Packaging-Compatible Microinductors and Microtransformers with Screen-Printed Ferrite Using Low Temperature Processes

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Abstract - **Fully integrated microinductors and microtransformers compatible with organic (low-temperature) electronic packaging are investigated for miniaturized power converters, filters, multichip modules (MCMs), and other consumer electronic products. Four differing geometries of ferrite-based integrated magnetic components have been designed, fabricated, and tested: sandwich-spiral, sandwich-meander, two layer vertically stacked spiral, and bar type (open and closed magnetic circuit). In the comparison of fabricated microinductors, two layers vertically stacked spiral inductors with 50 μm height has the largest inductance (15 μH/cm^2 at 10 MHz) and dc resistance (2.1ohms). The smallest inductance (1.2 μH/cm^2 at 1 MHz) and dc resistance (0.35 ohms) are achieved in the fabricated bar type microinductor with a closed magnetic core. In the comparison of fabricated microtransformers, the EMI shielded sandwich type spiral transformer has the best gain characteristics and the lowest resonant frequency (27 MHz), the EMI shielded sandwich- meander- type transformer has the worst gain characteristics, and the closed bar type transformer has the highest resonant frequency (38 MHz).**

Index Terms: Integrated, inductors, transformers, packaging, screen-printed, ferrite, composite, electroplating

I. INTRODUCTION

NiZn ferrite is widely used as a core material for high frequency inductors and transformers. Since it has higher resistivity than other magnetic materials, eddy current losses which are large at high frequency in metal-core inductors are reduced [1]. In order to create integrated magnetic devices (i.e., no hybrid device-to-package assembly) based on this material it is necessary to undergo a high temperature process. Screen printable ferrite magnetic pastes are commercially available and used for microwave devices and low power applications [2-3]. However, the temperature of firing these pastes, 750-950 °C is incompatible with organic substrates. And also, the fired pastes also show poor magnetic properties such as low relative permeability (eg. μ_r=10) [4]. In many cost-driven applications, the use of organic substrates (e.g., FR-4 or laminate (MCM-L) substrate) is desirable, which necessitates the use of low temperature (less than 230 °C) fabrication steps in realization of these components.

The purpose of this study is to develop ferrite composite materials, investigate fabrication techniques, and demonstrate appropriate geometries to realize integrated magnetic components for miniature DC/DC converters and other power supply applications which are compatible with electronic organic packaging.

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II. MODEL AND DESIGN

Bar, spiral, and meander type geometries are of interest to realize integrated magnetic devices. Bar type geometry in which the magnetic core is wrapped by conductor lines has short conductor lines resulting in low resistance, but has complicated fabrication sequences. Spiral type inductors are commonly used because of their simple geometries and easy fabrication sequences. However, these devices usually require large areas in order to achieve high inductance and quality factor, due to the area required for multiple conductor turns. To avoid this problem, conductor lines can be stacked vertically, and each layer of conductor line can be connected using a via. NiZn ferrite is an appropriate core material for integrated magnetic devices at higher frequencies due to its high resistivity and low dielectric constant. NiZn ferrite is also used as a shielding material at high frequency, which is desirable since integrated inductors, which may be in closer proximity to other components than hybrid-assembled devices, need to be shielded to reduce electromagnetic interference (EMI) during high frequency operation. Finally, integrated inductors should have compatible fabrication sequences with integrated capacitors and resistors to be used as integrated passives for multichip modules, miniaturized integrated power converters, and other miniaturized electronic systems.

III. FABRICATED FERRITE COMPOSITE MATERIALS

The magnetic composite material is composed of 1.2 μm NiZn ferrite particles produced by Steward company, and Dupont PI-2555 polyimide. The composite material was prepared from polymer binders, ferrite particles, dispersion agents, and a few ceramic balls were mixed was placed on a ball mill rotator for at least 48 hours to insure homogeneity of the mixed composite solution [5]. The well-mixed composite materials was deposited by screen printing or spin casting followed by photolithography at room temperature. The deposited films are cured at 160-300 °C to achieve final properties, the lower end of this temperature range is compatible with many organic substrates. The cure temperature of deposited composite materials is dependent on what binders (polymers or epoxy) are used to be mixed with magnetic powders.

The electrical resisitivity of polymer-filled NiZn ferrite was around 1 Mohm-cm and that of polymer-filled MnZn ferrite was about 0.01 Mohm-cm. The composite is desirable for high frequency magnetic devices to minimize eddy current losses. Magnetic properties of screen-printed composite materials were characterized using a Lake Shore vibrating sample magnetometer. The measured sample shows the MnZn ferrite composite material has higher saturation flux density (B_s = 0.31 T) and initial permeability (μ_i = 33) than NiZn ferrite composite material (B_s = 0.25 T, μ_i = 25)

IV. INTEGRATED MICRONDUCTORS AND MICROTRANSFORMERS

A. Fabrication of spiral type and meander type inductors and transformers with sandwich type composite magnetic core

The well-mixed NiZn ferrite composite was deposited on the substrate by screen printing and cured to remove the solvents. A metal seed layer (Ti/Cu/Ti) was deposited on top of the cured composite to be used as a seed layer during the electroplating of copper conductor lines. 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. The meander type magnetic devices have the same fabrication sequences as the spiral type devices. The only difference is conductor line geometry. Figure 1 shows an EMI shielded integrated inductor and transformer with spiral type coils.

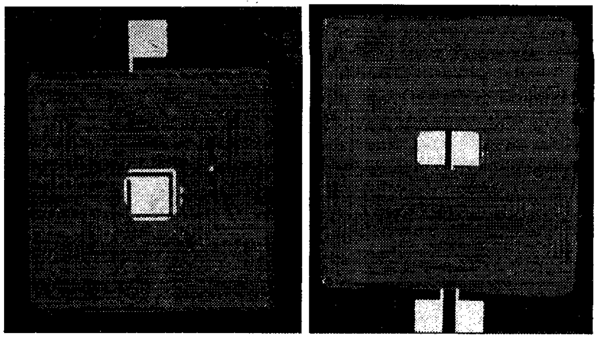
B. Fabrication of Two Layers Vertically Stacked Spiral Type Inductors and Transformers

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. Dupont PI2611 was spun on the top of the patterned seed layer to construct electroplating molds and cured. An aluminum hard mask 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 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 2 shows the photomicrographs of the two layers spiral coil inductors and transformers.

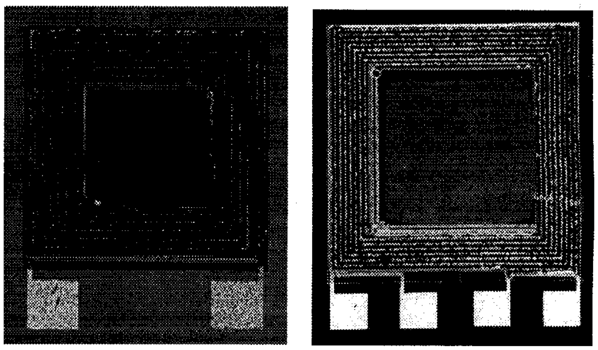
C. Fabrication of Bar Type Inductors and Transformers

The mesh-type seed layer was formed on the substrate. PI2611 was spun on the top of the patterned seed layer and cured. An aluminum hard mask was used to etch out the polyimide in order to form electroplating molds for solenoid-type lower conductor lines (20 μm thick). The molds



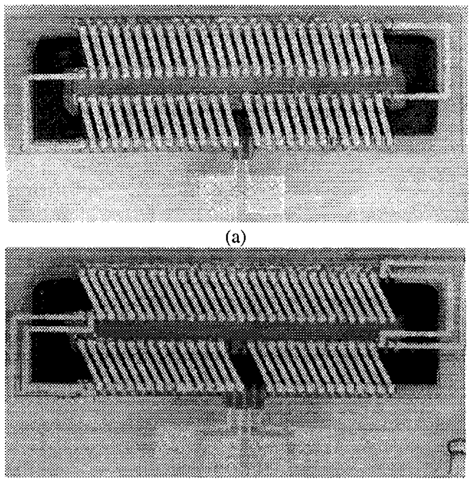
(a) (b)

Fig. 1. (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 coils (Dimension: 2.6mm x 2.6mm x 70 μm).



(a) (b)

Fig. 2. (a) Photomicrograph of two layers vertically stacked microinductor with ferrite composite and two layer spiral coils (Dimension: 2mm x 2mm x 50 μm), (b) Photomicrograph of two layers vertically stacked microtransformer with ferrite composite and two layer spiral coils (Dimension: 3mm x 3mm x 50 μm).



(a)

(b)

Fig. 3. (a) Photomicrograph of bar type microinductor with closed magnetic core (Dimension: 4mm x 1mm x 130 μm), (b) Photomicrograph of bar type micro transformer with a closed magnetic core (Dimension: 4mm x 1mm x 130 μm).

were filled with electroplated copper and NiZn ferrite composite was screen printed through the patterned (open and closed bar shape) mask and cured. 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 the 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 optionally masked and etched to the bottom. The bottom mesh-type seed layer the wet etched. Figure 3 shows the photomicrographs of the bar type integrated inductors and transformers.

D. Experimental Results and Discussion

The fabricated microinductors and microtransformers were characterized using a Hewlett-Packard 4194A impedance and gain/phase analyzer. As shown in Table I, the two layers vertically stacked spiral inductor with 50 μm height has the largest inductance (15 $\mu H/cm^2$ at 10 MHz) and dc resistance (2.1ohms). The smallest inductance (1.2 $\mu H/cm^2$ at 10 MHz) and dc resistance (0.35 ohms) are achieved in the fabricated bar type microinductor with a closed magnetic core. Meander-type devices have a negative mutual inductance which contribute to low total inductance due to the opposite current directions of two adjacent conductor lines, while spiral-type devices have a positive mutual inductance which contribute to high total inductance due to the same current directions of two adjacent conductor lines. As shown in Table II, sandwich type spiral transformer has the best gain characteristics and the lowest resonant frequency (27 MHz), sandwich type meander transformer has the worst gain characteristics, and closed bar type transformer has the highest resonant frequency (38 MHz). These integrated magnetic devices have high current capability (up to 2 A steady DC current) and are suitable for power applications. 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 turn ratio of the primary winding to the secondary winding of fabricated transformers is about 1.

TABLE I

COMPARSON OF INDUCTANCE, QUALITY FACTOR, AND DC RESISTANCE OF INTEGRATED MICROINDUCTORS

Four differing geometries of fabricated microinductors	**Inductance ($\mu H/cm^2$ at 10MHz)**	**Q-factor at 10 MHz**	**dc resistance (ohms)**
bar type with open magnetic core	2.1	5	0.65
bar type with closed magnetic core	1.25	7	0.31
Meander type with sandwich type magnetic core	5	8	1.15
Spiral type with sandwich type magnetic core	6.5	17	1.3
Two layers vertically stacked spiral type and open core	15	15	2.1

TABLE II

COMPARSON OF GAIN AND RESONANT FREQUENCY OF INTEGRATED MICROINDUCTORS

Four differing geometries of fabricated microtransformers (the ratio of turns 1 : 1)	**Gain characteristics (dB at 25 MHz)**	**Resonant frequency (MHz)**
bar type with open magnetic core	-11.5	33
bar type with closed magnetic core	-10	38
Meander type with sandwich type magnetic core	-13	31
Spiral type with sandwich type magnetic core	-1.25	27
Two layer vertically stacked spiral type and open magnetic core	-3.5	29

V. CONCLUSIONS

Batch-fabricated microinductors and microtransformers with ferrite composite magnetic core materials have been presented. Electroplated thick copper conductor lines and screen-printed ferrite magnetic composite materials were used to realize these integrated magnetic devices. 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 compatible 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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