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Simulation and Optimization of High Performance 3D Vertical Spiral Inductor

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Abstract: *In this paper, three inductor structures with different magnetic cores are established to explore the influence of magnetic core shape on inductor performance, based on the three-dimensional vertical spiral inductor. Through three-dimensional electromagnetic simulation, it is found that the introduction of the central magnetic column and the up and low magnetic leakage prevention plates greatly increases the inductance L and the quality factor Q of three-dimensional vertical spiral inductor by increasing the permeability of magnetic core and reducing the leakage loss. Based on this conclusion, a dumbbell-shaped magnetic core structure with the characteristics of central magnetic column and up and low magnetic leakage prevention plates is proposed. The three-dimensional electromagnetic simulation results verifies the excellent performance of inductor with dumbbell-shaped magnetic core which maximum quality factor is increased from 34 to 76, and the inductance value at the corresponding frequency is increased from 6nH to 64nH. It can be found that adding special magnetic cores is an effective way to improve the performance of three-dimensional integrated inductors, which provides a direction for the research on improvement of three-dimensional integrated inductor performance.*

Keywords: *MEMS, inductor, three-dimensional vertical spiral, dumbbell-shaped core, quality factor, magnetic core*

1. Introduction

As an indispensable passive device for IC design, inductor has been widely used in various circuit systems, such as DC-DC power conversion, low noise amplifier, integrated voltage regulator, etc [1-3]. With the development of integrated circuit technology, the demand for the enhancement of inductor integration becomes more and more urgent. In order to comply with the development trend of "miniaturization and low power consumption" of integrated circuits, it is of great significance in studying how to effectively reduce the inductor size without reducing inductance L and quality factor Q. Compared with the common silicon-based integrated planar spiral inductor, the three-dimensional vertical spiral inductor structure with high Q and high L fabricated by surface micromachining technology of MEMS technology[4] can reduce the size of inductor and ameliorate the adverse effects of parasitic capacitance and eddy current loss caused by low resistivity of silicon substrate, which provides a valuable research method for the design of inductors on silicon substrate[5-8].

Magnetic cores are often used in various inductor structures as their ability to significantly increase the inductance value. In addition to the permeability and resistivity of magnetic core materials, the structure and size of magnetic core are also important factors affecting the performance of inductors. Gardner et al. found that the inductance value can be significantly increased by using magnetic flux hole and slender magnetic film[9]. Wu et al. showed that by patterning the magnetic film into a combination of thin rods and laminations, the frequency of Q peak can be increased[10]. He et al. proposed an on-chip solenoid coupled inductor with spliced anisotropic and isotropic cores, and demonstrated its application in high efficiency DC-DC conversion[11]. The above studies on increasing the performance of inductors are all based on solenoid inductor, and the research on improving the performance of three-dimensional vertical structure inductors is still insufficient.

In this paper, based on the three-dimensional vertical spiral inductor, the influence of three different magnetic core structures on inductance L and quality factor Q is studied by three-dimensional electromagnetic simulation. Through the comparative analysis of the simulation results of different core structures, a high-performance dumbbell-shaped core structure is proposed, which improves the performance of the inductor by increasing the magnetic flux of the inductor and reducing the leakage loss. This structure can provide some guidance for the design of three-dimensional integrated inductor.

2. Design of Inductor Structure

Three dimensional vertical spiral inductor is an important inductor structure applied in MEMS technology, in which the parasitic capacitance and eddy current loss are lower than planar. Figure 1 shows a eight layers three-dimensional vertical spiral inductor fabricated on silicon substrate. In order to increase the distance between Si substrate and bottom coil for the further reduction of parasitic capacitance between substrate and bottom coil, a 10um SiO2 isolation layer was grown on the Si substrate. Above the SiO2 isolation layer is an eight-layer inductor coil winding made by Cu material, and it is composed of several single turn planar spiral inductor coils which are stacked vertically. The SiO2 dielectric layer is introduced to ensure the stability of the solenoid structure.

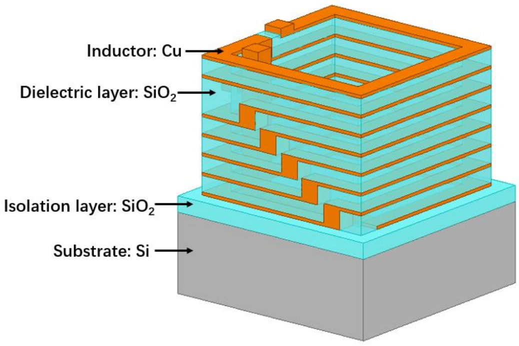


Figure 1: Three dimensional vertical spiral inductor without magnetic core.

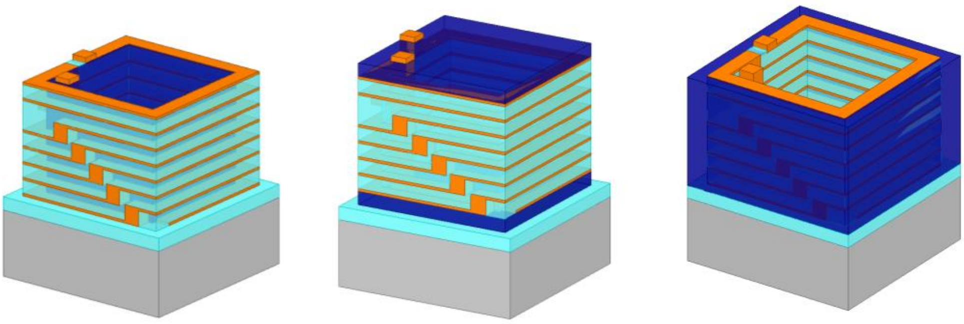
In order to further improve the performance of the inductor, we introduce a magnetic core structure based on the three-dimensional vertical spiral inductor, according to the calculation formula of solenoid inductance:

$$L = (k*\mu_0*\mu_r*S*N^2)/l \quad (1)$$

where μ0 is the vacuum permeability, μr is the relative permeability of the magnetic core, S is the cross-sectional area of the coil, N is the number of turns of the coil, l is the length of coil, and k is a coefficient determined by the ratio of the radius to the length of coil. Relative permeability μr of air core inductor is about 1, the introduction of magnetic material can improve the relative permeability of inductor core, thereby increasing the magnetic induction intensity inside the inductor. Selecting the appropriate magnetic core material to make it have higher permeability at the required frequency can significantly improve the inductance L.

In addition to increasing the permeability of the inductor core to improve L value, the other function of the magnetic core is to effectively bind the magnetic induction lines, so as to reduce the influence of magnetic leakage on the performance of the inductor and reduce the magnetic loss. The magnetic induction lines is a kind of closed curve, the magnetic induction lines in the center of inductor is the result of superposition of magnetic induction lines of several inductor coils. The density of magnetic induction lines inside inductor is high, and the magnetic field intensity is high. While, the magnetic induction lines outside inductor is divergent outward, and the magnetic field intensity is low. However, in practice, there is still a large magnetic field in small range of side wall and bottom of the inductor, and even higher than the internal magnetic field intensity in some positions, which is caused by the inductor magnetic leakage phenomenon. Therefore, by adding leakage prevention plate around the inductor to reduce the magnetic flux leakage phenomenon of three-dimensional vertical spiral inductor and strengthening the binding of magnetic induction lines of inductor, the magnetic loss of inductor is effectively reduced, and the inductance L and quality factor Q of inductor are improved.

Based on above analysis, we propose three kinds of core structure: the central magnetic column structure, the up and low magnetic leakage prevention plates structure and the side wall magnetic leakage prevention plates structure, as shown in Figure 2. The central magnetic column structure fills the central area of the inductor with magnetic medium; The structure of the up and low magnetic leakage prevention plates covers the upper and lower sides of the inductor with a certain thickness magnetic medium; The structure of side wall magnetic leakage prevention plates is to cover the side wall of inductor with a certain thickness magnetic medium.



(a) (b) (c)

Figure 2: (a) Central magnetic column structure; (b) Up and low magnetic leakage prevention plates structure; (c) Side wall magnetic leakage prevention plates structure.

3. Simulation Results and Discussion

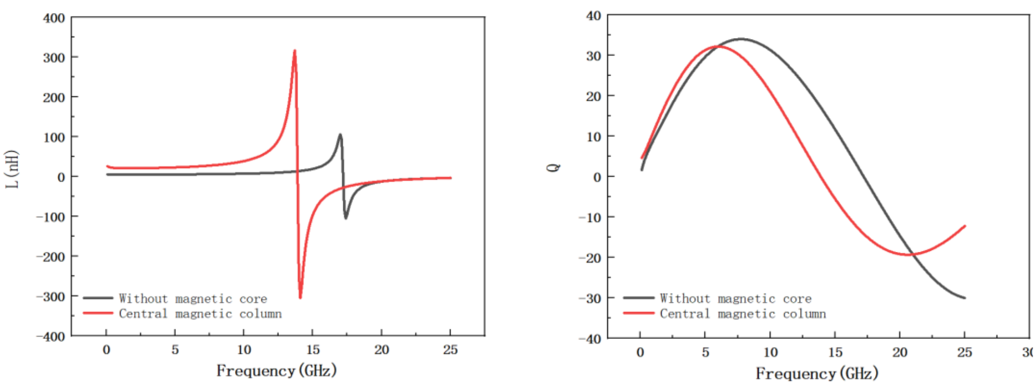
3.1. Simulation and Analysis of Three Inductors

In order to verify the influence of the three structures on the inductor's inductance L and quality factor Q, the corresponding electromagnetic models of the three structures is established in the three-dimensional electromagnetic simulation software Ansys HFSS, and the finite element simulation of their three-dimensional electromagnetic characteristics is carried out. The structure's corresponding inductance L and quality factor Q is calculated through formula (2) (3) by the extracted Y parameter.

$$L = im(-2/(Y(1,2)+Y(2,1)))/(2*\pi*Freq) \quad (2)$$

$$Q = im(1/Y(2,1))/re(1/Y(2,1)) \quad (3)$$

The structure of the central magnetic column is shown in Figure 2 (a). The magnetic core material is isotropic, and the relative permeability is set to 600 to make the change of the simulation results easier to be observed. Through simulation, we get the L value and Q value of the inductor with central magnetic column at different frequencies. Figure 3 shows the comparison of simulation results of the inductor with central magnetic column and inductor without magnetic core. By comparison, it is found that compared with the non-magnetic core structure, the inductance L of the central magnetic column structure has a significant increase. At the frequency of 10 GHz, L increases from the original 7nH to 40nH, the inductance value increases five times, which is consistent with the previous theoretical derivation.



(a) (b)

Figure 3: Comparison of the simulation results of inductor with central magnetic column structure and without magnetic core: (a) Inductance L; (b) Quality factor Q.

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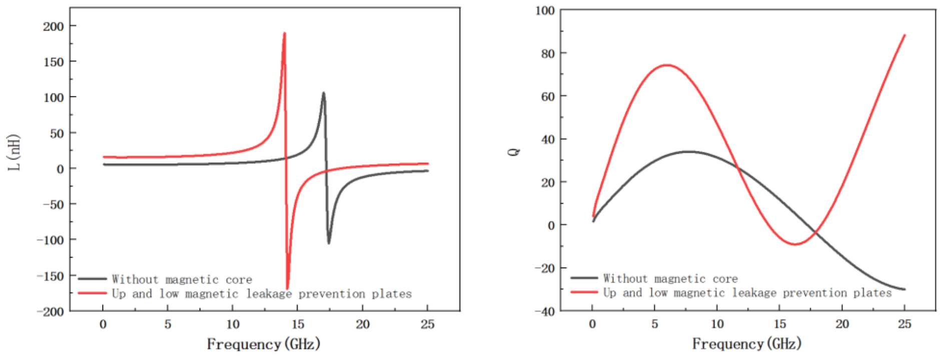
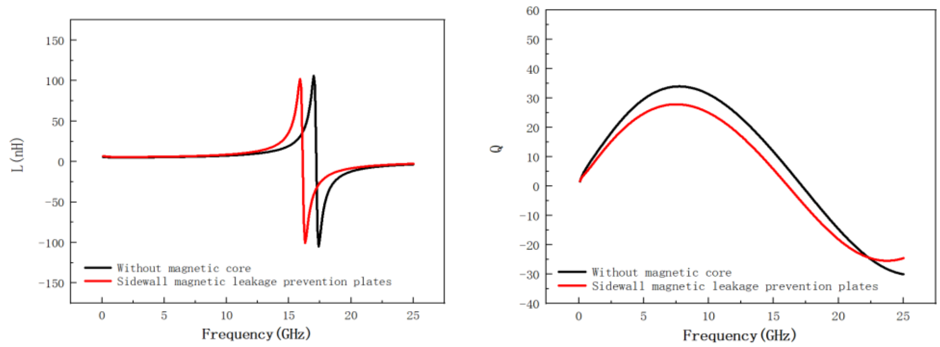
The structure of the up and low magnetic leakage prevention plates is shown in Figure 2 (b), in which the thickness of the magnetic plates is set to 10um, and the permeability of the magnetic plate is consistent with that of central magnetic column. The comparison of inductance L and quality factor Q of the up and low magnetic leakage prevention plates structure and the non-magnetic core structure are shown in Figure 4. By comparing the L and Q values of the two kinds of inductors, it is found that the introduction of the up and low magnetic leakage prevention plates is helpful to optimize the performance of the inductor. The maximum Q value is 40% higher than that of non-magnetic core structure, and the L value at the Q peak frequency is 60% higher. While the magnetic leakage is reduced to reduce the magnetic loss and increase the Q value, the magnetic flux inside the inductor is also increased, that is, the inductance L is improved. Therefore, it is an important way to cover the inductor with the up and low sandwich magnetic plates for the reduction of magnetic leakage and magnetic loss, and the extension of the structure along vertical direction will not increase the area of the inductor, which is more in line with the design concept of three-dimensional integrated inductor.



(a) (b)

Figure 4: Comparison of the simulation results of inductor with up and low magnetic leakage prevention plates and without magnetic core: (a) Inductance L; (b) Quality factor Q.

The structure of the side wall magnetic leakage prevention plates is shown in Figure 2 (c), in which the simulation setting is the same as the up and low magnetic leakage prevention plates structure. Compared with the up and low magnetic leakage prevention plates, the side wall magnetic leakage prevention plates does not help to improve the performance of the inductor, and even causes the decrease of Q value, as shown in Figure 5. This is caused by two reasons: (1) according to the magnetic field distribution of the non-magnetic core inductor, the magnetic flux leakage at the side wall of the inductor is smaller than that at the bottom of the inductor, so that the magnetic flux leakage at the bottom of the inductor is the main factor leading to the low Q value; (2) The introduction of magnetic materials will inevitably bring some additional magnetic losses, such as hysteresis loss and ferromagnetic resonance loss. When the loss of materials is greater than its contribution in reducing magnetic flux leakage, the Q value will decrease. From the magnetic field simulation results, it is observed that adding leakage prevention plate effectively restrain the magnetic induction lines and reduce the magnetic leakage. However, the increase of the internal magnetic field intensity of the inductor is small when the side wall magnetic leakage prevention plates added, which has little effect compared with the increase of the internal magnetic field intensity caused by the up and low magnetic leakage prevention plates.



(a) (b)

Figure 5: Comparison of the simulation results of inductor with side wall magnetic leakage prevention plates and without magnetic core: (a) Inductance L; (b) Quality factor Q.

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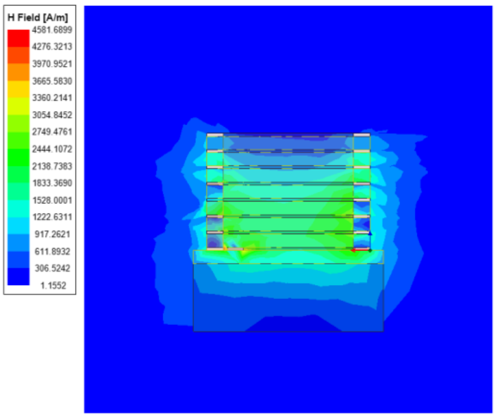
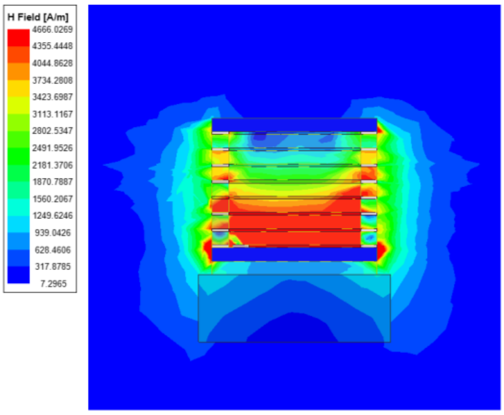


(a)



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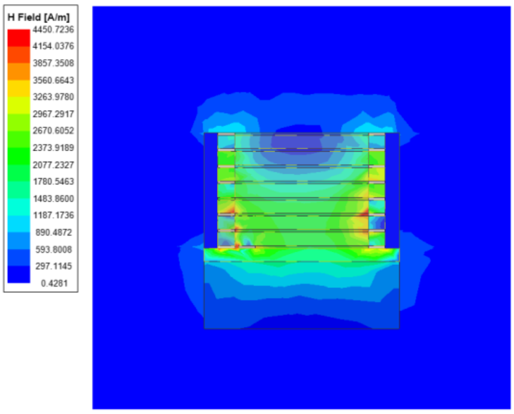

(c)

Figure 6: Magnetic field distribution of three kinds of inductors (a) Without magnetic core; (b) Up and low magnetic leakage prevention plates; (c) Side wall magnetic leakage prevention plates.

3.2. Dumbbell-Shaped Magnetic Core Structure

Through the simulation results, we can conclude that the central magnetic column structure and the up and low magnetic leakage prevention plates structure can significantly improve the inductance L and the quality factor Q, while the sidewall magnetic leakage prevention plates structure has little effect. Based on the above experimental results, in order to increase the inductance value and improve the quality factor at the same time, we propose a dumbbell-shaped magnetic core structure, on the basis of the silicon-based three-dimensional vertical spiral integrated inductor, in which the central magnetic column and the up and low magnetic leakage prevention plates are introduced at the same time. Figure 7 is the schematic diagram of the dumbbell-shaped core structure. The dumbbell-shaped core structure combines the advantages of the central magnetic column and the up and low magnetic leakage

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prevention plates, which not only improves the permeability of the inductor core, but also reduces the magnetic leakage of the device. Therefore, compared with other inductors, the dumbbell-shaped core structure shows a greater improvement in both the inductance L and the quality factor Q.

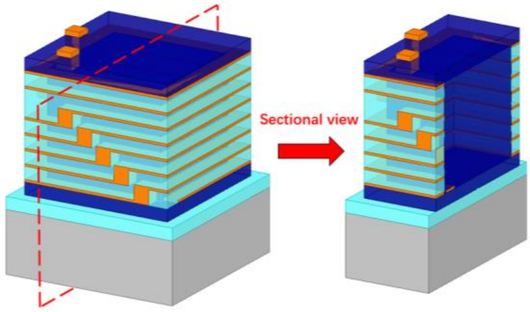
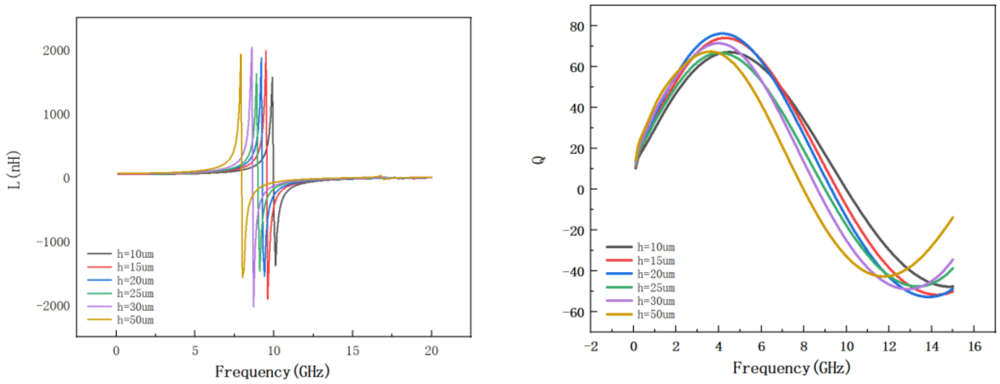


Figure 7: Dumbbell-shaped magnetic core structure.

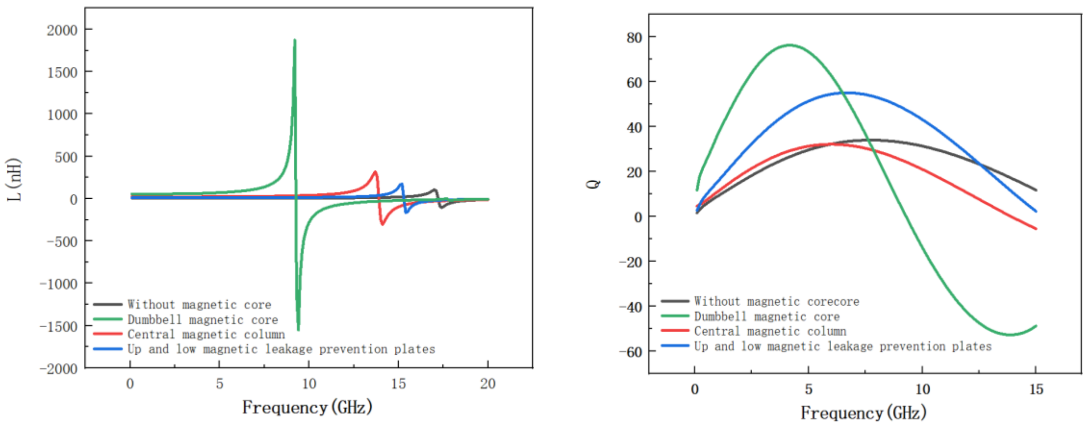
In addition to the permeability and resistivity, the thickness of the core material is also an important factor affecting the performance of the inductor, and a certain thickness of the core can bring better inductance optimization effect[12].

In order to verify the above theoretical analysis and consider the influence of the magnetic plate thickness on the inductor performance, we simulate the three-dimensional vertical spiral inductor with dumbbell-shaped magnetic core thickness of 10um, 15um, 20um, 25um, 30um and 50um. The simulation result under 20um thickness is selected to compare with the above three kinds of magnetic core structure: non-magnetic core, central magnetic column and up and low magnetic leakage prevention plates. The simulation results are shown in Figure 8.



(a) (b)

Figure 8: Dumbbell-shaped magnetic core structure simulation results under different magnetic plate thicknesses (a) L; (b) Q.



(a) (b)

Figure 9: Comparison of simulation results of four different magnetic core structures (a) L; (b) Q.

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By comparison, the three-dimensional vertical spiral inductor with dumbbell-shaped core structure has the best inductor performance. When the thickness of the magnetic plate is 20um, Q gets the maximum value of 76 at 4.2GHz, and the inductance L value is 65nH at this condition. Compared with the non-magnetic core inductor under the same situation, the inductance value of this structure is increased by 950%, and the quality factor is increased by 120%. Through the analysis of the simulation results of magnetic plates thickness of the dumbbell-shaped magnetic core, it is found that in the dumbbell-shaped magnetic core structure, Q no longer increases gradually with the increase of thickness, but shows a trend of first increasing and then decreasing, which is related to the fact that the excessively thick magnetic plate will introduce greater magnetic loss. Therefore, It is not necessary to blindly pursue a thick magnetic leakage prevention plate when manufacturing the dumbbell-shaped magnetic core vertical spiral inductor, which also simplifies the process difficulty and reduces the process cost.

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4. Conclusions

Based on the silicon-based three-dimensional vertical spiral inductor, in this paper three structures: central magnetic column, the up and low magnetic leakage prevention plates and sidewall magnetic leakage prevention plates are designed to explore the influence of different magnetic core structures on the performance of the inductor. Through the three-dimensional electromagnetic simulation results, it is found that the central magnetic column structure and the up and low magnetic leakage prevention plates structure have a greater contribution to increasing the inductor’s magnetic permeability and reducing the leakage loss, respectively. Based on this, a dumbbell-shaped magnetic core structure composed of a central magnetic column and up and low magnetic leakage prevention plates is proposed, which greatly improved the inductance value L and quality factor Q. Compared with the non-magnetic core inductor, the L value has increased by 10.5 times, and the Q value has increased by 2.2 Times. It is proved that introducing a suitable shape of the magnetic core is an effective way to improve the performance of the three-dimensional vertical inductor.

References

[1] H. K. Krishnamurthy et al., "A Digitally Controlled Fully Integrated Voltage Regulator With 3-D-TSV-Based On-Die Solenoid Inductor With a Planar Magnetic Core for 3-D-Stacked Die Applications in 14-nm Tri-Gate CMOS," IEEE Journal of Solid-State Circuits, 2018.

[2] C. C. Tang, C. H. Wu, and S. I. Liu, "Miniature 3-D inductors in standard CMOS process," IEEE Journal of Solid-State Circuits, vol. 37, no. 4, pp. 471-480, 2002.

[3] S. L. Selvaraj, M. Haug, C. S. Cheng, D. Dinulovic, and M. Wieland, "On-Chip Thin Film Inductor for High Frequency DC-DC Power Conversion Applications," in 2020 IEEE Applied Power Electronics Conference and Exposition (APEC), 2020.

[4] S. Seok, C. Nam, W. Choi, and K. Chnm, "A High Performance Solenoid-Type MEMS Inductor," J.semicond.tech, vol. 1, no. 3, 2001.

[5] J. B. Yoon, Y. S. Choi, B. I. Kim, Y. Eo, and E. Yoon, "CMOS-compatible surface-micromachined suspended-spiral inductors for multi-GHz silicon RF ICs," Electron Device Letters IEEE, vol. 23, no. 10, pp. 591-593, 2002.

[6] Kyuchul et al., "High-performance inductors integrated on porous silicon," Electron Device Letters IEEE, 2005.

[7] J. W. Lin, C. C. Chen, and Y. T. Cheng, "A robust high-Q micromachined RF inductor for RFIC applications," IEEE Transactions on Electron Devices, vol. 52, no. 7, pp. 1489-1496, 2005.

[8] Y. J. Kim and M. G. Allen, "Surface micromachined solenoid inductors for high frequency applications," Components Packaging & Manufacturing Technology Part C IEEE Transactions on, vol. 21, no. 1, pp. 26-33, 1998.

[9] D. S. Gardner, G. Schrom, P. Hazucha, F. Paillet, T. Karnik, and S. Borkar, "Integrated On-Chip Inductors with Magnetic Films," IEEE Transactions on Magnetics, vol. 43, no. 6, pp. 2615-2617, 2007.

[10] "Improved High Frequency Response and Quality Factor of On-Chip Ferromagnetic Thin Film Inductors by Laminating and Patterning Co-Zr-Ta-B Films," IEEE Transactions on Magnetics, vol. 49, no. 7, pp. 4176-4179, 2013.

ISSN 2616-5775 Vol. 4, Issue 7: 88-95, DOI: 10.25236/AJCIS.2021.040713

[11] A. Yh, A. Zz, R. A, G. B. Wei, A. Hz, and A. Fb, "On-chip coupled inductors with a novel spliced anisotropic and isotropic magnetic core for inductance and coupling enhancement - ScienceDirect," Solid-State Electronics, vol. 164.
[12] Y. G. Ma and C. K. Ong, "Soft magnetic properties and high frequency permeability in [CoAlO/oxide] multilayer films," Journal of Physics D Applied Physics, vol. 40, no. 40, p. 3286, 2007.