Three-dimensional miniaturized power inductors realized in a batch-type hybrid technology

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Abstract
We present a new hybrid technology for the realization of three-dimensional millimetre-size inductors for low-power (0.1–1 W) applications. Our devices consist of electroplated planar Cu coils, realized within a high-resolution (5 \( \mu \)m) polyimide flex-foil process, and mm-size ferrite magnetic cores, obtained by three-dimensional micropatterning of ferrite wafers using powder blasting microerosion. Our devices range in volume between 10 and 1.5 mm\(^3\) and we characterize their inductive and resistive properties as a function of frequency.

1. Introduction

Today there is an increasing demand for miniaturized and planar magnetic devices, such as inductors and transformers, for power electronics applications. Miniaturized switching converters operating at high frequency, high energy density and high efficiency are required for use in communications, military/aerospace applications and computer/peripheral or other portable devices.

It is also required that these inductive devices have high values of inductance, saturation current and quality factor (\( Q \)). Miniaturization also implies that operating frequencies increase, as at high frequencies (0.1–1 MHz) more power cycles can pass the inductive device within a given time. A lot of work has been done to replace discrete miniaturized magnetic components by fully integrated magnetic devices. However, the magnetic properties of such integrated structures may be very different from those of the bulk magnetic materials. For example, Park et al [1] and Ahn et al [2] reported on 4 mm \( \times \) 1 mm \( \times \) 0.13 mm size inductors based on 15 \( \mu \)m thick electroplated Ni\(_{80}\)Fe\(_{20}\) and Ni\(_{80}\)Fe\(_{50}\) magnetic cores. The structure is realized by a number of sputter deposition, electroplating, photore sist spinning and patterning steps. Inductance values of approximately 0.1–0.4 \( \mu \)H were reported at 1 kHz–1 MHz. Löchel et al [3] have used thick resist technology, sputtering and electroplating/etching methods to fabricate coils of a few mm size, based on NiFe core material. Inductance values of the order of 1 \( \mu \)H were reported at 125 kHz. Microtransformers of size 5 mm integrated with diodes on a Si wafer were also reported by Mino et al [4, 5]. These transformers are based on an amorphous magnetic core prepared by sputtering in the form of three separate layers of CoZrRe, each 5 \( \mu \)m thick, with 0.1 \( \mu \)m SiO\(_{2}\) spacer layers. This layered configuration was chosen exactly to reduce eddy current losses in the magnetic core. The reported inductance values were in the range of 0.5–1 \( \mu \)H. A specially configured transformer was realized by Yamasawa et al [6] by sandwiching primary and secondary coils in between two 10 \( \mu \)m thick amorphous CoZr layers. An inductance value of 8.5 \( \mu \)H at 1 MHz was obtained by this rather large planar device of dimensions 40 mm \( \times \) 30 mm. A spiral coil type thin film microtransformer (2.4 \( \times \) 3.1 mm\(^2\)), using RF-sputtered CoNbZr layers, was also proposed by Yamaguchi et al for MHz switching regulators [7]. These micromachined inductive devices are mostly based on metallic magnetic materials and are not primarily intended to function in a power application.

On the other hand, ferrite is one of the widely used magnetic core materials for high frequency power inductors and transformers. Since it has higher resistivity than metallic magnetic materials, eddy currents losses are strongly reduced [8]. During recent years, a large research effort has been
developed in the field of the so-called planar magnetics, where one integrates three-dimensional (3D) ferrite cores of reduced height with Cu windings realized in printed circuit board (PCB) technology [9–11]. In the microsystems field, ferrite-based inductors have been fabricated using screen printed polymer/ferrite layer composites, and inductances of the 0.5–1.5 μH range have been achieved [12, 13]. Here, fine ferrite particles are introduced into a polyimide matrix to form a composite magnetic core, but the magnetic permeabilities, and hence the inductance values, are much lower than those obtained when using conventional bulk ferrite materials. We have recently proposed a batch-type solution for the fabrication of 3D inductors, where we combined E-shaped magnetic ferrite cores, micromachined from ferrite wafers, with planar Cu coils, realized using commercially available flex-foil technology [14]. The commercial technology is based on the gluing of thin Cu foils on a polyimide substrate and their subsequent micropatterning in a wet etching process. Due to Cu foil/polyimide detachment problems and mask underetching effects, actually a minimum winding width \( w = 25–30 \, \mu m \) and a winding pitch \( p = 50–60 \, \mu m \) are feasible (see, for example, [15]). Clearly, this minimum dimension presents a strong limit to the extreme miniaturization of inductive power devices, as the inductance value scales with the square of the number of windings that can be fitted into a given inductor volume.

In this work, we propose an improved technology for the batch-fabrication of 3D inductors, with which we open the way to economically feasible ultra-miniaturized low-power (\( \leq 1 \, W \)) applications. Our devices consist of two E-shaped magnetic ferrite cores, sandwiching a polyimide-based coil carrying the electrical windings. As mentioned before, the 3D ferrite cores are microstructured out of mm-thick ferrite wafers using a batch-type micropowder blasting process [16]. In this way, we can realize many cores in parallel and assemble them at wafer-level with the electrical winding patterns. The electrical windings are realized using an in-house developed flex-foil process with high-resolution potential, consisting of several polyimide spinning, Cu electroplating and planarization steps. We have measured the electrical properties of our devices as a function of frequency and find inductance values up to 100 \( \mu H \) for inductor volumes of the order of 10 mm\(^3\).

2. Fabrication process

2.1. Magnetic cores

For the magnetic cores, we use high relative permeability (\( \mu_r = 1800 \)) 3F3 ferrite wafers of Philips [17]. The 3D ferrite E-cores are micromachined in 1 mm, 0.75 mm and 0.5 mm thick ferrite wafers using a mechanical microerosion by powder blasting [16]. A 0.5 mm thick stainless steel mask, which is in mechanical contact with the wafer, is used to protect non-eroded areas. The \( x \) - and \( y \)-axis translation of the nozzle provides a uniform exposure of the fixed ferrite wafer. An example of an array of ferrite cores, after fabrication and glueing on blue tape, is shown in figure 1(a). Figure 1(b) is a photomicrograph of a single E-core.

Figure 1. (a) Array of structured ferrite E-cores, powder blasted in a ferrite wafer and (b) a photomicrograph of a single microstructured ferrite E-core.

2.2. Coils

Presently, standard available flex-foil technology is resolution-limited to structures with a Cu width \( w = 25–30 \, \mu m \) and a winding pitch \( p = 50–60 \, \mu m \). To enable higher winding densities, we have elaborated a new flex-foil process, which takes advantage of standard clean room wafer-based microfabrication techniques. This process, the sequence of which is shown in figure 2, starts with a Si substrate (for mechanical support), which is laminated with a 12.5 \( \mu m \) thick polyimide (Kapton) foil, using 12.5 \( \mu m \) acrylic adhesive tape. To planarize the surface, a thin layer (7 \( \mu m \) after cure) of liquid polyimide (PI2611 from Dupont) is spun on the top of the Kapton layer after application of an adhesion promoter (VM651 from Dupont).

After coating, the polyimide is cured in nitrogen medium in a programmable oven (1 h at 150 °C, followed by 1 h at 200 °C). Normally, PI2611 polyimide series must be cured at 350 °C to eliminate all solvents. To protect the Kapton layer from excessive heating, the curing is limited to 200 °C in our process.

Subsequently, a 20 nm Cr adhesion layer is deposited on the polyimide, followed by 200 nm of Cu to form a seed layer for electroplating. A 8 \( \mu m \) thick layer of Shipley SJS5740 photoresist is then spun on, exposed with mask 1 and developed to obtain thick moulds for the lower part of the windings. Cu is then electroplated into the photoresist moulds using a CuSO\(_4\) bath (figure 2(a)). Subsequently, the Cu seed layer is removed using a H\(_2\)FeNO\(_3\)S\(_2\) solution, followed by removal of the Cr adhesion layer in a solution of KMnO\(_4\) and Na\(_3\)PO\(_4\).
One layer of polyimide is then spun and cured to isolate the Cu windings. After this step the topography of the surface was not flat and did not allow high-resolution patterning of the next level. Therefore a chemical mechanical polishing procedure is used for planarization, using a 0.05 µm silica slurry. (figure 2(b)). Next, via holes are plasma etched in O2, using a 800 nm thick PECVD SiO2 mask. Hereafter, the SiO2 mask is removed using wet etching (figure 2(c)).

From this point, fabrication continues with the next level of windings by depositing a new seed layer on the planarized surface and by repeating the sequence of steps described before (figure 2(d)). After removal of the seed layer, a polyimide passivation layer is applied and cured to protect the top of the windings from oxidation (figure 2(e)). Finally, a SiO2 mask is deposited and the polyimide is etched in an O2 plasma to create the through-holes for the positioning of the E-cores and to clear the contact paths (figure 2(f)). To separate the flexible structure from the Si substrate, a bath of acetone is used to remove the adhesive between the Kapton film and the wafer (figure 2(g)).

Figure 3(a) is a photograph of three different sizes of coils together with their respective ferrite E-cores. Figure 3(b) is an assembled inductor.

### Table 1

<table>
<thead>
<tr>
<th>Sample number</th>
<th>w (µm)</th>
<th>p (µm)</th>
<th>N</th>
<th>L (µH) @ 10 kHz</th>
<th>C_cal (pF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60</td>
<td>100</td>
<td>14</td>
<td>2</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>50</td>
<td>60</td>
<td>24</td>
<td>17</td>
<td>140</td>
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<td>40</td>
<td>50</td>
<td>30</td>
<td>90</td>
<td>145</td>
</tr>
</tbody>
</table>

3. Experimental results and discussion

Electrical properties of the fabricated samples are measured using a Hewlett Packard 4194A impedance/gain-phase analyser. Using a logarithmic frequency sweep between 10^3 and 10^7 Hz with a sinusoidal signal level of 500 mV rms, inductance and resistance are recorded. We present results on the samples described in table 1. Here, we present the winding width w, winding pitch p, the measured inductance L at 10 kHz and the calculated inter-winding capacitance C_cal of the coil for three different samples.

The results reported in table 1 are characterized by a minimum winding width of 40 µm and a minimum winding interspacing of 10 µm. Although we were able to produce windings widths down to 10 µm, solder contacts to these narrow lines proved to be difficult to realize (breaking of the line at the edge of the contact path) and we were not able to characterize these samples electrically. Therefore, we will...
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Figure 4. Dependence of the inductance and the resistance versus frequency for the samples of table 1 with air core and ferrite core.

Figure 5. 3F3 ferrite permeability as a function of frequency compared to a typical behaviour of the inductance of the coil, with and without core.

Figure 6. Power-law dependence of the inductance on the number of windings $N$ at 100 kHz, without and with ferrite core.

4. Conclusions

We have developed a high-resolution flex-foil process for the realization of miniaturized Cu coils and combined it with an original way of fabricating miniaturized E-cores from ferrite wafers to realize inductors in the mm$^3$ volume range. We have measured inductance values in the 100 µH range at frequencies below 0.1 MHz. We think that our technique opens interesting perspectives for extremely miniaturized power applications.
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References