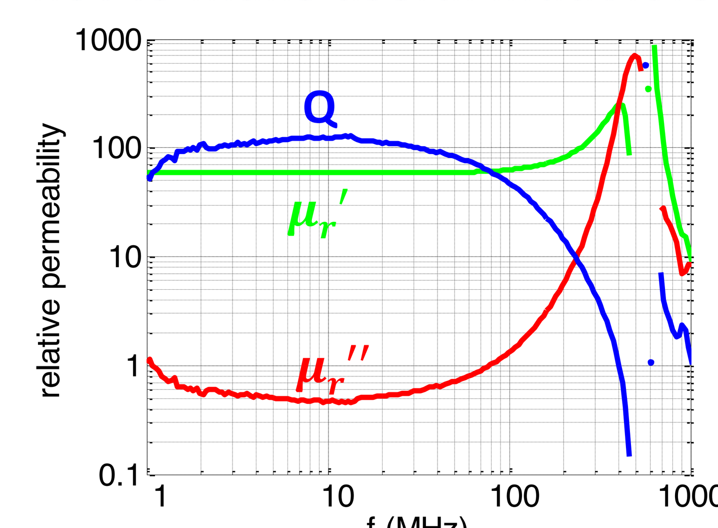
Hand-Wound Magnetic-Core Toroids

used to verify core characteristics – not to make useful inductors

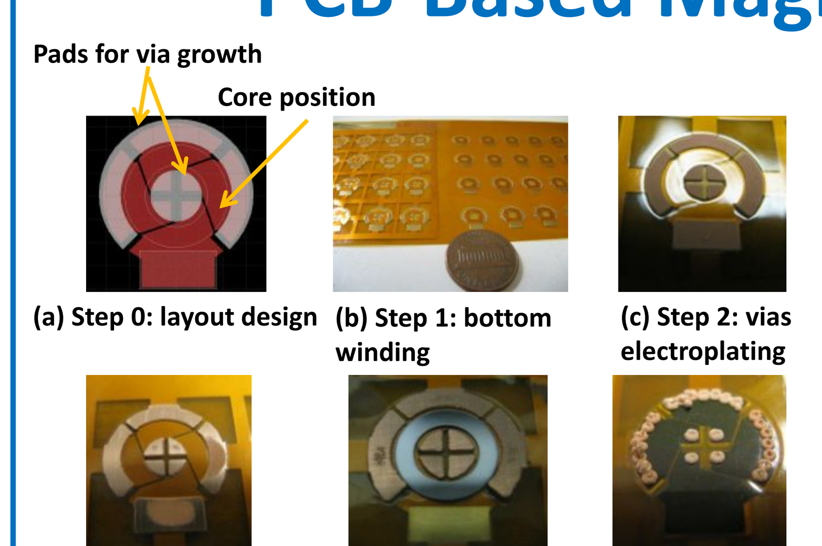


Bobbin height: 1 mm
Core OD: 5.5 mm
Core ID: 2.3 mm
Core thickness: 40 μm

Winding OD: ~7.5mm
Winding ID: ~1.2 mm
Wire size: AWG 32 (0.202 mm diameter)

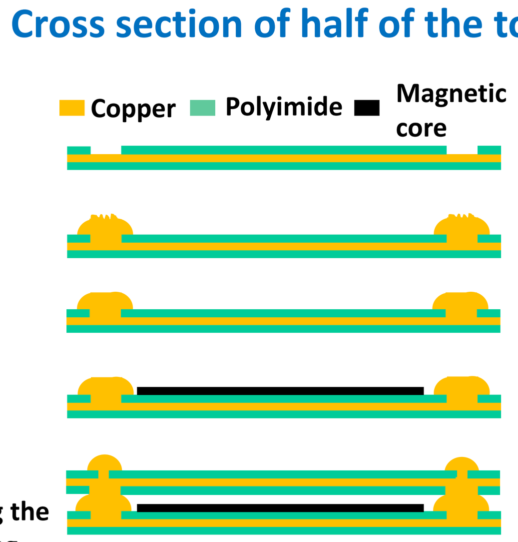


PCB-Based Magnetic-Core Toroids



(a) Step 0: layout design (b) Step 1: bottom winding (c) Step 2: vias electroplating (d) Step 3: polishing (e) Step 4: dropping the toroidal core (f) Step 5: covering the top layer of winding

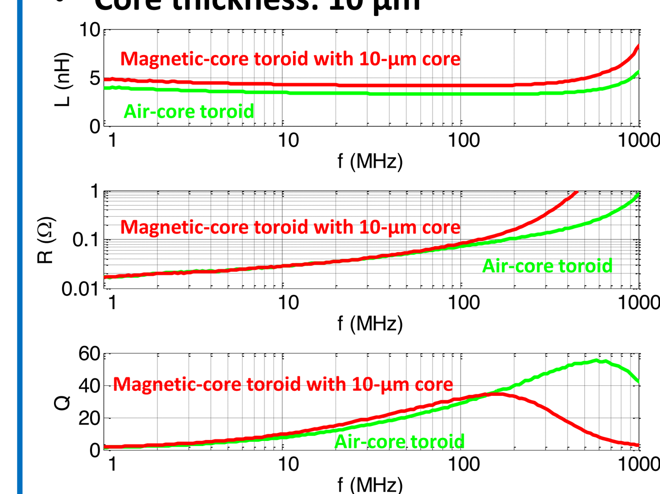
Cross section of half of the toroid



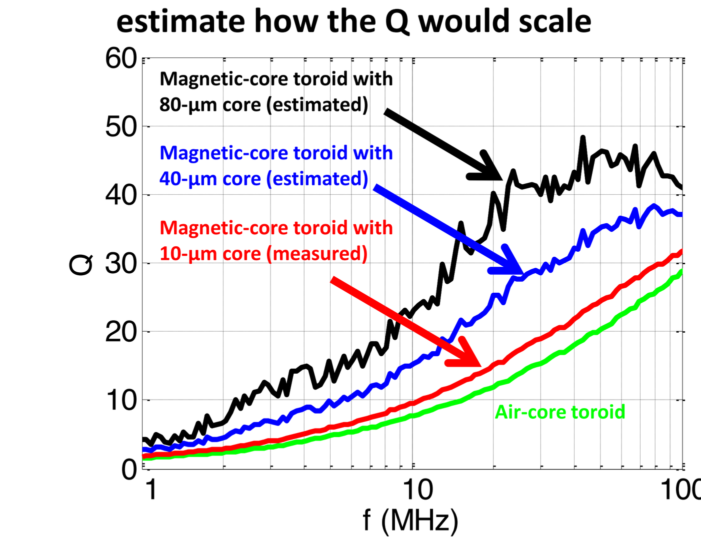
1. Toroidal bottom winding is patterned in a 1-layer PCB. Pads are not covered by polyimide to allow via growth.
2. Electroplating the vias
3. Polishing after the via plating
4. Dropping the magnetic core.
5. Covering the top layer of winding (1-layer PCB) by electroplating.

Measurements of PCB-Based Toroids

- 4-turn toroid
- Inductor thickness: ~350 μm
- Core thickness: 10 μm

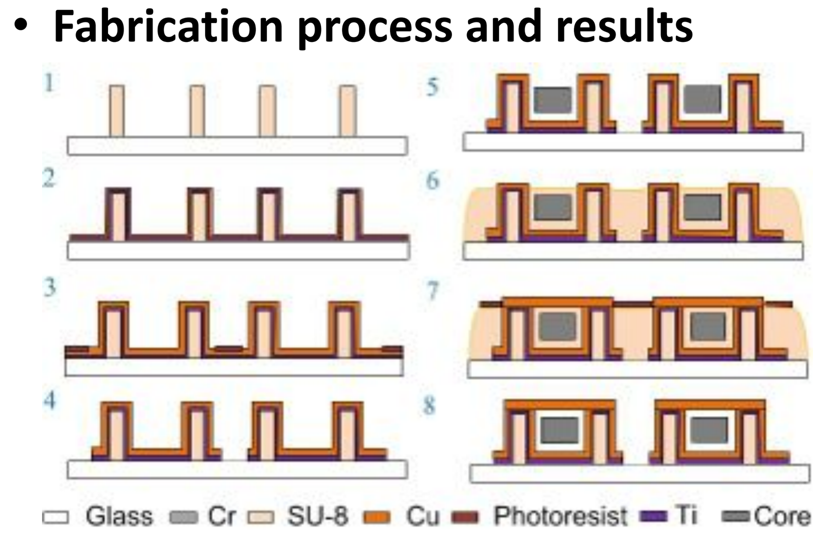


- What if we have a thicker core?
  - Based on the 10- μm measurements, we estimate how the Q would scale



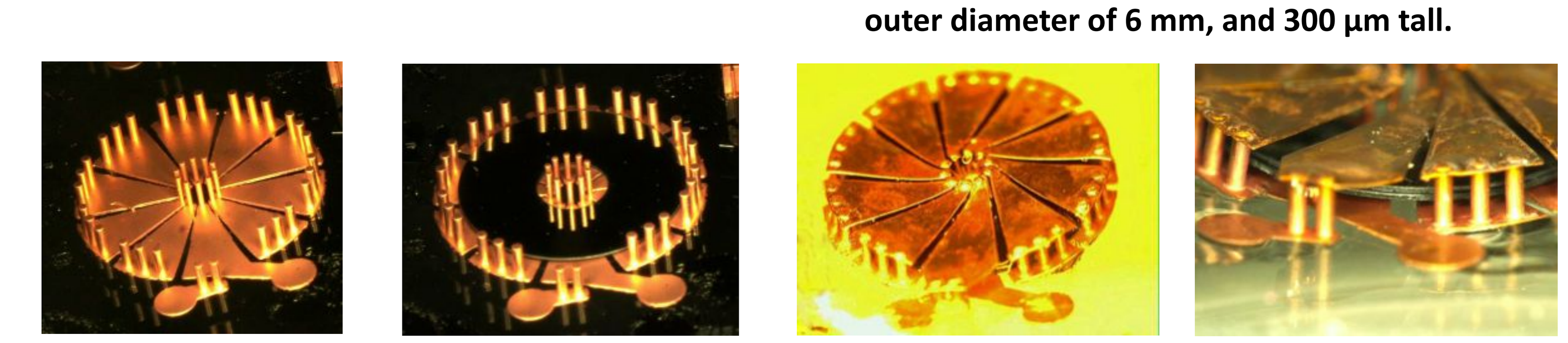
Microfabricated Magnetic-Core Toroids

- Fabrication process and results



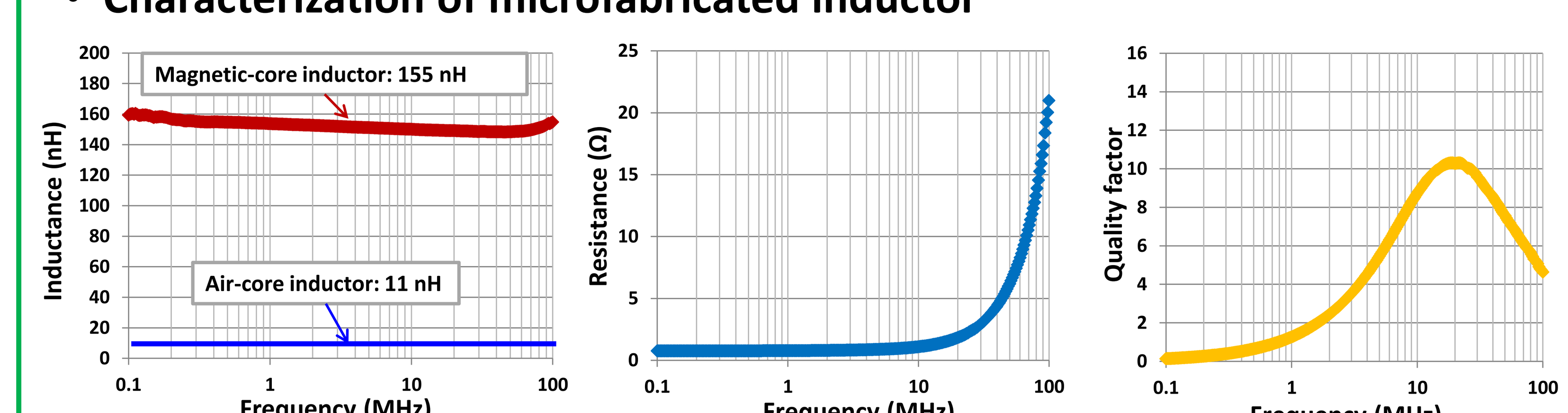
1. SU-8 pillar fabrication
2. Ti/Cu deposition by DC sputtering
3. Photopatterning of bottom and vertical windings and Cu electroplating
4. PR removal, Ti/Cu seed layer etch
5. Core integration
6. Non-photopatternable SU-8 filling
7. Top conductor patterning and Cu electroplating
8. PR removal, Cu seed etch, Non-photopatternable SU-8 removal

* Inductor has an inner diameter of 1 mm and outer diameter of 6 mm, and 300 μm tall.



Bottom and vertical windings; Core integration on bottom and vertical windings; Completed 10 turn core integrated inductor; Enlarged view of integrated core in windings

- Characterization of microfabricated inductor



Conclusion

- Low-profile magnetic-core toroidal power inductors
- Radial-anisotropy toroidal core showed good performance (Q > 100 at f < 100 MHz)
- Demonstrated two fabrication processes
  - PCB-based (co-package)
  - Microfabricated (CMOS-compatible)
- Functional magnetic-core toroidal inductors fabricated and tested at small-signal levels