3D Simulation of Thin Film Inductor using Permalloy as a Conductor

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Copper is generally used as a conductor in an air-core spiral thin film inductor. But the inductance of the air-core spiral inductor is very low. In order to improve the inductance, permalloy is used as a conductor in this simulation study. The inductance are 953 nH and 184 nH at 10 MHz with permalloy conductor and copper conductor, respectively. The resistance of the inductor with permalloy conductor is larger than that of the inductor with copper conductor about ten times and the quality factors are 1.4 and 2.5 at 10 MHz in the permalloy and copper coil inductor, respectively. Consequently, we propose the possibility of inductor using the permalloy as the conductor in 10 MHz range.

** Key word:** thin film inductor, conductor, permalloy, simulation

1. Introduction

MEMS(Micro-Electro Mechanical System) have been widely studied for the several different applications. Especially, the spiral inductor used as a component of micro-valve and micro-pump operating in low frequency range is to be advantageous to have large inductance. Copper is generally used as a conductor in an air-core spiral thin film inductor. Though an air-core spiral inductor with copper conductor has advantage easy to fabricate and good frequency dependency up to several hundreds of MHz, the inductance very low in whole frequency range. On the other hand, permalloy has higher permeability than copper and its core loss is low up to 10 MHz. And the conductivity of permalloy is comparatively higher among magnetic materials. To obtain higher inductance than air-core inductor, a magnetic core is required.

But in that case, the fabrication process becomes complicated because it needs more masks for magnetic core and insulation layers. Therefore, we propose new type air-core inductor using permalloy as a conductor. In this study, we investigate the properties of the permalloy inductor with the change of line width and gap width through 3D simulation.

2. Experimental procedure

A software package(Maxwell 2D/3D field simulator, Ansoft. Co.), which employs the finite element method(FEM), has been used to obtain numerical results. The calculation is carried out till the total error rate becomes below 5%.

Fig. 1 Schematic diagram of the model

The meshes are generated by an adaptive mesh generation method, in which meshes are generated in order to get the suitable error rate at high error energy range. The material properties of permalloy are obtained by electroplated permalloy. The permeability of permalloy is measured by an 8-figure coil method up to 10 MHz and the conductivities are measured by a 4-point probe method. The detailed material properties are shown in Table 1.

The models used for simulation have 5 and 1/2 wire turns and the size is fixed at 4 mm × 4 mm. The thickness of the model is 5 μm and the via length is 10 μm. The line width is changed 60 μm to 100 μm and gap width 40 μm to 100 μm. And the bias current is set to 1 mA. The schematic diagram of the model is shown in Fig. 1.

3. Results and Discussion

Fig. 2 shows the change of inductance of copper and permalloy air-core inductors. The inductance are 1233 nH and 184 nH at 1 MHz in permalloy conductor and copper conductor, respectively. By the Grover’s theoretical equations\(^1\), the self inductance of the rectangular shape

<p>| Table 1 The properties of the materials used in the simulation |
|-------------------|----------------|---------|----------------|</p>
<table>
<thead>
<tr>
<th>Conductivity (mho/m)</th>
<th>(\mu') (at 1MHz)</th>
<th>(\mu'') (at 1MHz)</th>
<th>coercive force (Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>(5.8 \times 10^7)</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>Permalloy</td>
<td>(6 \times 10^6)</td>
<td>1550</td>
<td>0.6</td>
</tr>
</tbody>
</table>
straight conductor is shown below.

\[ L = 0.0021 \left[ \ln \left( \frac{2l}{(a+b)} \right) + 0.25049 + \left( \frac{(a+b)}{3l} \right) + (\mu / 4) \right] \]

\( l \): conductor line length
\( a, b \): rectangular dimensions of the cross section
\( \mu \): permeability

Therefore, the difference of the inductances between two inductors is due to the permeability effect. Also the mutual inductance is affected by the permeability term.

The fact that the increase of permeability causes the increase of the inductance is confirmed by the comparison of the B-field of two type inductors. Fig. 3 shows the difference of the B-field with distance from the inductor's center point. The density of the magnetic flux in the permalloy inductor enormously increases comparing to the copper inductor. This is the reason why the inductance increases. The inductance of the copper inductor rarely changes with the frequency changes but that of the permalloy inductor decreases somewhat with increasing frequency. The frequency dependency of the effective permeability of electroplated permalloy is shown in Fig. 4. Due to the loss of the permalloy, the effective permeability decreases with frequency.

![Fig. 2 The inductance change as a function of frequency](image)

![Fig. 3 The B-field distribution of the inductors](image)

![Fig. 4 The permeability as a function of frequency](image)

The resistance and the quality factor of permalloy and copper inductor are shown in Fig. 5. The resistance is about 43 \( \Omega \) and 4.5 \( \Omega \) in permalloy and copper inductor at 1 MHz, respectively. In case that AC is applied, the skin depth effect is appeared. The skin depth \( \delta \) is obtained by the equation as below. The skin depth of permalloy is 5.2 \( \mu m \) at 1 MHz and 1.6 \( \mu m \) at 10 MHz. Hence the skin depth decreases with frequency and the resistance of permalloy inductor increases. But the resistance of copper inductor stays up to 10 MHz because

\[ \delta = \sqrt{\frac{2}{\omega \sigma \mu_0 \mu_r}} \]

\( \omega \): angular frequency
\( \sigma \): conductivity
\( \mu_0, \mu_r \): permeability of free space and relative permeability

The skin depth of the copper is about 21 \( \mu m \) at 10 MHz. The quality factors are 1.4 and 2.5 at 10 MHz for the permalloy and the copper, respectively. The quality factor of permalloy inductor is somewhat lower than that of copper inductor. That is because the increase of the inductance is lower than that of the resistance. Fig. 6 shows the inductance and resistance with the change of the line width when the gap width is fixed at 40 \( \mu m \). As the line width increases, the self inductance and mutual inductance decreases\(^{[1, 3]}\). So the inductance decreases with increasing line width. As mentioned before, the inductance decreases with frequency. The increase of the conductor line width results in the increase of the cross sectional area of the conductor line. So the resistance of the inductor decreases with increasing line width.

Fig. 7 shows the change of the inductance and resistance with the distance between the conductor lines when the line width is fixed at 60 \( \mu m \). As the gap width increases, the mutual inductance decreases. Hence the total inductance decreases with increasing of gap width. In this case that the gap width is above 80 \( \mu m \), the proximity effect does not show.
Fig. 5 The resistance and quality factor of the inductors as a function of frequency

Fig. 6 Variation of the inductance and resistance as a function of line width

Therefore, the resistance decrease slightly.

Fig. 7 Variation of the inductance and resistance as a function of gap width

4. Conclusions

We obtained the higher inductance using permalloy as conductor up to 10 MHz in an air-core inductor. The inductance of permalloy inductor are 1233 nH and 953 nH at 1 MHz and 10 MHz respectively and the quality factor is 1.4 at 10 MHz. These high inductances are obtained by increasing conductor’s permeability. The inductance decreases with increasing the line and gap width. Therefore, the permalloy inductor with proper line and gap width shows the possibility of an excellent air core spiral inductor up to 10 MHz.

References