Design Study and Fabrication Techniques for High Power Density Micro-Transformers.
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Abstract - This paper presents an investigation into the power density and efficiency achievable from micro-transformers suitable for integration on silicon. Results from the design study indicate that high aspect ratio conductors and laminated cores are required to achieve high power density. Fabrication techniques, using thick photoresist, which can be used to achieve high aspect ratios, have been developed and results are presented. Initial test results for the inductance and resistance of the coils are also presented.

I. INTRODUCTION

There is an increasing drive towards higher power densities in dc-dc power conversion. This is likely to become even greater as supply voltages for microprocessors move towards 0.5 V and currents of up to 400 A. Such power supplies will likely be required to be located as close as possible to the load in order to minimise losses due to interconnect resistance and inductance [1]. This will require the power supplies to be small and have a high power density, which in turn implies that they will switch at higher frequency and be constructed using greater degrees of integration.

One technology which may facilitate this increased integration, is the use of thin film magnetics to construct the magnetic components on the same silicon substrate as the active devices. The feasibility of using thin film magnetics for power conversion has been demonstrated [2] [3]. Mino et al. demonstrated a thin film transformer integrated with Schottky diodes [3] and recently Katayama et al. [4] demonstrated a 1 Watt dc-dc converter with a thin film inductor integrated on an IC with power switches and control circuitry which achieved an overall power density of 5.6 W/cm³.

However most of the thin film magnetic components demonstrated to-date have been restricted to low power conversion (typically < 2 W) and power densities for such micro-transformers are typically less than 1 W/cm³. Sullivan et al. [5] did address the design of micro-transformers for slightly higher powers (3 W) and predicted power densities of 59 W/cm³. The use of micro-inductors for higher powers has also been addressed by Mehas et al. [6], specifically in the context of rapid response, microprocessor power delivery.

This paper presents an investigation into the power density and efficiency achievable from micro-transformers suitable for integration on Silicon. In particular, it attempts to determine the winding and core construction techniques and technologies required to achieve high power density components. Although the analysis is restricted to low power levels (< 5 W), the techniques investigated also apply to higher power levels. Section II presents the basis of the design procedure. Sections III and IV use the design procedure to investigate how the choice of winding and core construction affects the transformer performance. In particular, it investigates how the application of MEMS (Micro ElectroMechanical Systems) technologies which allow high aspect ratios, and recent materials developments, could impact on the power density of the microtransformers. Section V will explain the processes and the fabrication of the proposed transformers. Finally, some results from the initial investigation into suitable technologies will be demonstrated in Section VI.

II. DESIGN

The two most common structures for magnetic components are the toroidal type [2] and the E-core type [5]. The E-core transformer is typically characterised by a small number of turns and a relatively large core cross-sectional area. On the other hand, the toroidal type is characterised by a relatively large number of turns encircling a small cross sectional area.

In this work the analysis is restricted to the E-core type transformer, the simplified structure of which is shown in figure 1. The E-core structure is preferred to the toroidal type mainly because it better suits the fabrication processes to be used. Also it is worth noting that Sullivan et al. [5] showed that the E-core type could be used to achieve higher power densities than the toroidal type. The aim of this study is to investigate the efficiency and power density achievable with micro transformers depending on the techniques used for the construction of the windings and core.

Fig. 1: Structure of the E type transformer for which the analysis is performed.
The procedure adopted for the design study is as follows:

1. The electrical specifications of the transformer, i.e. the frequency, $f$, Input voltage, $V_{in}$, transformation ratio, and output current $I_{out}$ are set.
2. The core and conductor material characteristics are set. The conductors are assumed to be copper and it is assumed that the magnetic core consists of multiple layers of magnetic material separated by thin insulating layers. The transformer is assumed to have the shape as shown in figure 1. In order to simplify the analysis, perfect lamination is assumed and no account is taken of losses in the end regions.
3. Given a footprint area and technology specifications such as the conductor width, $w$, spacing, $s$, thickness, $t$, core lamination thickness, $h$, and number of laminations, $n$ and materials characteristics, the electrical performance for a design is determined using the equations outlined in the following.

The efficiency of any design is computed according to

$$\eta = \frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{core}} + P_{\text{cu}}} \quad (1)$$

where $P_{\text{out}}$ is the output power, $P_{\text{core}}$ is the core loss and $P_{\text{cu}}$ the winding loss. Simple geometrical considerations can be used to determine the number of turns that can be accommodated in any footprint area, given the information in item 3 above. Hence the dc resistance of the windings can be computed from

$$R_{dc} = N^2 \frac{D l_{\text{MTL}}}{wt} \quad (2)$$

where $\rho$ is the resistivity of the copper windings and $l_{\text{MTL}}$ the mean turn length for the core. Of course, at high frequencies the resistance of the windings is increased due to skin and proximity effects. The AC resistance of the windings is commonly specified as a certain factor times the dc resistance;

$$R_{ac} = F_r R_{dc} \quad (3)$$

The factor $F_r$ will depend on the winding layout and the dimensions and can be computed by analytical means [5], however, for the present analysis the values of $F_r$ are calculated from Finite Element simulations. The power loss in the windings can then be computed according to

$$P_{\text{cu}} = F_r (I_{\text{pri}}^2 R_{\text{pri}} + I_{\text{sec}}^2 R_{\text{sec}}) \quad (4)$$

The flux density in the core can be determined from;

$$B_{pk} = \frac{V_{in}}{K N A_e f} \quad (5)$$

where $K$ is a constant depending on the waveform, and $A_e$ is the effective core cross-sectional area. Considering a core of total thickness $h_0$, divided into $n$ laminations each of thickness $h$, then the power losses in one lamination due to eddy currents alone can be computed according to [7,8].

$$P_{\text{ella}} = \frac{n (2\pi B)^2 2 XY h^3}{2A_{\rho}} \quad (6)$$

Hysteresis loss for one lamination can be approximated by [6];

$$P_{\text{hys}} = \frac{3}{4} 2 XY h (4B_{\rho} H_e) \quad (7)$$

The total core loss, $P_{\text{core}}$, is then the sum of the eddy current loss and the hysteresis loss. Equations (2)-(7) can now be used in (1) to determine the efficiency.

The open circuit inductance of the transformer can be computed from;

$$L_{oc} = \frac{\mu_0 \mu_{\text{core}} N_{\text{pri}}^2 A_e}{l_s} \quad (8)$$

with $l_s$ the magnetic path and $A_e$ the effective core area given by $n h Y$. This allows the effect of magnetising current to be included in the computation of the primary current $I_{\text{pri}}$.

Note that the expression for the eddy current loss in the core (6) and the expression for inductance (8) are only valid for the assumption of uniform flux density in each lamination, i.e. they both assume that the eddy currents in the core do not cause a non-uniform flux density. Hence, it is important to know for what ratio of lamination thickness to skin depth the expressions in (6) and (8) are valid.

The graph in fig. 2 plots the open circuit inductance simulated with finite element (FE) analysis, for an E-core type micro transformer with 3 different core configurations as follows;

- a) Single layer, 12 microns thick,
- b) 2 laminations, 6 microns thick,
- c) 3 laminations, 4 microns thick.

Instead of plotting the inductance against frequency it is plotted against the ratio of the lamination thickness to the skin depth $6$ in the magnetic material. When plotted in this manner all three inductance curves coincide and it is clear that the open circuit inductance can be expected to remain constant while the ratio of lamination thickness to skin depth is less than one.
Fig. 3 compares the eddy current loss computed analytically from (6) to that determined from FE simulation for the three core configurations, a), b) and c) over the frequency range 10 kHz to 10 MHz.

Clearly, the effect of lamination is to reduce the eddy current loss in the core, i.e. the core constructed from 3 x 4 micron laminations has the lowest loss, almost an order of magnitude lower than the single 1 x 12 microns core, at 2 MHz. Note also that the analytic expression for eddy current loss (6) (broken lines in the graph) agrees very closely with that predicted by the FE simulation, at least up to the frequency at which the lamination thickness becomes equal to the skin depth (marked by the arrow for each curve).

We can conclude from the above analysis that the expressions (6) and (8) are accurate for a lamination thickness less than one skin depth. Indeed it could be considered a design rule that the lamination thickness should not exceed the skin depth in the magnetic material at the frequency of operation.

For the structure shown in fig. 1 it is possible to have many different transformer layouts for any set footprint area, i.e. the transformer layout can be varied from long and thin - a high X/Y ratio, to short and wide - a low X/Y ratio. This ratio can affect the electrical performance of the transformer. For example fig. 4 plots the efficiency of a transformer for a fixed footprint area but for different layouts, i.e. the ratio of X/Y is varied. The graph clearly shows that the efficiency of the transformer increases with increasing aspect ratio of the device, i.e. the longer and thinner the device the better the efficiency. The corresponding plots of core and copper loss show that this is due to the fact that short, wide devices with many turns have high copper loss, and also have high flux density due to reduced core cross-sectional area. Obviously from a practical point of view the device aspect ratio must be limited to reasonable values and in the following analysis the maximum ratio allowed is 10.

Fig. 4: Variation of efficiency with the ratio of device width to length, X/Y for a 1W transformer design in a footprint area of 20 mm².

III. WINDING DESIGN.

The design procedure described in the previous section is now used to investigate how the efficiency and power density of the micro-transformers vary as a function of winding and core construction. The analysis is conducted for a transformer with the following fixed specifications. The first analysis considers the geometry of the windings.

<table>
<thead>
<tr>
<th>TABLE 1: SPECIFICATIONS FOR EXAMPLE TRANSFORMER DESIGN</th>
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<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>Input voltage</td>
</tr>
<tr>
<td>Output current</td>
</tr>
<tr>
<td>Output Power</td>
</tr>
<tr>
<td>Transformation ratio</td>
</tr>
</tbody>
</table>

With most micro-fabrication techniques, very high winding densities can be achieved, e.g. consider CMOS technologies which have minimum feature sizes now approaching 0.13 microns. However, for many technologies the thickness of the metal is limited and aspect ratios (ratio of conductor thickness to width, t/w) greater than 1 are uncommon, except with the use of expensive techniques such as LIGA. However with the recent growth in MEMS, less expensive techniques for achieving high aspect ratio structures have become available. Some of these are described later in Section V. Here, the impact of these technologies on the power density achievable with micro-fabricated transformers is investigated.

The graph in fig. 5 shows how the efficiency of a micro-transformer varies with the track width, spacing and aspect ratio. This graph has been generated by assuming a fixed core geometry of 6 x 2 microns permalloy laminations. For each combination of track width, space and aspect ratio, the efficiency is calculated for the minimum footprint device which satisfies the specifications given in table 1. Only cases where the width of the tracks, w, is equal to the spacing, s,
were considered. For each design, the core width to length ratio is chosen to maximise efficiency as explained in the previous section, but is never greater than 10.

![Graph showing transformer efficiency and power density](image)

**Fig. 5**: Variation of transformer efficiency and power density with track width and spacing. Track aspect ratio is a parameter and varies from 0.5 to 4.

For low aspect ratio conductors (\(t/w = 0.5\)) the efficiency increases with increasing track width as is expected because of decreasing winding resistance. Similarly, efficiency increases with increasing track aspect ratio, although the increase for aspect ratios over 3 is not significant. (This is due to the fact that the efficiency of these designs is limited by core losses.) However power density of the components decreases significantly with increasing track width.

Although Fig. 5 shows only the case for equal track width and space, other winding layouts, such as width greater than space, may easily be compared by doing a simple calculation. For example, a design with a track spacing of 20 microns but a width of 60 microns is equivalent, in terms of copper area and track pitch, to a design with \(w = s = 40\) microns and aspect ratio of 0.75. The graph in Fig. 5 indicates that such a design will have a reasonably high power density (45 W/cm²) but a low efficiency of approximately 0.8.

The way to achieve high efficiency and high power density is clearly to use high aspect ratio coils with a small width and spacing. Section V investigates fabrication techniques, which have the potential to achieve the coil constructions indicated in Fig. 5.

**IV. CORE DESIGN**

For the sake of the above analysis it was assumed that the core of the transformer was constructed from a 6 x 2 micron permalloy, multilayer. Permalloy (Ni₈₀Fe₂₀) has been widely used in the fabrication of micro-magnetic devices, especially hard disk write heads for many years. However, recently there has been considerable research into improved materials. Much of the research into improved materials is related to the recording head industry, where the focus is on obtaining materials with high saturation magnetisation, high resistivity and low coercivity. Osaka [9] reviews the latest developments in electroplated materials, mostly alloys of Cobalt, Nickel and Iron with additives which modify the properties. The use of nanocrystalline, sputtered materials [11][12] also shows significant improvements in magnetic properties. Table 2 summaries the magnetic properties of some of these recently developed materials.

**TABLE 2: SUMMARY OF MAGNETIC PROPERTIES OF RECENTLY DEVELOPED THIN FILM MAGNETIC MATERIALS**

<table>
<thead>
<tr>
<th>Material</th>
<th>(B_s) (T)</th>
<th>(H_c) (A/m)</th>
<th>(\rho) ((\mu)Ωcm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CoNiFe-A [9]</td>
<td>2.1</td>
<td>96</td>
<td>25</td>
</tr>
<tr>
<td>CoNiFe-B [9]</td>
<td>1.7</td>
<td>400</td>
<td>130</td>
</tr>
<tr>
<td>FeCo [10]</td>
<td>2.3</td>
<td>16</td>
<td>125</td>
</tr>
<tr>
<td>FeCoBn [12]</td>
<td>1.7</td>
<td>20</td>
<td>300</td>
</tr>
<tr>
<td>CoHfTaPd [4]</td>
<td>1.0</td>
<td>40</td>
<td>Not given</td>
</tr>
</tbody>
</table>

Clearly some of the sputtered materials have significantly higher resistivity than those of the electroplated materials and much reduced eddy current loss is to be expected from the use of these materials. The design approach outlined in section II can be used to investigate the effect of these material developments on the power density and efficiency of micro-transformers.

The use of thick magnetic cores will allow devices to be constructed in smaller footprint areas, thus improving power density (measured in W/cm²). The graph in figure 5 plots how the power density can be expected to improve by increasing the core thickness. The graph is generated by obtaining the minimum footprint device that satisfies the specifications in table 1, for fixed conductor dimensions and for a fixed magnetic layer thickness. The conductor dimensions are at 40 microns with an aspect ratio of 0.5. The magnetic layer thickness is fixed at 4 microns, which is approximately the skin depth in permalloy at MHz. The maximum power density achievable and the corresponding efficiency is plotted against the number of these layers used to construct the core.

The graph clearly shows the increases in power density which are achievable by increasing the thickness of the core. Significant improvements in power densities are also achievable by using materials with a higher saturation flux density such as the FeZrO (1.24 T) or the FeCo alloy (2.2 T), because these materials can be operated at higher flux densities. These materials also have high resistivity, therefore the efficiency is not significantly compromised by making use of their capability to handle higher flux density.
The graph in figure 5 shows how the power density can be improved by using thicker cores and better core materials. However some thought must be given to the feasibility of the fabrication of these constructions. We can consider this by taking one example transformer design. Using a conductor width and spacing of 40 micron and an aspect ratio of 2, and an overall core thickness of 10 micron, a transformer (with specifications given in table 1) can be designed in a footprint area of 10 mm². The graph in figure 6 plots the efficiency of this transformer for a different number of core laminations and different core materials, but for the same fixed overall core thickness.

The graph shows that in order to achieve an efficiency of approximately 90 % with a permalloy core, the core must be divided into 6 – 7 laminations. However, for a much higher resistivity material such as the FeCo alloy only 3 laminations is required, whereas for the sputtered material such as FeZrO (1040 μΩcm) a single layer is sufficient to achieve 90% efficiency.

Although sputtering layers of thickness 10 micron is possible [4], it may be prohibitive from a cost perspective because of the deposition times involved. Permalloy can be electroplated, the building of many layers separated by an insulator is an undesirable process due to the need for a lithography step for each layer. Thus the use of highly resistive electroplated alloys may present a compromise in that high efficiency can be achieved with only a few laminations.

V. PROCESS AND FABRICATION.

The previous sections showed the advantages of using high aspect ratio conductors and multi-layer cores for improving the power density and efficiency of micro-transformers. In this section the proposed fabrication techniques for the micro-transformers is described and in Section VI the initial results for the fabrication of the high aspect ratio conductors are presented. The processes required for the deposition of multi-layer cores are still under development. Initial transformers will be fabricated with a single layer Permalloy core.

A. Micro-transformer process.

The micro-transformer structure consists of a copper winding surrounded by two layers of magnetic material, as shown in Fig. 8. The main process steps are listed in table 1.

![Fig. 6. Efficiency for a transformer in a 10mm footprint area, power density of approximately 40 W/cm², using different core constructions, but having an overall core thickness of 10 microns.](image)

![NiFe Insulator](image)

**Fig. 7. Schematic of the fabricated micro-transformer.**

<table>
<thead>
<tr>
<th>TABLE 3: MICRO-TRANSFORMER PROCESS FLOW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Sputtering of seed layer (Cu/Ti)</td>
</tr>
<tr>
<td>2. Bottom core patterning - Electroplating of NiFe</td>
</tr>
<tr>
<td>3. Insulating layer patterning - BCB deposition</td>
</tr>
<tr>
<td>4. Sputtering of seed layer (Cu/Ti)</td>
</tr>
<tr>
<td>5. Coils patterning - Copper electroplating</td>
</tr>
<tr>
<td>6. Insulating layer patterning</td>
</tr>
<tr>
<td>7. Sputtering of seed layer (Cu/Ti)</td>
</tr>
<tr>
<td>8. Upper core patterning - Electroplating of NiFe</td>
</tr>
</tbody>
</table>

The method used for the metal deposition is electroplating. Permalloy is deposited by electroplating to form the magnetic core of the transformer. In order to reduce
hysteresis loss, anisotropy is induced in the magnetic core by depositing the permalloy in the presence of a magnetic field, supplied by permanent magnets placed on each side of the electroplating bath.

The next step of the fabrication is to provide an insulating layer between the magnetic core and the conductors. The insulating material is Benzocyclobutene (BCB), a photosensitive material which can thus be patterned.

The conductors of the transformer are then fabricated using the electroplating of copper. A mask with different coil sizes, from 30 micron to 100 micron, was designed in order to investigate the process window for the winding fabrication processes. As discussed in the design considerations, the target for the conductor aspect ratio (height over width) is at least 2 – 3 in order to achieve high power densities. In this case, since the minimum for the width is 30 micron, the use of thick photoresists is required (10's of microns thick) instead of standard photoresist.

B. Photoresist development.

Two photoresist processes were developed to achieve thick layers for the copper windings: EPON-SU8 a negative photoresist supplied by Microlithography Chemical Corp. [13], and AZ4562, a positive photoresist supplied by Clariant. SU8 is commonly used for micro molding in MEMS applications [14], and can be spun to a thickness of 2 mm with very high aspect ratio: up to 18:1. A standard thickness for the positive photoresist, AZ-4000 series, is 25 microns. In order to reach the 100 microns range, multilayers are applied [16,17]. The process with the positive photoresist AZ 4562 was developed in parallel with the process for SU8. SU8 was spun in a single step at different spin speeds on silicon and copper wafers to investigate the range of thickness achievable. For AZ 4562, four layers were spun on to achieve a 70 microns thick layer.

VI. RESULTS AND DISCUSSION.

A process window for each of the two photoresists, the positive AZ4562 and negative SU8, has been investigated in order to assess their suitability for the coil fabrication.

A. Comparison of SU8 and AZ4562.

Fig. 8 shows SU8 coil structures on a silicon substrate and Fig. 9 shows electroplated coils using the SU8 process. It can be seen that very straight sidewalls have been achieved. Coils with a width of 70 microns and a layer thickness of 160 microns were patterned on silicon substrates. However, on copper seed layer surfaces, the adhesion of SU8 is poor. The maximum thickness achievable for the windings is 70 microns with an aspect ratio of 1. For thinner layers of 45 micron, smaller coils can be plated to give a conductor aspect ratio of approximately 7:1 as shown in Fig. 9.

Apart from the adhesion issue, the SU8 process presents another drawback: after the copper electrodeposition the photoresist is difficult to remove leaving residues between the tracks.

Fig. 10a shows some structures fabricated with the positive AZ4562 resist. An aspect ratio of 1.5 was achieved. The side walls are not as good as with SU8: 82° on average but one advantage of this photoresist is that it is easily dissolved in acetone and small structures, from 20 micron are easy to achieve in thick layers as shown on Fig. 10b.

Fig. 10. a)AZ 4562 structures, 67 microns width, thickness of 75 microns b) 30 micron wide, 44 microns thick copper tracks, achieved with AZ 4562

The range of geometry covered is therefore bigger than with SU8 where we are restricted to larger structures. The positive photoresist seems to be the most promising photoresist for achieving high aspect ratio with a large range of geometry.

B. Winding inductance and resistance measurements.

Initial tests have been carried out on the fabricated coils in order to verify that they have the low resistance required and that test results agree with assumptions used in the design procedure. The resistance and the inductance of the coils
fabricated with both the SU8 process and the AZ4562 process were measured with an HP analyzer over a large range of frequency, from 1 kHz to 8 MHz. A blanket layer of permalloy was plated first and insulated from the coils.

Fig. 11 shows the resistance and inductance measurements of the primary and secondary windings taken for two different coil sizes: a 100 micron wide/100 micron track spacing coil, and a 70 micron wide/50 micron track spacing coil, with a permalloy thickness of 4 microns. The 2D Finite Element Analysis simulations of the large coil is plotted on the same curve.

The graphs show that low resistance coils have been fabricated. The increase in resistance for frequencies greater than 1 MHz is mostly due to eddy current losses in the permalloy layer and is predicted by the simulation results which agree quite closely with the measured results for both the resistance and inductance of the large coils.

VII. CONCLUSIONS

The design of E core type micro-inductors has been investigated. It has been shown that the use of high aspect ratio conductors can significantly increase the power density and efficiency of such devices. Two thick photoresists, SU8 and AZ4562, were investigated for building these high aspect ratio tracks. Initial results indicate that the AZ4562 resist presents the most promising solution for the fabrication of windings covering a range of dimensions from 30 microns up. Further process development will be done in order to get higher aspect ratio and complete transformer (closed core) for demonstrators purpose.

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