Batch Fabrication of Radial Anisotropy Toroidal Inductors

Charles R. Sullivan, Jizheng Qiu, Daniel V. Harburg, and Christopher G. Levey
Two types of inductors

Pot-core

- Core wraps winding

Toroidal

- Winding wraps core

- Many intermediate geometries are also possible
Inductors on Si

- Two magnetic depositions
- One magnetic deposition.
Magnetic anisotropy: common in thin-film magnetic materials

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

![Graph showing easy and hard axis loops](image)

- Easy Axis:
- Hard Axis: Near-perfect lossless loop
Microfabricated inductors

- Two magnetic depositions
- Uses magnetic material only in hard axis
- Does not work with uniaxial anisotropy
Racetrack inductors fabricated at Dartmouth
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 out-of-plane flux (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)

power.thayer.dartmouth.edu
Nano-composite magnetic materials

- Ferromagnetic (coupled particles)
- Some have strong anisotropy for low permeability and low hysteresis loss.
- High resistivity (300 ~ 600 μΩ·cm) reduces eddy-current loss for any flux direction.
- Eddy currents due to out-of-plane flux still dominate loss. $P_{OOPF}$ is still a problem.
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.

![Core](image1.png) ![Winding](image2.png) ![Flux](image3.png)
Fixture to deposit toroidal cores with radial anisotropy

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

Qiu and Sullivan, CIPS, 2012
Permeability of radial-anisotropy cores

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

<table>
<thead>
<tr>
<th>Outer diameter</th>
<th>Inner diameter</th>
<th>thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5 mm</td>
<td>3.4 mm</td>
<td>40 μm</td>
</tr>
</tbody>
</table>

Measured by both fixtures
Permeability of radial-anisotropy cores with different thicknesses

- 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.

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<td>40 μm</td>
</tr>
<tr>
<td>5.5 mm</td>
<td>3.4 mm</td>
<td>6 μm</td>
</tr>
</tbody>
</table>

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

- L [nH]:
  - 634 nH @ 10 MHz
  - 645 nH @ 0.1 MHz

- R [Ω]:
  - 0.73 Ω @ 10 MHz
  - 0.26 Ω @ 0.1 MHz

- Q:
  - 53 @ 10 MHz
  - 57 @ 20 MHz

- V sweep [V]:
  - 5 MHz
  - 10 MHz
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.
Can make any number of radial-field regions with only two magnets.

Can photo etch new top plate for a new design.
Process flow

Cu or Ti-Cu-Ti seed layer sputtered

Cu electroplated in photoresist mold

Seed layer etched and SU-8 insulator formed

Nanogranular magnetic core deposited and oriented

Additional SU-8 insulator layer

Top conductor and electrical vias fabricated together
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

- Effective utilization of laminated anisotropic materials:
  - Toroidal designs keep the flux in the plane so laminations effectively squelch eddy currents.
  - Radial anisotropy keeps hysteresis losses low.
- Radial anisotropy can be induced by applying a field during deposition.
  - Fixtures for discrete cores.
  - Shared-magnet fixture: any number feasible on a single substrate. (100?)
Thank you
Thin-film inductor geometries

Via loss in racetrack

<table>
<thead>
<tr>
<th></th>
<th>Racetrack</th>
<th>Toroid</th>
<th>Solenoid</th>
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<tbody>
<tr>
<td>Closed core</td>
<td>Yes</td>
<td>Yes</td>
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<tr>
<td>Core deposition steps</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Magnetic vias</td>
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<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Compatible with uniaxial anisotropy</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
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