Challenges in magnetics for PwrSoC - Development in high-frequency magnetics, materials and integration

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Overview - Integrated Magnetics

- Background
- Challenges
- Modelling – Thin film
- Integration aiming PSOC
- Developed Nanomagnetic Materials
- Fabricated Inductors
- Test Results
Market Opportunities for Miniaturised Point of Load Power supplies

- MP3
- Camcorder
- Mobile Phone
- PDA
- PC
- GPS / Marine electronics
- Household Electronics fixed / portable

Buck Type DC-DC Conversion

Market size billions of €!
Microprocessor Unit (MPU) Power Trends

Decreasing Voltage
Increasing Current

Increased current will result in increased interconnect losses

\[ P = I^2 R \]

Solution: Integrated power conversion module!
Passive Component Size Reduction with Increasing Frequency Enables Functional Integration
A number of different structures reported in the literature Constraints limit the usefulness of some structures

- Out-of-plane flux
- Negative mutual inductance in turns
- Fabrication complexity
Challenges – PSOC Inductor/transformers

**Challenges**

- **Modelling**
  - Magnetic modeling for Micron scale devices
  - Optimisation with converter for higher efficiency

- **Integration**
  - Low cost & high yield process
  - Non line of sight technique
  - CMOS compatibility

- **Materials**
  - Reducing Cu winding Loss
  - Magnetic materials with low loss at high frequency
    - Eddy current loss
    - Hysteresis loss
    - Ferromagnetic resonance loss
THIN-FILM MODELLING

Magnetic material properties differ substantially between as-deposited, wafer-scale films and patterned structures in a micro/nano-scale device.

It is easier to measure one film and scale the results using modelling.
Shape-Dependent Anisotropy

Modelled via Stoner-Wohlfarth model of Magnetostatic Free Energy- Particle Model
Still a good approximation of larger systems

Total free energy, $E_f$, along $\mathbf{M}$ in a system with an induced anisotropy $\mathbf{E}$ in the presence of an applied field $\mathbf{H}$

$$E_f = -K \cos^2 \alpha - Ms^2 \left( D_x (\sin \theta \cos \phi)^2 + D_y (\sin \theta \sin \phi)^2 + D_z \cos^2 \theta \right) + \mathbf{M} \cdot \mathbf{H}$$

- $K$ – Material Anisotropy Constant
- $M_s$ – Saturation Magnetization
- $D_i$ – Shape Demagnetization factor in $i$
- $H$ – Applied Field Vector
- $\mathbf{M}$ – Resultant Magnetization Vector
Shape-Derpendent Anisotropy

Shape Demagnetizing Factors Extremely geometry-dependent
For a thin-film, the rectangular prism model may be used:

\[
\pi D_x = \frac{y^2 - z^2}{2yz} \ln\left(\frac{\sqrt{x^2 + y^2 + z^2} - x}{\sqrt{x^2 + y^2 + z^2} + x}\right) + \frac{x^2 - z^2}{2xz} \ln\left(\frac{\sqrt{x^2 + y^2 + z^2} - y}{\sqrt{x^2 + y^2 + z^2} + y}\right) + \frac{y^2 - x^2}{2yz} \ln\left(\frac{\sqrt{x^2 + y^2 + z^2} - x}{\sqrt{x^2 + y^2 + z^2} + x}\right)
\]

\[
+ \frac{x}{2z} \ln\left(\frac{\sqrt{x^2 + y^2 + y}}{\sqrt{x^2 + y^2 - y}}\right) + \frac{z}{2x} \ln\left(\frac{\sqrt{x^2 + z^2} - y}{\sqrt{x^2 + z^2} + y}\right) + \frac{z}{2y} \ln\left(\frac{\sqrt{x^2 + z^2 - x}}{\sqrt{x^2 + z^2 + x}}\right) + 2 \arctan\left(\frac{xy}{z\sqrt{x^2 + y^2 + z^2}}\right)
\]

\[
+ \frac{x^2 + y^2 - 2z^2}{3xyz} + \frac{x^2 + y^2 - 2z^2}{3xyz} \sqrt{x^2 + y^2 + z^2} + \frac{z}{xyz} \left(\sqrt{x^2 + z^2} + \sqrt{y^2 + x^2}\right)
\]

\[
- \frac{(x^2 + y^2)^{1/2} + (y^2 + z^2)^{1/2} + (z^2 + x^2)^{1/2}}{3xyz}
\]

Total demagnetizing factor must always equal 1
Each axis in the rectangular prism model can be determined by applying the cyclic permutation

\[
\frac{D_x}{4\pi} + \frac{D_y}{4\pi} + \frac{D_z}{4\pi} = 1
\]

To determine the effect of shape on permeability, start with the equation for complex permeability (Van de Riet):

$$\mu_r = \left\{ \frac{\gamma M_s}{(\gamma H_k + i \omega \alpha)} \times \left[ 1 + \frac{\omega^2}{(\gamma H_k + \gamma M_s + i \omega \alpha)(\gamma H_k + i \omega \alpha) - \omega^2} \right] + 1 \right\} \left[ (1-i) e^{(1+i)d/\delta} - 1 \right]$$

At sufficiently low frequencies, the low-frequency intrinsic permeability may be simplified as the initial permeability, inversely proportional to anisotropy

$$\mu_i = \frac{M_s}{H_k} + 1$$

Anisotropy is made up of a number of elements

$$H_k = H_i + H_d + H_{mc} + H_{me}$$

- $H_i$ – Induced Anisotropy
- $H_{mc}$ – Magnetocrystalline Anisotropy
- $H_{me}$ – Magnetoelastic Anisotropy
- $H_d$ – Shape Anisotropy
THICKNESS-DEPENDENT ANISOTROPY/PERMEABILITY

3D Demagnetizing Factors include thickness

One model for anisotropy contains both thin-film shape and thickness

\[ H_k = \frac{H_m}{2} \cos^2 \alpha + M_0 \left( D_x (\sin \theta \cos \phi)^2 + D_y (\sin \theta \sin \phi)^2 + D_z \cos^2 \theta \right) \]
Complex permeability with the modified permeability equation

Measured 1 µm Co$_{91.5}$P$_{8.5}$ thin-film compared to a simulated CoP thin-film without a 50 nm Cu seed layer

Complex permeability with the modified permeability + conductivity equation

Measured 1 µm Co$_{91.5}$P$_{8.5}$ thin-film compared to a simulated CoP thin-film with a 50 nm Cu seed layer
Ni$_{45}$Fe$_{55}$ DC plated

- NiCl$_2$·6H$_2$O + FeCl$_2$·4H$_2$O + Additives
- Optimised plating current density
- Mechanical agitation
- Plated in magnetic field
- Alloy composition - Ni$_{45}$Fe$_{55}$
- Non-uniform deposition
- Fractal/dendritic growth across film
- Stressed film → limited thickness
Pulse Reverse Plating

- Voltage regulation & timer circuit
- Rectangular wave at particular frequency
- Milliseconds $\rightarrow$ Microseconds

Diagram showing control electronics, S1 and S2 switches, electrodes, and I_fwd, I_rev currents. A graph illustrating the timing parameters t_forward, t_off, t_rev, t_off for a rectangular wave at a particular frequency.
SEM - microfabricated inductors

Top cores (over 3D topology)

SU8

Ni\textsubscript{45}Fe\textsubscript{55} plated film

BCB

Ni\textsubscript{45}Fe\textsubscript{55} plated film

Substrate (Si+BCB)

Copper windings

10 um

35 um
Challenge – Next generation magnetic materials

- Coercivity (Hc) < 2 Oe
- Permeability (µr) - 300-1000
- Saturation Flux density (Bs) – 1.5- 2.4T
- Resistivity (ρ) - 30-500 µΩcm
- Cut-off frequency for eddy current loss (f_{ed}) – 100-500 MHz
- Anisotropy field (Hk) – 10-500Oe
- Natural ferromagnetic resonance frequency (f_{FMR}) – 1-3 GHz
Granular Magnetic Materials

Advantages: (granular materials)
- High resistivity of nanocomposite works better than thin film laminations for controlling eddy-current loss.
- At subnanometer particle separation distances the magnetic structure changes from dipolar coupled to exchange coupled.

Drawback: (sputtering)
Difficult to produce thicker films, hence, any reasonable power density.
Grand Challenge!

To develop a next generation integratable soft magnetic core material capable of operating at high frequency for Power Applications

Realisation of power supply on chip (PwrSoc)!
Nano-structured NiFe

- Create nano-crystalline structure
- Magnetic film for high frequency
- Higher resistivity
- Reduction in Anisotropy dispersion
- Pinning of domain wall in the film
- No Domain wall motion
- Only Domain wall rotation

Nanocrystalline grain structure (grains <10nm)
Magnetic characterization of Ni$_{45}$Fe$_{55}$

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation, $B_{\text{sat}}$</td>
<td>1.5 T</td>
</tr>
<tr>
<td>Coercivity, $H_c$</td>
<td>80 A/m</td>
</tr>
<tr>
<td>Resistivity, $\rho$</td>
<td>48 $\mu\Omega$ cm</td>
</tr>
<tr>
<td>Anisotropy, $H_k$</td>
<td>800 A/m</td>
</tr>
</tbody>
</table>

$H_c = H_{c\,\text{morph}} + H_{c\,\text{anis}}$

<table>
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<tr>
<th><strong>Electroplated CoNiFeP</strong></th>
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</thead>
<tbody>
<tr>
<td><strong>Saturation, $B_{\text{sat}}$</strong></td>
<td>1.6 - 1.8 T</td>
</tr>
<tr>
<td><strong>Coercivity, $H_c$</strong></td>
<td>95 A/m</td>
</tr>
<tr>
<td><strong>Resistivity, $\rho$</strong></td>
<td>24-85 $\mu\Omega$cm</td>
</tr>
<tr>
<td><strong>Anisotropy, $H_k$</strong></td>
<td>2500 A/m</td>
</tr>
</tbody>
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“Dependence of magnetic properties on micro to nanostructure of CoNiFe films”, Fernando Rhen, Saibal Roy; *J. Appl. Phys* 103, 103901, (2008)

- High resistivity >100 μΩ.cm → Increased skin depth → Increased operational frequency
- DC plated films have perpendicular anisotropy & low permeability
- Use of Pulse Reverse plating to achieve in-plane anisotropy
- To produce multi-nano layer structures

- Pulse Reverse plating:
  - Composition of M layer Co$_{74}$P$_{26}$, thickness-30 nm
  - Composition of NM layer Co$_{66}$P$_{34}$, thickness-2-5 nm
Magnetic characterization of CoP

**Electroplated CoP**

<table>
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<th>Property</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Saturation, $B_{\text{sat}}$</td>
<td>1.2 T</td>
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<tr>
<td>Coercivity, $H_c$</td>
<td>8 A/m</td>
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<tr>
<td>Resistivity, $\rho$</td>
<td>130 $\mu$Ω cm</td>
</tr>
<tr>
<td>Anisotropy, $H_k$</td>
<td>1500 A/m</td>
</tr>
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</table>

Nanostructured CoPRe

- Addition of Re to CoP thin films for increased thermal stability
- Co$_{100-x-y}$, P$_x$, Re$_y$ where; 9.7 at% $<$ x $<$ 17.5 at% and 0.4 at% $<$ y $<$ 7.6 at%

Fabrication - Inductor/Transformer

Anisotropy induced in material during deposition
Micro-inductor: Structure

- 5 Mask Layers
- Electroplated copper windings.
- Thin-film, electroplated magnetic core.
- Design optimisation process
  - Focus on efficiency and footprint.
  - Coupled to validated models.

- Race-track shape to achieve:
  - Good frequency response
  - High inductance density
  - Low DC resistance

- CMOS-compatible process:
  - Copper coils deposited by electroplating
  - Core consists of thin film of NiFe alloy deposited by electroplating
Electrical Characterisation of Microinductors

Inductor Electrical performance

Inductor Current handling performance

www.tyndall.ie
Tyndall- Brice Jamieson, Jeffrey Godsell, Paul McCloskey*, Fernando Rhen+, Ningning Wang, Santosh Kulkarni, Shunpu Li, Terence O’Donnell*, Cian O’Mathuna
INTEL – Donald Gardner

Thank you for your attention

*Currently with Enterprise Ireland
+Currently with University of Limerick