Original
Received December 26, 2005
Accepted for Publication April 3, 2006
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3D Field Simulation of Magnetic Thin Film Inductor

Toshiyasu FUJIWARA, Kyung-Ku CHOI and Shigeki SATO

Advanced Process Technology Center, TDK Corporation
2-15-7, Higashi-Ohwada, Ichikawa-shi, Chiba, 272-8558 Japan
E-mail : tfujiwr@mb1.tdk.co.jp

The 3D magnetic field simulations with FEM (finite element method) have been performed to predict and understand the performance of Magnetic Thin Film Inductor (MTFI). Inductor structures of planar electroplated Cu spiral coil, which are sandwiched and underlaid with magnetic thin films, are considered as the simulation models. The inductance increment of 300% compared to air-core inductor was predicted when the sandwiched 5 μm thickness magnetic thin film with relative permeability of 600 was adopted. Impedance measurement for the fabricated MTFI showed a good agreement with the simulation result. We also found that the undesirable increment of resistance at high frequency was originated from the eddy current flow through magnetic thin film.

Key Words : Thin film inductor, Magnetic thin film, Eddy current

1 INTRODUCTION

There is a strong demand on thin film electromagnetic devices, such as inductors and transformers, for the purpose of applying them to SiP (system-in-package) and SoC (system-on-chip) which mounted more circuits and functions together [1]. Recently, much effort has been focused on the development of magnetic thin film inductors (MTFI) using semiconductor process and MEMS (micro electro mechanical systems) techniques [2],[3]. 3D magnetic field simulation with FEM (finite element method) is very useful to understand the electromagnetic function of each structural element in MTFI construction [4], because reliable simulation results with a model close to the real device is expected.

In this study, the structures of planar electroplated Cu spiral coils, which are sandwiched and underlaid with magnetic thin films, are considered as the simulation model. The effects of design parameters, such as magnetic thin films thickness and the gap between coils and magnetic thin films, are studied and compared with air-core inductor. Impedance measurement for the fabricated MTFI was performed and compared with simulation results.

2 EXPERIMENTAL PROCEDURE

2.1 Simulation model

A FEM software package (Maxwell 3D field simulator, Ansoft Co.) has been used to obtain numerical results. The air-core Cu spiral inductor model used for simulation is rectangular shaped spiral coils, which has 11 wire turns with line width of 200 μm, line gap of 20 μm and line height of 5 μm, as shown in Figure 1. In this study, two types of MTFI models are used for simulation. One is the spiral coil sandwiched by magnetic thin films and the other is the same coil underlaid with bottom magnetic thin film. The cross sectional schematic diagrams of the MTFI models are shown in Figure 2. In the simulation procedure, the space between the magnetic thin film and Cu coil is considered as air.

2.2 Material properties used for the simulation

For the magnetic thin films, we used Co-based amorphous alloy. The real part of permeability (μ') along with the magnetic hard axis is about 600. The imaginary part of permeability (μ") and hysteresys loss are not considered in our simulation. The material properties used for the simulation are shown in Table 1.

2.3 Fabrication and electrical measurement

In order to confirm the validity of above simulation, air-core inductor (Cu coil thickness: 5 μm) and MTFI (Cu coil thickness:

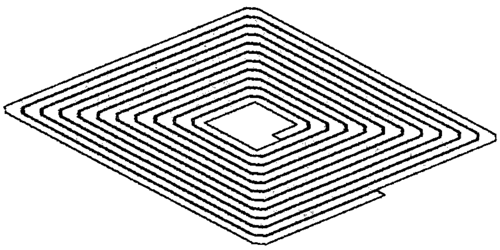
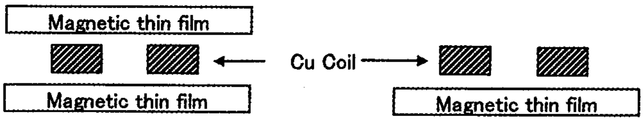


Figure 1 Schematic diagram of the air-core spiral inductor model.



(a) sandwiched-type (b) underlaid-type

Figure 2 Cross sectional schematic diagram of the MTFI model.

Table 1 The material properties used for the simulation

	Resistivity [$\mu\Omega$cm]	Permeability (μ')	Thickness (μm)
Cu	1.8	1	4-5
Co-based amorphous alloy	100	600	5

4 μm, Co-based alloy film thickness: 5 μm, gap width: 3 μm) were fabricated. Cu spiral coil was electroplated on SiO_2/Si substrates and Co-based amorphous film was sputter deposited on the resin, which is used as the insulating layer between the coil and magnetic film. The electrical characteristics of both inductors were measured by using impedance analyzer (4294A, Agilent Technologies Inc.).

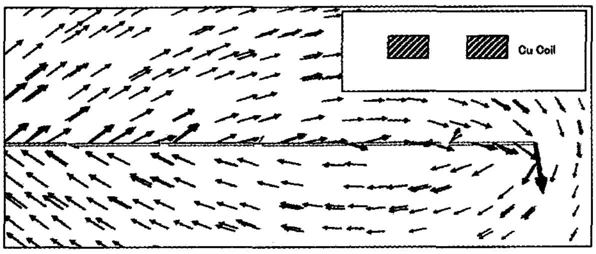
3 RESULTS AND DISCUSSION

3.1 Structural dependence

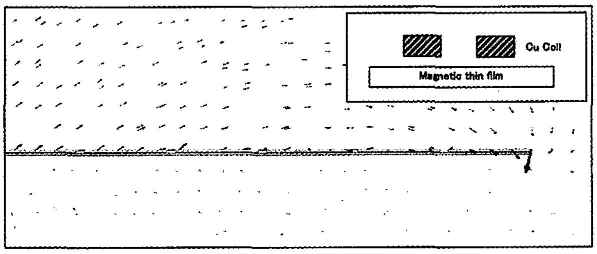
In order to investigate the thickness effect of magnetic films on the inductance, simulated inductance values of the air-core and the MTFIs are compared in Figure 3. As seen in Figure 3, the inductance value of MTFIs is increased along with the thickness of magnetic film and the inductance increment of sandwiched-type is much larger than that of underlaid-type MTFI. For example, when the sandwiched magnetic film thickness is 5 μm, the inductance value of sandwiched-type MTFI exceeds 1 μH, although those of the air-core inductor and undrlaid-type MTFI are 0.4 μH and 0.5 μH, respectively.

Figure 4 shows the cross sectional view of simulated magnetic flux distribution around the outer 6 coils when the current of 1 A is applied to the Cu spiral coils. The arrows indicate the intensity and direction of magnetic flux. As seen in Figure 4, the magnetic flux distribution is quite different according to the inductor structure. In the case of air-core inductor (Figure 4 (a)), magnetic flux spreads over the space and magnetic energy concentration seem to be small. When the high permeability Co-based amorphous film is positioned under the coil (underlaid-type MFI, Figure 4 (b)), magnetic flux is concentrated on the magnetic film thus the spread of magnetic flux over the space reduces effectively. In the sandwiched-type MTFI (Figure 4 (c)), the top and bottom magnetic films shunt the flux into the MTFI thus most of the magnetic flux is used as inductance increment. Magnetic flux arrows are very large at the right edge of the outest coils. But this behavior doesn't occur for the real devices. It is originated from the divergence of the calculated magnetic energy at the ideal corner of rectangular FEM model, which is the common problem for FEM simulation.

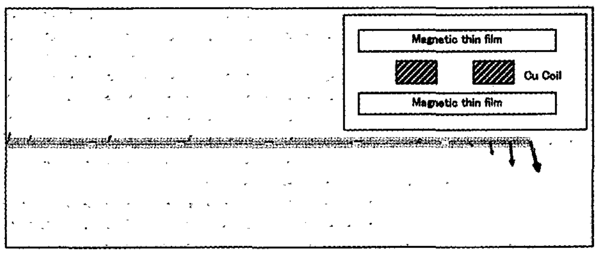
Figure 5 shows inductance as function of the insulation gap width of the sandwiched-type MTFI structure together with the



(a) air-core



(b) underlaid-type



(c) sandwiched-type

Figure 4 Cross sectional view of magnetic flux distribution for (a) air-core, (b) underlaid-type MTFI, and (c) sandwiched type MTFI.

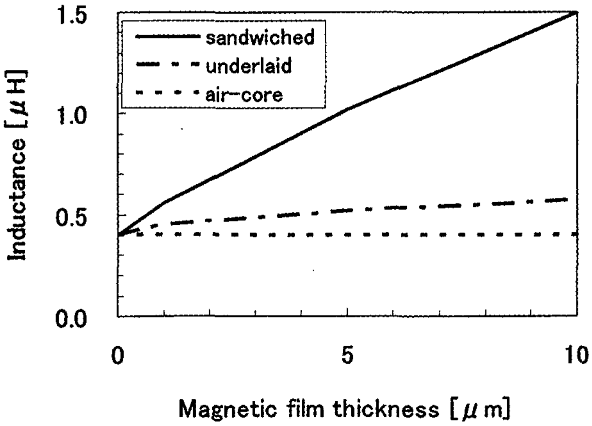


Figure 3 Inductance values of the air-core inductor and MTFIs as Ifunction of the magnetic film thickness.

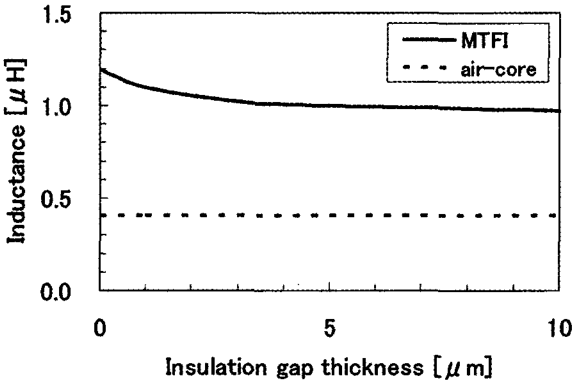
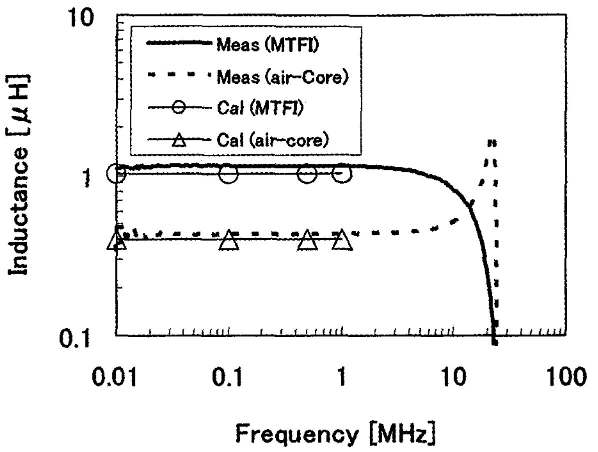


Figure 5 Inductance values of air-core and MTFI as function of the insulation gap width.

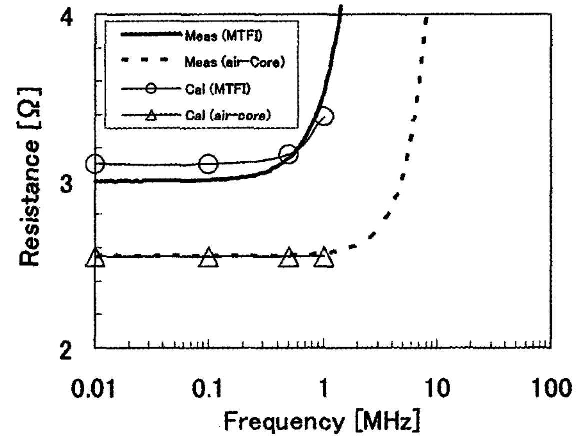
air-core inductor. The inductance of MTFI is a function of the insulation gap thickness, however it shows almost constant value when the gap thickness is larger than 4 μm. In the thinner gap of less than 4 μm, the inductance increases as the gap thickness becomes thinner. About 10% of inductance increment is expected when the gap thickness is controlled to 1 μm.

3.2 Comparison between simulation and measurement

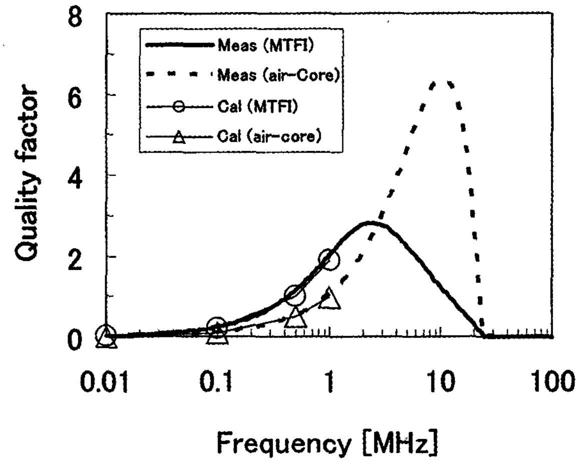
The frequency characteristics of the inductance, the resistance and the quality factor of fabricated inductor are compared with the simulation results in Figure 6. Inductance increment of 300% is expected when the magnetic film of 5 μm thickness is inserted at the top and bottom of Cu spiral coil, and the measured result shows a good agreement with the simulated value, as seen in Figure 6 (a).



(a) inductance



(b) resistance



(c) quality factor

Figure 6 Frequency characteristics of the MTFI and the air-core inductor: (a) inductance, (b) resistance and (c) quality factor.

In general, the effect of electromagnetic coupling is not considered in the magnetic field simulation thus the simulation result is effective only when the LC resonance effect doesn't appear. In this study, magnetic field simulation results under 1 MHz are discussed because the simulation results are not affected by the LC resonance in this frequency region. The measured LC resonance frequencies are about 25 MHz for both inductors as seen in Figure 6 (a). At the resonance frequency, the abrupt increase of inductance is observed in the air-core inductor. On the other hand, the inductance of the MTFI shows no peak and slight decrement is observed when the frequency is between 1 MHz to resonance. We think these frequency characteristics of MTFI are originated from the stray reactance between the coil and the magnetic layers. For the clear understanding of these behaviors, more precise analysis based on the electrical equivalent circuit is needed [5].

The frequency characteristics of the resistance for the air-core inductor and the MTFI are shown in Figure 4 (b). The resistance of air-core inductor is constant up to 1 MHz and then largely increases near the LC resonance frequency. On the other hand, the increment of the resistance of the MTFI starts at around 0.5 MHz. In the MTFI, eddy current effect is considered as the origin of the undesirable increment of resistance at lower frequency, because eddy current is considered in our simulation and the simulated resistance shows good agreement with the measured value. As mentioned before, LC resonance is negligible up to 1 MHz. Micro patterning of the magnetic film [3] could be effective for reducing the eddy current flow and improving the frequency characteristics of MTFI.

Figure 6 (c) shows the quality factor (Q) of air-core inductor and MTFI. It should be noticed that the Q of MTFI is larger than that of air-core inductor when the frequency is lower than the peak frequency of 3 MHz. The decrement of Q at the frequencies higher than 3 MHz seems to be the effect of the inductance decrement (Figure 6 (a)) and resistance increment (Figure 6 (b)), as easily supposed by the well-known relation:

$$Q = \omega L / R \tag{1}$$

where ω is the angular frequency.

Structural optimization of MTFI by way of reducing the stray reactance between coil and magnetic layer and eddy current through magnetic film could show the guide line for higher Q.

4 CONCLUSIONS

We studied electrical characteristics of magnetic thin film inductor (MTFI) by using 3D magnetic field simulations. Inductance increment of 300% compared to air-core inductor was predicted when the sandwiched 5 μm thickness magnetic thin film with relative permeability of 600 was adopted. Impedance measurement for the fabricated MTFI showed a good agreement with the simulation result in the cases of inductance, resistance and quality factor. This simulation reveals that the undesirable increment of resistance at high frequencies was originated from the eddy current flow through magnetic thin film.

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