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Design and fabrication of a 29 µH bondwire micro-transformer with LTCC magnetic core on silicon for energy harvesting applications

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Abstract

This paper presents the design of a 1 : 50 bondwire micro-transformer assembled with IC gold bonding wires and a toroidal LTCC magnetic core with race-track shape. The transformer is fabricated on-top of a standard BCD IC in a 15 mm² footprint area for micro-power energy harvesting applications. Measurements show a secondary self-inductance up to 29 µH with a maximum Q-factor of 11.6 at 1.3 MHz, and a coupling coefficient of 0.65 with an effective turns ratio of 19. This miniaturized technology finds also applications in power supply in package (PwrSiP) and power supply on chip (PwrSoC).

Keywords: bonding; harvesting; inductors; integrated; low-temperature co-fired ceramic; LTCC; magnetics; silicon; toroidal; transformers.

1. Introduction

Considerable efforts are currently dedicated in developing high performance magnetics compatible with integrated circuit (IC) processes [1]. Besides, ferromagnetic materials are now available as low-temperature co-fired ceramic (LTCC) tapes with high resistivity [2]. An overall size reduction of magnetic devices for step-up converters which use external discretes [3] is a strategic issue, as well as the minimization of power losses.

Bondwire micro-magnetics is a simple approach which uses standard IC bonding wires based on solid phase welding to enclose a magnetic core [4]. The proposed technique is suitable for incorporation of efficient bondwire magnetics on-top of an IC in a frequency range between 10 kHz and 5 MHz with high inductance.

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2. Fabrication of the LTCC Core

The proposed bondwire transformer is composed by bonding wires as coils and an LTCC core fabricated from the ESL 40012 tape as a magnetic core. The 40012 is a cast film of magnetic powder [2] designed to be sintered at high temperature to give a ceramic body and get large grains thus achieving substantial magnetic properties (see Table 1).

<table>
<thead>
<tr>
<th>Supplier</th>
<th>ESL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part number</td>
<td>40012</td>
</tr>
<tr>
<td>(\mu_r) (after firing)</td>
<td>(\approx 500)</td>
</tr>
<tr>
<td>(\rho_c) ((\Omega\text{ cm}))</td>
<td>(&gt; 10^3)</td>
</tr>
<tr>
<td>(H_c) (A m(^{-1}))</td>
<td>330</td>
</tr>
<tr>
<td>(B_s) (mT)</td>
<td>350</td>
</tr>
<tr>
<td>(B_r) (mT)</td>
<td>250</td>
</tr>
</tbody>
</table>

The fabrication of the LTCC core involves three main steps: lamination, cutting, and firing (see left picture of Fig. 1). In the lamination step 9 layers each with thickness 60 \(\mu\)m are stacked with a warm isostatic press (Jenoptik Hot Embosser) at 14 MPa/70°C. In the cutting step the stack is cut in a race-track shape with a laser equipment (Coherent AVIA Laser 355 nm 7 W). In the sintering step the sample cut is fired in an oven (Nannetti KL 20) at a peak temperature of 915°C. The sintering phase comprises several stages shown in the right picture of Fig. 1. During the firing the sample contracts its dimensions due to frictional forces, yet this can be included in the design phase to get the desired size. The ceramic core has a relative permeability of \(\mu_r \approx 500\) and a shrink of \(\approx 20\%\) in all directions.

3. Assembly of Devices

Loops around the magnetic core are performed with bonding wires and completed on the last metal layer of a 0.32 \(\mu\)m BCD silicon chip (see left picture of Fig. 2). The top metal is made of AlCu with thickness \(t_m = 1.6 \mu\)m and resistivity \(\rho_m = 1.6 \cdot 10^{-6} \Omega\text{ cm}\). The transformer has two windings with \(n_1\) and \(n_2\) turns for the primary and secondary side, respectively. The device is designed to maximize the turns ratio \(n_{12} = n_2 / n_1\) in an area of \(A_c = 3.93 \times 3.81 \text{ mm}^2\) with a metal width of \(w_m = 90 \mu\)m, a spacing of \(s_m = 20 \mu\)m, and a bond pad pitch (BPP) of 112 \(\mu\)m. The minimum outer/inner pad distances from magnetic core are 450 \(\mu\)m and 225 \(\mu\)m, respectively, with gig-gag pads.

The 1 : 50 transformer is assembled with a Kulicke & Soffa (K&S) 8208PPS wire bonder with gold round wires (diameter \(d_b = 25 \mu\)m and resistivity \(\rho_b = 2.44 \cdot 10^{-6} \Omega\text{ cm}\)) and the LTCC core mounted on-top of the IC (see right picture of Fig. 2). The fabricated device has the following characteristics: fired core thickness \(t_c \approx 390 \mu\)m, core size 3.8 mm \(\times 2.0 \text{ mm} \times 0.5 \text{ mm}\) \((l \times p \times w_c)\), core cross-sectional area \(A_c \equiv 0.20 \text{ mm}^2\), core mean magnetic path length (MPL) \(l_c \equiv 9.6 \text{ mm}\), 1-turn mean metal length \(l_m \equiv 1.32 \text{ mm}\), and 1-turn mean wire length \(l_b \equiv 3.0 \text{ mm}\). An epoxy core with the same size is used to assess the advancements obtained by the LTCC core.
4. Analytical Modelling

The DC self-inductances of the coils $L_{11}^{DC}$ (H) and $L_{22}^{DC}$ (H) are calculated by the classic reluctance formula as:

$$L^{DC} = \frac{\mu_0 \mu_m n^2 A_c}{l_c} = \frac{\mu_0 \mu_m n^2 l_c w_c}{2(l + p - 2w_c)}$$ (1)

where $n$ is the number of turns of the winding considered with $\mu_0 = 4 \times 10^{-7}$ H/m as the free-space permeability. The DC winding resistances of the coils $R_{w1}^{DC}$ ($\Omega$) and $R_{w2}^{DC}$ ($\Omega$) are evaluated by summing the resistances of a single bonding wire $R_b^{DC}$ ($\Omega$) and of a single metallization $R_m^{DC}$ ($\Omega$) multiplied by the number of turns as:

$$R_w^{DC} = n(R_b^{DC} + R_m^{DC}) = n \left( \frac{\rho_b d_b}{\pi (d_b / 2)^2} + \frac{\rho_m t_m}{w_m t_m} \right)$$ (2)

In order to avoid core saturation, the ampere-turn limit for a transformer is given by:

$$(n_1 I_1 + n_2 I_2) \leq I_{max} = \frac{B_s I_s}{\mu_0 I_{rc}}$$ (3)

where $B_s$ (T) is the saturation flux density, $I_{max}$ (A) is the equivalent saturation current, while $I_1$ (A) and $I_2$ (A) are the amplitudes of the currents flowing in the coils. Table 2 shows the modelling results of the DC self-inductances and winding resistances of the bondwire devices. The LTCC core provides an up of 466 times in $L$ compared to the epoxy mold with a $I_{max} \equiv 4.9$ A which results in a maximum $I_2 \equiv 0.1$ A with the only secondary coil (i.e. $I_1 = 0$ A).

<table>
<thead>
<tr>
<th>Core</th>
<th>LTCC</th>
<th>Epoxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{11}^{DC}$ (nH)</td>
<td>12.8</td>
<td>0.027</td>
</tr>
<tr>
<td>$L_{22}^{DC}$ (µH)</td>
<td>30.8</td>
<td>0.066</td>
</tr>
<tr>
<td>$R_{w1}^{DC}$ ($\Omega$)</td>
<td>0.30</td>
<td>0.24</td>
</tr>
<tr>
<td>$R_{w2}^{DC}$ ($\Omega$)</td>
<td>14.8</td>
<td>11.9</td>
</tr>
<tr>
<td>$I_{max}$ (A)</td>
<td>4.9</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

n.a.: data not available.
At high frequencies skin effect arises in the conductors while the permeability becomes a complex quantity. The AC self-inductances \( L_{11} \) (H) and \( L_{22} \) (H) are calculated by the series complex permeability model. Similarly, the AC series resistances \( R_{11} \equiv R_{w1} + R_c (\Omega) \) and \( R_{22} \equiv R_{w2} + R_c n_{12}^2 (\Omega) \) include the core equivalent series resistance (ESR) \( R_c (\Omega) \) calculated by the same complex permeability model, and the AC winding resistances \( R_{w1} (\Omega) \) and \( R_{w2} (\Omega) \) obtained by considering the skin depths in both bonding wires and metallizations.

5. Experimental Measurements

The prototypes are measured with open-circuit and short-circuit tests with a precision E4980A LCR Meter with no bias to extract the coupling coefficient \( k = L_{12} / (L_{11} L_{22})^{1/2} \) and the effective turns ratio \( n_e = k (L_{22} / L_{11})^{1/2} \) with \( L_{12} \) (H) as the mutual inductance. Experimental measurements show that the use of the ferromagnetic LTCC core compared to the epoxy mold improves \( L_{22} \) to 29 \( \mu \)H with an \( R_{22} \) of 13.5 \( \Omega \) (see left graph of Fig. 3) with a maximum secondary \( Q \)-factor of 11.6 at 1.3 MHz, and enhances \( k \) to 0.65 with an \( n_e \) of 19 (see right graph of Fig. 3).

![Fig. 3. LTCC core transformer: (left) measured and calculated \( L_{22} \) and \( R_{22} \) versus frequency; (right) measured \( k \) and \( n_e \) versus frequency.](image)

Conclusions

An LTCC core device has been fabricated based on repeatable wire bonding process on-top of a BCD silicon substrate. Measurements report the achievement of high inductance and high turns ratio toroidal magnetics useful for energy harvesting applications [4] and PwrSiP and PwrSoC for wafer integration. With respect to the current state-of-the-art for bondwire magnetics on silicon [5] this transformer has the highest secondary self-inductance.

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