Optimization of soft magnetic thin films structures in on-chip inductors for efficient power conversion in integrated voltage regulators

Hao Wu, Donald S. Gardner, and Hongbin Yu

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Motivation

Different Strategies for Induction integration

- Need to integrate more functionalities into limited area
- Need better power management for longer battery life

System in Packages make by Package On Package

- Continued miniaturization at the system level:
  - Power Control
  - Sensors
  - Analog/RF
  - Passives

- Inductors in package with magnetic cores
- Sub 100 µm size on-chip magnetic thin film inductors

On-chip magnetic thin film inductors can benefit RF and power delivery applications:
- High inductance density -> Reduces area
- High quality factor -> Reduces loss

Important magnetic material properties
- High permeability, high resistivity, high FMR, CMOS compatibility
- Material engineering required such as patterning and laminating

Discrete inductor on mother board

Inductor on/in package

Air core inductor

Direct integration of magnetic core?
Advantages: Smaller footprint; low height profile
Challenges: material compatibility; thermal effect

Inductor on Si chip

Post CMOS: Intel
Si interposer: IBM/Columbia
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Materials Chnoice

- High saturation magnetization
- Controllable anisotropy
- High resistivity
- Single domain state, for low magnetic loss
- Low magnetostriction to reduce the stress in fabrication

Thin Film Growth and Characterization

- DC magnetron sputter deposition: Co-4%Zr-4%Ta-8%B (at.%)
- Co oxide is used as insulation layer in laminated film.
- An external DC magnetic field was applied during deposition.
- B-H loop was measured by VSM.

<table>
<thead>
<tr>
<th>Ni-Fe</th>
<th>Co-Zr-Ta-8</th>
<th>Co-Zr-Ta-8</th>
</tr>
</thead>
<tbody>
<tr>
<td>µ &lt;650</td>
<td>1000</td>
<td>1070</td>
</tr>
<tr>
<td>ρ 20 µΩ·cm</td>
<td>100 µΩ·cm</td>
<td>115 µΩ·cm</td>
</tr>
<tr>
<td>FMR 640 MHz</td>
<td>1.4GHZ</td>
<td>1.6GHz</td>
</tr>
</tbody>
</table>
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Materials Comparison: NiFe vs CoZrTaB

Inductor Performance

Fabricated inductor has small size, high inductance density

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Mag Mat.</th>
<th>Gain of L</th>
<th>L density nH/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>320x50</td>
<td>CoZrTa</td>
<td>0.11</td>
</tr>
<tr>
<td>2</td>
<td>340x200</td>
<td>Ferrite</td>
<td>0.9</td>
</tr>
<tr>
<td>3</td>
<td>60x120</td>
<td>NiFe</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>380x380</td>
<td>CoNbZr</td>
<td>8</td>
</tr>
</tbody>
</table>

Higher resistivity CoZrTaB leads to higher frequency response to GHz range
Magnetic Core Inductors Fabricated on Organic Substrates
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Lamination Effect

- 4-turn rectangular spiral inductors
  - W: 88 μm, L: 160 μm
  - Laminations can suppress eddy current loss in the conductive magnetic films and skin depth effect resulting in better frequency response.

Finger-shaped Via

- Finger-shaped magnetic via: W: 5 μm, L: 4 μm × 13

Regular Magnetic Vias

- With Co-Zr-Ta-B film, a maximum 3.5X inductance increase and a 3.9X increase in the Q-factor at 1 GHz were achieved.
- Finger-shaped magnetic vias improved Q by >30%.

HFFS 3D EM Simulations at 1GHz


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1. Integrated Magnetic Materials into Package RF and Power Inductors for System in Package (SIP) Applications 
2. Fabricated Inductors on ABF/glass substrate (scale bar: 80 μm)

Inductors Fabricated on Package substrate

DC Current Bias

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Donald Gardner, Wei Xu, Tawab Dastagir
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Publications