Soft ferrite cores characterization for integrated micro-inductors

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Abstract. Ferrite-based micro-inductors are proposed for hybrid integration on silicon for low-power medium frequency DC-DC converters. Due to their small coercive field and their high resistivity, soft ferrites are good candidates for a magnetic core working at moderate frequencies in the range of 5-10 MHz. We have studied several soft ferrites including commercial ferrite film and U70 and U200 homemade ferrites. The inductors are fabricated at wafer level using micromachining and assembling techniques. The proposed process is based on a sintered ferrite core placed in between thick electroplated copper windings. The low profile ferrite cores of 1.2 × 2.6 × 0.2 mm³ are produced by two methods from green tape-casted films and ferrite powder. This paper presents the magnetic characterization of the sintered ferrite films cut and printed in rectangular shape and sintered at different temperatures. The comparison is made in order to find out the best material for the core that can reach the required inductance (470 nH at 6 MHz) under 0.6A current DC bias and that generate the smallest losses. An inductance density of 285 nH/ mm² up to 6 MHz was obtained for ESL 40011 cores that is much higher than the previously reported devices. The small size of our devices is also a prominent point.

1. Introduction
Nowadays, the trend toward miniaturization of mobile electronic products, with the demand of improving functionality and performance confronts challenges on power management. The effort to fabricate more compact electronic devices, having more features will require higher power density systems such as the DC-DC converters. Up to now, the control circuits and the power semiconductor devices can be fully integrated but the passive components especially inductors and transformers, which are bulky and off-chip components, are still an obstacle for further reducing the size of DC-DC converters. Plenty of researches have been carried out to achieve inductor integration on-chip or in-package with different technologies like sputtering, electroplating and screen printing. Some demonstrators of air-core inductors, thin film magnetic inductors, and ferrite based ones have shown that each method has its own merit and difficulties [1-3].

The approaches to the fabrication of micro-inductors involving sputter deposition and electrodeposition of magnetic cores have been demonstrated over last thirty years. Sputtering can be used to deposit a wide range of magnetic materials including alloys and oxides with high resistivity which is useful in limiting eddy current losses such as Co-Zr based, Co-Hf-Ta-Pd, Co-Fe-Hf-O, Ni_{80}Fe_{20}, Fe-B-N, Fe-Co-B-C amorphous thin films. That shows promising characteristics at frequency from several MHz to several GHz [4]. However, the problem arises when the film is thicker than several micrometers due to the process of etching thick metallic films. Dry etching of thick films usually involves long etch time resulting in heating of the substrate and degradation of the magnetic film properties.
while wet etch of thick films results in severe undercutting. Electroplating is a less costly method than sputtering and more suitable for micro-inductor cores with large cross-sectional areas. The films deposited by electroplating have the thickness of several micro-meters to several tens of micro-meter including alloys of NiFe with different composition such as Ni_{80}Fe_{20}, Ni_{45}Fe_{55}, Ni_{50}Fe_{50} and others like CoFeNiC, CoPFe, CoNiFe, CoFeCu, NiFeMo [5-7]. A problem is that only conductive materials can be electroplated; hence, eddy currents can be considerable and should be controlled by lamination, especially for thick films. Screen printing of ferrite materials or magnetic composites is an alternative approach compared to the two above-mentioned methods. It has strong advantages of easy deposition and much larger achievable thickness up to several hundreds of micro-meter. By cons, the magnetic composite needs to be sintered at high temperature to achieve desired magnetic properties. Besides the technique, the choice of magnetic materials and the design play an important role in the inductors final performance. This article presents a possible solution for integrating very small size (< 3 mm²) micro-inductor in a PwrSiP (Power system in Package) approach based on ferrite films and ferrite powder.

2. Specifications and design

In this work, the target is to integrate micro inductors in silicon wafers with a good compromise between performance and cost. In order to achieve an integration of the inductor with high specific inductance, it is necessary to work at high switching frequencies. NiZn ferrites are good candidates for a magnetic core working at moderate frequencies (5-10 MHz). The targeted specifications of our inductors are 470 nH of inductance, equivalent serial resistance < 0.1 \( \Omega \) at bias current of 0.6 A and operating at 6 MHz. The inductors are constituted by a thin film ferrite in a rectangular shape wrapped by multi-level metal windings as shown in figure 1.

![Figure 1. Schematic of micro-inductor](image)

Based on target specifications of the inductor, the design is made by adjusting the parameters of core’s properties and winding dimensions. For a given footprint area (3 mm²), the geometrical input parameters are: core width (x), core length (y), magnetic core width (w), magnetic core thickness (t), thickness and width of copper wire and number of turns. The output parameters are the DC and AC resistance, the total inductance and maximum magnetic induction. After taking into account these parameters, in order to meet specifications of inductance and resistance and to avoid saturation in the core at the given DC current, the copper windings should have a cross section of at least 50 x 50 \( \mu \text{m}^2 \) and the desired magnetic core thickness should be 150 \( \mu \text{m} \).

3. Component realization process

Figure 2 presents the fabrication steps for the ferrite-based inductors. 50 \( \mu \)m thick copper bottom tracks are deposited on Si/SiO₂/Ti/Cu wafer by photolithography and electroplating. Then, the copper tracks are planarized by spin coating with a thin layer of SU8. Ferrite cores are placed on Cu tracks and covered by another thin layer of SU8. Vias positions are opened by process of photolithography and a seed layer of Ti/Au is deposited on the wafer and then, coated with a layer of BPN photo-resist [8]. Vias and 50 \( \mu \)m thick copper top tracts are deposited by photolithography and electroplating technique. Finally, residues of BPN and seed layer are removed.
4. Experiments and results

There are two proposed approaches to fabricate ferrite cores.

- From commercial ferrite film: Two layers of thin film ferrite (ESL 40010® and ESL 40011®), about 70 µm each, are needed. The layers are bonded together by a wafer bonding machine. The double-layer films (140 µm thick) are then cut by a micro-milling machine into the expected and compensated dimension.

- From home-made ferrite powder: Synthesized NiZn ferrite powder is mixed with organics to form a magnetic slurry or paste. The thick photo-resist mold is formed by photolithography technique. The ferrite paste is then filled into the mould by screen printing technique followed by thirty minutes vacuum treatment to degas the paste. The ferrite composite is dried at 110°C for ten minutes and collected. Thicknesses of printed cores are 90-105 µm; the width and length are similar as mill cores.

The dimension of the fabricated magnetic core is 1.2 x 2.6 mm² with the magnetic core width of 350 µm. Then, the milled cores are sintered at 885°C and 950°C during 3 and 2 hours respectively; the printed cores are sintered at 980°C during 2 hours. Microstructures of cores are observed by scanning electron microscopy. Compositions of different ferrites are estimated by energy dispersive analysis (EDS). The magnetic properties of thin film ferrites are characterized by a vibrating sample magnetometer. To extract the complex permeability (µ' and µ'') of the used ferrite materials, tore-shape samples are also prepared and measured by a permeameter (Agilent 16454A). For electrical characterization, sintered cores are placed on gold/copper tracks on silicon wafer; wires are bonded to make the winding around the cores (see figure 3). Bonded cores are measured by an impedance analyzer (Agilent 4294) to determine the inductance versus frequency and versus DC bias and on a LCR meter (Agilent 4284A) to extract core losses versus AC current.

4.1. Magnetic material characterization

Figure 4 shows the microstructure of different ferrites after sintering. The grain sizes of thin film ESL 40010 and 40011 have a bimodal distribution, with large grains of 5-8 µm, covering around 50%vol, and small grains of 2-3 µm in diameter. Grain sizes of printed ferrite U70 and U200 are in the range of 1.5-6 µm. The microstructure of printed ferrites can be sharpened if one presses the ferrite paste after they are printed in the mould. For all cores, the shrinkage was measured to be 15-20%. Sintering temperature of each ferrite is determined after the shrinkage peak identified by the dilatometry characterization. The compositions of these ferrites are identified by EDS as listed in table 1.

The B-H characteristics of ferrites are presented in figure 5 for sintering temperatures 950°C. The induction saturation is in the range of 0.22-0.30 T, with a coercive field of 0.66-5.8 Oe (or 53-462 A/m). Magnetic remanences are 0.8-8%.
Table 1. Composition of different ferrite estimated by EDS

| Ferrite       | Composition                          |
|---------------|--------------------------------------|
| ESL 40010 (Ni/Zn = 1.49) | Ni_{0.49}Zn_{0.33}Cu_{0.18}Fe_{4}O_{4} |
| ESL 40011 (Ni/Zn = 0.47)  | Ni_{0.28}Zn_{0.60}Cu_{0.12}Fe_{4}O_{4} |
| U70 (Ni/Zn = 0.54, Co = 0.035) | Ni_{0.30}Zn_{0.55}Cu_{0.15}Co_{0.035}Fe_{4}O_{4} |
| U200 (Ni/Zn = 0.43, Co = 0.035) | (Ni_{0.24}Zn_{0.56}Cu_{0.20})_{0.965}Co_{0.035}Fe_{4}O_{4} |

Figure 4. Microstructure a) b) ESL 40010 and 40011 sintered at 950°C/2hours, c) d) U70 and U200 sintered at 980°C/2hours

Figure 5. B-H curves of thin film ferrite. Samples were sintered at 950°C/2h with temperature ramp 3.3°C/min

4.2. Electrical characterization

The complex permeability of each material (ESL 40010, 40011, U70 and U200) is extracted as a function of frequency (as shown in figure 6). U200 and ESL 40011 films show a high primary permeability: 190 and 300 respectively up to 10 MHz. However, the secondary permeability of ESL 40011 increases quickly from 1-3 MHz while that of U200 remains small up to 10 MHz, which means that the core losses of ESL 40011 are more important than that of U200.

The complex permeability of the magnetic films was extracted from impedance of the test fixture with the tore mounted $Z'_m$ compared to the impedance of the text fixture without the tore $Z'_{sm}$ using the following formula:

$$\mu'_r = \frac{2\pi(Z'_m - Z'_{sm})}{j\omega\mu_0 h \ln \frac{c}{b}} + 1$$

in which $\omega$ is measurement pulsation $\omega = 2\pi f$, $\mu_0$ is permeability of free space, $h$ is thickness of the tore; $c$ and $b$ are external and internal diameter of the tore respectively.

Figure 6. Complex permeability: ESL 40010 a) and 40011 b) ferrite sintered at 950°C/2h and 885°C/3h (b=4 mm, c=6 mm and h= 108 µm), U70 c) and U200 d) home-made ferrite sintered at 980°C/2h (b=5 mm, c=14 mm and h=1.5 mm)

Electrical characterizations were performed for different magnetic cores with 21 turns coil. Figure 7 a) shows the inductance of the test inductors as a function of frequency for cores sintered at 885°C and 950°C. An inductance as high as 860 nH or 285 nH/mm² was obtained for the ESL 40011 core and 287 nH or 95 nH/mm² for ESL 40010 core at 6 MHz while the air core inductor has only an inductance of 18 nH. These high values of inductance density are an advantage of our small rectangular inductors comparing to other reported ferrite inductors [9-11]. However, ESL 40011 shows a big decrease of permeability as superimposing DC bias current; this is a weak point of these materials for high DC current applications as compared to other magnetic composites [9-11]. Meanwhile, ESL 40010 cores
have permeability more stable with DC bias current, yet they have lower permeability (see figure 6 and figure 7 b)). The core losses per unit volume were extracted from the under-probe measurements of test inductors with varying sine-wave amplitudes. ESL 40010 cores sintered at 885°C show the smallest losses at 1 MHz that are in the range of 100mW/cm³-300mW/cm³ at a current of 100mA-150mA (see figure 7 c)). In term of magnetic induction, the loss is about 100 mW/cm³ at 10mT and 1MHz, which is comparable with the reported value 100mW/cm³ at 1.5 MHz and 10mT by Mu[12].

Figure 7. Inductance of the test inductor made of different cores as a function of a) frequency, and b) bias current at 6 MHz, c) Magnetic losses (mW/cm³) of ESL 40010 and 40011 cores as a function of amplitude of IAC at 1 MHz

5. Conclusions and perspectives
Ferrite rectangular cores were fabricated and sintered at different temperatures. The higher sintering temperature brings the material a higher permeability but also higher losses. These ferrites are very interesting in term of permeability and our inductors achieve a very high inductance density comparing to other reported micro ferrite inductors. For the moment, at 6 MHz, 285 nH/mm² of inductance is recorded for ESL 40011 cores and 95 nH/mm² for ESL 40010 cores. However, as superimposing a DC bias current all cores of four materials present a big decrease of permeability, which is a disadvantage of soft ferrite cores for high DC current application. It might be necessary to increase the core’s volume or introduce air gaps in order to increase the saturation current. In term of losses, ESL 40010 shows the smallest losses beside its lowest permeability. A thorough consideration is needed to find out the material in a suitable design to achieve the target specification of inductor.

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References
[1] T. Sato, H. Tomita, A. Sawabe, T. Inoue, T. Mizoguchi, M. Sahashi, IEEE Transactions on Magnetics 30 (1994).
[2] Y. Fukuda, T. Inoue, T. Mizoguchi, S. Yatabe, Y. Tachi, IEEE Transactions on Magnetics 39 (2003).
[3] N. Wang, E.J. O’Sullivan, P. Herget, B. Rajendran, L.E. Krupp, L.T. Romankiw, B.C. Webb, R. Fontana, E.A. Duch, E.A. Joseph, S.L. Brown, X. Hu, G.M. Decad, N. Sturcken, K.L. Shepard, W.J. Gallagher, Journal of Applied Physics 111 (2012).
[4] K.H. Kim, J. Kim, H.J. Kim, S.H. Han, IEEE Transactions on Magnetics 38 (2002).
[5] E.J. Brandon, E. Wesseling, V. White, C. Ramsey, L. Del Castillo, U. Lieneweg, IEEE Transactions on Magnetics 39 (2003) 2049.
[6] T. El Mastouli, J.P. Laur, J.L. Sanchez, M. Brunet, D. Bourrier, M. Dilhan, in: M.A. Maher, J.C. Chiao, P.J. Resnick (Eds.), Micromachining and Microfabrication Process Technology Xiii, 2008, p. A8820.
[7] M. Brunet, T. O’Donnell, L. Baud, N.N. Wang, J. O’Brien, P. McCloskey, S.C. O’Mathuna, IEEE Transactions on Magnetics 38 (2002) 3174.
[8] D. Bourrier, M. Dilhan, A. Ghannam, H. Granier, Comparisons of the new thick negative resist to Su8 resist, Conference on Advances in Resist Materials and Processing Technology XXVIII, San Jose, CA, 2011.
[9] D.H. Bang, J.Y. Park, IEEE Transactions on Magnetics 45 (2009) 2762.
[10] M.L. Wang, J.P. Li, K.D.T. Ngo, H.K. Xie, IEEE Transactions on Power Electronics 26 (2011) 1310.
[11] X. Fang, R. Wu, L. Peng, J.K.O. Sin, IEEE Electron Device Letters 34 (2013) 292.
[12] M. Mu, Y. Su, Q. Li, F.C. Lee, IEEE Energy Conversion Congress and Exposition (Ecce) (2011).