Design and Fabrication of Bond Wire Micro-Magnetics with LTCC core

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Outline

- More than Moore systems
- Bond wire magnetics and example of applications
- Ferromagnetic LTCC
- Miniaturized bond wire transformer and applications
- Optimization of the inductance value
- Conclusions
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Introduction

- Technology improvements is leading towards miniaturization of circuits.
- Shrunken systems allow a **lower production cost** and **are less power demanding**.
- The powered delivered by transducers/devices (inductors) depends on their volume.
- Magnetic devices can be **integrated at package level** together with the dedicated IC through MEMS technologies (IMEMS).
- Nevertheless, devices embedded through MEMS techniques can be viewed as IC pre- or post-processing steps, or sometimes need a processing on a separate wafer.
- In addition to MEMS processes, **bond wire technology** is able to give additional value to **More than Moore (MtM)** systems.
More than Moore (MtM)

- Moore’s law is valid only for digital systems.
- A capacitor cannot be shrunk without new materials, as well as inductors.
- High voltage devices and power devices have self-defining sizes, dictated by the laws of physics and they scale poorly.
- The majority of analog applications fall in the technology node of 0.13µm and above.

- With increasing miniaturization of systems, analog ICs allow the possibility of further embedded functionalities.
- MtM systems provide additional value in different ways to migrate from the system board-level into the package (SiP) or onto the chip (SoC).
Typical Power Converters w/o Magnetic Components

**Linear regulator**

- **Pros**: no reactive devices. Easily integrable
- **Cons**: Very low efficiency if $V_{\text{OUT}}/V_{\text{IN}}<<1$.
  - No boost voltage.

- Switched capacitor circuits offer more flexibility compared to linear ones, at the expenses of higher system complexity

**Switched capacitor circuit (charge pump)**

- **Pros**: no reactive devices. Easily integrable. Higher efficiency compared to linear reg.
- **Cons**: Higher complexity. Losses proportional to frequency. $P_{\text{lost}} = \frac{1}{2}C(\Delta V)^2f$
Evolution of SMPS (Switched Mode Power Supply) Technology

- Increase of switching frequencies leads to smaller and smaller systems
- Passive components are potentially integrable at System on Chip (SoC) level
- At $f > 50$MHz, air-core inductors, or magnetic core-based inductors?
  - Efficient systems cannot exclude magnetic-core devices [1]

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Bond Wires Applications

Generally used for chip interconnection for applications ~ GHz

...can be used as standalone inductors (~1-2nH/mm), providing much less resistance than IC metal layers

...or as solenoids [2]

Bond Wire Magnetics
Advantages

- Inductors/transformers can be embedded using standard IC bond wire technology.
- The upper metal layer is used for the bottom winding, bond wire for winding closure.
- Complementary technique compared to MEMS LIGA processes and simpler (no need of post processing steps or sacrificial layers):
  - Circuits can lay under the inductor and designed independently from the top magnetic, allowing SoC structure. With MEMS bulk/surface micromachining processes this is not possible (MEMS should be processed on a separate wafer).
- Allows for planar magnetic cores, the $B$ field does not leak into the bottom circuit (with toroidal core no interferences, no latch-up, higher efficiency).
- Typical MEMS implementations are spiral inductors using very thick metallizations, and a top thin magnetic layer (inductance enhancement 10-20X $\rightarrow$ high demagnetization $\rightarrow$ $B$ leaking outside the device)
Bond Wire Microtransformer with Ferrite Core (on pcb)

*Top view (MnZn 75 ferrite core)* [3]

- Core thickness \( \approx 500\mu m \)
- External (internal) diameter = 3.95 (2.15) mm
- 1:2 ratio = 1:38
- \( L_{22} \approx 315 \mu H \) @ \( f=100 \) kHz & \( V=100 \) mV
- Effective footprint area \( \approx 25 \) mm\(^2\)

- \( R_{dc} = 4.3 \) \( \Omega \)
- \( Q @ f=100 \) kHz \( \approx 6.2 \)
- Very high Inductance density \( \approx 12.8 \mu H/mm^2 \)
- Ferrite core \( \mu_r = 5000 \)

Application of Bond Wire Transformers

- Typical power converters cannot boost voltages lower than the $V_{TH}$ of the power MOS.
- A **battery-less start-up circuit** is used to store energy in a capacitance.
- The energy is used to drive the gate of the power devices (high voltage, low current).
Boost Oscillator with Bond Wire Microtransformer and Ferrite Core

Converts 228 mV into 0.7 V dependent on the $Q$-factor of the transformer

Boost oscillator designed in a CMOS 0.35µm using DeplMOS [4]

Bond Wire Microtransformer with LTCC Core (on pcb)

\[ l \times p \times w_c \times h = 7.0 \times 3.0 \times 1.0 \times 0.4 \text{ (mm)} \]

ESL 40011 [4]
Ferrite core \( \mu_r \approx 200 \)

- Core thickness \( \approx 400 \mu \text{m} \)
- Major (minor) axis = 7.0 (3.0) mm
- \( 1:N = 1:52 \)
- \( L_{22} \approx 30 \mu \text{H} @ f=100 \text{ kHz} \) & \( V=100 \text{ mV} \)
- Effective footprint area \( \approx 28 \text{ mm}^2 \)

Converting 104 mV into 0.7 V

- The start-up voltage is inversely proportional to the turns ratio \( N \) and parasitic series \( R_{dc} \) resistance at the primary of the transformer.
- Increasing \( N, R_{dc} \) increases \( \rightarrow \) no benefit.
- High \( \mu_r \) (1000-5000) \( \rightarrow \) \( R_{dc} \) increases in the MHz range
  \( \rightarrow \) Need of lower \( \mu_r \) material and high resistivity \( \rho_c \) like magnetic LTCC

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Example of Soft Magnetic Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity $\rho_c$ (Ω cm)</th>
<th>Relative permeability $\mu_{rc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co ferrite</td>
<td>$10^7$</td>
<td>10 – 60</td>
</tr>
<tr>
<td>Mg ferrite</td>
<td>$10^7$</td>
<td>150</td>
</tr>
<tr>
<td>NiZn ferrite</td>
<td>$10^6$</td>
<td>250</td>
</tr>
<tr>
<td>Cu ferrite</td>
<td>$10^5$</td>
<td>600</td>
</tr>
<tr>
<td>Mn ferrite</td>
<td>$10^4$</td>
<td>50% Ni, 50% Fe (orthonol)</td>
</tr>
<tr>
<td>MnZn ferrite</td>
<td>$10^2 - 10^3$</td>
<td>1000 – 4000</td>
</tr>
<tr>
<td>Zn ferrite</td>
<td>$10^2$</td>
<td>0.25% Si iron</td>
</tr>
<tr>
<td>Fe ferrite</td>
<td>$4 \cdot 10^{-3}$</td>
<td>48% Ni alloy</td>
</tr>
<tr>
<td>Metallic glass</td>
<td>$125 \cdot 10^{-6}$</td>
<td>2.5% Si steel</td>
</tr>
<tr>
<td>NiFe (permalloy)</td>
<td>$45 \cdot 10^{-6}$</td>
<td>4% Si steel</td>
</tr>
<tr>
<td>SiFe (silicon steel, 2.5% Si)</td>
<td>$40 \cdot 10^{-6}$</td>
<td>50% Co alloy</td>
</tr>
<tr>
<td>Co alloy (50%)</td>
<td>$35 \cdot 10^{-6}$</td>
<td>Metallic glass</td>
</tr>
<tr>
<td>SiFe (silicon iron, 1% Si)</td>
<td>$25 \cdot 10^{-6}$</td>
<td>Nanocrystalline</td>
</tr>
<tr>
<td>SiFe (silicon iron, 0.25% Si)</td>
<td>$10 \cdot 10^{-6}$</td>
<td>80% Ni, 4% Mo alloy</td>
</tr>
<tr>
<td>Fe (iron)</td>
<td>$9.6 \cdot 10^{-6}$</td>
<td>Mumetal 75% Ni, 5% Cu, 2% Cr</td>
</tr>
<tr>
<td>Nanocrystalline</td>
<td>$1.2 \cdot 10^{-6}$</td>
<td>99.96 % pure iron</td>
</tr>
</tbody>
</table>

- Generally, as rule of thumb, the higher the permeability, the lower the resistivity
- Lower resistivity implies higher losses and lower frequencies application

The Ferromagnetic LTCC Material Properties

LTCC = Low Temperature Co-fired Ceramic

- Ceramic material with relatively high $\mu_r$: $<500$-$1000$
- High resistivity $\rho_c$: $<10^3$-$10^6$ $\Omega\cdot m$
- Sheet thickness $t_l \sim 60$ $\mu$m
- Fired shrinkage $S \sim 17\%$ (X, Y & Z)
- Suitable for high frequency magnetics (hundreds of MHz)

Two commercial samples of ESL 40011 and ESL 40012

The magnetic properties of the ESL 40012 have been extensively investigated in literature [7]:

- The real part of the permeability can range from 400 (Firing temperatures ~ 900°C) up to 1000 (Firing temperatures ~ 1300°C), with a cut-off frequency $f_c$ between 2 and 3 MHz, for toroids with $n_l = 62$ layers (~3.5 mm of thickness).

- The peak of the imaginary part of the permeability (losses) can range from 250 (Firing temperatures ~ 800°C) up to 400 (Firing temperatures ~ 1300°C) at frequencies between 2 and 3 MHz, for toroids with $n_l = 62$ layers (~3.5mm of thickness).

- For ferrites the cut-off frequency relative to the eddy currents losses of the real and imaginary part goes with the square of the thickness of the sample: thinner samples might provide better performances (at low frequencies hysteresis losses dominate).

The LTCC core Fabrication Procedure

1), 2), 3) \( n_l = 9 \) layers of green tapes of thickness \( t_l = 60 \, \mu m \) are stacked with a warm isostatic press @ 14 MPa and \( T=70^\circ C \)

4) In the cutting step the stack is cut in a toroidal race-track shaped pattern with a laser equipment (\( \lambda=355 \, \text{nm} \) and \( P=7 \, \text{W} \))

5), 6) Firing phase and final sintered device.
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LTCC Microtransformer on-top-of-chip

- Bottom winding realized in a 0.35µm CMOS process.
- Bottom winding realized with top metal level
- The minimum distance between the turns is coherent with the minimum distance allowed by the technology
The Fabricated Device

The final device after the bonding phase
\[ l \times p \times w_c \times h = 3.8 \times 2.0 \times 0.5 \times 0.39 \text{ (mm)} \]

laminated single stack of the ferromagnetic LTCC core before (top) and after (bottom) the firing step.

PwrSoC integration: hybrid solution

- LTCC ferrite core requires high-temperature firing
- CMOS compatibility can be tackled by using hybrid integration
  - Fully sintered ferrite core with higher inductance density is fabricated off-chip
  - Core is assembled on-top of the SoC with upper windings made of bonding wires
  - Cost-effective solution with high throughput wire bonding machines
- Control circuitry and switches devices can be fabricated with standard silicon technology $\rightarrow$ PwrSoC integration

Experimental Measurements

- Obtained @ 100 mV
- $Q_{max} = 11.6$ @ 1.3 MHz
- $L_{22} = 31 \, \mu H$ @ 1.3 MHz
- Density = $2.23 \, \mu H/mm^2$
- $L/R_{DC} \sim 2.6 \, \mu H/\Omega$

**Summary**

<table>
<thead>
<tr>
<th>Core</th>
<th>LTCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{11}^{LF}$ (nH)</td>
<td>12.8</td>
</tr>
<tr>
<td>$L_{22}^{LF}$ (μH)</td>
<td>30.8</td>
</tr>
<tr>
<td>$R_{w1}^{LF}$ (Ω)</td>
<td>0.30</td>
</tr>
<tr>
<td>$R_{w2}^{LF}$ (Ω)</td>
<td>14.8</td>
</tr>
<tr>
<td>$I_{max}$ (A)</td>
<td>4.9</td>
</tr>
<tr>
<td>$f_{min}$ (kHz) @ 0.1 V RMS</td>
<td>246</td>
</tr>
<tr>
<td>$Q_{max}$ @ 1.3MHz</td>
<td>11.6</td>
</tr>
</tbody>
</table>
## Comparison with Commercial Transformers

<table>
<thead>
<tr>
<th>Parameter</th>
<th>This device</th>
<th>LPR4012</th>
<th>LPR6235</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Core type</strong></td>
<td>LTCC Ferrite</td>
<td>Ferrite</td>
<td>Ferrite</td>
</tr>
<tr>
<td>$n_{12}$</td>
<td>50</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$k^*$</td>
<td>0.65</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>$A_r$ (mm$^2$) x $h$ (mm)</td>
<td>15 x 0.5$^a$</td>
<td>16 x 1.1</td>
<td>36 x 3.5</td>
</tr>
<tr>
<td>$L_{22}$ (µH)$@Q_{\text{max}}$</td>
<td>31</td>
<td>190</td>
<td>2500</td>
</tr>
<tr>
<td>$L_{22}/R_{DC}$ (µH/Ω)</td>
<td>2.4$^c$</td>
<td>16.4</td>
<td>213.7</td>
</tr>
<tr>
<td>$L_{22}/A_r$ (µH/mm$^2$)</td>
<td>2.1</td>
<td>11.9</td>
<td>69.4</td>
</tr>
<tr>
<td>$L_{22}/A_r x h$ (µH/mm$^3$)</td>
<td>4.1</td>
<td>10.8</td>
<td>19.8</td>
</tr>
<tr>
<td>$Q_{22}^{b}\text{(max)}$</td>
<td><a href="mailto:11.6@1.3MHz">11.6@1.3MHz</a></td>
<td>57@850kHz</td>
<td>88@158kHz</td>
</tr>
<tr>
<td>$I_{\text{max}}$ (A)</td>
<td>≈ 1.0$^c$</td>
<td>1.7$^d$</td>
<td>1.3$^d$</td>
</tr>
<tr>
<td>Integration</td>
<td>on-chip</td>
<td>discrete</td>
<td>discrete</td>
</tr>
</tbody>
</table>

$^a$: without substrate.  
$^b$: at 0.1 V RMS.  
$^c$: recommended to avoid wires damage.  
$^d$: due to core saturation.  
$^e$: can be increased by increasing the diameter of bonding wires  
$^*$: can be enhanced by a higher tightening of the winding.
Applications of the Device

Step-up oscillators based on Armstrong topology

PT (Piezoelectric Transformer) based step-up oscillators

Compact PT based, resonant DC/DC converters
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Optimization Based on the Winding

Higher turn number and width constant → L/R ratio unchanged, but higher footprint area [9]

Higher turn number and width constant → L/R ratio unchanged

Optimization cannot be based on the winding

Optimization of the Core Width

Inductance of a toroidal inductor:

\[
L < \frac{4n_0^2 \left( L_B - 2 \cdot W_C \right)^2 \cdot t_C \cdot W_C \cdot \mu_0 \cdot \mu_r}{(L_B - 1.44 \cdot W_C)}
\]

- \( L_B^2 = 16 \text{mm}^2 \rightarrow L_A (L_B) \rightarrow \text{internal (external) side} \\
- t_C \cdot \mu_r = 10^{-1} \text{m} \rightarrow t_C \rightarrow \text{core thickness, } t_C << W_C \\
- n_0 = 5 \cdot 10^3 \text{ m}^{-1} \rightarrow n_0 = \text{linear turn density}

Maximum achievable inductance \( L_{\text{max}} \)

\[
L_{\text{max}} / L_B^2 < 0.509 \cdot n_0^2 \cdot t_C \cdot \mu_r
\]

Optimum Core Width \( W_{\text{opt}} \)

\[
W_{\text{opt}} = \frac{5}{24} L_B \cong 0.208 \cdot L_B
\]

Correct estimation of the inductance

Developed formula for MPL taking into account

Magnetic non-uniformity in the core
Folding Effect (not a round toroid) F.E.

MPL_{eff} \approx \frac{5.78W_C}{\ln(\frac{4L_A + 5.78W_C}{4L_A})}

Inductance formula:

\[ L = \frac{N^2}{\mathcal{R}} \]
\[ \mathcal{R} = \frac{MPL}{\mu_0\mu_r A_C} \]

MPL \neq \frac{4L_A + 4L_B}{2} \text{ (A.A.)}
MPL \neq \sqrt{4L_A \cdot 4L_B} \text{ (G.A.)}

A Further Optimization

• Some considerations
  - The magnetic flux density is not uniform not even in the optimized structure: this is a waste of area
  - The External borders of the core, give little contribution to the whole magnetic path
  - Narrower cores provide more uniform magnetic fields.
Serpentine Toroid

Advantages:
- Thinner core $\Rightarrow$ B is more uniform $\Rightarrow$ less waste of used area
- Higher area used $\Rightarrow$ less waste of unused area
- Intuitively can present higher performances

\[
L < \frac{\left( \int_0^{P_T} n(x)dx \right)^2}{\mathcal{R}} = \frac{n_0 \left[ P_T - 4 \cdot (K/2 - 1) \cdot W \right]}{\mathcal{R}}
\]

\[
A = \frac{L_B - (K/2 - 1) \cdot G}{(K/2)}
\]

\[
B = L_B - G - 2 \cdot W
\]

\[
W = \frac{(A - G)}{2}
\]

$K$ number of parallel arms along y

One DoF $G=200 \mu m$

With $L_B=4 mm$
Parameters for DC resistance evaluation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Width $W_C$</td>
<td>$W_{opt}$ (at $L_B = 4$ mm)</td>
</tr>
<tr>
<td>Metal conductivity $\sigma_M$</td>
<td>$3.25 \times 10^7$ S/m</td>
</tr>
<tr>
<td>Metal thickness $t_M$</td>
<td>3.2 $\mu$m</td>
</tr>
<tr>
<td>Metal Width $W_M$</td>
<td>180 $\mu$m</td>
</tr>
<tr>
<td>Metal stripe Length $l_M$</td>
<td>$W_C$</td>
</tr>
<tr>
<td>Metal spacing $s$</td>
<td>20 $\mu$m</td>
</tr>
<tr>
<td>Bonding wire diameter</td>
<td>32 $\mu$m</td>
</tr>
<tr>
<td>Bonding wire conductivity $\sigma_G$</td>
<td>$4.5 \times 10^7$ S/m</td>
</tr>
<tr>
<td>Bonding wire length $l_{BW}$</td>
<td>$\pi W_C / 2$</td>
</tr>
</tbody>
</table>

Two bond wires in parallel for each metal stripe
# Optimum Square Toroid vs Optimum Serpentine

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SSTC</td>
</tr>
<tr>
<td>$L_{\text{MAX}}$</td>
<td>18.16 µH</td>
</tr>
<tr>
<td>$I_{m}$</td>
<td>20.3 mA</td>
</tr>
<tr>
<td>$f_{\text{min @ 1 V}}$</td>
<td>436 kHz</td>
</tr>
<tr>
<td>$L_{\text{MAX}} / R_{\text{DC}}$</td>
<td>6.9 µH/Ω</td>
</tr>
<tr>
<td>$e_{M}$</td>
<td>236 pJ/mm$^2$</td>
</tr>
<tr>
<td>$W_{c}$</td>
<td>0.83 mm</td>
</tr>
<tr>
<td>$N$</td>
<td>48</td>
</tr>
</tbody>
</table>

- $L_B^2 = 16 \text{mm}^2$
- $B_S = 1 \text{T}$
- $t_C \mu_r = 10^{-1} \text{m}$
- $\mu_r = 10^5$
- $n_0 = 5 \cdot 10^3 \text{ m}^{-1}$
- $t_C = 1 \mu\text{m}$

- Serpentine: lower saturation current.
- Lowering the turn number in the serpentine in order to obtain the same $I_{m}$ of the SSTC, allows in any case to have better performances of the SSTC

---

Evaluation of Inductor losses in a power converter

- Buck converter case:

\[ \Delta i = \frac{V_{OUT} (1 - D)}{2 f_{sw} L_S} \]

Given the same footprint area and same \( \Delta i \), Serpentine toroid can achieve a higher inductor performance wrt Optimized Toroid, up to:

- \( 7.8 \mu\text{H}/\Omega \)
- \( 6.9 \mu\text{H}/\Omega \) = +13%

Assuming the inductor losses a \(~10-15\%\) of the total losses, the power converter can experience an increased efficiency of 1.5\%-2\%
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- Bond wire magnetics give additional value to MtM systems
- PwrSoC are thus possible using standard bondwire technology
- No additional post-processing steps are required
- LTCC cores can be easily patterned and embedded (100% compatible with bonding wire technology)
- LTCC material is good for the MHz range (good $\mu_r$ and high $\rho_c$)
- Through high resolution patterning techniques the inductance value can be augmented and optimized.
Thank you for your attention!!

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