Design, Simulation and Fabrication of A MEMS-based Double-layer Spiral Planar Inductor with Patterned Permalloy as Magnetic Layers

Xiaomin Zhu,1 Ping Cheng,1 Mingming Chen,1 and Guifu Ding1
1National Key Laboratory of Science and Technology on Micro/Nano Fabrication, Department of Micro/Nano Electronics, School of Electronic Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai 200240, CHINA
xmin_zhu@163.com

Abstract. There have been significant efforts to boost the inductance value by adopting the sandwich structures using permalloy magnetic shielding layers. However, this structure will introduce high ac conductor losses and high eddy currents. In order to solve these problems, patterned permalloy can solve this problem effectively. According to the simulation results based on the application of finite element method in the frequency domain, the optimum permalloy pattern is which the blank of the permalloy are perpendicular to the coil inside. The double-layer planar inductor has a size of 1.5×1.5×0.1mm consisted of 13-turn spiral Cu coil for each layer and a 20-μm-thick patterned permalloy magnetic shielding layer. The inductor shows a higher inductance than the traditional planar inductor. The patterned permalloy made the inductor more stable in high frequency than the none-patterned. And the inductor has an inductance of 1.3μH and quality factor of 2.8 at 1.5MHz, with an inductance per unit of 578nH/mm², which is much higher than that in the reported literatures.

1. Introduction
On-chip spiral inductors have played an increasingly important role in integrated circuits, such as converters, filters, mixers, and oscillators [1]. Due to the widespread use in the wireless communications technology and the strongly desire of smaller size for integrated packaging, the planar spiral inductors have gained interest in this area. The challenge of integrating inductors on-chip have stood the way of fully integration of many electronic systems such as power converter devices [2]. In the current inductive elements market, the conventional large size winding coils are still dominant. However, there have been increased efforts to reduce the size of inductor without sacrificing the performance. Planar spiral structures are often desirable for inductors because the parallelized fabrication processes can make it easy for packaging while the spiral configurations can ensure the number of turns in a very small size.

The size of the inductor can be reduced by MEMS technology. The development of MEMS technology make it possible to fabricate the planar spiral micro-inductors by some micro-fabrication processes like photolithography, wet etching, electroplating technique, etc. And the performance should be insured while used in the packaging. In recent years, there have been significant efforts to
boost the inductance value by adopting the sandwich structures using magnetic shielding layers. Permalloy is a kind of soft magnetic materials with high relative permeability. It shows great compatibility with MEMS technology and plays significant role in increasing the inductance and quality factor of planar spiral inductors [3]. The permalloy magnetic films are often deposited above and below the spiral plane using the photolithography and electroplating techniques.

Now the plane sandwich structure are greatly applied in fabricating micro-inductor due to its stability and small size and compatibility with processing procedure. The metal layers of the sandwich structure can prevent the magnetic field lines from spreading outside and thus keep the magnetic field loops around the conductor lines. However, this structure will introduce high ac conductor losses and high eddy currents. Patterned permalloy can solve this problem effectively. As the magnetic shielding layers, appropriate patterned method can also reduce the eddy currents while it play a role in shielding the magnetic field lines outside.

Many researches have focused on the packaging micro-inductor applied in the DC/DC power conversion. Many electronic systems have the module of DC/DC power conversion. Figure 1 (a) shows the typical circuits of the principal components of a DC/DC converter [2]. Some electronic components such as PWM logic, OSC, Slope comp and UVLO have already integrated in the Control IC part. However, the inductor is the most difficult to be integrated in the power converter chip. At present, the series of XCL205 with a size of 2mm*3mm fabricated by TOREX have integrated the inductor on chip successfully. The X-ray scanning picture of the device is shown in figure 1 (b). The inductor is pressed on the chip part and connect with each other inside by lead wire. In addition, the inductance value at 1MHz is 1.5μH. It can be seen that the inductor is a handmade device and thus is poor at mass production.

![Figure 1.](image)

**Figure 1.** (a) Schematic illustration of the DC/DC converter circuits. The components in the dashed box would be integrated together; (b) The X-ray scanning picture of the XCL205 fabricated by TOREX.

Mishra et al. [4] developed a toroid-based inductor using multilayered ferromagnetic-polymer composites as magnetic cores, which was fabricated by laminating NiFeMo magnetic foils and BCB polymer adhesive layer by layer. The inductor had a size of 7mm × 4mm × 1.5mm, with an inductance of 1.96nH/mm². Fukuda et al. [5] designed a single-layer planar inductor using screen printed NiZnCu/resin ferrite composite layer to improve its inductance. The inductor had a size of 6mm × 6mm × 0.2mm. At 1.5MHz, the inductance was 1.5μH with an inductance value per unit of 42nH/mm². Sadler D J et al. [6] developed a spiral-type inductor with 4.52μH using AZ-4000 series photoresist as dielectric layer and using Ni/Fe permalloy as core. The inductor had a size of 4.2mm × 4.2mm, with an inductance value per unit of 256nH/mm². Kowase et al. [7] developed a large-current planar inductor with a sandwich structure, which consisted of two-turn Cu square spiral coil, top and bottom
ferrite magnetic cores. The inductor had a size of 15mm × 15mm × 1.4mm, and an inductance of 140nH, with an inductance value per unit of 0.62nH/mm². For the above reported inductor, the size of device was too big and the inductance value per area was relatively small.

This study aimed to get a high inductance value in a small device size. A double-layer planar inductor with up and below patterned permalloy magnetic shielding layers have been fabricated. The patterned permalloy figure which the blank of the permalloy are perpendicular to the coil inside have been proved better than other figures. The inductor with a small device size of 1.5×1.5×0.1mm can been packaged easily which oversize is satisfied with the application DT8515 buck DCDC converter. And the inductor has an inductance of 1.3μH and quality factor of 2.8 at 1.5MHz, with an inductance per unit of 578nH/mm².

2. Inductor Design

2.1. The Structure of the Inductor
Planar, rectangular spiral geometry was chosen as a well-tested technique for maximizing inductance per area, and a nominal inductor size of 1.5mm × 1.5mm was selected. within these parameters, The number of turns was varied as an inductance vs. coil resistance tradeoff. However, a 13-turn design was qualitatively selected as a most likely candidate for fabrication and integration and all extended characterization was performed with 13-turn inductors by simulation. Single-layer coils are easy to fabricate, but the multi-layer coils have more coil turns without increasing the device size [9]. All the above factors and the microfabrication processes considered, figure 2 (a) shows the illustrated structure designed of the planar spiral inductors [8]. Double-layer structure is adopted and each coil layer consists of 13 turns. Each turn is 20μm in width and each coil spacing is 20μm. The area of the inductor is 1.5mm×1.5mm except the two metal test pads. The part of via connects the coil layers effectively above and below to form a double-layer structure. The thickness of each layer is 20±2μm and the two layers are 10±2μm apart from each other. And the above and below layers are permalloy magnetic layers which play a role in shielding the magnetic field lines outside the inductor structure. To find the optimum permalloy pattern and bring some laws of the geometric figures, eight different patterned permalloy figures were designed and simulated. Figure 2 (b) illustrated these eight geometric figures. Type7 is a reference and other pattern were started from Type8. There are two basic categories. Type3 and Type5 are which permalloy blank are perpendicular to the coil inside. And Type2 and Type4 are which permalloy blank are parallel to the coil inside. It can be seen obviously from the figure 2 (b).

![Figure 2](image)

Figure 2. (a) The illustrated structure of the inductor; (b) Eight geometric figures of the patterned permalloy designed as magnetic layers.
2.2. The simulation results of the inductor designed above

2.2.1. The method of the analysis and the mathematical description. Inductances are a fundamental component in electronic field, thus it is important to know how it can be modeled. For arbitrary complex structures, numerical procedures are developed either in time domain or in frequency domain and among them, then the Finite Element Method (FEM) can be used to computed. FEM analysis requires a convenient mesh grid study to obtain a correct and optimized solution of the model. The optimization of the mesh is related to some specific physics characteristics, like the skin depth [9]. This work was developed based on the application of finite element method in the frequency domain, using the software COMSOL Multiphysics with the ACDC module [10]. The simulations have made in a frequency domain with the ACDC module and the Magnetic Field Interface. The equations (1) are computed by COMSOL Multiphysics:

\[
\begin{align*}
(j \omega \sigma - \omega^2 \epsilon) A + \nabla \times H &= J_e \\
B &= \nabla \times A
\end{align*}
\]  

(1)

where: \( \omega \) – the angular frequency of a magnetic field, \( \sigma \) – the electrical conductivity of materials, \( \epsilon \) – permittivity of materials, \( A \) – a magnetic vector potential, \( H \) – magnetic field intensity, \( B \) – magnetic flux density, \( J_e \) – externally generated current density.

This system of equations is computed to each finite element of the model. Solving the given equations allows us to obtain the magnetic flux distribution. In order to find a close solution it must be imposed a constrain in the outer boundaries:

\[ n \times A = 0 \]  

(2)

This equation fixes the tangential component of the magnetic potential \( A \) to zero.

Additionally, the winding is supply by a constant voltage, this imposes the following equations:

\[ J_e = \sigma \frac{V_{\text{coll}}}{L} \]  

(3)

where: \( V_{\text{coll}} \) – the applied voltage specified, \( J_e \) – current density in windings, \( \sigma \) – the conductivity of materials, \( L \) is equal to the physics interface’s thickness [12] [19] [20].

2.2.2. The Simulation Results from COMSOL Multiphysics. The simulation results of the inductance value \( L \) and the quality factor \( Q \) are shown in figure 3. Figure 3 (a) shows that the inductor with the patterned permalloy of Type 2, Type 4 and Type 6 do not show a better inductance value than the others. In addition, the inductor of Type 1 and Type 7 are unstable in high frequency. At 1.5MHz, the comparision of the inductance value \( L \) is Type5> Type3> Type8, and the Type3 shows a better stability than the Type5. Figure 3 (b) shows that the maximum value of the quality factor \( Q \) are in the comparision of Type3> Type5> Type2> Type6> Type8> Type4> Type1> Type7. And the corresponding frequency \( f \) of the maximum value \( Q \) are in the comparision of Type4> Type2> Type6> Type3> Type5> Type8> Type1> Type7.
Figure 3. Simulated results of the eight types. (a) Variation of the inductance value with the frequency; (b) Variation of the quality factor with the frequency.

According to the simulation results above, the final designed inductor structure with patterned permalloy is shown in figure 4. The Type3 and Type 5 pattern are chosen due to their excellent properties in the simulation results. And the Type 7 is chosen to be a reference object. The coil inside was a double-layer spiral planar inductor and each coil layer consists of 13 turns. The size of the inductor is 1.5mm×1.5mm.

3. Fabrication Procedure
Firstly, the Cu film was prepared on a 1mm thickness glass substrate by electroplating process. The photoresist was spin coated on the electroplated Cu film, and patterned using photolithography and wet etching [11]. Then the spiral Cu conductor line was obtained. The main fabrication processes of the double-layer spiral planar inductor are illustrated in the figure 5. The double-layer structure was realized by a through-hole filled with Cu connecting two layers of Cu coil [6]. The second coil layer is electroplated after the spin-coating. The via connected the upper and lower coil and the distance between the two coil layers was designed as 10μm. The permalloy magnetic films are deposited above and below the spiral plane using the photolithography and electroplating techniques. The pictures of the inductor samples fabricated by some MEMS technology are shown in figure 6.
Figure 5. Main fabrication processes (a)-(i).

Figure 6. Fabricated inductor samples.

4. Results and Discussion
Figure 7 showed the relationship between the inductance L and the quality factor Q with the frequency at a testing voltage of 5V. The testing frequency range was 10kHz-10MHz. All the testing results are from the inductor with the patterned permalloy of Type 3, Type 5 and Type 7. Figure 7 (a) shows that the inductor of Type 7 are unstable in high frequency. At 1.5MHz, the comparison of the inductance value L is Type 7> Type 5> Type 3, and the Type3 shows a better stability than the Type5. Figure 7 (b) shows that the maximum value of the quality factor Q are in the comparison of Type 3> Type 5> Type 7. And the corresponding frequency f of the maximum value Q are in the comparison of Type 3> Type 5> Type 7. The trend are achieved agreeable to the simulated results.
Figure 7. Experimental data of the chosen three types of the planar inductors with patterned permalloy magnetic layers filled with MnZn ferrite/PI composite materials. (a) Relation between inductance L and frequency; (b) Relation between the quality factor Q and frequency.

5. Conclusions
In conclusion, the MEMS-based spiral-type double-layer planar inductor was designed, simulated, fabricated and tested. The patterned permalloy inductor structure can reduce the eddy currents and improve the quality factor effectively at the same time boosting the inductance value. The optimum permalloy pattern is which the blank of the permalloy are perpendicular to the coil inside. In this study, the novel structure inductor have been fabricated by some MEMS technologies. The double-layer planar inductor has a size of 1.5×1.5×0.1mm consisted of 13-turn spiral Cu coil for each layer and a 20-μm-thick patterned permalloy magnetic shielding layer. And the inductor has an inductance of 1.3μH and quality factor of 2.8 at 1.5MHz, with an inductance per unit of 578nH/mm². The results indicated that the patterned permalloy made the inductor more stable in high frequency than the non-patterned. It will have many potential applications in magnetic sensors and actuators, and electronic circuit components.

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