Thin-film Magnetic Inductors for Integrated Power Management

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Abstract—This paper presents the design considerations for thin-film magnetic power inductors for integrated voltage regulator (IVR). Optimum design parameters for solenoid inductors are arrived at that maximize key performance metrics such as quality factor, inductor efficiency, inductance density, and operation frequency. A fabrication approach to integrate the solenoid inductor with thin-film magnetic material within the redistribution (RDL) layers is presented. Non-idealities that could impact the inductance performance are illustrated. Finally, electrical characterization of a set of test inductors is carried out and the results are presented.

Keywords- power management; inductor; passive component; RDL; integrated voltage regulation, PMIC

I. INTRODUCTION

Today’s multicore application processors (AP) operate on nominal supply of ~1V. The power management IC (PMIC) employs DC-DC converter to step down from the battery voltage to 1V (nominal). Recognizing that the AP can be operated at <1V to save power during light computation loads, dynamic voltage and frequency scaling (DVFS) technique is employed, where the supply voltage to AP is decreased and increased according to the computational load. Modern APs need multiple supplies from the PMIC to power multi-cores, memory sub-system and others independently. DVFS is accomplished by commanding the PMIC to step-down/up its output voltage to individual cores, over a 1V to 0.5V range, as per the computation load of that core. Fast transition in PMIC output voltage is necessary for DVFS to be effective, and enable power saving to the tune of 20%[1]. Standalone PMIC connected to the AP through PCB has large time constants limiting the transition speed of PMIC output voltages to ~10μS timescale, which is insufficient to closely track the computational load of AP. Integration of the PMIC in close proximity to AP, either on the same die or package eliminates the large time constants and reduces transition times to <100ns. This also needs the PMIC to operate at higher switching frequencies, such as 100MHz compared to today’s standalone PMICs that switch at~5MHz.

The integration of PMIC with AP on die or package to enhance supply dynamism (<100ns transition), needs associated inductors and capacitors to be integrated as well. However, conventional air core inductors on-chip or package suffers from high ohmic loss, and not suitable for high efficiency power converters. Magnetic core inductors are needed to enhance inductance density and lower ohmic losses.

II. DESIGN OF THIN-FILM MAGNETIC INDUCTORS

In this section, we illustrate the design of solenoid inductor with magnetic core. Given that the PMIC operating frequency is expected to be in 100MHz range for IVR, the inductor values are typically in the 15nH-50nH range. The load current of an AP core is in 1A range. Hence these set the target for magnetic thin-film inductors. The design involves analysis and 3D EM simulation to arrive at the optimum design parameters, within technology limitations.
A. Design Considerations

The design equation for a solenoid inductor is given in (1). To maximize inductance, a material with high $\mu_r$ is needed. The rest are design parameters, and choices leading to best figure-of-merit are described below. For inductance, key considerations are aspect ratio and thickness of magnetic film, and number of turns ($N$) per unit length ($l_m$) while the resistance (2) depends on coil width ($w_c$) and thickness ($t_c$).

$$L \approx \frac{\mu_0\mu_r N^2 w_m t_m}{l_m[1 + N d(\mu_r + 1)]} \quad (1)$$

Note: ignores air-core inductance. Approx. if $\mu_r >> 1$ & $t_m / h_o$ is close to 1

$$R = 2N \rho \frac{l_c}{w_c t_c} \quad (2)$$

The factor $N_d$ called the demagnetization factor has inverse effect on inductance. It’s in turn dependent on the aspect ratio ($l_m/w_m$) of the magnetic core [6]. The thickness $t_m$ of magnetic core is limited by the process capability, while $w_m$ and $l_m$ are design parameters. Similarly thickness $t_c$ of copper is process capability, while $w_c$ and $s_c$ are design parameters.

B. Demagnetization and Aspect ratio

The parameter $N_d$ is inversely proportional to the ratios $c/\sqrt{ab}$ and $a/b$, with $c/\sqrt{ab}$ having a larger influence on $N_d$ [6]. This indicates that ideally the magnetic core should be shaped as long thin cylinder. Recognizing that $w_m$ is same as $2a$, and that it has opposite influences on cross-sectional area and demagnetization factor, there is clearly an optimum value for the aspect ratio of the magnetic film. Simulations using Ansoft HFSS$^\text{TM}$ are used to explore the design parameter space to arrive at optimum values to enhance the inductor performance metrics.

By fixing the width of the copper coil ($w_c$) and spacing ($s_c$) between adjacent turns, an inductor of $\sim$20nH is designed with different aspect ratios ($l_m$ & $w_m$) and the requisite number of turns ($N$). The thickness ($t_m$) of the magnetic core

is also fixed at 3µm. The inductors are then simulated in HFSS, with and without magnetic core, to compute the inductance boost factor due to the magnetic core. Figure 3 plots the inductance, resistance and boost factor for a range of aspect ratios. The presence of an optimum aspect ratio is clear from the plots, at which the popular figure-of-merit, $L/R$, peaks with a value of 77nH/Ω.

C. Coil width and spacing

While $w_c$ and $s_c$ do not figure explicitly in inductance, the number of turns $N$ per unit length, is determined by the sum of $w_c$ and $s_c$. Given a fixed magnetic film width $w_m$ and thickness $t_m$, optimum values of $w_c$ and $s_c$ are arrived at by HFSS simulations, to 65µm and 30µm respectively, for the criterion of maximum quality factor at 100MHz. The loss components include DC, which is ohmic loss in coil, and AC, which includes ohmic loss in coil and eddy current loss in magnetic film. Quality factor is also determined by the self-resonant frequency of the inductor, which is inversely proportional to coil width.

D. Laminated Magnetic film

While ohmic loss in coil is reduced by thick copper coils, eddy current loss in magnetic film is minimized by stacking up multiple thin layers of magnetic films insulated by oxide. Thickness of each layer has to be smaller than the skin depth in the magnetic material at the operating frequency.

![Figure 2: Structure and equation for solenoid inductor with magnetic core](image)

![Figure 3: Inductance, boost factor and resistance vs magnetic film aspect ratio](image)

![Figure 4: Quality factor vs frequency for 1 and 6-layer films](image)
The inductor current has spectral content at harmonics of the switching frequency. Hence it’s essential to keep the thickness of magnetic film lower than the skin depth of at least the 3rd harmonic. In the analysis on Figure 4, the magnetic film considered has 6 layers of 500nm films with a naturally oxidized insulating CoO layer separating the CoZrTa films reaching a total thickness of 3µm. The single layer thickness of 500nm is less than half the skin depth at 300MHz, assuming 100MHz switching frequency.

With the given magnetic film and Cu coil thickness, the design process arrives at magnetic film aspect ratio, width and spacing of the Cu windings to achieve the required inductance, resistance and quality factor.

III. FABRICATION OF THIN-FILM MAGNETIC INDUCTORS

A. Process flow overview

The solenoid inductors are fabricated on 12” wafer within RDL layers, with additional steps to allow insertion of the magnetic film between the RDL layers. The Cu RDL layers which constitute the inductor coils are fabricated by standard electroplating technique. Figure 5 shows the build cross-section diagram and pictures that show base capability in plating 5µm Cu RDL with 7µm polyimide layer. Planarity and roughness of the surface on which the magnetic material is deposited has to be planar and smooth to ensure good magnetic properties such as permeability and low coercivity with sputtered deposition and etch are described below.

B. Magnetic film deposition and etch

The magnetic alloy used is Cobalt-Zirconium-Tantalum (CoZrTa) which is known to yield fine amorphous films, with sputtered deposition leading to good magnetic properties. Resistivity of CoZrTa is ~100µΩ-cm resulting in lower eddy current loss at the intended high operation frequency. The magnetic properties of the film are listed in Table 1. The relative permeability of CoZrTa is ~500.

![Cross-section diagram of typical inductor build](image)

Table 1: Magnetic properties of the film

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coercivity (Hc)</td>
<td>0.3Oe</td>
</tr>
<tr>
<td>Saturation field (Hs)</td>
<td>~30Oe</td>
</tr>
<tr>
<td>Saturation Magnetization (Ms)</td>
<td>975 emu/cc</td>
</tr>
<tr>
<td>Relative permeability (μr)</td>
<td>477</td>
</tr>
</tbody>
</table>

![Undercut after wet etch](image)  
(a) undercut after wet etch

![4-layer magnetic film](image)  
(b) 4-layer magnetic film

Figure 6: Cross-section of magnetic film and undercut after wet-etch

However, as described earlier effective permeability drops due to the demagnetization factor. The saturation field determines the current carrying capability of the inductor, while low coercivity is necessary to minimize hysteresis loss. The magnetic film is etched to the desired patterns of the magnetic core by a wet-etch process with a proprietary chemical composition that etches the CoZrTa/CoO stack of multi-layered magnetic film. It has been shown that the undercut can be controlled at best to 3µm. Currently, this is achieved on manual wet-bench and fine tuning with auto etch tool is ongoing. Figure 6 shows cross-section view of the film stack and undercut after the wet-etch process.

IV. RESULTS AND DISCUSSION

A set of solenoid test inductors are fabricated with following parameters: 50µm wide, 3 and 5µm thick Cu coils for RDL 1/2 in BEOL / Polyimide respectively. The CoZrTa magnetic film was 2µm thick deposited as 4-layers of 500nm each insulated by CoO formed by natural oxidation. Inductors are characterized on wafer by 2-port S-parameters measured with Network Analyzer, and, inductor and quality factor are extracted from S-parameters.

![Photograph of a 9.5 turn solenoid inductor with magnetic core. 2-port S-parameter measurements are carried out with GSG probes.](image)
Inductance (L) and quality factor (Q) of 3.5 to 12.5 turn inductors are captured in Figures 8 & 9 below. The data is over a frequency range from 30MHz to 500MHz. The test chip had inductors of same dimensions with and without magnetic core. A comparison of inductance of identical structures with and without magnetic core is shown in Figure 10 for 3.5 to 12.5 turn inductors. An inductance boost factor of >16X is obtained with a 2µm thick magnetic film as the core of the solenoid inductor. Simulations with optimum aspect ratio and 3µm thick magnetic film showed 30X boost factor. However, as fabricated test inductors had 2µm thick film, the inductance boost factor should be lower by a factor of 2/3. Moreover as aspect ratio for test inductors was not the optimum, the boost factor is at 16X.

In Figure 11, measured DC resistance (R) of the inductors is shown. The ratio of inductance-to-resistance (L/R) is a figure-of-merit that indicates the inductor efficiency, higher the better. Both thick Cu, for low DC resistance and thick magnetic film for high inductance density are needed. However, this would reduce the self-resonant frequency of inductor and shift the peak Q factor to lower frequency. Hence this would be design parameter based on target specification of the voltage regulator.

In voltage regulator application the solenoid inductor is expected to carry DC current. The inductance of the 12.5 turn single inductor was measured by varying the DC current through the inductor from 0 to 400mA. The value of N12.5 inductor drops due to magnetic saturation in the core, while the N4.5 (9nH) inductor value does not drop significantly.
Single solenoid inductor structures have limited current carrying ability and cannot fulfill the 1A requirement. PMIC topologies such as Multi-phase which employ multiple inductors in parallel and coupled inductors with DC current flow in opposite directions are needed. In such coupled inductors the resultant DC magnetic field in the film is low enough not to cause magnetic saturation.

Consistency of the thin-film inductor at multiple locations on the wafer has also been checked. In summary a comprehensive set of measurement results have been presented for thin-film magnetic inductors.

V. CONCLUSION

The design process of thin-film magnetic inductors was presented. The process integration flow was described. A set of thin-film inductors were fabricated and the inductance, quality factor, DC resistance, and inductance boost factor have been measured. For inductors in the 20nH to 45nH range an inductance boost factor of 16X was obtained compared to the air-core counterparts, for 2µm thick magnetic core. The peak quality factor was 8 at 60MHz for 30nH inductor. With a proven design and integration flow, further optimization is possible to achieve the required inductor efficiency for IVR applications.

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REFERENCES