Fabrication of Planar Power Inductor for Embedded Passives in LSI Package for Hundreds Megahertz Switching DC-DC Buck Converter

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Recently, research and development of integrated low-voltage DC-DC converter to LSIs has been active. In order to realize such integrated dc power supply, power magnetic devices must be integrated in it. The authors have fabricated planar power inductor embedded in LSI package for hundreds megahertz switching dc-dc buck converter. In this study, two types of planar power inductors have been fabricated, one was spin-sprayed Zn-ferrite thick film magnetic core inductor, the other was composite magnetic core (Fe-based amorphous/polyimide) inductor. Foot-print of the fabricated inductors was 850X850 μm, their inductance was about 10 nH and quality factor *Q* was about 20 at 100 MHz. The rating current which depends on the superimposed dc current characteristic was at least up to 2 A.

***Index Terms*—Planar power inductor, Zn-ferrite thick film core, Fe-based amorphous/polyimide composite core, embedded passives, LSI package, dc-dc converter**

I. INTRODUCTION

MANY researchers reported the high-frequency planar magnetic devices and their application to micro switching DC-DC converter [1]-[5]. Also, various on-chip magnetic thin film inductors for RF applications were reviewed by D. S. Gardner et al. [6]. In order to apply such planar magnetic device as a power device to dc-dc converter, it should have the following features; a low production-cost (foot-print as small as possible: large inductance density per unit area, higher operating frequency), a higher *Q*-factor (large inductance and low loss at high-frequencies), small dc copper-loss (dc coil resistance as low as possible), and a large rating current (excellent superimposed dc current characteristic; large saturation magnetic field of the magnetic core). The authors think it is not so easy to apply the soft magnetic thin film to power magnetic devices, because it is difficult to obtain large magnetic core cross-section for obtaining large inductance and large rating current without increase of production cost.

On the other hand, recently, research and development of the integrated low-voltage/large-current DC-DC converter to LSIs has been active [7], [8], where in order to obtain small foot-print of magnetic device, very high switching frequency around hundreds megahertz has been selected. P. Hazucha et al. reported a 233 MHz switching 4-phase buck DC-DC converter chip developed by using 90 nm CMOS process [7], where four air-core chip inductors on package were used. Although thick coil air-core inductor has large rating current and small loss, undesired local EMI noise owing to the leakage magnetic flux will influence on the electronic circuit operation in LSI. Therefore, to suppress the EMI noise, magnetic core should be used for integrated power inductor.

This study focuses on a possibility of the planar power inductor embedded in LSI package for hundreds megahertz switching DC-DC converter. A block diagram of the integrated power supply with power inductor and capacitor embedded in LSI package is shown in Fig. 1. Since the current LSI package process consists of metallization for distributed conductor line and interlayer insulation, the planar power inductor will be embedded in package by introducing magnetic core fabrication to package process.

In this study, in order to investigate the application of Zn-ferrite thick film and Fe-based amorphous/polyimide composite thick film to the planar power inductor, planar power inductors have been fabricated using two kinds of magnetic cores, and their electrical properties have been evaluated.

II. MAGNETIC CORE AND PLANAR POWER INDUCTOR

A. *Magnetic core materials for planar power inductor*

In this study, two types of magnetic core materials were used for planar power inductor, one was spin-sprayed Zn-ferrite thick film magnetic core, and the other was Fe-based amorphous/polyimide composite core. Zn-ferrite thick film ($Zn_{0.36}Fe_{2.64}O_4$) was made by spin-spray method [9], [10]. Fe-

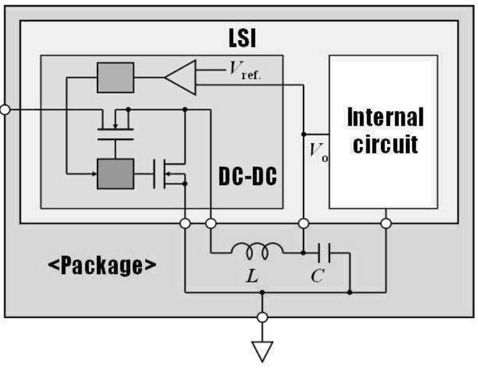

Fig. 1 Inductor embedded in LSI package for dc-dc converter.

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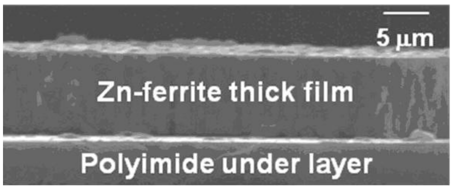
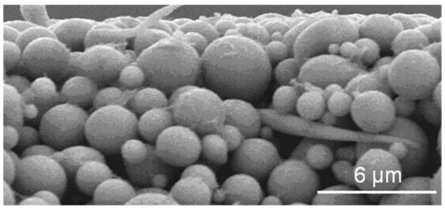


(a)Zn-ferrite thick film



(b) Fe-based amorphous/polyimide composite thick film

Fig. 2 Cross-section of thick magnetic core used for planar power inductor.

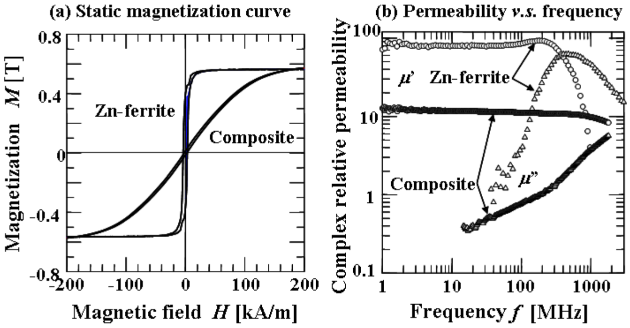


Fig. 3 Magnetic properties of 10 µm thick Zn-ferrite film and 35 µm thick 50 vol.% Fe-based amorphous/polyimide composite film, (a) : static magnetization property, (b) : complex permeability *v.s.* frequency.

based amorphous/polyimide composite thick film made by screen-printing consisted of 50 vol.% Fe-Si-B-Cr amorphous particles [11] and polyimide binder.

Fig. 2 shows the cross-sectional view of 10 µm thick Zn-ferrite thick film and 35 µm thick Fe-based amorphous/ polyimide composite thick film. Since the Zn-ferrite film can be deposited through the low temperature of 90 degree-C [9], it was easy to obtain a patterned structure using photo-resist lift-off process. Fe-Si-B-Cr amorphous particle [11] with a thin SiO_2 surface layer had a mean diameter of 2.6 µm and saturation magnetization of 1.2 T. The magnetic paste with magnetic particles and polyimide precursor solution was printed using screen mask and then was fired at 300 degree-C in temperature.

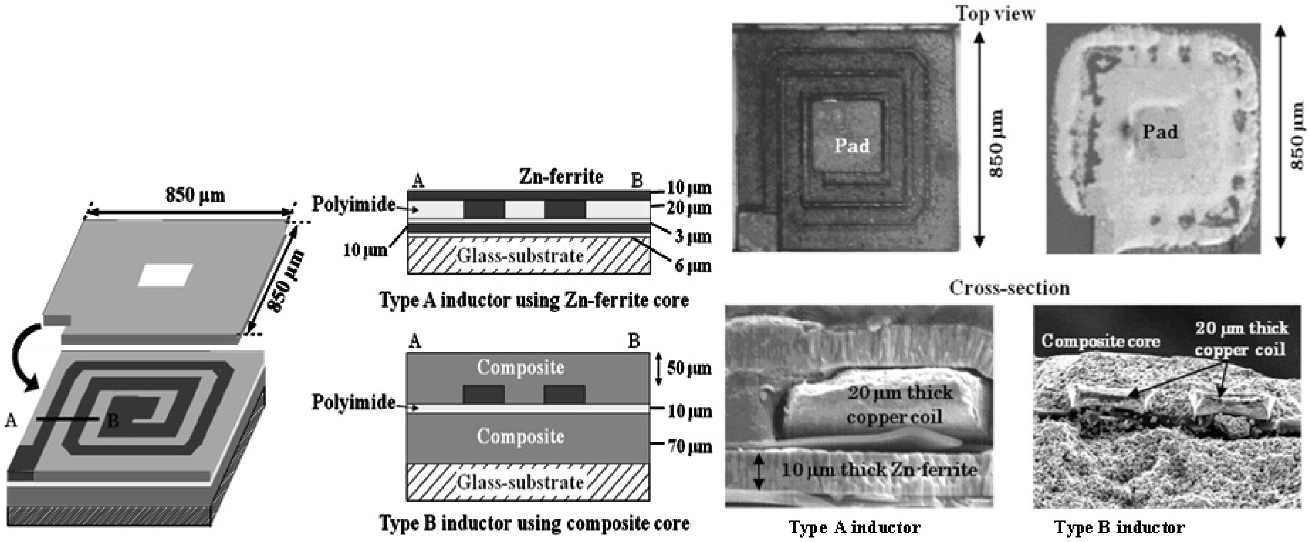
Since two thick magnetic cores can be fabricated without using expensive machines such as sputtering apparatus, the production cost will be reduced.

B. Magnetic properties of core materials

Fig. 3 shows the typical magnetic properties of 10 µm thick Zn-ferrite film and 35 µm thick 50 vol.% Fe-based amorphous composite film, (a) is the static magnetization curve measured by using vibrating sample magnetometer (BHV-55; Riken Denshi Co.), and (b) is the complex permeability measured by using coaxial method for toroidal composite sample and thin film permeameter method [12] for Zn-ferrite sample.

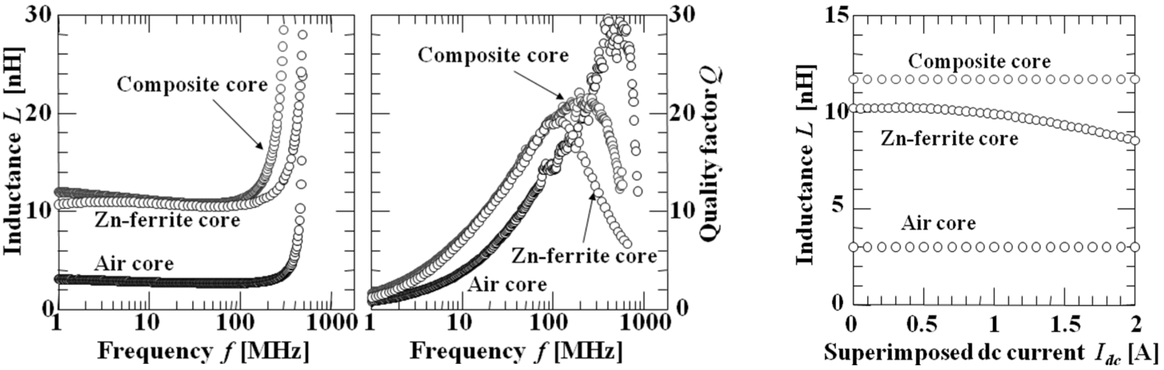
In the static magnetization properties shown in Fig. 3(a), saturation magnetization of Zn-ferrite core was 0.57 T, and that of composite core was 0.61 T. The composite core had the diluted magnetization and had low permeability magnetization curve.

In the complex permeability *v.s.* frequency shown in Fig. 3(b), the low frequency relative permeability of Zn-ferrite core was 80, and that of composite core was 11. Zn-ferrite core had a natural resonance frequency of 500 MHz. Such higher natural resonance frequency may be due to the



(a) Schematic view (b) Photograph

Fig. 4 Schematic view and photograph of fabricated planar power inductors using Zn-ferrite thick film core and 50 vol.% Fe-based amorphous/polyimide composite thick film core.



(a) Inductance and quality factor *v.s.* frequency (b) Superimposed dc current characteristic of inductance

Fig. 5 Electrical properties of fabricated planar power inductors.

magnetization aligned in the film plane by demagnetizing field perpendicular to the film plane. The loss tangent (*tan*δ) of both magnetic cores was small enough at around 100 MHz.

C. Inductor structure and fabrication method

Fig. 4 shows the schematic view and photograph of the fabricated planar power inductors using two kinds of core materials. The inductors with a footprint of 850X850 μm had a structure consisting of top and bottom outer magnetic core and an inner 650 μm-square, 2-turn square spiral coil. Target inductance, quality factor and rating superimposed dc current were 10 nH, over 20 at 100 MHz, and 2 A, respectively.

Spin-sprayed 10 μm thick Zn-ferrite film core was used for Type A inductor with a open magnetic circuit. Thicker magnetic core gives a larger rating current. However, it was hard to obtain Zn-ferrite film with over 10 μm thickness because of undesired film removal from underlayer owing to the internal film stress.

Since the composite magnetic core had lower permeability than that of Zn-ferrite core, Type B inductor consisted of thicker composite magnetic core (top core thickness; 50 μm, bottom core thickness; 70 μm) and a closed magnetic circuit. When the top core was made by screen-printing, the composite paste was not only printed on the top of coil conductor line but also filled in the spacing between conductor lines. Therefore the top composite core thickness became smaller than that of bottom core fabricated on the flat surface.

Inner 2-turn spiral coil with 20 μm thickness and 50/40 μm line/space was made by copper electroplating, and it had a dc resistance of 50 mΩ.

III. RESULTS AND DISCUSSION

A. Electrical properties

Fig. 5 shows the electrical properties of the fabricated planar power inductors, (a) is the inductance and quality factor *v.s.* frequency, and (b) is the superimposed dc current characteristic of inductance. Experimental data of air-core inductor are also shown in the figure.

As shown in Fig. 5(a), Type A and B inductors exhibited 10 nH inductance which was 3.4 times higher than that of air-core value. Quality factor of two inductors was about 20 at 100 MHz, which was comparable with air-core value.

As shown in Fig. 5(b), Type A inductor using Zn-ferrite core exhibited 17% degradation of inductance owing to the superimposed dc current of 2A. On the other hand, inductance of the Type B inductor using composite core was constant even at superimposed dc current of 2A, which was due to the low permeability magnetization curve shown in Fig. 3(a).

B. Magnetic flux density distribution under superimposed dc current

In order to investigate the magnetic flux density distribution of the magnetic core when flowing superimposed dc coil current, nonlinear magnetic field analysis (JMAG-Studio, JSOL Co.) was done, where nonlinear *B-H* characteristic of the magnetic core was obtained from nonlinear *M-H* curve measured by VSM, that is, $B = M + \mu_o H$.

Fig. 6 shows the magnetic flux density distribution of the magnetic core when superimposed dc current was 2 A, (a) is in case of 10 μm thick Zn-ferrite film for Type A inductor, and (b) is in case of 50 μm thick top composite film for Type B inductor. The maximum flux density $B_{max.}$ at 2A superimposed dc current in Type A and B were 0.4 T (70% of saturation magnetic flux density B_s) and 0.14 T (25% of B_s), respectively. From results of Fig. 5(b) and 6, it was considered that the Type A inductor with 10 μm thick Zn-ferrite core had a typical rating superimposed dc current of about 2 A.

On the other hand, since Type B inductor had low permeability composite thicker magnetic core, it exhibited enough margin for magnetic saturation even at superimposed dc current of 2 A. However, superimposed dc current characteristic over 2 A is not shown in Fig. 5(b), this was owing to the increase of dc copper loss ($I_{dc}^2 R_{dc}$, R_{dc} = 50 mΩ) with increasing I_{dc}. For example, when I_{dc} is 5 A, the dc copper loss becomes 1.25 W and will cause undesired temperature rise. For getting larger rating dc current, the dc resistance should be reduced as low as possible.

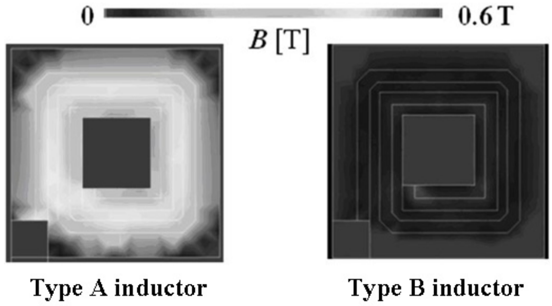


Fig. 6 Magnetic flux density distribution in the magnetic core when superimposed dc current was 2 A.

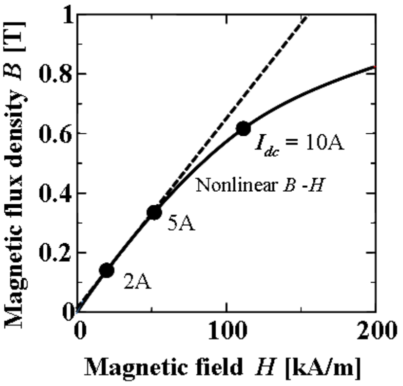


Fig. 7 Operation point on nonlinear *B-H* curve *v.s.* superimposed dc current I_{dc} of 50 μm thick top composite core in Type B inductor, which was estimated by nonlinear magnetic field analysis.

Fig. 7 shows a predicted operation point on nonlinear *B-H* curve *v.s.* superimposed dc current I_{dc} in the 50 μm thick top composite core of Type B inductor, which was estimated by nonlinear magnetic field analysis. In the figure, a broken line means a linear *B-H* relation. Since the operation point for I_{dc} of 5 A is on the linear *B-H* relation, constant inductance will be kept at least up to I_{dc} of 5 A. If the lower dc coil resistance can be realized, Type B inductor will have 5 A rating current.

IV. CONCLUSION

In order to investigate a possibility of planar power inductor embedded in package for hundreds megahertz switching dc-dc converter, two types of planar power inductors using Zn-ferrite thick film and Fe-based amorphous/polyimide composite thick film have been fabricated and evaluated.

The fabricated inductors with 850X850 μm foot-print, 20 μm thick 2-turn copper spiral coil exhibited an inductance of 10 nH and quality factor of 20 at 100 MHz. The rating superimposed dc current was at least up to 2 A. Especially, since the thicker composite magnetic core had the low permeability magnetization curve, the rating current of 2-turn spiral inductor is expected to be up to 5 A by introducing very low dc- resistance coil.

In the future, LSI-package TEG (Test Element Group) including the embedded planar power inductor will be developed and applied to hundreds megahertz switching dc-dc converter.

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