Ferrite-Based Integrated Planar Inductors and Transformers Fabricated at Low Temperature

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Abstract - **Fully integrated microinductors and microtransformers based on two different geometries and ferrite composite materials are designed, fabricated, tested, and compared. These devices are based on screen printed polymer/ferrite composites and electroplated copper coils, and are deposited at low temperature, making them compatible with organic electronic packaging substrates.**

I. Introduction

Although magnetically soft NiZn and MnZn ferrites are widely used as core materials for inductors and transformers operating at high frequency due to their high resistivity characteristic, their application to the realization of integrated microinductors and microtransformers on low temperature organic substrates (e.g., printed wiring board or FR-4) has been limited due to the obstacle of low temperature deposition. In this work, magnetic devices are formed by the combination of fine, lithographically patterned coils with screen-printed ferrite composites [1,2] in a polymer binder to form fully integrated microinductors and microtransformers. This approach is attractive since it is not only low temperature, but also allows the incorporation of relatively thick magnetic cores into the structures, which gives a larger energy storage capability required for magnetic power devices. The application of ferrite magnetic materials as core materials for integrated inductors and transformers is appropriate to minimize eddy current losses as well as to act as a shielding material to reduce device-to-device electromagnetic interference (EMI) at high frequencies.

II. Model And Design

Fully integrated inductors and transformers can be designed with differing geometries such as spiral, meander, and solenoid type. Spiral type devices are commonly used because of their simple geometries, easy fabrication sequences, and high inductances. However, these devices may have high electrical resistance due to their long conductor lines and also occupy large areas compared with other type devices. To avoid this problem, conductor lines can be stacked vertically and each layer of conductor line can be connected using a electroplated via. The spiral type design is also preferred for integrated microtransformers to reduce leakage flux from the windings and the core. Leakage flux causes imperfect coupling which results in nonideal transformer behavior, e.g., the transformer voltages are no longer related simply by the turns ratio.

The characteristics of integrated inductors and transformers are strongly dependent on many parameters such as device structure, number of windings, conductor width/space sizes, device substrate, and the magnetic properties of the core. The inductance of multilayer spiral inductors with m layers and N turns per each layer can be calculated by the following equation [3]:

$$L = m^2 \sum_{j=1}^{N}\left(L_{jj} + 2\sum_{k=j+1}^{N} L_{jk}\right) - L_1 \quad (1)$$

where L_{jj} is the self inductance, L_{jk} is the mutual inductance between the j^{th} turn and k^{th} turn of one layer spiral inductor, and L_l is the leakage inductance. The dominant factor is the core inductance, L_c, in the expressions of self inductance and mutual inductance defined as:

$$L_C = (mN)^2 / R \quad (2)$$

where R is the the reluctance in the core. The core inductance can also be dominant in the calculated total inductance.

III. Magnetic Core Materials

A. Fabrication of Polymer Filled NiZn and MnZn Ferrite

The magnetic composite materials used for the integrated inductors and transformers are composed of 1.12 μm NiZn and 1.08 μm MnZn ferrite particles and Dupont Polyimide 2555. Various additives are used to disperse particles and a ball mill rotator is used for insuring the homogeneity of the mixed composite materials. The well-mixed materials can be deposited by spin casting and screen-printing, but screen-printing is preferred for achieving thick magnetic films required for improved performance characteristics of the fabricated inductors and transformers. The deposited films are cured at low temperatures compatible with organic substrates. Magnetic fields can be applied to improve magnetic properties before and after curing.

B. Experimental Results and Discussion

Screen printed composite materials were characterized using a Lake Shore vibrating sample magnetometer. The measured sample show the MnZn ferrite composite material has higher saturation flux density (0.31 T) and initial permeability (33) than NiZn ferrite composite material (B_s = 0.25 T, μ_i = 25) as shown in Figure 1. The composite materials show negligible electrical conductivity which is desirable for high frequency magnetic devices; thus, eddy current losses can be neglected.

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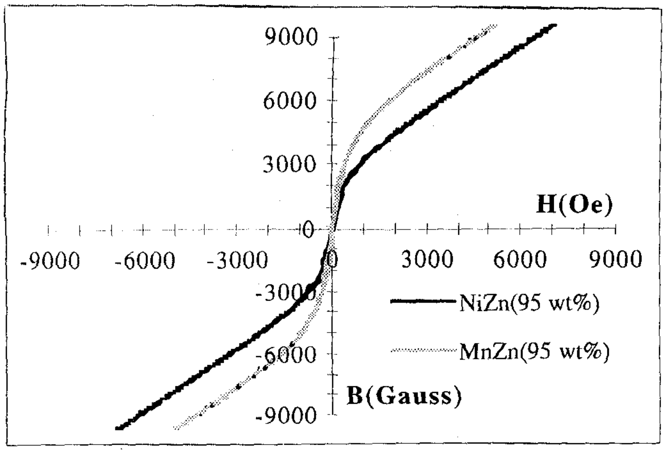


Fig. 1. Comparison of B-H characteristics of spin cast ferrite composites

IV. Integrated Inductors And Transformers

A. Fabrication of EMI Shielded Inductors and Transformers

As shown in Figure 2, the well-mixed ferrite composite was deposited on the substrate by screen printing and cured to remove the solvents. A metal seed layer was deposited on top of the composite for electroplating conductor lines using electron beam evaporation. Thick photoresist (25 μm) was spin-cast and patterned into spiral molds. The molds were filled with electroplated copper and removed. After removing the seed layer to isolate conductor lines, ferrite composite was screen printed on the top of copper conductor lines and between the conductor lines and cured. Figure 3 shows an EMI shielded integrated inductor and transformer with spiral type coils.

B. Fabrication of Two Layer Spiral Coil Inductors and Transformers

Figure 2 shows the brief fabrication sequences. The patterned seed layer was formed on the substrate to form a conductor network to be removed after serving as the seed layer for plating of the conductor and via [4]. Dupont PI2611 was spun on the top of the patterned seed layer to construct electroplating molds for lower conductor lines and cured.
Aluminum hard mask in patterned spiral type was used to etch out the polyimide in order to form electroplating molds for lower conductor lines. The molds were filled with electroplated copper and one coat of polyimide was applied to isolate the lower conductor lines and the upper conductor lines. Via holes were formed by plasma etching and filled with electroplated copper.

After depositing another metal seed layer, molds for the upper conductor lines were formed using thick photoresist and filled with electroplated copper. After removing the photoresist molds and the seed layer, a polyimide passivation layer was coated and cured to passivate the top conductor lines. The polyimide was etched to expose the bottom patterned seed layer and open the area for the screen printed magnetic core. The patterned seed layer was wet-etched and ferrite composite was screen-printed and cured. Figure 4 shows the photomicrograph and the scanning electron micrograph (SEM) of the two layer spiral coil transformers.

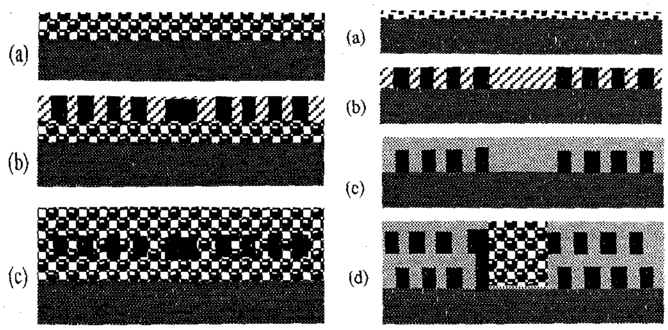
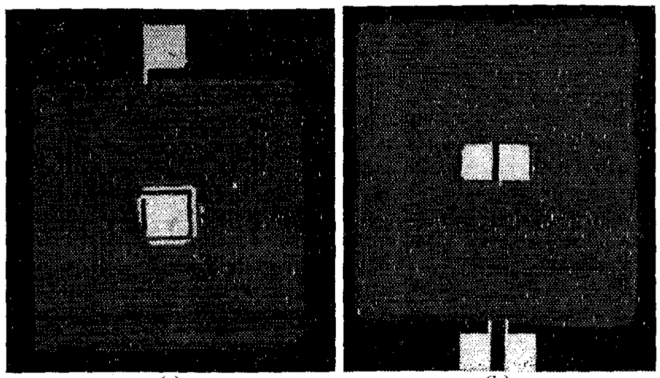
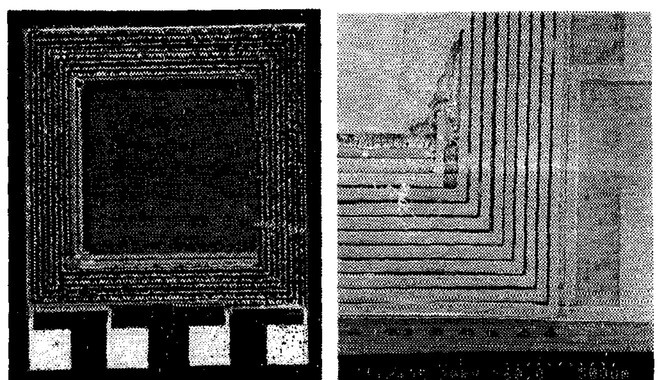


Fig. 2. (Left) Fabrication sequences of EMI shielded inductors and transformers: (a) Polymer filled ferrite screen-printed on substrate, (b) Plating mold is formed for conductor lines and plated with copper, (c) After removing the mold, composite is screen-printed again. (Right) Fabrication sequences of two layer inductors and transformers: (a) Patterned seed layer formed, (b) Plating mold formed and filled with copper, (c) Insulation material is applied, and via is formed and plated, (d) Step (b) is repeated, Core is patterned and filled with screen-printed composite, and cured



(a) (b)

Fig. 3. (a) Photomicrograph of EMI shielded microinductor with ferrite composite and spiral type copper coils (Dimension: 2.6mm x 2.6mm x 70 μm), (b) Photomicrograph of EMI shielded microtransformer with ferrite composite and spiral type colis (Dimension: 2.6mm x 2.6mm x 70 μm)



(a) (b)

Fig. 4. (a) Photomicrograph of vertically stacked microtransformer with ferrite composite and two layer spiral coils (Dimension: 3mm x 3mm x 50 μm), (b) Scanning electron micrograph of upper and lower conductor lines, ferrite core, and bonding pads of two layer spiral type microtransformers

C. Experimental Results and Discussion

These integrated inductors and transformers were characterized using a Hewlett-Packard 4194A impedance and gain/phase analyzer. As shown Figure 5, the integrated inductors and transformers incorporating MnZn ferrite composite have higher inductance than the corresponding NiZn ferrite composite devices, corresponding to the B-H characteristics of tested core materials shown in Figure 1.

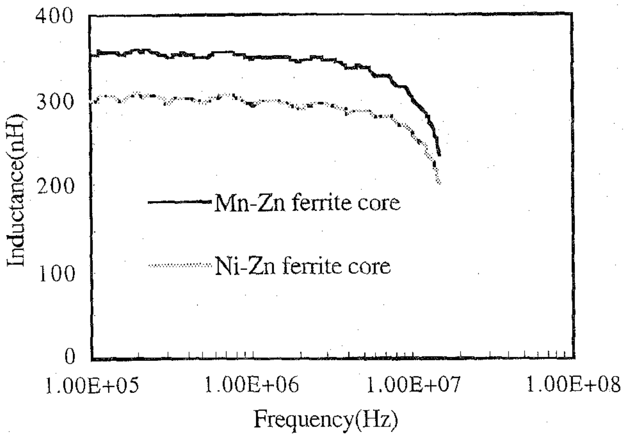


Fig. 5 Comparison of inductance of EMI shielded sandwich type spiral inductors with dimension 2.6mm x 2.6 mm x 70 μm and 12 turns

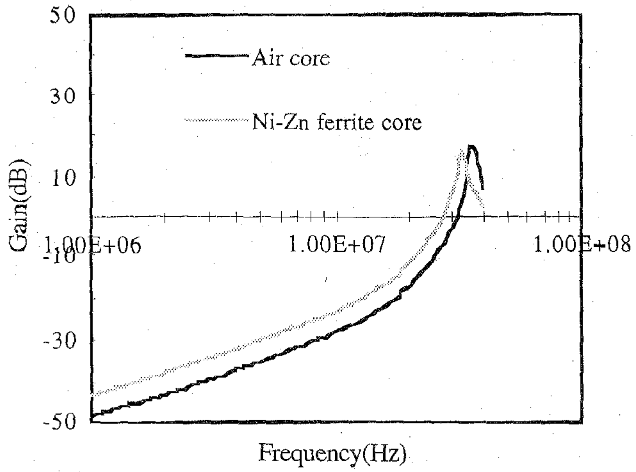


Fig. 6 Comparison of gain of EMI shielded sandwich type spiral transformers (dimension 2.6 mm x 2.6 mm x 70 μm, primary coils are 7 turns, and secondary coils are 6 turns)

Figure 6 shows gain-phase characteristics of integrated sandwich type spiral coil microtransformers with and without composite magnetic materials. The composite based microtransformers have higher gain characteristics than microtransformers without composite. The reduced leakage flux due to the applied ferrite composite between conductor lines and on the top and bottom of conductor lines may increase coupling factor between the primary and the secondary coils. As shown in Figure 7, two layer spiral coil microtransformers which have the same geometry and different magnetic core materials have the same characteristics of gain and phase. As seen, the gain-phase characteristics of microtransformers are dependent not on the magnetic core materials but on the geometry of the fabricated devices. The inductances of the primary and the secondary coils in two layer spiral transformers are ranged from 350 to 550 nH. The primary inductance is slightly higher than secondary inductance corresponding to the ratio, 1.17 : 1, of the primary winding to the secondary winding.

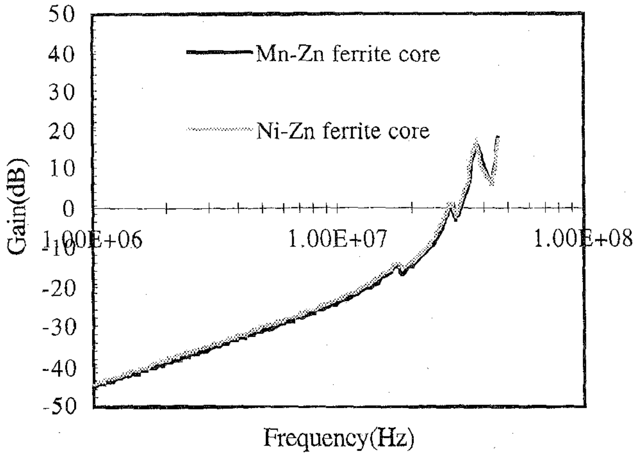


Fig. 7 Comparison of gain and phase of two layer spiral coil transformers (dimension is 3mm x 3mm x 50 μm, primary coils are 8 turns, and secondary coils are 7 turns)

V. Conclusions

Fabricated microinductors and microtransformers with ferrite composite magnetic core materials have been presented. Such devices have many advantages in integrated passives (resistors, capacitors, and inductors) modules applications. These advantages include: a variety of promising geometries, ease of fabrication, higher silicon packaging density due to the feasibility of vertically stacked devices, reducing the need of assembly, and low temperature processing comparable with low cost organic substrates. Since the fabricated integrated inductors and transformers have comparable fabrication sequences with other integrated passives such as capacitors and resistors, they are promising devices for multichip modules, miniaturized power converters, and other miniaturized electronic systems.

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