Fabrication of package embedded spiral inductors with two magnetic layers for flexible SIP point of load converters in Internet of Everything devices

Mohamed L.F. Bellaredj*, Colin A. Pardue, Paul Kohl, Madhavan Swaminathan

Center for Co-Design of Chip, Package, System (C3PS), Georgia Institute of Technology, Atlanta, GA 30332, USA

Abstract

Inductive DC-DC converters are key elements in power delivery units for the development of Internet of Everything (IoE) architectures made of interconnected networks of smart devices, self-powered from different energy sources. The ultra-low power levels involved in IoE devices in addition to cost reduction of final products requires the development of new technologies for the miniaturization of all the active and passive components. In this paper, a low temperature, cheap and simple two-steps fabrication process of embedded planar inductors with two magnetic layers on a very thin, flexible and lightweight FR4 organic substrate is demonstrated for flexible System in package (SIP) based point of load DC-DC converters in IoE devices. The process uses standard printed wiring board (PWB) copper etching to define the square geometry of the planar inductors and trenches underneath the inductor copper traces. Very thick top and bottom magnetic layers are deposited using stencil printing of an FR4 compatible epoxy-NiZn ferrite composite magnetic material on top of the copper traces and into the trenches. At 30 MHz, the permittivity is 3.4 and 6.23 while the dielectric loss tangent is 0.014 and 0.009 for the epoxy and composite magnetic material respectively. The composite material has a permeability of 8.46, a loss tangent value of 0.1 at a frequency of 30 MHz and saturates around 0.13 Tesla. The DC resistance varies from 136 $\Omega$ to 386 $\Omega$ while at 30 MHz the AC resistance varies from 1.9 $\Omega$ to 10.1 $\Omega$ for an inductance value from 180 nH to 715 nH, corresponding to an inductance density between 5.69 nH/mm$^2$ and 12.47 nH/mm$^2$ and a quality factor between 13 and 17. Flexibility and its effect on the electrical parameters of the fabricated inductors is demonstrated through bending tests. A variation of $<3\%$ for the DC resistance is obtained for 5 mm bend radius. At 30 MHz and for a bend radius (both upward and downward) from 3.7 mm to 5 mm, the flat state (unbent) AC resistance and inductance values (1.9 $\Omega$ to 10.1 $\Omega$ for 180 nH to 715 nH) decrease by 6.5$\%$ to 18$\%$ and by 2$\%$ to 4.4$\%$ respectively which increase the self-resonant frequency by 3$\%$ to 3.4$\%$ and the quality factor by 2.2$\%$ to 20$\%$. The characterized inductors are modeled in ANSYS HFSS electromagnetic simulator and simulation results show a good correspondence with the measured inductances and quality factors, which allows a reliable prediction of the inductors behavior for DC-DC converter design and implementation for IoE devices.

© 2017 Elsevier B.V. All rights reserved.

1. Introduction

The Internet of Everything concept aims at interconnecting a network of ultra-low-power smart objects (automotive vehicles, Home Automation, metering and Security systems etc.) and smart sensors for real time monitoring and/or decision-making. For an autonomous operation, these devices have to be self-powered and different powering schemes need to be implemented simultaneously such as batteries, energy harvesting from surrounding environment and wireless power transfer. The presence of different power sources at the same time in addition to different power consumption levels for a given operation mode (standby or active mode) imply voltage levels varying over a wide range. To ensure an optimal use of power for such situations, a power delivery/management system using switching mode DC-DC converters is required. Among the voltage converters topologies, inductive DC-DC converters, in which the inductor is the key power transfer element from input to the load represent the dominant architecture for high efficiency power delivery units [1–2]. Because of the small size and cost requirements for IoE applications due to the number of interconnected devices and very low power levels involved, special care needs to be given to the converter in terms of size reduction and cost effectiveness when optimizing efficiency and integration density [3–5]. However, commercially available power inductors are relatively bulky discrete components that preclude the downsizing of the converter [6]. By switching the converter at high frequency and using embedded
planar power inductors with a high frequency magnetic material core, significant miniaturization of the inductor and thus of converter is achieved through size reduction and the performance is enhanced through higher inductance density and parasitics suppression. Also, the fabrication process is simplified compared to 3D inductors such as toroidal inductors and more design flexibility is achieved as the inductors can be placed as close as desired to the IC chips. Different technologies have been developed for the fabrication of planar power inductors depending on the used integration approach/substrate and magnetic core material. Planar inductors using ferromagnetic metal alloys (CoZrTa–[7–9], FeSi–[10], FeNi–[11–15]) and nanogranular metal oxides (CoZrO–[16–17], CoFe8–SiO2–[18]), built on inorganic substrates such as semiconductor [19–22], ceramic [23–25], magnetic [26–28] and glass [29–30] wafers are not suitable for high frequency IoE power inductors because of their low resistivity which increase eddy losses at high frequency and the heavy clean room installations and complicated micromachining processes involved which increase processing times and cost expensiveness [19–22]. Organic substrates/packages such as FR4 and polyimide [31–34] represent a valuable alternative to inorganic technologies because they present the advantage of cheapness, low processing temperatures (<200 °C) and combined fabrication, connection and assembly flexibility with the IC chips on the same package either in a side by side or in a stacked configuration [35–36]. Ferrite materials show high resistivity with a wide selection of permeability from moderate to high values for applications within the range of 100 kHz to 100 MHz [21–22,37–38]. By mixing powders of Ferrite materials with a polymer, ferrite composite magnetic materials [15, 38–39] [19,34] can be deposited using screen printing [30,15,38] for planar power inductors. Screen printing requires only patterned screens for printing which makes the deposition process simple, fast and cost effective compared to microfabrication processes. Very thick layers of magnetic material (hundreds of microns) can be deposited at a much higher deposition rate than sputtering or electroplating. Moreover, the printing is generally done at room temperature and accommodates organic substrates. In this work, we demonstrate a new, low temperature, simple and cheap fabrication process of planar power inductors with two magnetic layers deposited using a cost effective stencil printing process on a very thin, thus lightweight and flexible FR4 organic substrate for high efficiency voltage converter applications in IoE devices. The process allows the fabrication of power inductors with different size and inductance densities in the same batch which can be used in IoE based DC-DC converters with a multitude of switching frequency options based on the inductor self-resonance frequency. The paper is organized as fellows. Section 2 presents the design and modeling procedure of the planar inductors. In Section 3, the fabrication process of the planar inductors is demonstrated. The characterization results of the fabricated inductors are discussed in the last section of the paper and compared to the simulation results.

2. Design and modeling

2.1. Overall IoE architecture

The objective is to design spiral power inductors to be used in a SIP based point of load DC-DC converter using energy harvesting as input power source for an IoE device. Because of the low power levels involved at the input, single or multistage boost regulators are required to power the different analog and digital circuits of the IoE device. Assuming the basic configuration of a boost converter given in Fig. 1, the converter inductor L can be estimated using (1) [40]:

\[ L = \frac{V_{IN} \cdot (V_{OUT} - V_{IN})}{\Delta I_s \cdot f_{SW} \cdot V_{OUT}} \]

(1)

where \( V_{IN} \) is the input voltage, \( V_{OUT} \) the desired output voltage, \( f_{SW} \) the switching frequency of the converter and \( \Delta I_s \) the estimated inductor ripple current. By using (1) and assuming a switching frequency between 10 MHz to 30 MHz, an inductor ripple current of 50 mA for a duty cycle value between 0.4 and 0.6, a wide range of inductance values comprised between 170 nH and 750 nH can be selected for the boost converter depending on the output voltage as can be seen in Table 1.

2.2. Inductor geometry

The designed inductors are square planar inductors with two magnetic layers defined on both sides of a two copper layer (35 μm copper thickness for each side) FR4 PWB. The top copper layer is used to define the inductor traces which will be covered with the first magnetic layer. The bottom side copper is used to define trenches underneath the inductor which will be filled with the second magnetic layer. The bottom side copper is also used as a ground plane to reduce the EMI between the inductor and its surrounding. The square shape was chosen for ease of fabrication while the 35 μm copper thickness was selected for DC resistance and inductance tuning. The considered inductor geometry is shown in Fig. 2(a).

The design parameters of the inductors are the outermost length, \( d \), the metal trace width, \( w \), the trace separation \( s \) and the number of turns \( N \). The trace separation \( s \) is set to be equal to the metal trace width \( w \) for each inductor design. SMA pads are included in the design for inductance measurements as well as a simple deembedding structure (microstrip line) with the same width and length as the inductor feedline to eliminate the contribution of the SMA connector and feedline to the inductor inductance.

2.3. Modeling approach

A 3D model of the planar inductor of Fig. 2(b) with two magnetic layers defined on both sides of the inductor was created in the electromagnetic simulator ANSYS HFSS v17. A lumped port simulation was achieved by connecting the top copper traces (port 1) to the bottom (ground) plane (port 2). A current excitation was created through the lumped port to compute the voltage reflection and the corresponding S-parameter (S11). From this S-Parameter, the Z-Parameter (Z11) was extracted and the inductance and Q factor were calculated using (2) and (3). The considered magnetic material is a NiZn ferrite-epoxy composite [41]. The permeability spectrum used for the simulations is shown in Fig. 12(a). The top and bottom magnetic layer thicknesses were set to 200 μm while the design parameters \( d \), \( w \), \( s \) and \( N \) were varied to get various inductance densities for an inductance range from 200 to 600 nH. The modeling parameters and results are summarized in Table 2 where \( L_{air} \) and \( Q_{air} \) are the inductance and the quality factor for the air core inductor, \( L_{mag} \) and \( Q_{mag} \) are the inductance and the quality factor for the magnetic core inductor and \( f_{SW} \) is the self-resonant frequency factor for the magnetic core inductor and \( f_{SW} \) is the self-resonant frequency factor.

<table>
<thead>
<tr>
<th>( D )</th>
<th>( \Delta I_s ) (mA)</th>
<th>( f_{SW} ) (MHz)</th>
<th>( V_{OUT} ) (V)</th>
<th>( L ) (nH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4–0.6</td>
<td>50</td>
<td>10–30</td>
<td>1.1–1.5</td>
<td>170–750</td>
</tr>
</tbody>
</table>
frequency of the magnetic core inductor.

\[ L = \frac{\text{Im}(Z_{11})}{\omega} \quad \text{(2)} \]

\[ Q = \frac{\text{Im}(Z_{11})}{\text{Re}(Z_{11})} \quad \text{(3)} \]

2.4. PWB and stencil design

The PWB design was done in Keysight ADS v.2016.01. It includes the three considered inductors as well as alignment marks defined symmetrically at its edges on both sides of the board as shown in Fig. 3(a–b) so that only one stencil is used for printing the magnetic layers on both sides of the PWB. The stencil design was done in AutoCAD 2017 v N.52.0.0 and includes square openings of the same size as the square planar inductors for the stencil printing of the magnetic material as well as alignment marks defined symmetrically at the edges of the layout for precise alignment with the PWB alignment marks as can be seen in Fig. 3(c).

3. Fabrication of the planar inductors

The fabrication process flow of the planar inductor is shown in Fig. 4. A 270 μm thick, lightweight and flexible, 2 copper layer (35 μm thick for both layers and 200 μm thick FR4 layer) FR4 PWB was used as the substrate. First, the planar inductor windings on the top side of the substrate and trenches on the backside of the substrate underneath the inductor windings were defined using standard PWB copper etching process Fig. 4. The patterned planar inductors and trenches are shown in Fig. 5. The copper traces width and separation were measured using an optical microscope. The copper trace width and separation were 171 μm and 268 μm for both Inductor_1 and Inductor_2 and 194 μm for Inductor_3 as can be seen in Figs. 5(b) and 5(c). The copper trace thickness and trench depth were obtained using the Veeco Dektak 150 surface profilometer. The copper trace thickness is around 42 μm and the trench depth is 35 μm for all designed inductors as seen in Fig. 6.

Then, the top magnetic core was deposited with stencil printing (MPM SPM 7279 Semiautomatic Stencil Printer) on the top side of the PWB using a custom made FR4 compatible composite magnetic paste fabricated by mixing a silane activated magnetic powder (FP350 NiZn ferrite from pptechnology) with a Bisphenol-A-Diglycidyl ether (BPADGE) based epoxy polymer binder at 85 wt% (which corresponds to 78% volume fraction) [41]. After stencil printing the top magnetic layer, the boards are cured for 1 h at 180 °C to form the top magnetic composite core. The use of BPADGE polymer makes the composite magnetic material FR4-compatible which allows a better adhesion of the magnetic composite to the organic substrate and reduces significantly the built up stress that arises from the different thermal treatments of the boards. The resulting composite material showed no reaction to commonly used solvents such as acetone, good electrical insulation through a measured very high DC resistance (beyond 30 MΩ) and...
very strong adhesion to the substrate assessed after >24 h of high power sonication in an acetone bath. Using the same stencil screen and previously prepared paste, the bottom magnetic core was stencil printed on the backside of the PWB and the boards were cured again for 1 h at 180 °C to form the bottom magnetic composite core. An example of a fabricated inductor is shown in Fig. 7(a). A cross section micrograph of Inductor_3 is shown in Fig. 7(b). The measured profiles of the top and bottom side magnetic layers are shown in Fig. 8. The average thicknesses of the top and bottom side layers are around 400 μm and 300 μm respectively.

4. Experimental section

The phase identification of the NiZn ferrite powder was done using the Panalytical X’Pert PRO Alpha-1X ray diffraction tool. The elemental composition of the NiZn ferrite powder was confirmed by Energy-dispersive X-ray spectroscopy (EDS) using the LEO 1530 SEM. The electromagnetic properties of the epoxy and epoxy-NiZn ferrite magnetic composite material were measured from 1 MHz to 400 MHz using Keysight 4291B RF Impedance/Material Analyzer, 16453A Dielectric Material Test Fixture and 16454A Magnetic Material Test Fixture.

The magnetization curves of the magnetic composite material was measured at room temperature (300K) between −150 kOe and 150 kOe at a sweep rate of 25 Oe/s using a vibrating sample magnetometer (VSM) from Quantum Design. The DC resistance of the fabricated inductors was measured using the 4-wire mode of the 3478a multimeter from HP. The RF parameters of the inductors were characterized between 20 MHz and 400 MHz using the Agilent H8363B Vector Network Analyzer as shown in Fig. 9(a). One port S-Parameters were measured and subsequently converted to Z-Parameters. The inductance L and quality factor Q were extracted in post processing using (2) and (3). To study the effect of the mechanical loading on the DC resistance and the RF parameters of the inductors, the inductors were bent using an adjustable mechanical clamp up to a bend radius of 5 mm. Beyond 5 mm, cracks appeared either in the bent substrate or in the composite magnetic material. The bend radii were measured using a caliper and the corresponding DC resistance and the RF parameters were obtained using the 4-wire mode of the multimeter and the network analyzer respectively as shown in Fig. 9(b–c).

5. Results

5.1. Characterization of the materials

The XRD diffraction spectrum of the NiZn ferrite powder is shown in Fig. 10(a) where the phase is identified as $(\text{Ni}_0.5\text{Zn}_0.5)\text{Fe}_2\text{O}_4$. The Ni:Zn, Ni:Fe and Ni:O molar ratios are found after EDS measurements to be 1, 4, 8 respectively, which corresponds to the $(\text{Ni}_0.5\text{Zn}_0.5)\text{Fe}_2\text{O}_4$ phase.

The dielectric properties of the epoxy and the composite magnetic materials are shown in Fig. 11. The permittivity/dielectric loss tangent values for the epoxy and composite magnetic material are 3.4/0.014 and 6.23/0.009 respectively at 30 MHz. The composite material shows a higher permittivity and a lower dielectric loss tangent value than the epoxy material. This indicates good electrical insulation properties of the composite material which allows its direct deposition on top of the inductor windings without the need of an insulation layer. The measured permeability spectrum of the epoxy-NiZn ferrite material is shown in Fig. 12. The composite has a permeability of 8.46 and a loss tangent value of 0.1 at a frequency of 30 MHz. The magnetic loss tangent value of the composite material is ten times higher than the dielectric loss tangent value. The losses in the composite material are thus dominated by the magnetic losses. The magnetization curve of Fig. 12(b) shows that the composite material saturates around 0.13 Tesla.

5.2. Electrical characterization of the inductors

The effective inductance of the inductors is obtained by removing the average measured inductance of the deembedding structure (7 nH) from the measured inductance value. The measured inductance L and quality factor Q are shown in Fig. 13, in a frequency range between 20 MHz and 60 MHz where the reactance is mainly inductive. Higher frequencies are excluded to remain far from the inductor's self-
resonant frequency. Compared to the air core inductors, the magnetic core inductors show an inductance increase by almost 100% for all inductors at 30 MHz as shown in Table 3. This is attributed to the two magnetic layers applied to both sides of the substrate, and to the increased coupling between the magnetic layers through the reduced separation resulting from the use of a thin FR4 layer in the 200 μm thick PWB. However, the use of two coupled magnetic layers affects significantly the quality factor of the inductors, which decreases significantly with frequency (>50% decrease compared to the air core inductors at 30 MHz). This is explained by the increase of the magnetic losses in the composite material with the frequency increase as indicated by the loss tangent spectrum shown in Fig. 12(a).

The measured inductance and quality factor are compared to simulation using updated modeling parameters based on the characterization measurements. A good match is observed between the updated simulation and measurement results for both inductance and quality factor as shown in Fig. 13. The slight difference between the simulations and the measured data can be attributed to the use of an averaged thickness value for both magnetic layers.

5.3. Bending results

It is worth mentioning that although the main objective of this paper is to demonstrate a cheap and simple fabrication process for planar
spiral inductors using a composite magnetic material on a very thin FR4 board, bending tests of the fabricated inductors were carried to demonstrate the flexibility achieved through the thin organic substrate despite the FR4 nature of the substrate and the use of an FR4 compatible epoxy based magnetic composite material. Fig. 14 shows the variation of the DC resistance of the air core inductors for different bend radii up to 5 mm. The mechanical loading effect is almost negligible with a variation of <3% for both Inductor_1 and Inductor_3. This is an expected result since no stretchable copper windings were used to build the inductors. As the copper did not undergo any dimensional modification, the overall RDC value remained almost constant.

The magnetic core inductors were measured both under upward and downward bending conditions to investigate the effect of the bending direction on the RF parameters of the inductors for a given magnetic field orientation. When bent upward, the substrate is oriented in the same direction as the magnetic field while when bent downward, the substrate is oriented in the reverse direction of the magnetic field. To get rid of the effect of the SMA connector, the feedline and the substrate
on the measured RF parameters under mechanical loading, the deembedding structure used previously was also submitted to the same mechanical bending as the inductors and the measured RF parameters were extracted from the measured inductors parameters for a given bend radius.

Figs. 15–18 show the inductance and AC resistance variation spectra of Inductor_3 for different upward and downward bend radii respectively. The same trend is observed for both upward and downward bending where the inductance and the AC resistance decrease with the increase of the bend radius with a variation from the initial flat (unbent 0 mm) state of 2% for the inductance and 18% for the AC resistance at 30 MHz for a bend radius of 5 mm. Both the inductance and AC resistance decrease can be explained by the decreased effective area of the inductors resulting from the mechanical bending. Since the resulting effective area is the same for either an upward or a downward bending, the same magnetic field density was obtained for a given effective area/bend radius and no significant inductance and AC resistance variations were observed. The inductance decrease resulted in an increase of the self-resonant frequency (SRF) of the inductors with the increased bend radius. For 5 mm bending (at 30 MHz), the 2% inductance decrease resulted in a 3.4% increase of the SRF.

Since the AC resistance variation is much more important than the inductance variation for a given bend radius, the Q factor of the bent inductor increased with the bent radius increase for both upward and
downward bendings. For a 5 mm bend radius, a 20% variation increase of the quality factor was observed at 30 MHz as seen in Fig. 19 and Fig. 20.

Compared to Inductor_3, Inductor_1 which has smaller area showed somehow a similar decrease ratio of both the inductance and the AC resistance (and consequently a less pronounced increase in the quality factor) due to applied mechanical bending as can be seen in Fig. 21. At 30 MHz and a 3.8 mm bend radius, the inductance and the AC resistance decreased by 4.4% and 6.5% respectively which resulted in an increase of the self-resonant frequency and the quality factor of 3% and 2.2% respectively.

6. Conclusion

In this work, we demonstrated a new easy and cheap process for the fabrication of embedded planar power inductors with two magnetic layers on a very thin, flexible and lightweight two copper layers organic substrate. The top copper layer was patterned to define the inductors tracks while the bottom copper layer was used to etch trenches underneath the inductors tracks and as a ground plane. The top and bottom magnetic layers were deposited by stencil printing an FR4 compatible NiZn ferrite-epoxy magnetic composite material on top of the inductor tracks and into the trenches to increase the coupling between the two magnetic layers through the very thin 200 μm separation layer representing the substrates FR4 dielectric thickness. Bendability tests of the inductors were carried out to demonstrate the flexibility achieved through a 270 μm thick FR4 organic substrate despite the use of a cured epoxy based magnetic material. The process allows the batch fabrication of inductors with different inductance densities, quality factors and self-resonance frequencies, which can be reliably characterized and modeled. Stretchability and more flexibility can be obtained by replacing both the FR4 thin substrate material and the epoxy polymer for the magnetic composite material with a stretchable elastomer such as polydimethylsiloxane (PDMS), styrene-butadiene rubber (SBR), and polyurethane (PU). The embedded planar inductors will be used in the design and fabrication of a high frequency flexible System in Package (SIP) DC-DC converter in an IoE device.

Acknowledgment

This work was supported by the Power Delivery for Electronic Systems (PDES) consortium at Georgia Tech and performed in part at the Georgia Tech Institute for Electronics and Nanotechnology, a member...
Fig. 18. AC resistance variation of Inductor_3 for different downward bend radii (a) full spectrum (b) around 30 MHz (c) around SRF.

Fig. 19. Quality factor variation of Inductor_3 for different upward bend radii (a) full spectrum (b) around 30 MHz.

Fig. 20. Quality factor variation of Inductor_3 for different downward bend radii (a) full spectrum (b) around 30 MHz.

Fig. 21. RF parameters variation of Inductor_1 for different upward bend radii (a) inductance (b) AC resistance (c) quality factor Q.
of the National Nanotechnology Coordinated Infrastructure, which is supported by the National Science Foundation (Grant ECCS-1542174).

References
