Planar Power Inductor with Magnetic Film for Embedded LSI Package

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Abstract

A power inductor component is relatively very thick and large shape. Therefore, these components are not appropriate feature to be embedded into a LSI package and mounted nearby a LSI chip, it is challengeable to make the embedded application. However, LSI power delivery system is going for low voltage and large current, and losses between power supply and loads impacts on the power supply efficiency characteristic. In order to solve this problem, miniaturization for a power inductor is needed to realize the embedded applications.

As one of approaches to realize the power delivery systems, the planar power inductor with Zn-Ferrite film has been studied for the next generations. A structure of planar power inductor was designed to be configured 2-turn inner copper spiral coil covered with top and bottom magnetic core. The Zn-Ferrite film used as a magnetic core has a high resonance frequency around 300MHz and high saturation magnetization of 0.6T or more, and this film can be formed in low temperature, which can be handled in parallel way to fabricate an organic package.

We have developed the organic package with employing the power inductors covered with Zn-Ferrite as prototype of the embedded application, and evaluated the electrical and magnetic characterizations.

The thickness of embedded planar power inductor covered with Zn-ferrite film is 50um, and the size is 850um squares. Q factor is 10 to 13 in 30MHz to 100MHz. The degradation of inductance caused by the superimposed current does not happen without changing until 3A.

Key word: Miniaturized power inductor, Magnetic film, Embedded packaging, and Organic LSI package

1. Introduction

As shown in the ITRS2011 road map of Fig. 1, it is predicted that LSI in PC and portable equipment are going for the low power consumption, and the low voltage supply [1].

In the conventional, the power delivery system to drive LSI is centralized around center area where one power supply allocates two or more LSI.

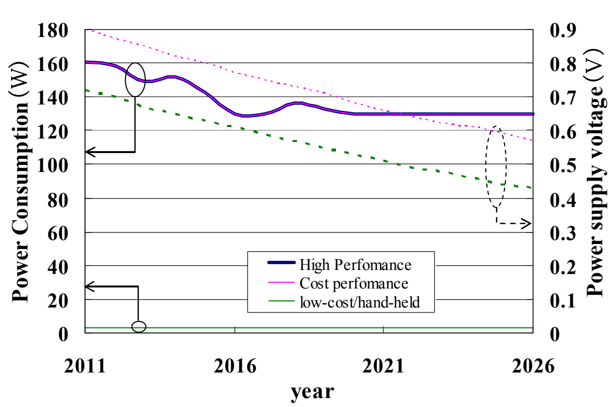

Fig. 1 Trend of power consumption and voltage supply the ITRS2011 road map.

In resent years, the distributed power supply system called POL (Point of Load) has been employed as the main power delivery system. As one of the advantages, POL can make shorten the distance between a DC-DC converter and its supplied LSI. Therefore, the power consumption induced by parasitic resistance along the power supply rail can be reduced.

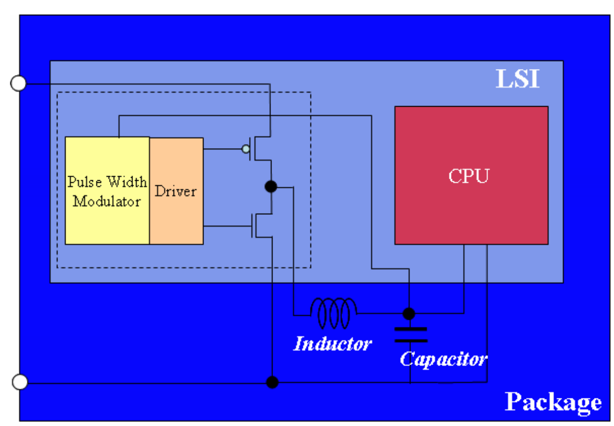

Fig. 2 The circuit diagram of concept of POL.

Fig. 2 is a schematic circuit diagram showing a concept of POL, in where a DC-DC converter switch is integrated into a LSI and the passive components (inductor and capacitor) are embedded in a LSI package. In order to realize this power delivery system in next generation, some examinations were studying [2, 3].

In the previous work [4], there was a report on the DC-DC converter which consisting of the four phases in the LSI package. Air core power inductors and capacitors components were mounted on the package surface. However, the air core power inductor made of nonmagnetic material causes leakage with magnetic flux toward circumference. Therefore, the problems with EMI (Electro Magnetic Interference) and EMS (Electro Magnetic Susceptance) are happened in the LSI package. To improve such affect, in general, the inductor component should be fabricated with a magnetic material, it is mounted on a LSI package, or embedded into it, so which possibly result in larger size package and also causes to make restrictions for additional other wiring formations.

In order to realize the next generation POL, we have developed how to build thinner POL and how to embed it into a LSI package to apply to the next generation power delivery system in the portable equipment. At first, development of a thin and miniaturize inductor is essential, so we focused and remarked on the spinel shape formed with Zn-Ferrite film which was arranged by plating technology using the spin spraying method for magnetic a core material.

This magnetic material is expected high Q [5]. Since this Zn-Ferrite film can be formed at low temperature, the power inductor covered with Zn-Ferrite film can be formed on the way of the manufacturing process of an organic LSI package. Furthermore, an iron overload composition Zn-Ferrite film has high saturation magnetization around 0.60T or more in the characteristics. In addition, the permeability is about 80, and the resonance frequency is relatively higher up to around 300MHz. The electrical resistivity is also comparatively high 10^2 Ω·m.

In this study, remarkable advantages are as followings in technical view:

- The high volume of power inductor can be made in small shape.
- DCR (Direct Current Resistance) of power inductor can be made in small.
- Q factor of power inductor becomes higher.
- EMI and EMS issued in a LSI package are improved.
- The high efficiency and the miniaturization of the power delivery system are possibly achievable.

For the optimal design of our planar inductor, a voltage regulator model (VR model), which was proposed in the literature [6], was used for calculating the target inductance and resistance of the power inductor. This VR model provides an analytical solution for the power losses in accordance with the switching capacitance, resistive loss, and conductive loss in the inductor. The analytical solution for the VR model is given by the following equation:

$$P_{loss} = V_{in} I_L \sqrt[3]{24 \frac{R_0 C_0}{\tau_L} \mathrm{D}(1-D)} \propto \sqrt[3]{\frac{R_0 C_0}{\tau_L}} \quad (1)$$

where parameters appeared in the equation (1) are as following: R_0 is the parasitic resistance in CMOS switch; C_0 the parasitic capacitance in CMOS switch; τ_L the ratio of inductance to resistance in planar inductor wiring; I_L the target load current.

As seen from this design equation, it is found that the power loss in the DC-DC converter decreases as the τ_L increases.

With considering the design equation and taking into account the other factors (process criteria, substrate size and so on.), we have determined target specification for DC-DC converter as shown in Table 1.

As well as that, based on the Table 1, the target specification on the planar power inductor was also determined as shown in Table 2.

In this paper, the design, the electrical characteristics, and the features of the power inductor are presented. In section two, a design on a package with embedded the power inductor is introduced, in which designed via 2-dimentional are configured.

Table 1 Target specification on a DC-DC converter.

Target specification of DC-DC converter	
Switching frequency (MHz)	26
Input Voltage (V)	1.8
Output Voltage (V)	1
Output current (A)	1

Table 2 Target of a power inductor for a DC-DC converter.

Target specification of power inductor	
L (nH)	7～8
R_{DC} (mΩ)	<50
R_{AC} (mΩ)	<200
Area (mm^2)	<1
Thickness (um)	<50
The degradation of inductance owing to the superimposed current (A)	<3 [<30%]

In section three, it will be reported on the structure of planar power inductor embedded in an organic package and the results calculated by the 3-dimnetional finite element simulations. In section four and five, we will report on the fabrication results and electrical characteristics. In the section six, we will discuss the subjects of our planar power inductor. In section seven, we will summarize our work in this study.

2. Examination on the power inductor structure to be embedded into a package

In this section, with considering a suitable feature, the planar power inductor covered with Zn-Ferrite film will be designed. We will determine the cross sectional geometries as the candidate of the planar power inductor as shown in Fig. 3.

This model shows cross-section of the planar power inductor covered with Zn-Ferrite film. The advantage of this structure can reduce magnetic flux leakage and minimize the volume of inductor. In consideration of the magnetic characteristic and the lamination process with build-up resin, the thickness of Zn-Ferrite film gets 10um which is placed on both the top layer over spiral coil and the bottom layer under it. It is estimated that a current of 1A or more flows in the wiring of the spiral coil, the wiring width of one is 127um and the thickness of one is 20um. The spiral coil is consisting of two turns, with taking into consideration of the inductor size 850um square, as shown in Table 2. It result in the structure that the spiral coil is covered with Zn-Ferrite.

We calculate in the method based on the microstrip coupled-line method [7]. In this method, a planar inductor is treated as a coupled transmission line section as shown in Fig. 4.

The coupled length is 2mm, which is considered as the average of inner and outer lengths of the original inductor. The electrical characteristics of the original spiral inductor can be approximately equivalent to the coupled line section.

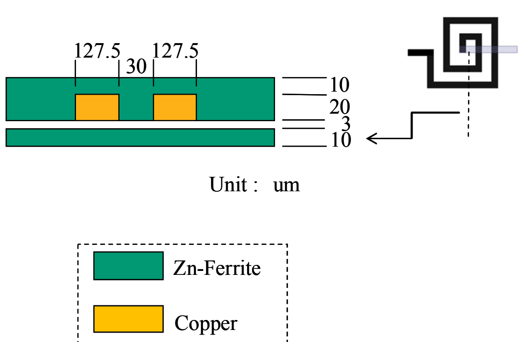

Fig. 3 The model as a candidate of the power inductor.

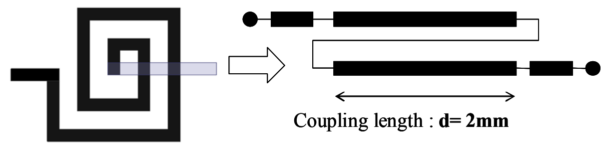

Fig. 4 Consider a spiral inductor as a coupled transmission line section.

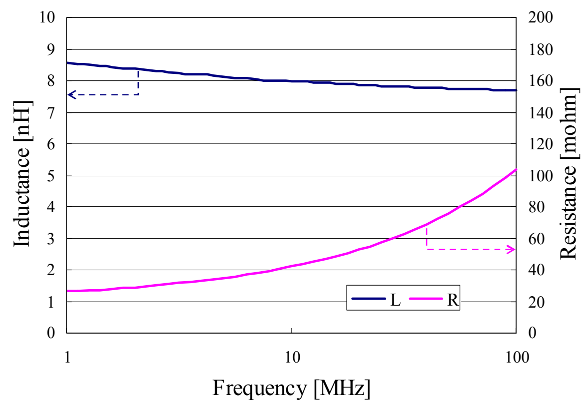

Fig. 5 The inductance and the resistance values calculated in the microstrip coupled-line method.

In more detail, the inductance L and resistance R for the original spiral are given by:

$$R = (R_{11} + R_{12} + R_{21} + R_{22}) \times d \quad (2)$$

$$L = (L_{11} + L_{12} + L_{21} + L_{22}) \times d \quad (3)$$

where Lij and Rij are the coupled-line inductance matrix and coupled-line resistance matrix component, respectively, and d is the coupled length. L_{ij} and R_{ij}, are extracted from the cross sectional geometry of coupled line section by using a commercial simulation tool, ANSYS Q3D.

The resistance and the inductance were calculated in this method, respectively.

For the characteristics value used in this simulation, a conductivity of copper is 5.8×10^7 (S/m), a permeability of Zn-Fe used as magnetic materials is 80. And thus, the characteristic of dielectric is not considered in this simulation.

Fig. 5 shows the inductance and the resistance value calculated in this method.

The calculation results in that both inductance and resistance of this model are showing that it is over our target values as shown in Table 2 in a range from 1MHz to 100MHz.

3. The structure and characteristics of design on the planar power inductor

In this section, an appropriate inductor covered with Zn-Ferrite will be designed and also to embed it into the organic package, a proper test vehicle (TV) structure will be designed.

With considering both process availabilities, the Zn-Ferrite feature and the TV structure are investigated. As the result of that, in the design the planar power inductor covered with Zn-Ferrite which gets in film shape, and which can be embedded into an organic package. Besides we also design the air core power inductor in comparison to the original under the same conditions.

Fig. 6 shows both the top view and cross section structure for two type power inductors. The spiral coil area of the two type inductors is 850um square. However, the inductor area is a little bigger than one. It is necessary for the re-wiring onto surface of organic package. The thickness of planar power inductor covered with Zn-Ferrite is 50um to enable to be embedded into a build-up resin.

The planar power inductor covered with Zn-Ferrite becomes flat planar shape by depositing resin between spaces of spiral coils, and made it the structure which does not deposit the Zn-Ferrite between coils. In this part, it is different from the model of section two.

The magnetic flux is generated from each wiring flows across between wirings. As a result, the effect of mutual inductance between coils is obtained, and the increasing of inductance is predicted.

In the case that an inductor is embedded into a LSI package, it is assumed that metal plane and the other wirings are placed and integrated near one. And thus, designs of two inductors are placed the metal plane through dielectric near the inductor. Each inductor is integrated by via and copper wiring to a top pattern of organic substrate.

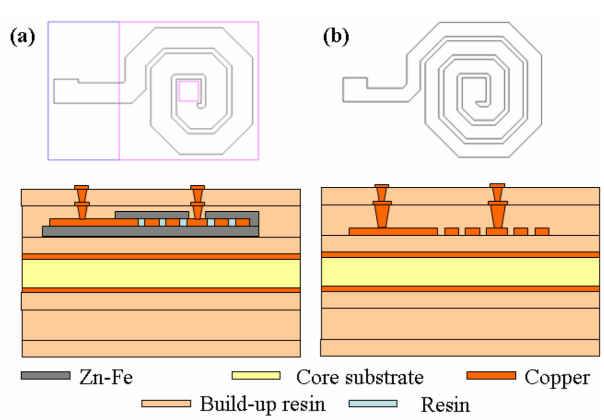

Fig. 6 The top and cross views of the structure of two type inductors embedded into an organic package.
(a) The planar power inductor covered with Zn-Ferrite film, (b) The air core planar power inductor

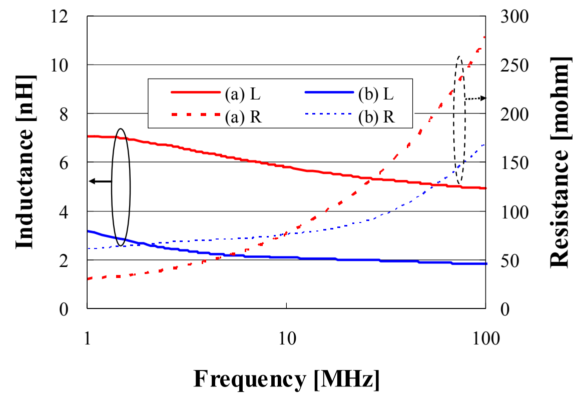

Fig. 7 The characteristics of two type designed planar power inductors. (a)The inductor covered with magnetic film, (b)The air core inductor

Fig. 7 shows simulation results of designed two planar power inductors. The simulation results of inductance and resistance are calculated by ANSYS HFSS, which is the three dimensional electromagnetic field simulators based on the finite element method.

It should be noted that these simulation results are considered with including characteristics of via, copper wirings, metal plane, and so on.

The planar power inductor covered with Zn-Ferrite film shows high inductance as compared with the air core power inductor in the same size. We have considered the following about the causes of this result. In the air core power inductor, there is no magnetic material around the spiral coil. As a result, the magnetic flux generated from the spiral coil of air core power inductor is shielded by the metal plane. Therefore, the inductance is decreasing.

On the other hand, the resistance has become higher than air core power inductor which is not covered with a magnetic material. This is the causes why the magnetic loss of Zn-Ferrite is bigger as increase frequency. However, this result can be confirmed that the planar power inductor covered with Zn-Ferrite film has become the design satisfied with our target specification.

4. The fabrication process and results

In this section, the fabrication process of the planar power inductor embedded into an organic package will be described.

It is indicated the method of fabrication to embed the planner power inductor covered with Zn-Ferrite film into an organic package. The epoxy resin with glass-cloth is set on the core layer. Asumming that the metal plane is placed near the power inductor in an organic package, both sides of core layer are all copper planes.

The build-up resin is laminated on the surface of copper plane, and the Zn-Ferrite as magnetic film is formed on it. The surface of build-up layer has been roughened several micrometers roughness. Therefore, between Zn-Ferrite layer and build-up layer can be expected high adhesion by the anchor effect.

In addition, the Zn-Ferrite film is plated by the spin-spray method. Since it is a low-temperature process using an aqueous solution under 100 degrees or less, the Zn-Ferrite film can be formed on the way of the process to fabricate an organic package. In this prototype Zn-Ferrite film has become the composition of the $Zn_{0.22}Fe_{2.78}O_4$ expected both of high saturation magnetization and high permeability. After the formation of Zn-Ferrite film at the bottom side of spiral coil, a spiral coil is formed by the thin film process on it. In finally, forming Zn-Ferrite film at top side of spiral coil, the formation of power inductor is completed. And then, re-wiring process is accomplished by laminating the build-up resin, plating copper, etching copper, and so on. From these processes, the planer power inductor covered with Zn-Ferrite film is embedded into an organic package.

On the other hand, the air core power inductor as comparison is fabricated in the normal process of organic substrate.

The surface of package is formed with the patterns to evaluate the inductance, the resistance, and the degradation of inductance with considering the superimposed current DC bias characteristics with the probe.

Fig.8 shows both the top view and the cross sectional photo of planar power inductor covered with Zn-Ferrite film.

This structure is similar to our target structure. From this result, it is confirmed that the planar power inductor covered with Zn-Ferrite film can be formed in parallel way to fabricate organic substrate (LSI package) at the same time.

However, in actual substrate fabrication, about the details, some parts of dimension slightly got different from the target value in the design. Although the thickness of spiral coil becomes 20um in the same design value, the thickness of Zn-Ferrite had become 7.5um for 10um in design value. Zn-Ferrite film is formed by plating at the space between the spiral wirings, or not. Since the space between the spiral coils are 20um, it has a little bit of gap to be filled with resin, flattening process. In particular, the center part of spiral coil can not be covered with Zn-Ferrite film. This time, structure of the planar power inductor covered with Zn-Ferrite film is not designed to get the closed magnetic circuit.

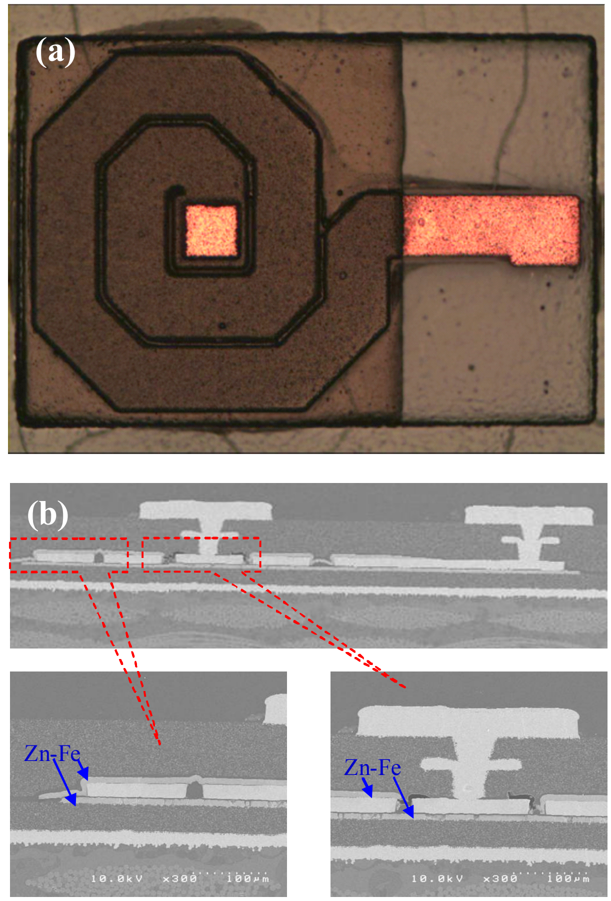

Fig. 8 (a) The top view and (b)the cross section photo of planar power inductor covered with Zn-Ferrite film.

5. The measurement results of characteristics

In this section, the evaluation results are reported on the magnetic characteristics of Zn-Ferrite film and the electric characteristics of planar power inductors covered with Zn-Ferrite film embedded into organic package. As a reference, the air core planar power inductor will be evaluated in the same case.

Measurement items on magnetic characteristics are taken placed to the static magnetization and the complex permeability characteristics. In addition, as other measurement items for electric characteristics, the resistance, the inductance and Q-factor of power inductors are checked. And then, the degradation of inductance owing to the superimposed current was measured, which is one of the important characteristics of power inductor.

(1)The Static magnetization and the complex permeability characteristics

Since the performance of Zn-Ferrite has a big influence on the electric characteristics of power inductor, Zn-Ferrite film is evaluated on the magnetic properties.

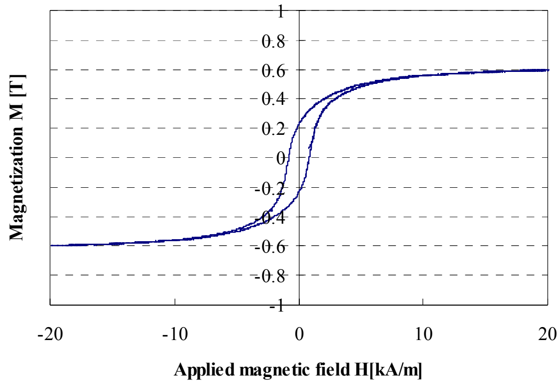

Fig. 9 The measurement result of static magnetization of $Zn_{0.22}Fe_{2.78}O_4$ film.

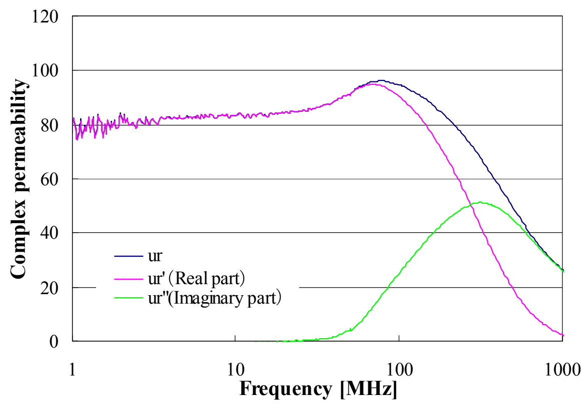

Fig. 10 Frequency characteristics of complex relative permeability of $Zn_{0.22}Fe_{2.78}O_4$.

As these measurement samples, we used the Zn-Ferrite film plated onto the flat planar with smooth face which is polyimide film formed on the glass substrate.

A static magnetization of the Zn-Ferrite film is measured with the vibrating sample magnetometer system (VSM, BHV-55: Rika Denshi Co., Ltd.) is shown in Fig. 9[8].

Since this composition is iron overload, the saturation magnetization showed a high value of 0.60T or more.

Fig. 10 shows the result of the frequency characteristic of complex relative permeability. This result is measured by the high frequency magnetic permeability measurement equipment (PMM-9G1: Ryowa Electronics Co., Ltd.) based on the shielded loop coil method [10, 11]. Real part ur of complex relative permeability is about 80 until 30 MHz, and natural resonant frequency is about 300 MHz.

These results indicate that there is agreement with our target specifications on magnetic characteristics of Zn-Ferrite film without any problems.

(2)The resistance, the inductance and Q-factor

The resistance and the inductance are measured in the probing method with the two ports contact by the vector network analyzer (PNA, E8364B, Agilent Technologies Inc.,).

Fig. 11 shows the measurement results of inductance for two type inductors. And Fig. 12 shows the measurement results of resistance for these.

The measurement result of inductance for planar power inductor covered with Zn-Ferrite film shows the lower value than the calculation results based on the design value. For the air core inductor, the measurement result of inductance and the calculation result of one show almost equivalent to the design value. As well as that, the measured resistances of two inductors show the equivalent value.

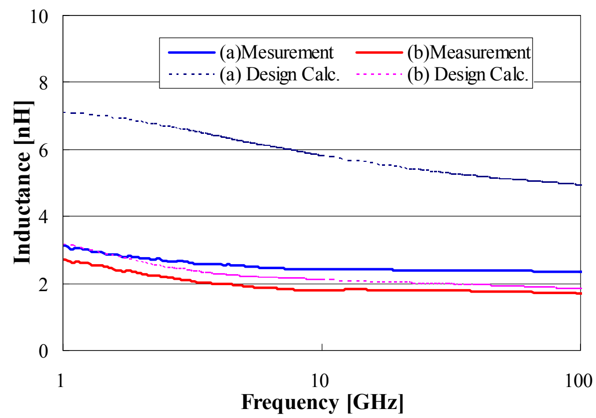

Fig. 11 The measurement results of inductance.
(a) The inductor covered with Zn-Ferrite
(b) The air core Inductor

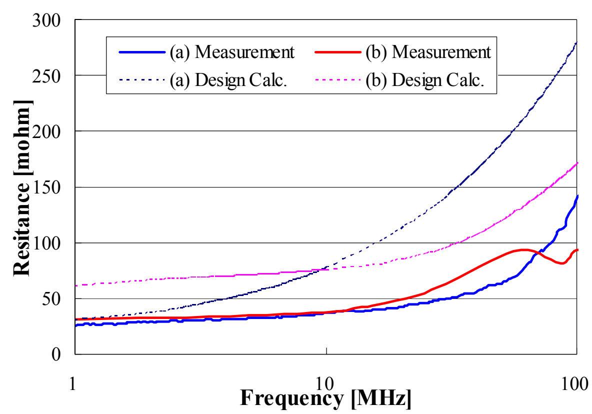

Fig. 12 The measurement results of resistance.
(a) The inductor covered with Zn-Ferrite
(b) The air core Inductor

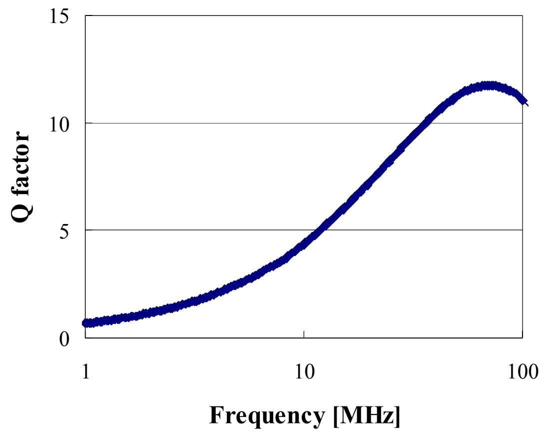

Fig. 13 Q-factor of planar power inductor covered with Zn-Ferrite film.

And then, Q-factor of planar power inductor covered with Zn-ferrite from these measurement values was calculated by the following equation (4):

$$Q = \frac{\omega L}{R} \tag{4}$$

Fig. 13 shows Q-factor of planar power inductor covered with Zn-Ferrite film.

Although Q-factor is 10 to 13 in 30MHz to 100MHz, the planar power inductor covered with Zn-Ferrite can not be obtained greater value than 15 for our target.

(3) The degradation of inductance by superimposed current

Fig. 14 shows a schematic circuit diagram to measure inductance change influenced by superimposed current bias characteristics.

The measurement of inductor is used the impedance analyzer (Hewlett-Packard Dep. Co, L.P: HP4291A). The calibration for the residual impedance of the measurement system and lead wires has been calibrated in the OPEN and the SHORT.

Fig. 15 shows the measurement results of the degradation by the superimposed DC current characteristics of planar power inductor covered with Zn-Ferrite film. Decreasing of inductance shows a characteristic of less than 30% at 3A.

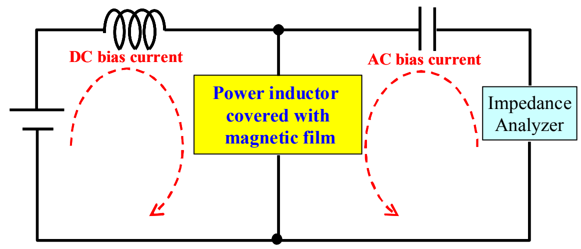

Fig. 14 The measurement circuit of superimposed DC current characteristics of planar power inductor covered with Zn-Ferrite film.

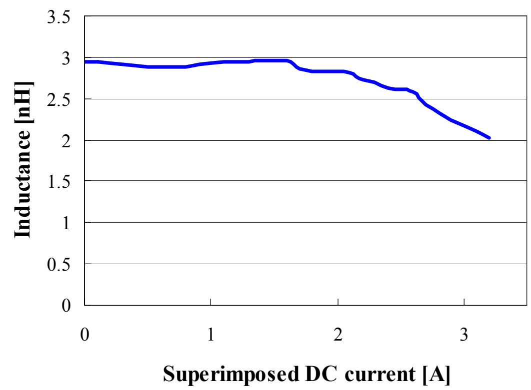

Fig. 15 The superimposed DC current characteristics of planar power inductor covered with Zn-Ferrite film.

6. Discussion

The purpose of this study is to find an availability of the planar power inductor embedded into a LSI package.

The developed power inductor is a spiral coil covered with Zn-Ferrite film in shape. The inductor allowable to be embedded into organic substrate can be obtained, in which the resistance value and the superimposed DC current characteristics are set for the target specification, as shown in Table 2.

As the result of that, the inductance of the inductor shows a higher value than the air core power inductor in same size which is arranged as the comparison. This is caused by the reason why the magnetic material impacts on the effects of metal plane. However, this inductor can not be obtained the inductance value which meets the target specification. In order to investigate this cause, it has been confirmed the details structure of planar power inductor covered with Zn-Ferrite film. Based on obtained dimensions, the reverse simulation model is designed and analyzed by the ANSYS HFSS, which is a simulator with calculating electromagnetic field in three dimensional directions.

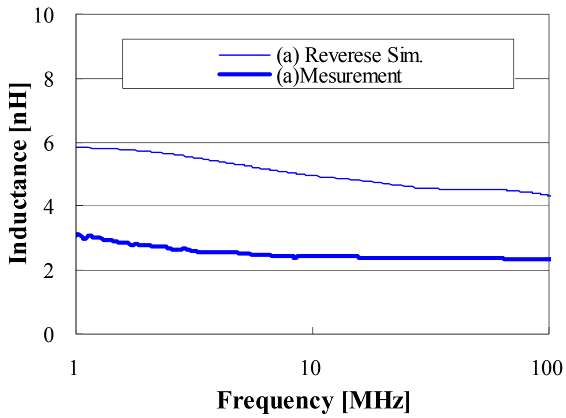

Fig. 16 The comparison of reverse simulation result and measurement result for planar power inductor covered with Zn-Ferrite.

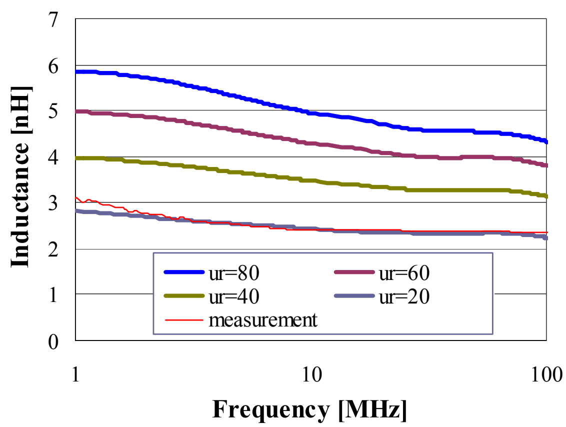

Fig. 17 Simulation results owing to the changing permeability of planar power inductor covered with Zn-Ferrite film.

Fig. 16 shows the comparison of reverse simulation result and measurement result of this inductor.

Although the inductance of reverse simulation result shows the lower value than that of original design model in Fig. 7, and is different from the measurement result. Therefore, it is considered the possibility that the magnetic characteristic is not obtained to satisfy our target specification.

And then, it is used the reverse simulation model, and simulated with changing permeability of the Zn-Ferrite film from 20 to 80.

Fig. 17 shows the simulation results. Simulation tool is also used ANSYS HFSS in this analysis. In the case that the permeability is 20, the simulation result has been close to the measurement result of the power inductor covered with Zn-Ferrite film.

On the other hand, as shown in Fig. 10, about the

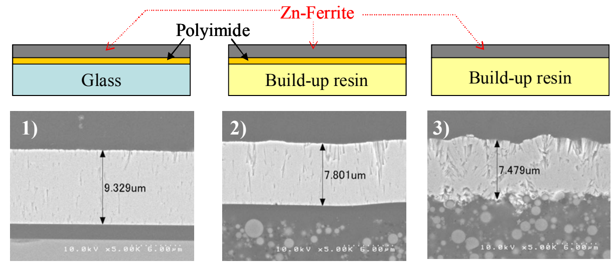

Fig. 18 The cross section photo of samples to evaluate Zn-Ferrite film.

sample with an ideal shape prepared as the reference, the measurement permeability of Zn-Ferrite film prepared in the same batch has been obtained 80. In, this sample, Zn-Ferrite is formed the polyimide deposited on the glass substrate. These results indicated that the Zn-Ferrite film formed into an organic substrate is not possibly adequate form to be reached to 80 in the permeability. As this reason, it is assumed that the differences from 80 are probably caused by crystalline shape and magnetic performance especially formed nearby surface of Zn-Ferrite which may be slightly shifted from ideal shape and performance.

Therefore, we investigated about the crystalline and the magnetic features to detect the causes as conducting SEM observation on each sample at cross view and as conducting others. There are differences among each in the feature.

Fig. 18 shows the views on each sample arranged Zn-Ferrite formed onto the different kinds of materials for the evaluation, in whose process, Zn-Ferrite is formed on build-up resin.

As shown in cross section photos of three samples, it is found that the growth rate and formation of crystal are different among each.

In the future, as further investigation will be continued to clearly the cause and the behavior on magnetic and crystalline properties of Zn-Ferrite to get the ideal performance with resin base material.

As another approach to improve the inductance value, we are also considering a change of inductor design. Since our design method is confirmed that it is a higher accuracy in comparison with measurement results, a change of one is studied in this method.

7. Conclusion

The present work suggests that a LSI package with the miniaturized inductor used Zn-Ferrite film embedded into inside of the package would be realized in extension from the POL technologies for next generation as an application.

We have successfully developed the planar power inductor covered with Zn-Ferrite film, which is embedded into an organic package on the way of the package fabrication process simultaneously.

From the measurement results of electric characteristics, the inductance value can not be achieved in our target specification, but the resistance value can be achieved. Therefore, Q-factor can not meet the expected results.

However, the DC superimposed current characteristic can be achieved our target specification until 3A.

With reverse simulation results, the permeability of Zn-Ferrite film formed into an organic package shows a different value from 80.

We have considered that the characteristics change of crystalline and magnetic is probably caused by the difference of surface condition formed Zn-Ferrite.

These causes is continued to investigate in now. After solving this problem related to the forming method for Zn-Ferrite, the DC-DC converter embedded into a LSI package will be developed by using this inductor technology.

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