Low Temperature Fabrication and Characterization of Integrated Packaging-Compatible, Ferrite-Core Magnetic Devices

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Abstract - Integrated magnetic components compatible with organic (low-temperature) electronic packaging for miniature DC/DC converters and other power supply applications are investigated. Two inductor types have been fabricated incorporating a polymer/ferrite composite core, deposited and patterned at low temperature. For the fabricated inductors, inductances in the 0.5-1.5 μH range and Q-factors on the order of 17 are achieved. In all cases, the incorporation of the polymer filled ferrite improved the characteristics of the integrated inductors.

I. INTRODUCTION

Magnetically soft NiZn ferrite is widely used as a core material for high frequency inductors and transformers in miniaturized power supply applications. 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 devices (i.e., no hybrid device-to-package assembly) based on this material it is usually necessary to undergo a high temperature fabrication step such as firing of ferrite-based pastes. However, in many cost-driven applications, the use of organic substrates is desirable, which necessitates the use of low temperature fabrication steps in realization of these components.

Much research has been performed for the deposition of ferrite films at low temperature, e.g., using spin spray coating, electroplating, RF sputtering, and magnetron sputtering [2-4]. However, these methods have relatively low deposition rates and usually produce thinner films than required. Thicker films are necessary to achieve high inductance, quality factor, saturation current, and other good performance characteristics in integrated inductors and transformers. The purpose of this study is to investigate fabrication techniques which are compatible with organic packaging to create integrated magnetic components for miniature DC/DC converters and other power supply applications.

II. INTEGRATED MAGNETIC DEVICES DESIGN

Integrated inductors for miniaturized power converters working in MHz frequency ranges should have desirable characteristics such as high inductance, quality factor, saturation current, and low resistance [5]. Integrated inductors can be designed with differing geometries such as spiral, meander, and bar type. Spiral type inductors are commonly used because of their simple geometries and easy fabrication sequences [6]. 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. In addition, magnetic cores are necessary to achieve high inductance and quality factor. NiZn ferrite is an appropriate core material for integrated power 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 comparable 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.

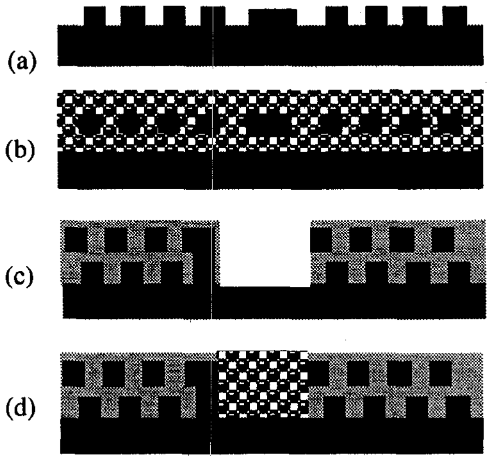

Fig. 1. The comparison of cross-sectional views of integrated magnetic devices; (a) Single layer spiral type inductor, (b) EMI shielded sandwich type spiral inductor with ferrite, (c) Two layer spiral type inductor with air core, (d) Two layer spiral type inductor with ferrite core

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In order to achieve the above discussed conditions, two different inductor designs are fabricated, tested, and compared in this paper. Figure 1 shows the cross section of the proposed integrated magnetic devices. The first inductor is an EMI shielded sandwich type spiral ferrite inductor, in which polymer filled ferrite is applied at the bottom, top, and between conductor lines using screen printing as shown in Figure 1-(b). An advantage of this geometry is its ease of fabrication. The second inductor is a two layer spiral type device, in which a spiral type layer with multiple conductor turns is vertically stacked and connected through the via as shown in Figure 1-(c), (d). Inductors of both types with and without polymer filled ferrite cores were fabricated to assess the effect of the ferrite in inductor performance.

Previously-developed models found in the literature of the inductance of planar spiral inductors of both geometries were used for design purposes [7-8]. The inductance is dependent on many parameters such as the inductor structure, number of windings, conductor line/space sizes, and the magnetic properties of the core. The dominant inductance comes from the path through the magnetic core, and the inductance is calculated by the following equation:

$$L = \frac{N^2}{\Re} \tag{1}$$

where $\Re$ is the magnetic reluctance and N is the number of coil turns. Once the inductance is known, the quality factor can be defined as:

$$Q = \frac{\omega L}{R}, R = \rho \frac{\ell_w}{A_w} \tag{2}$$

where R is the DC resistance, A_w is the cross-sectional area of the conductor, ω is the radian frequency, ℓ_w is the length of the conductor lines, and ρ is the resistivity of the conductor material. If the cross-sectional area of the magnetic core is increased, the inductance value will increase since the magnetic reluctance is decreased. If the cross-sectional areas of the magnetic core and the conductor lines are increased, the Q-factor will increase since the dc resistance is decreased, and the inductance is increased.

The other parameter of interest for integrated magnetic devices is the DC saturation current, defined as:

$$I_{sat} = \frac{B_s \Re A_c}{N} \tag{3}$$

Equation (3) shows that the DC saturation current is related to the magnetic properties of the core and the geometry of the magnetic device [9].

III. MAGNETIC CORE MATERIAL

A. Fabrication of Polymer Filled NiZn Ferrite

The composite material for the magnetic core is composed of 1.2 μm NiZn ferrite particles produced by Steward company, and Dupont PI-2555 polyimide. The measured magnetic particles are mixed into the polyimide, and various additives are used to disperse the particles [10-11]. The mixed composite materials are placed on a ball mill rotator for at least 48 hours to insure homogeneity of the mixed composite solution. The well-mixed composite materials are deposited by spin casting or screen printing. Due to the difficulty of etching thick layers of the composite materials, the screen printing method is preferred for micromagnetic devices. The deposited films are cured at 200 - 300 °C; the lower end of this temperature range is compatible with many organic substrates. Application of a magnetic field during the processing can improve the magnetic properties.

B. Experimental Results and Discussion

Screen printed polymer filled NiZn ferrite films were characterized using a Lake Shore vibrating sample magnetometer. The test sample shows a saturation flux density of 0.25 T and a initial permeability of 25 as shown in Figure 2. The material shows negligible electrical conductivity. Therefore, eddy current loss can be neglected.

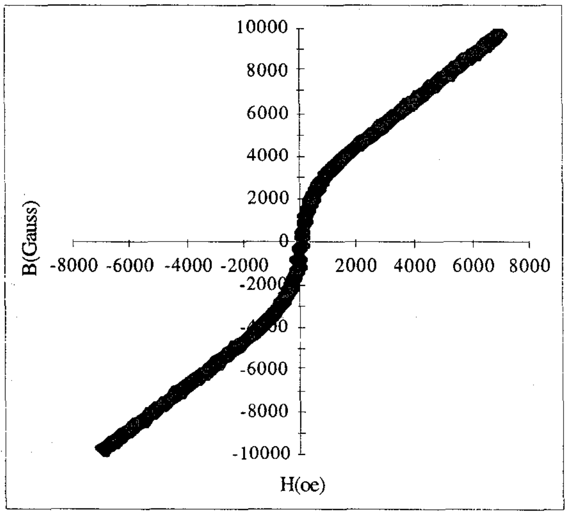

Fig. 2. B-H characteristics of polymer filled ferrite film

IV. INTEGRATED MAGNETIC DEVICES

A. Fabrication of EMI Shielded Sandwich Type Spiral Polymer Filled Ferrite Inductor

Figure 3 shows a brief fabrication sequence of the EMI shielded sandwich type spiral inductor. The process started with a glass substrate, which is both low cost and low dielectric constant compared with silicon. Polymer filled ferrite was deposited on the substrate by screen printing. The screen printed magnetic material was cured at 200-300 °C for 1 hour in nitrogen. Chromium/copper/chromium layers were deposited to form an seed layer for electroplating using electron-beam evaporation. Thick photoresist was coated , and molds were formed. After removing the top chromium layer, copper was electroplated into the photoresist molds to form the spiral conductors, and the molds were removed. The seed layer was wet-etched to isolate the conductor lines. Polymer filled ferrite was screen printed on the top of electroplated copper conductor lines and between the conductor lines, and cured to remove the solvents. Upon completion of the fabrication, the samples were diced and tested. Figures 4 and 5 show a single layer spiral inductor with air core and a sandwich type spiral inductor with polymer filled ferrite. Figure 6 shows the application of the integrated EMI shielded sandwich type spiral inductor in a fully integrated passive module containing resistors, capacitors, and inductors.

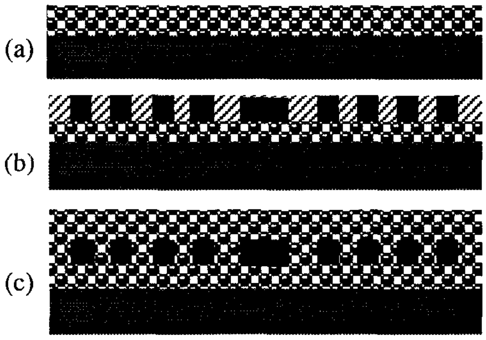

Fig. 3. Fabrication steps of EMI shielded spiral type ferrite inductors; (a) Composite material is screen-printed on glass, (b) Plating mold is formed and filled with plated copper, (c) Mold is removed and composite is screen-printed

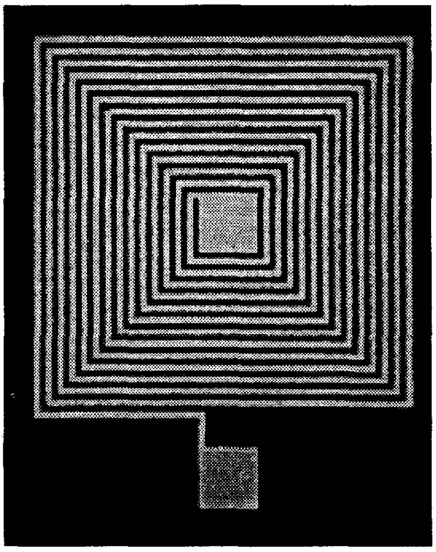

Fig. 4. Photomicrograph of spiral type inductor with no magnetic material (dimension: 2.6mm x 2.6mm x 15μm)

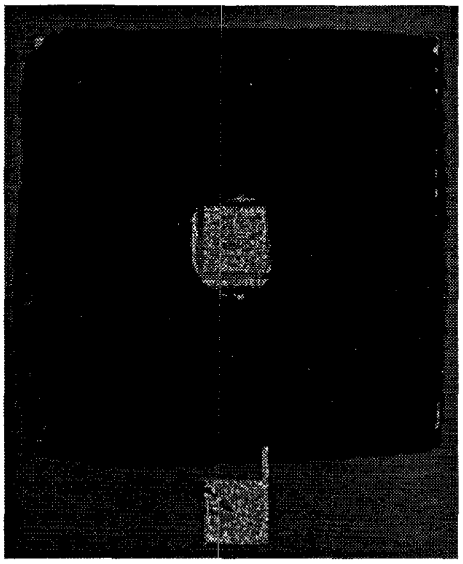

Fig. 5. Photomicrograph of EMI shielded spiral type ferrite inductors (dimension: 2.6mm x 2.6mm x 60μm)

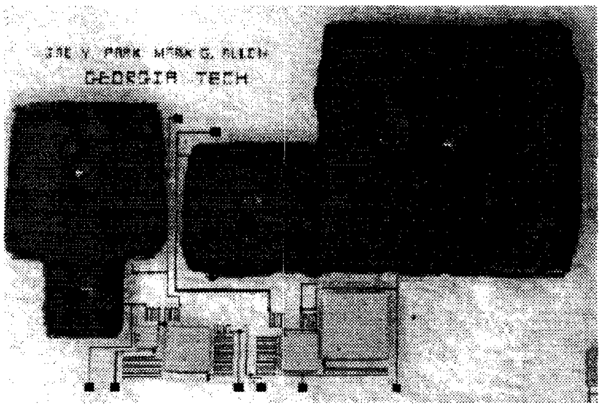

Fig. 6. Photomicrograph of integrated passives module (resistors, capacitors, and inductors; dimension: 8mm x 10mm)

B. Fabrication of Two Layer Spiral Inductors with and without Polymer Filled Ferrite

As shown in Figure 7, the fabrication of these devices also began with a glass substrate. Chromium/copper/chromium layers were deposited to form a seed layer for electroplating using electron-beam evaporation. The mesh-type seed layer was patterned to form a conductor network to be removed after serving as the seed layer for plating of the conductor and via. Polyimide (Dupont PI2611) was spun on the top of the mesh type seed layer to construct electroplating molds for the lower spiral conductor lines. Two coats were made to obtain 20 μm thick polyimide molds. After coating, the polyimide was cured at 200-300 °C for 1 hour in nitrogen. An aluminum layer (0.2 μm thick) was deposited on top of the cured polyimide as a hard mask for dry etching. Molds for lower

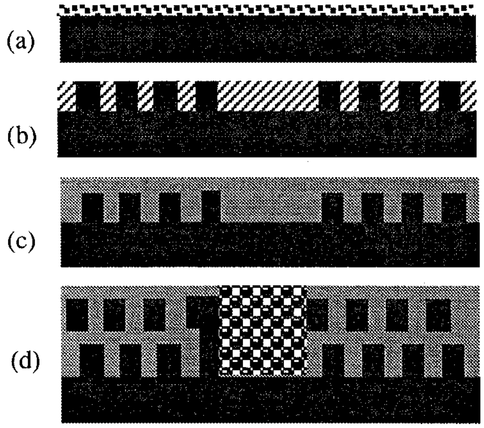

Fig. 7. Fabrication steps of two layer spiral type ferrite inductors; (a) Mesh type seed layer is patterned on glass, (b) Plating mold is formed and filled with plated copper, (c) Insulation material is applied, and via is formed and plated, (d) Step (b) is repeated, insulation material is applied, core is patterned, dry-etched, screen-printed with polymer filled NiZn ferrite, and cured.

conductor lines were patterned and etched using a plasma etcher until the seed layer was exposed. After etching the aluminum hard mask and the top chromium of the seed layer, the molds were filled with electroplated copper using standard electroplating techniques.

One coat of polyimide was spin-cast and cured to isolate the lower conductor lines and upper conductor lines. A via hole was patterned on a sputtered aluminum hard mask and etched through the polyimide layer using plasma etcher. The via hole was filled with plated copper. A copper/chromium seed layer was deposited, and molds for the upper conductor lines were formed using thick photoresist. The molds were filled with electroplated copper and removed. After removing the seed layer, a polyimide passivation layer coated and cured to protect the top conductor lines from oxidation.

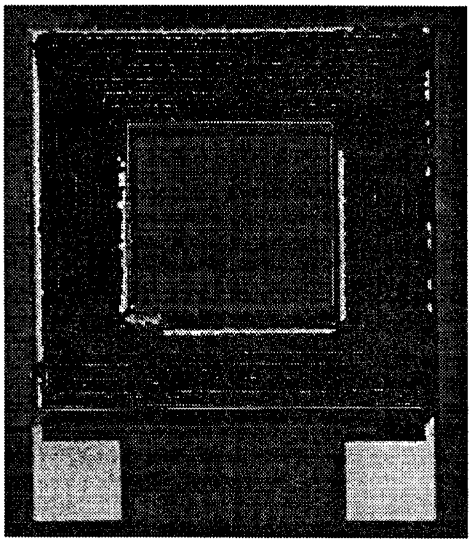

Fig. 8. Photomicrograph of two layer spiral type inductor with air core (dimension: 2mm x 2mm x 50μm)

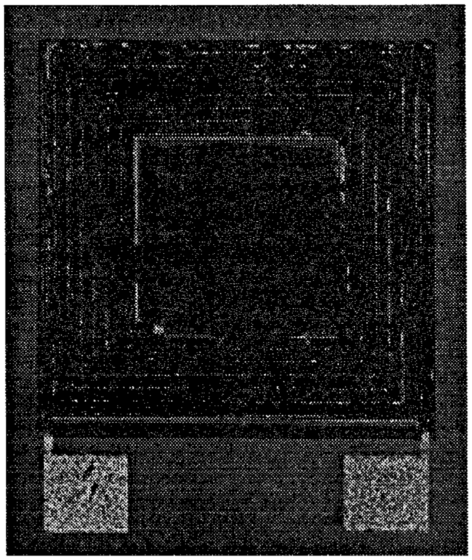

Fig. 9. Photomicrograph of two layer spiral type ferrite inductor (dimension: 2mm x 2mm x 50μm)

The polyimide was optionally masked and etched to the bottom layer. The bottom mesh seed layer was then wet etched. Polymer filled ferrite was screen printed on the dry etched core mold and hard-cured. After the completion of fabrication, samples were tested. Figures 8 and 9 show two layer spiral inductors with and without polymer filled ferrite core, respectively. Figure 10 shows a scanning electron micrograph top view, screen printed core, a via interconnection, lower and upper conductor lines, and a bonding pad to test the device.

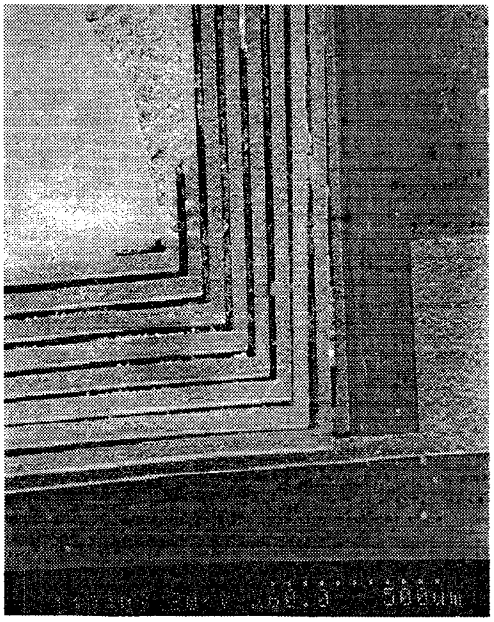

Fig. 10. Scanning electron micrograph of upper and lower layer conductor lines, via interconnection, ferrite core, and bonding pad of two layer spiral type ferrite inductor. Both coil layers are evident.

C. Experimental Results and Discussion

The inductance and Q-factor of the fabricated inductive components were measured by a Hewlett-Packard impedance/gain-phase analyzer 4194A.

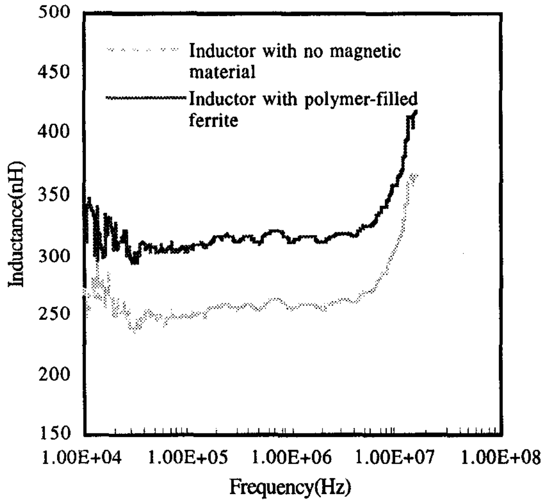

Fig. 11. Comparison of inductance of spiral type inductors with and without composite material (width of conductor line: 40μm, spacing between lines: 40μm, number of turns: 13)

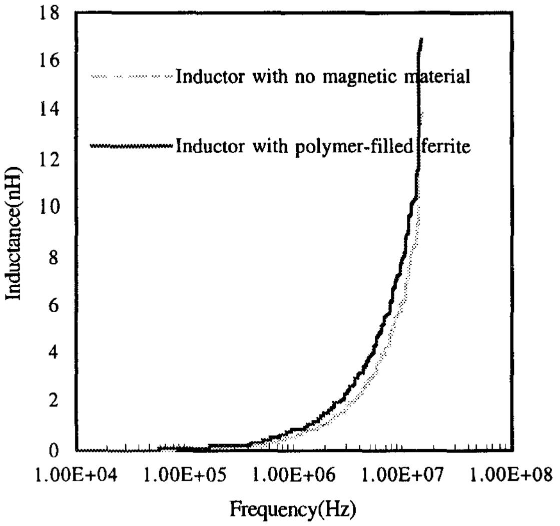

Fig. 12. Comparison of quality factor of spiral type inductors with and without composite material (width of conductor line: 40μm, spacing between lines: 40μm, number of turns: 13)

Figures 11, 12, 13, and 14 show the inductance and Q-factor characteristics of single layer spiral coil inductors with air core and sandwich type spiral inductors with polymer filled ferrite core as a function of frequency and show that the inductors incorporating polymer filled ferrite have higher inductance and quality factor than the corresponding air core inductors. The increase of the width of the conductor and the decrease of the spacing between the conductor lines produces higher inductance and quality factor. Figures 15, 16, 17, and 18 show the inductance and Q-factor characteristics of the two layer spiral coil inductors with and without polymer filled ferrite core as a function of frequency and also verifies the good performance of integrated inductors with polymer filled ferrite core. The measured Q-factor is high (15-17 at 15 MHz), and due to the material properties, higher Q-factors at higher frequencies are expected. Ferrites with better magnetic properties than those used are expected to yield even more favorable results.

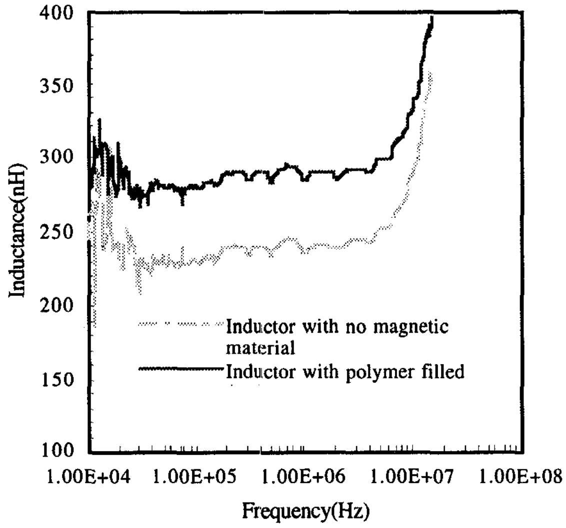

Fig. 13. Comparison of inductance of spiral type inductors with and without composite material (width of conductor line: 30μm, spacing between lines: 50μm, number of turns: 13)

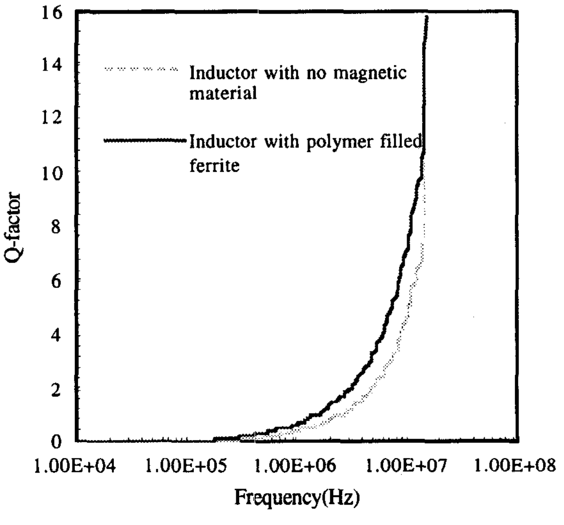

Fig. 14. Comparison of quality factor of spiral type inductors with and without composite material (width of conductor line: 30μm, spacing between lines: 50μm, number of turns: 13)

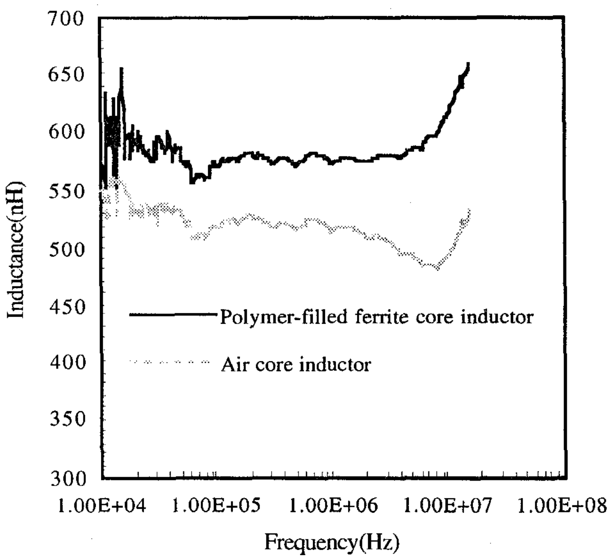

Fig. 15. Comparison of inductance of two layer spiral type inductors with and without composite material (width of conductor line: 30μm, spacing between lines: 30μm, number of turns: 16)

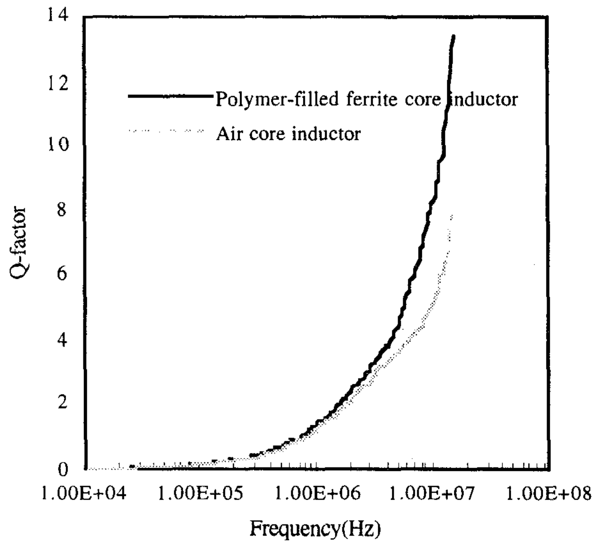

Fig. 16. Comparison of quality factor of two layer spiral type inductors with and without composite material (width of conductor line: 30μm, spacing between lines: 30μm, number of turns: 16)

Integrated magnetic inductors should have high DC saturation current, specially for power converter applications, since the inductors should maintain a constant inductance even when high currents flow through the inductor. As an example, the DC current is proportional to the load current when the integrated inductors are applied to switched DC/DC boost converters. DC saturation current was measured using a Wayne-Kerr 3245 precision inductance analyzer. DC saturation current I_{80} is defined as the current at which the inductance value falls to 80% of the measured inductance without the applied DC current. Figure 19 shows that the integrated polymer filled ferrite inductor has high saturation current , I_{80} = 280 mA comparable to iron-core integrated passive inductors previously fabricated [12].

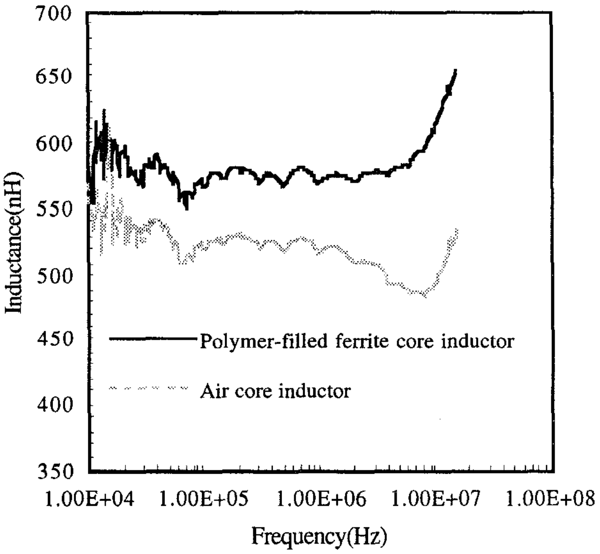

Fig. 17. Comparison of inductance of two layer spiral type inductors with and without composite material (width of conductor line: 20μm, spacing between lines: 20μm, number of turns: 20)

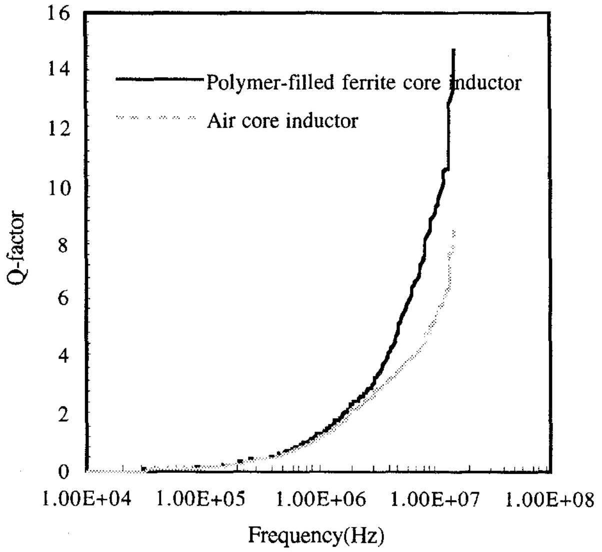

Fig. 18. Comparison of quality factor of two layer spiral type inductors with and without composite material (width of conductor line: 20μm, spacing between lines: 20μm, number of turns: 20)

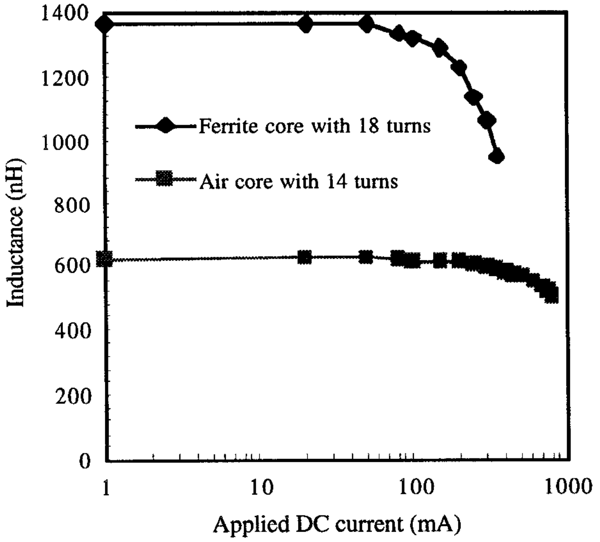

Fig. 19. Comparison of saturation current of two layer spiral type inductors with and without composite material measured at 10 kHz frequency

V. CONCLUSIONS

The fully integrated spiral inductors with and without composite material presented in this paper have the following characteristics: a variety of promising geometries, ease of fabrication, low cost, and low temperature processing. Therefore, the proposed integrated magnetic devices can be integrated with other passives on low cost organic substrates. In addition, sandwich type spiral inductors are automatically EMI shielded by applying polymer filled ferrite on top, bottom, and between the conductor lines. The fabricated magnetic devices have high saturation current and quality factor, particularly applicable to integrated miniaturized power converters, as well as integrated passives for multichip modules, miniaturized power converters, microfilters, magnetic microsensors, and magnetic microactuators.

ACKNOWLEDGMENT

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