Carbonyl-iron/epoxy composite magnetic core for planar power inductor used in package-level power grid

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Our research objective is to realize the basic technology for a next generation Package-Level Power Grid (PLPG) for plural application LSIs. In this study, a carbonyl-iron powder (CIP)/epoxy composite magnetic core, for large-current power inductor used for the main dc-dc converter in the PLPG, has been fabricated and evaluated. 54 vol.%-CIP/epoxy composite core made by screen-printing had a relative permeability of 7.5 and loss tangent of about 0.03 at 100 MHz. The planar power inductor using composite core was fabricated and evaluated, which had a quasi closed magnetic circuit consisting of low permeability composite core and embedded 35 µm thick, 2-turn copper spiral coil. The fabricated inductor with a 1mm-square in size had 5.5 nH inductance, Q-factor of 15 at 100 MHz and 18 mΩ dc coil resistance. Inductance was constant even when the superimposed dc current increased up to around 5.5 A.

Index Terms— **Package-level power grid, planar power inductor, carbonyl-iron/epoxy composite magnetic core**

I. INTRODUCTION

In the future, monolithic dc-dc converter will be established for a Chip-Level Power-Grid (CLPG), that is, Power Supply on Chip. Research and development of CMOS switch dc-dc converter has been done in order to realize the CLPG [1]-[4], where the power inductor on chip must be realized. P. Hazucha et al. [1] reported the hundreds MHz switching 90 nm-CMOS switch dc-dc converter using air core chip inductors with 6 nH inductance on package. K. Onizuka et al. [2] developed a CMOS switch buck converter using air core spiral inductor on Si interposer. Although such air core inductor can be fabricated easily using metal process only, there is serious demerits such as a low inductance, large footprint and undesired EMI noise owing to wide spread alternating magnetic flux. These will be serious obstacles for Power Supply on Chip.

On the other hand, many researchers have tried to establish the power magnetics on chip technology. D. S. Gardner et al. [3] discussed the performance comparison in the various on-chip magnetic thin film inductors from the inductance-areal-density point of view. In order to apply the on-chip magnetic thin film inductor for dc-dc conversion application, the rating current is also important issue. N. Sturcken et al. [4] developed an integrated voltage regulator using coupled-magnetic-core inductor, where they used two sets of four coupled power inductors on Si-interposer. The inductor topology was an elongated spiral with a Ni-Fe magnetic thin film core encasing the copper windings on the long axis. Inverse coupling between adjacent inductors was utilized to avoid magnetic saturation of the core and consequently improved rating current density. We consider it is not so easy to obtain low coil-resistance power inductor on Si-interposer because of a difficulty of very thick conductor process.

We forecast that the next generation power delivery to LSIs will become a Package-Level Power-Grid (PLPG) before

CLPG (Power Supply on Chip). Fig. 1 shows an example of PLPG concept. The PLPG will consist of a main dc-dc converter with large current inductor and Point-of-Load (POL) dc-dc converter for each application LSI. The POL converter will have an embedded magnetics in package, semiconductor switches and control circuit. In order to realize the embedded power magnetics, we have developed a Zn-ferrite planar power inductor embedded in plastic interposer package [5]-[8].

As shown in Fig. 1, in order to establish the PLPG, a large-current inductor will be required for the main dc-dc converter, which will be mounted on the package because of relatively thick shape to realize the low dc resistance by using very thick coil. We consider that the metal-composite magnetic core made by screen printing is suitable for large current inductor because its low permeability contributes toward larger margin for magnetic core saturation and it can be easily fabricated using low cost screen printing method.

In this study, in order to develop the composite magnetic core used for large-current inductor mounted on package, a carbonyl-iron powder (CIP) has been introduced and applied to the CIP/epoxy composite core.

II. CARBONYL-IRON/EPOXY COMPOSITE CORE

A. Carbonyl-iron powder (CIP)

Carbonyl-iron powder (CIP) made by BASF Co. [9] was used for the starting material for composite core. The CIP was produced by thermal decomposition of iron-pentacarbonyl $(Fe(CO)_5)$, which was previously distilled to high purity. The CIP used was "Hard Grades", which was an as-decomposed powder without non-reduction. Typical specifications of the CIP are shown in Table 1. BASF Co. showed that the non-reduction CIP has an onion-skin structure [9], which may be due to the spherical iron layers form on a nucleus in the Fe-particle growth. Fig. 2 shows the particle-size distribution and SEM image of the CIP, it exhibited a narrow particle-size

Table 1 Typical specifications of Carbonyl-iron powder (CIP).

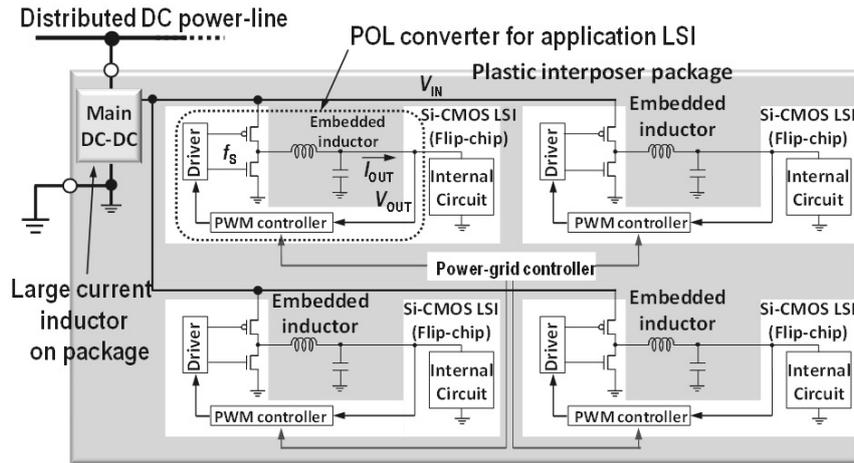|	
Composition wt.% [9]	Fe content ; up to 97.8%, C ; $1.0\%_{max.}$, N ; $0.9\%_{max.}$, O ; $0.5\%_{max.}$
Mean diameter [9]	1.1 µm
Saturation magnetization	2 T (measured using VSM)
Coercive force	1 kA/m (12.5 Oe, measured using VSM)

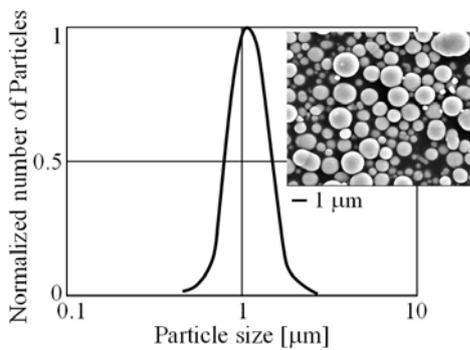Fig. 1 Package-Level Power-Grid concept.

Fig. 2 Particle-size distribution of carbonyl-iron powder (CIP) [9].
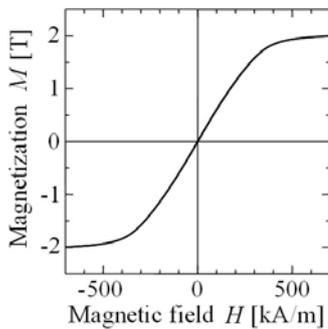

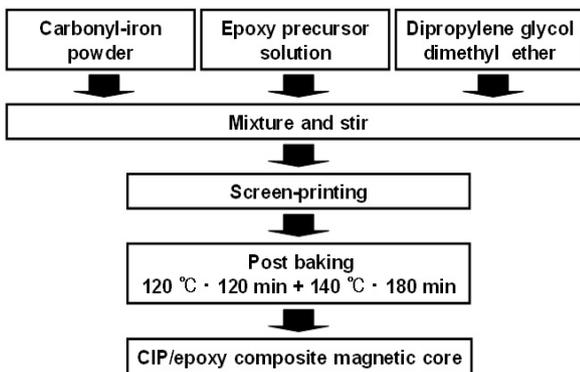Fig. 3 Static magnetization curve of carbonyl-iron powder (CIP).

Fig. 4 Fabrication procedure of CIP/epoxy composite core.

distribution with a mean diameter of 1.1 μm.

M. Koeda et al. [10] investigated the CIP in detail. From the Scanning Transmission Electron Microscopy observation, it was found that the non-reduction CIP consists of 20 nm-size fine grains. Such fine-grain nanostructure causes small crystalline magnetic anisotropy [11]. From the Electron Beam Holography technique, it was found that the non-reduction CIP has a rotational magnetic moment distribution structure (curling magnetic structure). Such magnetic structure causes small magneto-static energy.

Fig. 3 shows the static magnetization curve of the CIP measured using a vibrating sample magnetometer (RIKEN DENSHI; BHV-55). The CIP had a saturation magnetization of about 2 T and small coercive force. Such small coercive force maybe due to small crystalline magnetic anisotropy based on the fine grain nanostructure .

B. Carbonyl-iron/epoxy composite core

When making the composite paste composed of the CIP and epoxy precursor solution, the composite paste is expected to have good CIP-dispersion inside the epoxy precursor solution because of small magneto-static coupling between adjacent powders with small magneto-static energy.

Fig. 4 shows the composite core fabrication procedure. The CIP and epoxy precursor solution were mixed and then stirred up using planetary rotating stirrer machine. In order to obtain composite core with different CIP volume fraction, some composite pastes with different ratio of CIP and epoxy precursor solution were prepared. The composite paste was printed using screen mask and then fired at 120 and 140 degree C in air. The viscosity of the CIP composite paste increased with increasing CIP volume fraction, and it was difficult to print the paste uniformly. Therefore 54 %-CIP volume fraction in the post-fired composite core was an upper limit when using the screen printing method.

The square shape composite core was used for the magnetization measurement, and the ring shape core was used for the measurement of complex permeability vs. frequency.

C. Magnetic properties of composite core

Three kinds of CIP composite cores with 47 %, 51 % and 54 %-CIP volume fraction were fabricated. Fig. 5 shows the static magnetization curve and complex permeability vs. frequency of CIP/epoxy composite core with different CIP volume fraction. In Fig. 5(a), the CIP volume fraction was calculated on the basis of simple magnetization dilution due to
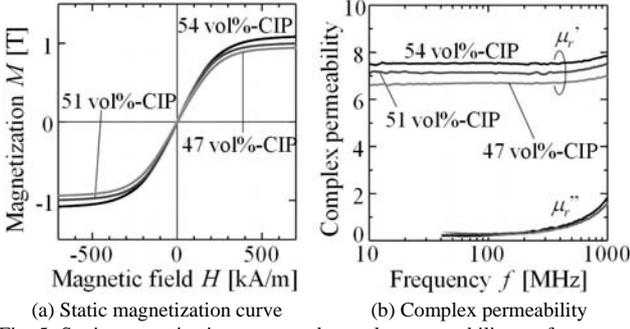
(a) Static magnetization curve   (b) Complex permeability

Fig. 5 Static magnetization curve and complex permeability *vs.* frequency of CIP/epoxy composite core with different CIP volume fraction.
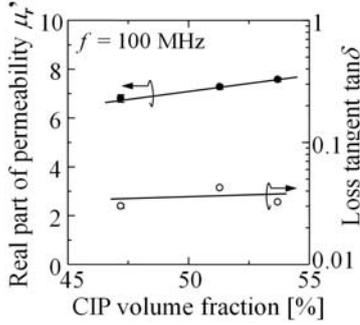

Fig. 6   Relation between permeability, loss tangent and CIP volume fraction of CIP/epoxy composite core (f = 100 MHz).

non-magnetic epoxy resin. For example, 54 vol.%-CIP/epoxy composite core had a saturation magnetization of 1.08 T and small coercive force of about 2 kA/m (25 Oe). In Fig. 5(a), "constant susceptibility" was observed even when increasing magnetic field up to around 80 kA/m (1 kOe). Such constant susceptibility may be due to the distributed air gap (non-magnetic epoxy resin).

Fig. 5(b) shows the complex permeability *vs.* frequency of three kinds of the CIP/epoxy composite cores. The initial complex permeability was measured using a material impedance analyzer (HP4291A) with coaxial waveguide test-fixture. In the figure, real part of initial relative permeability in each sample was below 10 and nearly constant up to around 500 MHz. Loss tangent μ_r"/μ_r' was about 0.2 even at 1 GHz.

D. CIP volume fraction dependence of permeability and loss tangent

Fig. 6 shows the relation between real part of initial relative permeability, loss tangent and CIP volume fraction of the composite core, which were measured at 100 MHz. The initial relative permeability increased slightly up to 7.5 with increasing CIP volume fraction from 47 to 54 %. Loss tangent at 100 MHz was around 0.03-0.04 and its CIP volume fraction dependence was relatively small.

As already reported [5], Fe-based amorphous/polyimide composite core for planar inductor was fabricated, which consisted of 2.6 μm size Fe-Si-B-Cr amorphous powder and polyimide. 50 vol.%-amorphous composite had a loss tangent of about 0.08 at 100 MHz. If the high frequency loss of the composite core is dominated by eddy current inside the magnetic metal powder, loss tangent can be written as follows;

$$\tan\delta = Kd^2/\rho \qquad (1)$$

where d and ρ are the diameter and electrical resistivity of magnetic particle, K is a constant related to frequency and spherical shape. When both spherical CIP and Fe-based amorphous are exposed to the same frequency magnetic field, K_{CIP} and K_{AMO} are identical. From the diameter and resistivity of CIP and Fe-based amorphous particle; d_{CIP} = 1.1 μm, ρ_{CIP} = 10^{-7} Ωm in CIP, $d_{AMO.}$ = 2.6 μm, $\rho_{AMO.}$=1.3X10^{-6} Ωm in Fe-based amorphous powder, $\tan\delta_{AMO.}$ is calculated to be half of $\tan\delta_{CIP}$. From the experimental result shown in Fig. 6, 50 vol.%-CIP/epoxy composite core is estimated to have $\tan\delta_{CIP}$ of 0.03 at 100 MHz. On the other hand, $\tan\delta_{AMO}$ of same vol.% Fe-based amorphous composite core was 0.08, which is 2.7 times larger than that of CIP composite core. It was considered that the Fe-based amorphous composite has the cluster consisting of plural amorphous particles, hence the eddy current flowing inside large cluster causes larger high frequency loss. Since the CIP composite core has good CIP-dispersion in the epoxy resin, the high frequency loss may be due to the eddy current inside the iron particle.

III. Planar Power Inductor Using Composite Core

A. Planar power inductor structure

A planar power inductor with 1mm-square in size was fabricated on a glass-substrate using 54 vol.%-CIP/epoxy composite core. Fig. 7 shows the schematic view and cross-sectional SEM image of the fabricated planar power inductor. As shown in Fig. 7(a), a 35 μm thick, 2-turn electroplated copper spiral coil with an 880 μm-square in size was arranged

(a) Schematic view

(b) Schematic A-A' cross-section

(c) Cross-sectional SEM image
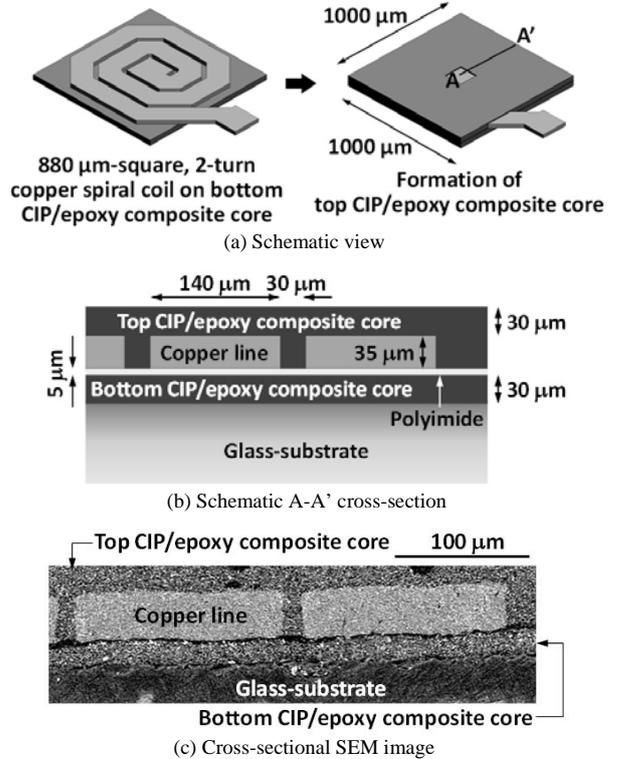
Fig. 7 Schematic view and cross-sectional SEM image of fabricated planar power inductor with 54 vol.%-CIP/epoxy composite core and 35 μm thick electroplated copper 2-turn spiral coil.

(a) Inductance *vs.* frequency   (b) *Q*-factor *vs.* frequency

(c) Superimposed dc current characteristic
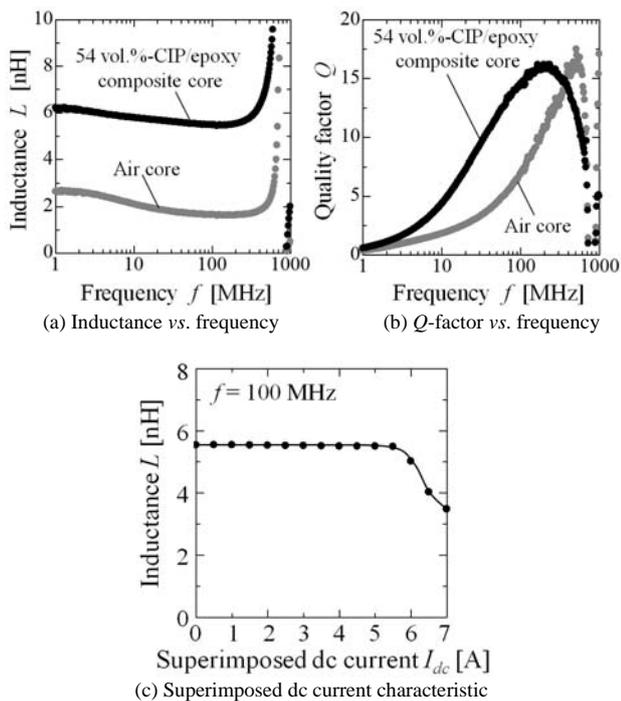Fig. 8 Electrical characteristics of the planar power inductor fabricated.

on a bottom 30 μm thick composite core made by screen-printing method. In order to planarize the rough surface of the bottom composite core, low-temperature (180 degree-C) fired 5 μm thick polyimide under layer for copper spiral coil was used. As shown in Fig.7 (b) and (c), the top composite core was formed directly on the spiral coil and filled in the spacing between thick conductor lines. Hence the fabricated planar power inductor had a quasi closed magnetic circuit consisting of an embedded thick copper spiral coil in the low permeability composite core and polyimide air gap.

B. Electrical characteristics of planar power inductor

Fig. 8(a), (b) and (c) show the electrical characteristics of the planar power inductor fabricated. Result of air core 2-turn spiral inductor is also shown. In Fig. 8(a), the composite core inductor had 5.5 nH inductance at 100 MHz, which was 3.7 times larger than that of air core inductor. Resonant frequency was about 600 MHz, which was slightly lower than that of air core spiral. In Fig. 8(b), *Q*-factor of the composite core inductor was 15 at 100 MHz, which was 2.4 times higher than that of air core spiral. The dc coil resistance R_{dc} was about 18 mΩ, which was close to the calculated value of 16 mΩ on the basis of designed parameters of copper spiral coil.

Fig. 8(c) shows the superimposed dc current characteristic of the fabricated composite core inductor. Inductance was constant even when the superimposed dc current increased up to around 5.5 A. Such excellent superimposed dc current characteristic is mainly due to the "constant permeability" of the CIP/epoxy composite core.

IV. CONCLUSIONS

1.1 μm size carbonyl-iron powder (CIP)/epoxy composite core, for large-current power inductor used for main dc-dc

converter in the Package-Level Power Grid, has been fabricated and evaluated. 54 vol.%-CIP/epoxy composite core had a relative permeability of 7.5 and loss tangent of about 0.03 at 100 MHz. The CIP/epoxy composite core had "constant permeability" even when increasing magnetic field up to 80 kA/m (1 kOe). Such constant permeability may be due to the distributed air gap (non-magnetic epoxy resin).

As a first trial application, a planar power inductor with 1 mm-square in size has been fabricated using 54 vol.% CIP/epoxy composite core. The fabricated composite core inductor had 5.5 nH inductance, *Q*-factor of 15 at 100 MHz and 18 mΩ dc resistance. In the superimposed dc current characteristic, inductance was constant even when the superimposed dc current increased up to around 5.5 A.

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