Limitations to Miniaturization of Magnetic Components

Eyal Aklimi, Ph.D.
May 2017
Outline

• Background: Why Miniaturize Power Electronics?
• From Discrete to Integrated Inductors
  • Fabrication
  • Structures
  • Limitations
  • Comparison
• Advance Topics and Innovative Reports
Improve Energy Efficiency through Miniaturization

**Size ∝ Speed**

- Making DC-DC converters **smaller**, faster, more efficient, and with higher conversion ratio is key to achieving many desirable improvements to electronics:
  - **Deeper PDN** reduces $I^2R$ losses, volume, weight, and heat dissipation management requirements
  - Techniques that require better converters: DVS | Cycle and terminate power | **Faster response** | Sub-threshold

- There are similarities between ultra-low power systems and very-high power systems

- **Efficiency** is gaining increased interest as more electronics run off of indispensable sources (batteries) and high-conversion ratio as DC microgrids emerge.
Miniaturizing DC-DC Converters

Size Trend | I/O count

(a) Non-Integrated voltage regulator
(b) Package-Integrated voltage regulator
(c) Fully-Integrated voltage regulator

Ericsson BMR450
Altera ENS364QI
E. Burton, et al., APEC 2015
Miniaturizing DC-DC Converters - Terminology

• **Integrated voltage regulator** (IVR) brings the last stage of voltage conversion into IC package

• **Fully IVR** (FIVR) refers to monolithic integration, where converter switches are implemented using same transistors as load IC
  
  - Pros: easy integration, significantly reduced interconnects parasitics
  
  - Cons: limited to low input voltages as core voltages decrease <1V

• Due to input voltage and conversion ratio limitations, IVRs currently only complement POLs

• Caveat: IVRs shift complexity, and thermal management complications, into package
Miniaturizing DC-DC Converters

What prevents switching power supplies from shrinking (POL → IVR)?

• Three major elements of SMPS (in order large → small):
  • Magnetic component (inductor) – biggest challenge
  • Switches
  • Controller, switches gate drivers

• Losses and size are intertwined through switching frequency:
  • Smaller switches → higher conduction losses
  • Larger switches → higher switching losses

• High frequency is often limited by interconnects parasitics, which, constantly gets better (lower) with better integration

\[ L_{\text{ind,min}} \propto \frac{1}{f_s} \]
Discrete and Integrated Magnetic Components

- Inductors require current carrying **winding** (typically copper), and:
  - No **core** ("air core")
  - High permeability **core** (yoke)

Discrete

- **Coilcraft**, 2014

Integrated (and micro-magnetic)

- **D. Harburg**, 2012
- **Vishay**, 2017
- **P. McCloskey**, 2014

- **K. L. Shepard**, 2012
Magnetic Core in Inductors

• The motivation for adding higher permeability soft magnetic material core, is to increase inductance density; magnetic flux is how inductors store energy (compare to capacitors that store charge) and higher flux → higher energy storage capacity
  • The core provides low reluctance path ("concentration") for the magnetic flux
  • $B \propto \mu_r H$ magnetic field is amplified by the core to higher levels of magnetization flux
Fabrication Comparison

**Copper**
- Winding copper wire: around bobbin/core, or self supported
- Size limited, must be able to swivel
- Serial production

**Magnetics**
- Multiple options (outside the scope of this talk)
- Materials: solid, powdered metals, etc.
- Techniques: machining, sintering, lamination pressing

**Wire-wound**
- Large size microelectronics methodologies, using hard materials
- **Sputtering:** very slow, difficult to pattern/etch
- **Electroplating:** Through mask/PR
- Chip conscious!

**Planar**
- Same as BEOL: fabrication in layers, patterning by lithography, with vias/spacers
- Size and volume limited

**Discrete component**

**Integrated component**

**Fabrication Structures Limitations Comparison**

J.-B. Yoon, 2002

D. S. Gardner, 2010
Micro-Magnetic Components Structures

Pseudo-planar (layered) integrated inductor structures

- Spiral air-core (useless for power applications), or single / very few turns
  - **Cladded** (race-track) usually elongated; multi turns or single (also stripline, or slab)
  - **Solenoid** (toroidal)
- Meander

Fabrication Structures Limitations Comparison
Major Integrated Magnetics Limitations

Most limitations are not unique to integrated magnetics, but some are rather acute

Copper cross-section is small → high inductor resistance (ESR)

Solutions:

• Deposit as thick as possible copper
• Design very few turns:
  • Copper resistance $ESR \propto N$ (number of turns) and inductance $L \propto N^2$ so it is very tempting to design more turns
• Significant copper losses are usually not acceptable. Exceptions:
  • One high-conversion-ratio converter replaces many 2:1 converters
  • If efficiency is less of a priority
Major Integrated Magnetics Limitations

Small cores saturate fast at low currents
(= permeability non-linearity)

Solutions:

- Deposit **thick** magnetic cores. But still, it is very difficult to go above a few $\mu m$
  - Electroplating is inferior but gives good rates
  - Sputter deposition is very slow (@0.1Å/sec, each 1µm takes ±28 hours)
- Design very few turns to reduce magnetic flux
  - Low inductance
Eddy currents give rise to significant losses at high frequency, and skin-effect.

Solutions:

• **Increase electric bulk resistivity** (Sputtered CoZrTa 100\(\mu\Omega\)-cm, Electroplated CoWP >100 \(\mu\Omega\)-cm), versus low resistivity NiFe 45\(\mu\Omega\)-cm

• **Laminate**
  - Cannot electroplate laminations. Must sputter-deposit: layers are thin
  - Laminate with thickness \(\cong\) skin depth

• **Decrease frequency**
  - Higher inductance is needed

R. Clarke, 2008
Major Integrated Magnetics Limitations

Other challenges:

• Hysteresis loss of magnetic yoke $\propto f$

• Integrated inductors are very thin, typically 100’s of $\mu m$ laterally but only a few $\mu m$ thick

• Difficulty closing magnetic loop laterally with small structures
  • Solution: add 2nd magnetic layer (cladded structure)

• Analytical inductors design formulas and expressions vary too much from actual behavior. Requires:
  • Simulations to estimate inductor parameters and behavior
  • Fabricating inductors catalog and fit models parameters using measurement results

$$L = \frac{\mu N^2 A}{l}$$
Gains from adding magnetic materials to inductors are complicated and require tailoring inductor and architecture together; For example:

- Quality factor $Q = \frac{\omega L}{R}$ indicates inductor’s performance
- Increasing inductance by adding magnetic material is limiting both peak quality factor, and the frequency band in which it is obtained

$$Q_{MC} = \omega \cdot \frac{L_{AC} + \Delta L}{R_{AC} + \omega \cdot \left(\frac{\mu''}{\mu'}\right) \cdot \Delta L}$$

D. W. Lee, 2008

D. S. Gardner, 2009
Major Integrated Magnetics Limitations

Existing metrics paint a confusing picture of inductors’ usefulness in the context of an actual converter (e.g. Q-factor lacking info on current saturation!)

- Examples: Inductance $L [H]$ | Inductance density $[nH/mm^2]$ | Quality Factor | Peak Quality Factor | Current Density $I_{DNS} [A/mm^2]$ | Effective Inductor Efficiency $\eta_{L\_EFF}$ | $L_{AC}/R_{DC} [nH/\Omega]$

Non-linear behavioral models are required to account for large currents distortion

- Lumped model (L) → non-ideal linear model (S-parameters) → non-linear model (X-parameters)
# Integrated Magnetic Components - Comparison

## Inductor Structures

<table>
<thead>
<tr>
<th></th>
<th>Mag Layers</th>
<th>Cu Layers</th>
<th>Inductance</th>
<th>Copper losses</th>
<th>Current saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel FIVR Singe turn air core</td>
<td>none</td>
<td>1</td>
<td>LOW</td>
<td>LOW</td>
<td>HIGH (none)</td>
</tr>
<tr>
<td>Intel w/magnetic Multi-turn racetrack cladded</td>
<td>2, +1via</td>
<td>1</td>
<td>HIGH</td>
<td>MED</td>
<td>LOW</td>
</tr>
<tr>
<td>IBM Watson (racetrack) Single-turn racetrack cladded</td>
<td>2, +1via</td>
<td>1</td>
<td>MED</td>
<td>LOW</td>
<td>MED</td>
</tr>
<tr>
<td>Ferric (toroid w/magnetic)</td>
<td>1</td>
<td>2</td>
<td>HIGH</td>
<td>MED</td>
<td>LOW</td>
</tr>
<tr>
<td>Columbia Core-Clad (Multi-turn cladded)</td>
<td>2, +1via</td>
<td>2</td>
<td>HIGH</td>
<td>MED</td>
<td>MED</td>
</tr>
</tbody>
</table>

*E. T. Burton et al., 2015*

*D. S. Gardner, 2010*

*N. Wang, 2012*

*N. Sturcken, 2013*

*E. Aklimi, 2016*
Integrated Magnetic Components - Comparison

- Low copper losses (only one turn)
- No current saturation (air core)
- Low fabrication complexity
- Low inductance

<table>
<thead>
<tr>
<th></th>
<th>Mag Layers</th>
<th>Cu Layers</th>
<th>Inductance</th>
<th>Copper losses</th>
<th>Current saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Intel FIVR</strong></td>
<td>none</td>
<td>1/1via</td>
<td>LOW</td>
<td>LDW</td>
<td>HIGH (none)</td>
</tr>
<tr>
<td><strong>Singe turn air core</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intel w/magnetic</td>
<td>2/1via</td>
<td>1/1via</td>
<td>HIGH</td>
<td>MED</td>
<td>LOW</td>
</tr>
<tr>
<td>Multi-turn racetrack cladded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBM Watson (racetrack)</td>
<td>2/1via</td>
<td>1/1via</td>
<td>MED</td>
<td>LOW</td>
<td>MED</td>
</tr>
<tr>
<td>Single-turn racetrack cladded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferric (toroid w/magnetic)</td>
<td>1/2/1via</td>
<td></td>
<td>HIGH</td>
<td>MED</td>
<td>LOW</td>
</tr>
<tr>
<td>Columbia Core-Clad</td>
<td>2/1via</td>
<td>2/1via</td>
<td>HIGH</td>
<td>MED</td>
<td>MED</td>
</tr>
<tr>
<td>(Multi-turn cladded)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

E. T. Burton et al., 2015
Integrated Magnetic Components - Comparison

- High inductance density
- Medium copper losses
- Medium fabrication complexity
- Low saturation current

<table>
<thead>
<tr>
<th></th>
<th>Mag Layers</th>
<th>Cu Layers</th>
<th>Inductance</th>
<th>Copper losses</th>
<th>Current saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel FIVR</td>
<td>none</td>
<td>1</td>
<td>LOW</td>
<td>LOW</td>
<td>HIGH (none)</td>
</tr>
<tr>
<td>Singe turn air core</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intel w/magnetic</td>
<td>2</td>
<td>1</td>
<td>HIGH</td>
<td>MED</td>
<td>LOW</td>
</tr>
<tr>
<td>Multi-turn racetrack cladded</td>
<td>+1via</td>
<td>+1via</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBM Watson (racetrack)</td>
<td>2</td>
<td>1</td>
<td>MED</td>
<td>LOW</td>
<td>MED</td>
</tr>
<tr>
<td>Single-turn racetrack cladded</td>
<td>+1via</td>
<td>+1via</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferric (toroid w/magnetic)</td>
<td>1</td>
<td>2</td>
<td>HIGH</td>
<td>MED</td>
<td>LOW</td>
</tr>
<tr>
<td>Ferric (toroid w/magnetic)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Columbia Core-Clad (Multi-turn cladded)</td>
<td>2</td>
<td>2</td>
<td>HIGH</td>
<td>MED</td>
<td>MED</td>
</tr>
</tbody>
</table>

D. S. Gardner, 2010
Integrated Magnetic Components - Comparison

- Low copper losses
- Medium to low inductance
- Medium saturation current
- Medium fabrication complexity

<table>
<thead>
<tr>
<th></th>
<th>Mag Layers</th>
<th>Cu Layers</th>
<th>Inductance</th>
<th>Copper losses</th>
<th>Current saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel FIVR</td>
<td>none</td>
<td>1</td>
<td>LOW</td>
<td>LOW</td>
<td>HIGH (none)</td>
</tr>
<tr>
<td>Single turn air core</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intel w/magnetic</td>
<td></td>
<td>1</td>
<td>HIGH</td>
<td>MEDIUM</td>
<td>LOW</td>
</tr>
<tr>
<td>Multi-turn racetrack cladded</td>
<td>2</td>
<td>+1via</td>
<td>MEDIUM</td>
<td>LOW</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>IBM Watson (racetrack)</td>
<td>2</td>
<td>+1via</td>
<td>MEDIUM</td>
<td>LOW</td>
<td>MEDIUM</td>
</tr>
<tr>
<td>Single-turn racetrack cladded</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ferric (toroid w/magnetic)</td>
<td>1</td>
<td>+1via</td>
<td>HIGH</td>
<td>MEDIUM</td>
<td>LOW</td>
</tr>
<tr>
<td>Columbia Core-Clad (Multi-turn cladded)</td>
<td>2</td>
<td>+1via</td>
<td>HIGH</td>
<td>MEDIUM</td>
<td>MEDIUM</td>
</tr>
</tbody>
</table>

Note: versions of this topology (stripline, slab) have been proposed by many others (Intel, Tyndall, etc.)
High inductance density

Medium fabrication complexity

Medium copper losses

Low saturation current
Integrated Magnetic Components - Comparison

- High inductance density
- Medium copper losses
- Medium saturation current
- High fabrication complexity

<table>
<thead>
<tr>
<th>Component</th>
<th>Mag Layers</th>
<th>Cu Layers</th>
<th>Inductance Density</th>
<th>Copper Losses</th>
<th>Current Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel FIVR</td>
<td>none</td>
<td>1</td>
<td>LOW</td>
<td>LOW</td>
<td>HIGH (none)</td>
</tr>
<tr>
<td>Single turn air core</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intel w/magnetic</td>
<td>2</td>
<td>1</td>
<td>HIGH</td>
<td>MED</td>
<td>LOW</td>
</tr>
<tr>
<td>Multi-turn racetrack cladded</td>
<td>+1via</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBM Watson (racetrack)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-turn racetrack cladded</td>
<td>2 +1via</td>
<td>1</td>
<td>MED</td>
<td>LOW</td>
<td>MED</td>
</tr>
<tr>
<td>Ferric (toroid w/magnetic)</td>
<td>1</td>
<td>2 +1via</td>
<td>HIGH</td>
<td>MED</td>
<td>LOW</td>
</tr>
<tr>
<td>Columbia Core-Clad (Multi-turn cladded)</td>
<td>2 +1via</td>
<td>2 +1via</td>
<td>HIGH</td>
<td>MED</td>
<td>MED</td>
</tr>
</tbody>
</table>

Eyal Aklimi, 2017

E. Aklimi, 2016
Advanced Topics

Influence of projected digital microelectronics trends

- Availability of chip real-estate for Inductors ↓ as transistors density ↑
- IVR current requirements ↑ as power density ↑
- Integrated inductors share IC real estate with I/O, so area for inductors ↓ as I/O density ↑. Nonetheless, IVR usually means ↑ power with ↓ I/O
Advanced Topics

• Better high frequency behavior is demonstrated when magnetic flux is aligned with hard axis (HA) of the core (because domain magnetization rotation dominates over domain wall motion)
• Elongated rectangular shapes usually induce easy axis (EA) shape anisotropy to the long edge of as-deposited films
• Anisotropy must be induced:
  • In-situ: this is a new deposition tools requirement for both PVD-sputtering, and electroplating
  • Post-deposition by annealing in strong magnetic field: limited by thermal budget of ICs front-end
• Cladded structures are better at aligning flux with HA throughout the core
Advanced Topics

• Magnetics films are particularly challenging to pattern (even in comparison to thick Al/Cu metallization):
  - Additive: photoresist lift-off of thick sputtered layers
  - Additive: through-mask electroplating
  - Subtractive: hard-mask deposition, and etch of ferrous alloys
  - Subtractive: damascene requires CMP

• Worse with laminations
Creative Ways to Make Inductors

**Molded inductors**
Serial method, not suitable for mass-production

**Microtube inductors**
Processes in 2D but functions in 3D

S.-Y. Wu, 2015

X. Yu, 2015
References

- ENS364QI Datasheet, Altera (formerly Enpirion), 2013
- Electronics at its best, working voltage ratings for inductors, Coilcraft 2014 [https://kenvins.wordpress.com/2014/10/09/working-voltage-ratings-for-inductors/]
- Dan Harburg, Dartmouth Thayer School of Engineering, Microfabricated Inductors, 2012 [http://engineering.dartmouth.edu/microeng/inductors%20full.jpg]
- Assembly Masters (AMI), [http://www.assemblymasters.com/air-core-inductors-air-coils.cfm]
- Design and realisation of integrated inductor with low DC-resistance value for integrated power applications,
- B. Estibals, Design and realisation of integrated inductor with low DC-resistance value for integrated power applications, HAIT 2005
- E. A. Burton, et al., FIVR - Fully Integrated Voltage Regulators on 4th Generation Intel (R) Core (TM) SoCs, APEC, 2014
- N. Wang, et at., Integrated on-chip inductors with electroplated magnetic yokes, JAP, 2012
- J. Kim, et al., Anisotropic nanolaminated CoNiFe cores integrated into microinductors for high-frequency dc–dc power conversion, J. of physics D, 2015
- J. ~B. Yoon, CMOS-compatible surface-micromachined suspended-spiral inductors for multi-GHz silicon RF ics, IEEE EDL, 2002
- Chipworks, 2011, [https://semimd.com/chipworks/page/6/]

Eyal Aklimi, 2017
References

- Power losses in wound components, http://info.ee.surrey.ac.uk/Workshop/advice/coils/power_loss.html
- N. Sturcken, et al., Magnetic Thin-Film Inductors for Monolithic Integration with CMOS, IEEE IEDM, 2015
- E. T. Burton, Package and Platform View of Intel’s Fully Integrated Voltage Regulators (FIVR), APEC, 2015
- D. V. Schravendijk, Powering multicore processors with multiphase DC/DCs, TI, 2015 https://e2e.ti.com/blogs_/b/fullycharged/archive/2015/08/18/powering-multicore-processors-with-multiphase-dc-dcs
- H. Jia, Package level integration of a monolithic buck converter power IC and bondwire magnetics, 2010
- CoolMOS™ Benefits in both Hard and Soft Switching SMPS topologies, Infineon Technologies, 2011
Questions?