Magnetic materials and design trade-offs for high inductance density, high-Q and low-cost power and EMI filter inductors

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Abstract— **This paper investigates the trade-offs in inductance density and quality factor of inductors with and without magnetic-cores through modeling, design, fabrication and model-validation through characterization. Two type of inductors, one for power-supply and the other for EMI filters, are investigated. Parametric analysis was performed to study the enhancement in inductance density without compromising the current handling and efficiency. For EMI filter inductors, the inductance and quality factor (Q) were improved by 13X and 4X respectively with and without magnetic cores. For power inductors, the inductance and quality factor were improved by 5X and 1.6X respectively. The fabricated magnetic core inductors achieved 5X reduction in thickness, compared to the stage-of-the-art air-core inductors which use multilayered and thick solenoid.**

Keywords—magnetic materials; power inductors; EMI filter inductors

I. INTRODUCTION

Increased power levels in consumer electronic systems are driving the need for integrated power supply modules in 3D architectures for efficient power management. Delivering noise-free power with the required voltage and current levels is a major barrier to such systems, in power efficiency and system miniaturization. Various voltage regulators and noise filters are incorporated currently between the power source and device load in order to regulate the power supply. These regulators consist of a network of switches and storage components such as capacitors and inductors that transfer power to the load at the desired levels. The key barriers to miniaturization, performance and cost in integrated voltage regulators arise from the lack of suitable magnetic materials with required properties such as permeability, loss, frequency-stability and current-handling. Today's inductors for power supply are either components that are surface-mount assembled on the board or integrated in the package or on-chip. Trade-offs between power handling, efficiency and size impose key constraints to inductor design, which forms the key focus of this paper.

Current power-supply inductors are primarily based on ferrites, and are surface-mounted as discrete components. This results in high parasitics, thus degrading their performance. The size of ferrite inductors are typically ~1.8×1.12×0.91 mm^3 with inductances of upto 1.5 microhenries and Q of 18 at 1-10 MHz [1]. Their large component thickness also creates additional challenges with respect to component embedding. Most high-permeability ferrites are usually stable upto 5 MHz, as suggested by the Snoek's limit [2], which further limits their performance.

Integrated inductors provide performance and miniaturization benefits compared to discrete thick ferrite inductors because of their suppressed parasitics and reduced board or package real estate. A schematic cross section of integrated inductors is shown in Fig.1 where inductors are integrated on substrate, together with capacitors and IC chips to achieve miniaturization of power modules [3]. They can be nonmagnetic or combined with magnetic materials to enhance the inductance and reduce the size. The combination of magnetic materials with inductors can be categorized into two types [4]. In one type, the conductor is wrapped around a planar magnetic core using metal windings e.g. toroid inductors, as shown in Fig. 2. In another type, planar coils of inductors are enclosed by magnetic materials e.g. spiral inductor which have high inductance, low dc resistance and high Q factor [5-7], as shown in Fig. 3. The final goal for integrated inductors is to miniaturize inductors as thinfilms, well-within the IC footprint. Such inductors are recently demonstrated by Intel and TSMC, using cobalt alloy based nanoscale films with peak inductance density of $290nH/mm^2$, quality factor 15 at 150MHz, current density exceeding $11A/mm^2$ [8].

The magnetic materials used in integrated inductors should have high permeability, high frequency-stability and low loss. They should also be easily integrated with package processes for manufacturability such as screen-printing, lamination and patterning. Magnetic composites, comprising of magnetic metals to provide high permeability and high saturation magnetization and non-conducting polymers to provide high resistivity to reduce eddy current losses [2] are ideally suited for low-cost package integration.

This paper investigates trade-offs in inductance and quality factor (Q) of thin-film inductors with and without magnetic cores. The first part of the paper describes the miniaturization and Q improvement with magnetic cores, through modeling and design. The second part of this paper focuses on nonmagnetic core inductors for power supply and EMI filter applications. The third part of the paper focuses on inductors with magnetic cores.

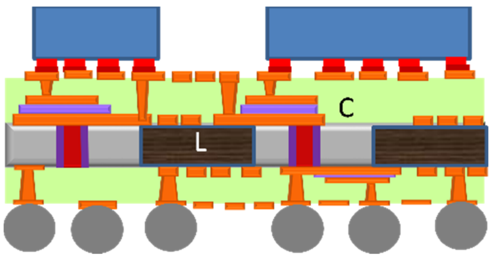


Figure 1. 3D IPD with integrated thin-film inductors.

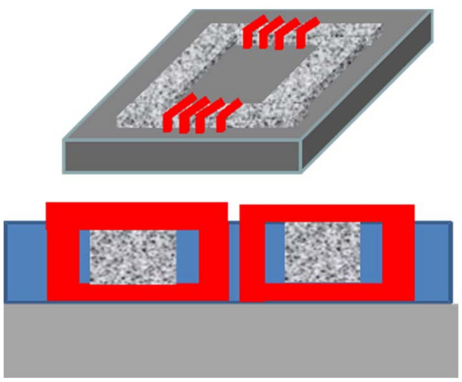


Figure 2. Top view and cross section of toroid inductors.

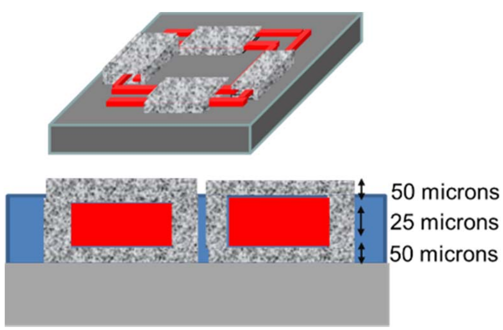


Figure 3. Top view and cross section of spiral inductors.

II. Performance Trade-off Analysis

Inductance density is typically enhanced by increasing the number of copper coil turns, however, at the expense of the coil resistance, which degrades the quality factor. In general, incorporation of magnetic materials as inductor cores can enhance the inductance density and reduce the need for the number of copper coil turns, thereby increasing the quality factor. However, magnetic materials introduce other challenges because of intrinsic eddy currents, hysteresis losses and magnetic saturation at low currents which causes the inductance to droop with the DC current. The inductor design and magnetic materials selection, therefore, need to be optimized based on the desired frequency, power handling, efficiency and inductance density.

Three inductors were designed and modeled with SONNET, Type-a inductor with magnetic core, Type-a inductor with nonmagnetic core and Type-b inductor with nonmagnetic core as shown in Fig. 4.

Type-a inductors were designed to maintain a net DC resistance of 50 milli-ohms. At this resistance, the calculated quality factor from DC losses were ~18. As seen in Table I, inductance was enhanced at the expense of quality factor and size for Type-a nonmagnetic core inductors compared to Type-b nonmagnetic inductors. For Type-a magnetic core inductors, both the inductance and quality factor are enhanced compared to Type-a nonmagnetic core inductors.

The net quality factor of the inductor is estimated according to Equation 1.

$$\frac{1}{Q} = \frac{1}{Q_1} + \frac{1}{Q_2} \tag{1}$$

where Q reflects the net quality factor for the power inductors, Q_1 reflects the losses caused by DC resistance and Q_2 reflects the AC losses caused by materials such as eddy current and hysteresis losses. The quality factor of the advanced magnetic films used in this paper was estimated to be much higher (25-50) based on initial small–signal measurements. Therefore, AC losses from magnetic materials do not significantly affect the overall power efficiency.

Although magnetic cores improve inductance without scarifying quality factor, cores also set a limit on power handling which could be estimated based on Equation 2 [9].

$$I_{max} = \frac{B*A*N}{L} \tag{2}$$

where B is the magnetic flux density, A is the cross section of the inductor magnetic loop with integrated magnetic materials, N the number of turns and L is the inductance. For Type-a magnetic core inductors with 250 nH/mm^2, the Imax set by the magnetic cores was calculated to be 3.6 amps or 40 A/mm^2. The current handling with higher density inductors of 1000 nH/mm^2 is much smaller (0.6 A/mm^2). Therefore, inductor design and magnetic materials selection trade-offs need to be understood in order to simultaneously meet the target power efficiency (Q) and power handling (A/mm^2).

Table I. Inductor Parameters

#	Core	Size (mm^2)	L (nH)	R_{DC} (micro-Ω)	Q_1
a	Magnetic	0.3x0.3	25.6	55.8	17.9
a	Air	0.3x0.3	2.3	55.8	17.9
b	Air	1x1	25.9	460	2.2

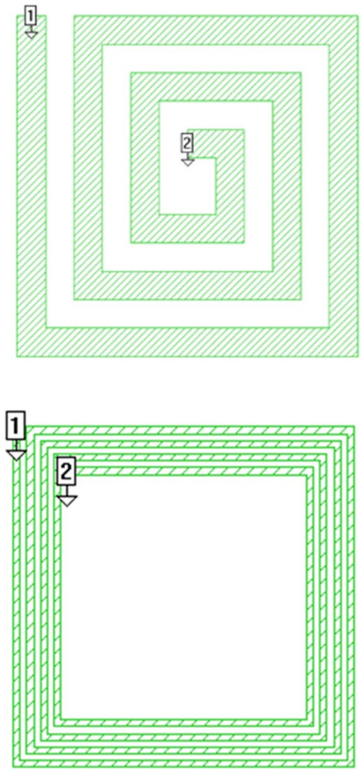


Figure 4. Power inductors with two different designs.

III. NONMAGNETIC CORE INDUCTORS

Inductors with high inductance (~1000 nH) and quality factor (~16) with small size (~1x1 mm^2) are targeted for power-supply applications. Inductors with inductance of ~15 nH, Q of ~ 16 and size of 0.6x0.6 mm^2 are targeted for EMI filter applications.

A. Simulation

Both power and EMI filter inductors were designed and simulated with SONNET, a 2.5 D magnetic simulation software, to obtain inductance and quality factor at 7 MHz as shown in Table II. Parametric analysis study showed that the designed inductor without magnetic cores had inductance density of less than 3 nH/mm^2 when the quality factor was targeted to be above 15 at 7 MHz. Inductors with higher density showed lower Q because of high coil resistance. Inductor designs are shown in Fig. 5. For power inductors, the designed line width was 20 microns, line spacing was 20 microns and thickness was 25 microns. For EMI filter inductors, the designed line width was 230 microns, line spacing was 80 microns and thickness was 25 microns.

B. Fabrication and Characterization

Nonmagnetic core inductors were fabricated and characterized to validate the models. The fabricated inductors were shown in Fig. 6. A 5-micron ABF™ layer was vacuum-laminated onto an organic substrate. Photoresist was then laminated on the ABF™ and went through lithography process to form traces with designed dimensions. Copper spirals were then electroplated inside the traces and photoresist was removed leaving inductors with designed dimensions. The process flow was shown in Fig. 7. The fabricated inductors for power supply applications had copper line width of ~13 microns, copper line spacing of ~33 microns and thickness of ~17 microns. For EMI filter inductors, the copper line width was ~222 microns, copper line spacing was ~113 microns and copper thickness was ~20 microns. The fabricated inductors were then characterized with LCR meter to measure inductance and quality factor at 7 MHz which was the operational frequency of EMI filter and wireless power devices as shown in Table II. The measured values were consistent with simulation results.

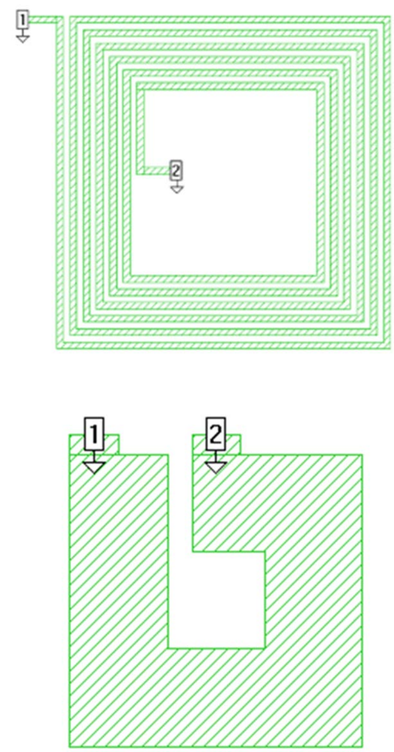
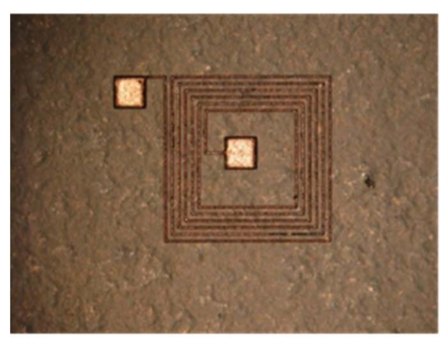


Figure 5. Deisgned indcutors, top) power inductor and bottom) EMI filter inductor.



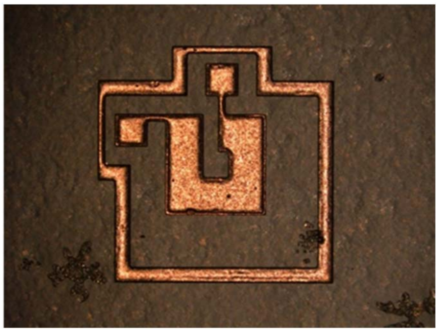


Figure 6. Fabricated inductors , top) power inductor and bottom) EMI filter inductor.

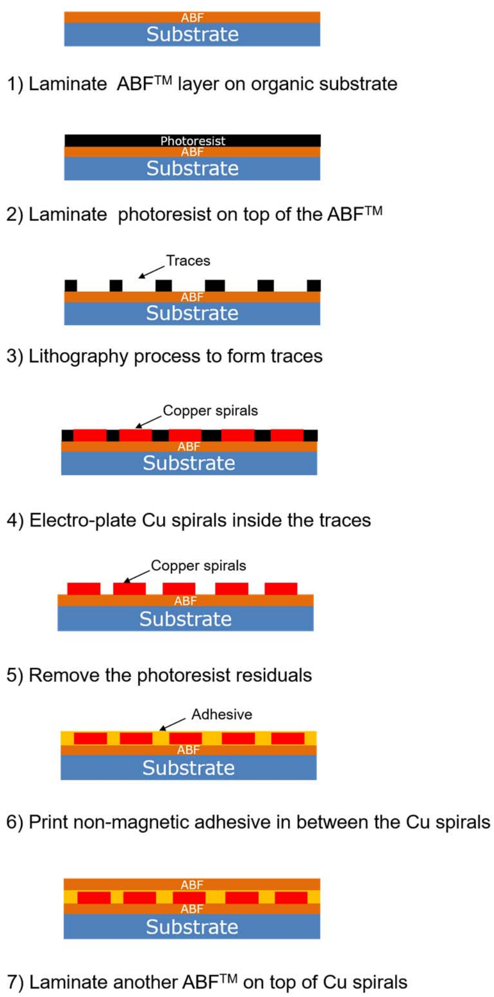


Figure 7. Process flow of fabrication of nonmagnetic core inductors

TABLE II. SIMULATED AND MEASURED VALUES OF INDUCTANCE AND QUALITY FACTOR FOR POWER AND EMI FILTER INDUCTORS

	Inductors	L (nH)	Q
Simulated values	Power	40	2.4
	EMI filer	0.61	3.6
Measured values	Power	33.4	2.09
	EMI filer	0.626	3.69

TABLE III. SIMULATED AND MEASURED VALUES OF INDUCTANCE AND QUALITY FACTOR FOR POWER AND EMI FILTER INDUCTORS WITH MAGNETIC CORES

	Inductors	L (nH)	Q
Simulated values	Power	1050	16
	EMI filer	15	16
Measured values	Power	160	3.34
	EMI filer	8	14.3

IV. MAGNETIC CORE INDUCTORS

A. Simulation

A low-loss (loss tangent of 0.02 till 10 MHz) magnetic film with permeability of 100 was used as the magnetic core. SONNET simulation showed that power inductors with the same design as nonmagnetic core inductors had inductance of ~1050 nH and quality factor of ~ 16 when the advanced magnetic films were integrated with the Cu spirals. For EMI filter inductors, the inductance and quality factor increased to 15 nH and 16 respectively with the advanced magnetic films were integrated with the spirals. The simulation results were shown in Table III. Magnetic core spiral inductors were then fabricated to validate the models.

B. Fabrication and Characterization

Magnetic films were first laminated onto an organic substrate with a 5-micron ABF^{TM} as the adhesive layer. Another 5-micron ABF^{TM} layer was then laminated onto the top of the magnetic film. Photoresist was then laminated on the ABF^{TM} and went through lithography processing to form traces with designed dimensions. Copper spirals were then electroplated inside the traces and photoresist was removed leaving inductors with the designed dimensions. Adhesive was printed on copper spirals after electroplating. Another magnetic film was then laminated above the adhesive. The inductance and quality of fabricated inductors were shown in Table III. The process flow was shown in Fig. 8. The fabricated magnetic inductors were shown in Fig. 9.

EMI filter inductors with integrated magnetic cores showed ~13X improvement in inductance and ~4X improvement in quality factor. For power inductors, the measured inductance showed ~5X improvement in inductance and ~1.6X improvement in quality factor. The actual improvements were smaller than the predicted improvements. The inconsistences arised from two factors. One factor was the large opening in the magnetic film that was drilled for measurement, as shown in Fig. 10. This opening caused magnetic flux leakage, resulting in lower inductance in comparison with the simulated values which assumed no opening on magnetic film. The other factor was the nonmagnetic adhesive used, which has a relative permeability of 1. The model assumed that the copper spirals are covered with a magnetic adhesive of high permeability.

Fig. 11 showed a schematic of a magnetic core inductor under simulation condition where there was no large opening in the magnetic film and the inductor was covered with a magnetic adhesive. However, even with the nonmagnetic adhesive, the data clearly illustrates the enhancement in inductance density and quality factor with the innovative magnetic films and their process integration.

The total thickness of fabricated power and EMI filter inductors was less than 150 microns as shown in Fig. 3. These inductors achieved 5X reduction in thickness compared to the state-of-the-art air-core inductors which used multilayered and thick solenoid designs to achieve the same inductance area density.

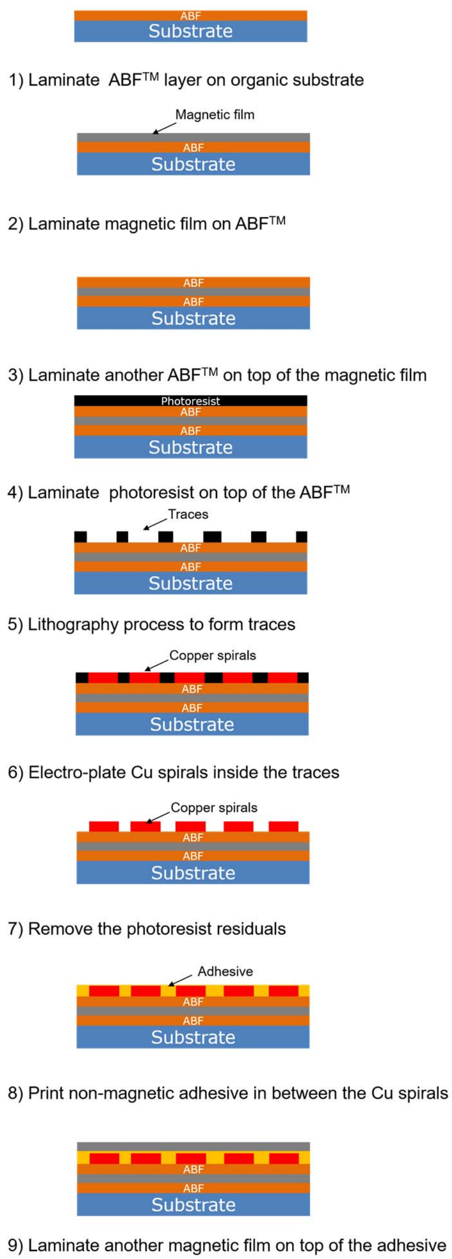


Figure 8. Process flow of magnetic core inductors fabrication

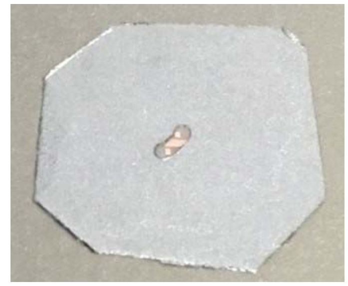


Figure 9. Fabricated magentic core inductors

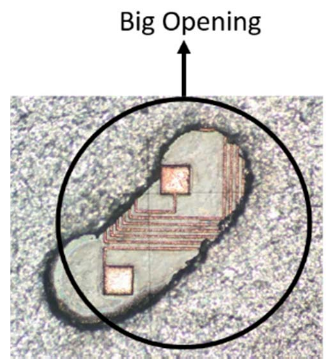


Figure 10. Probing of spiral inductors through openings in the top magnetic film.

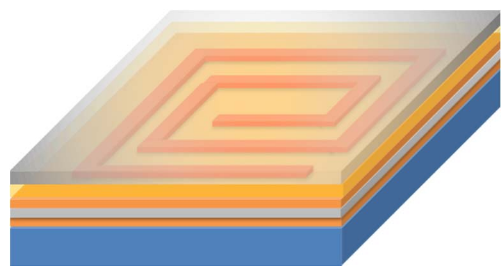


Figure 11. The schematic of a magnetic core inductor under simulation condtion.

V. SUMMARY

Modeling, design and analysis of inductance density, quality factor and current-handling were performed to understand the performance improvements with innovative magnetic films compared to nonmagnetic dielectrics. Incorporation of magnetic films increases the inductance by 11X without sacrificing the quality factor. In order to achieve the same improvement without magnetic films, the inductor's size need to be increased by 11X which also results in 8X increase in resistance and DC-loss. Thus, the incorporation of magnetic materials is critical to improve inductance without compromising the quality factor and size. The current handling limit for each design was also estimated to understand the trade-offs in power handling and efficiency.

Inductors for power supply and EMI filter applications, were investigated through modeling, design, fabrication and model-validation. EMI filter inductors showed 13X improvement in inductance and 4X improvement in quality when magnetic films were integrated. Power inductors showed 5X improvement in inductance and 1.6X improvement in quality factor when magnetic films were integrated. The magnetic core inductors achieved 5X reduction in thickness and the same inductance area density when compared to the state-of-the-art air-core inductors which use multilayered and thick solenoid designs.

VI. References

[1] Coilcraft product, Ferrite chip inductors – 0603af.

[2] Raj, P. M., Mishra, D., Sharma, H., Swaminathan, M., & Tummala, R. Nanomagnetic Materials and Structures, and their Applications in Integrated RF and Power Modules.

[3] Raj, P. M., Chakraborti, P., Mishra, D., Sharma, H., Gandhi, S., Sitaraman, S., & Tummala, R. (2015). Novel Nanostructured Passives for RF and Power Applications: Nanopackaging with Passive Components. In *Nanopackaging: From Nanomaterials to the Atomic Scale* (pp. 175-189). Springer International Publishing.

[4] Mathúna, C. Ó., Wang, N., Kulkarni, S., & Roy, S. (2012). Review of integrated magnetics for power supply on chip (PwrSoC). *Power Electronics, IEEE Transactions on*, *27*(11), 4799-4816.

[5] E. J. Brandon, E. Wesseling, V. White, C. Ramsey, L. D. Castillo, and U. Lieneweg, "Fabrication and characterization of microinductors for distributed power converters," *IEEE Trans.Magn.*, vol. 39, no. 4, pp. 2049–2056, Jul. 2003.

[6] Y. Katayama, S. Sugahara, H. Nakazawa, and M. Edo, "High power density MHz—Switching monolithic DC–DC converter with thin film inductor," in *Proc. 31st IEEE Annu. Power Electron. Spec. Conf.*, Jun. 2000, pp. 1485–1490

[7] C. H. Ahn and M. G. Allen, "Micromachined planar inductors on silicon wafers for MEMS applications," *IEEE Trans. Ind. Electron. (Special Issue for MEMS)*, vol. 45, no. 6, pp. 866–876, Dec. 1998.

[8] Sturcken, N., Davies, R., Wu, H., Lekas, M., Shepard, K., Cheng, K. W., & Wu, J. Y. Magnetic Thin-Film Inductors for Monolithic Integration with CMOS.

[9] Ludwig, M., Duffy, M., O'Donnell, T., McCloskey, P., & Mathùna, S. C. Ó. (2003). PCB integrated inductors for low power DC/DC converter. *Power Electronics, IEEE Transactions on*, *18*(4), 937-945