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Performance Analysis of RF Spiral Inductor with Gradually Changed Metal Width and Space *

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Abstract : To decrease the metal losses of RF spiral inductor ,a novel layout structure with gradually reduced metal line width and space from outside to inside is presented. This gradual changed inductor has less eddy-current effect than the conventional inductor of fixed metal width and space. So the series resistance can be reduced and the quality (Q) factor of the inductor relating to metal losses is increased. The obtained experimental results corroborate the validity of the proposed method. For a 6nH inductor on high-resistivity silicon at 2. 46GHz , Q factor of 14. 25 is 11. 3 % higher than the conventional inductor with the same layout size. This inductor can be integrated with radio frequency integrated circuits to gain better performance in RF front end of a wireless communication system.

Key words : RF spiral inductor ; quality factor ; eddy-current effect ; metal losses
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1 Introduction

Recently ,there has been a strong interest in RF spiral inductors with the growing demand for radio frequency integrated circuits[1~3] . Unfortunately ,the parasitic effects such as coupling capacitance and losses will affect inductor performance , especially at radio frequency.

Some methods have been proposed to address the substrate issues. In one case , a selectively-formed semi-insulating ($\sim 10^6 \Omega \cdot$cm) Si technology was developed by ion implantation or by fabricating porous Si layers[4,5] to reduce substrate losses. With this method Q factor can be raised from 12. 5 to 45. In another case ,inserting a pattern ground shield between the inductor and Si substrate or forming pn junction isolation in the Si substrate[6,7] also reduced the substrate losses.

Besides substrate losses there remain other factors that degrade inductor performance. Among these factors the eddy currents may be the most significant at high frequencies[8] . Usually a conventional spiral inductor has a fixed metal width and space. In this inductor the influence of magnetically induced losses is much more significant in the inner turns of the coil where the magnetic field reaches its maximum. Accordingly ,it has been proposed to use a hollow coil to reduce losses[8] as eddy currents generate at high frequencies ,and the inner-

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most turns of the coil suffer from an enormous increase in resistance. However, this method increases the technical complexity.

In this paper, we propose to optimize RF spiral inductor layout by applying gradually changed metal line width and space. Based on the analysis of the eddy-current effect in the coil by HFSS, Q factor of this novel inductor structure is up to 11.3% compared to that of a conventional structure. Using this method we can design and fabricate a better performance spiral inductor that can be integrated with RF IC to improve circuit performance.

2 Inductor metal losses analysis

Q factor of RF integrated inductors is mainly affected by the substrate losses and metal losses. For high-resistivity silicon substrate, the energy losses in the coil are the primary sources of energy dissipation and are intrinsic to the spiral structure. Energy losses inside the nonzero-resistivity metal lines come from current flowing through the spiral inductor itself and this current flowing will generate ohmic losses and eddy-current losses.

Figure 1 shows a conventional square inductor with fixed metal line width and space. It can be clearly seen that the metal line width and inter-turn space of each inductor coil are the same. The structure parameters of the inductor include number of turns (N), inner opening diameter (D_{in}), outer opening diameter (D_{out}), metal line width (W), conductor inter-turn space (S), and two metal layers (M1 and M2).

Q factor of the inductor is defined as[5]

$$Q = \frac{\omega L_s}{R_s} \times \text{substrate losses factor} \times \text{self-resonance factor} \quad (1)$$

where $\omega L_s / R_s$ accounts for the magnetic energy stored and the energy losses in the series resistance, L_s represents the series inductance of the inductor coil, R_s represents the series resistance of the inductor coil.

As operating frequencies entering multi-GHz,

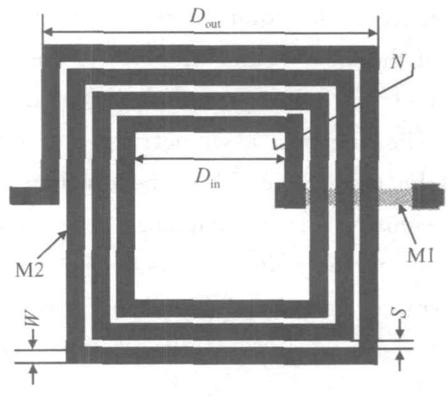

Fig. 1 Top view of a conventional spiral inductor with fixed metal line width and space

the eddy-current loss is generated by inductive coupling between turn-to-turn metal lines as illustrated in Fig. 2.

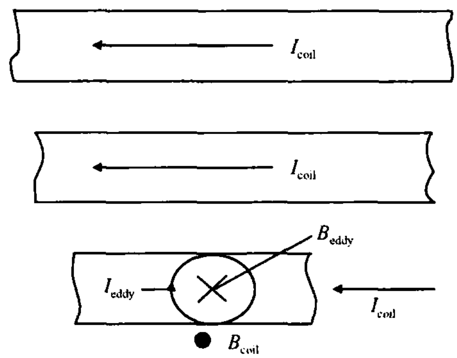

Fig. 2 Inductive magnetic field and the eddy-current

The bars in Fig. 2 represent three metal segments from inside to outside. I_{coil} represents the ac current that leads to a changed magnetic field B_{coil}. The associated magnetic field B_{coil} has a maximum intensity in the center of the coil, as shown in Fig. 3. The closer the segments are to the center, the greater the density of magnetic field. From Faraday's Law, the eddy-current I_{eddy} will be produced by the B_{coil}. From Lenz's Law, this ac current will produce a changed magnetic field B_{eddy} that has the opposite direction to the B_{coil}. So the total magnetic field $B_{coil} + B_{eddy}$ is reduced, and the total inductance is also decreased. Thus the metal segments close to the center contribute little to the inductance. Nevertheless, there are I_{eddy} in the coils. Inside the metal segments I_{eddy} has the same direction as I_{coil}

which enlarges the total current density. At the outside of the metal segments I_{eddy} has the opposite direction of I_{coil} which reduces the total current density. The current is asymmetric in the cross section of the metal line. This phenomenon will be more obvious at a radio frequency. The metal segments close to the center results in more asymmetric current. So series resistance will become greater[8]. This eddy-current effect will reduce Q factor of the inductor at high frequency.

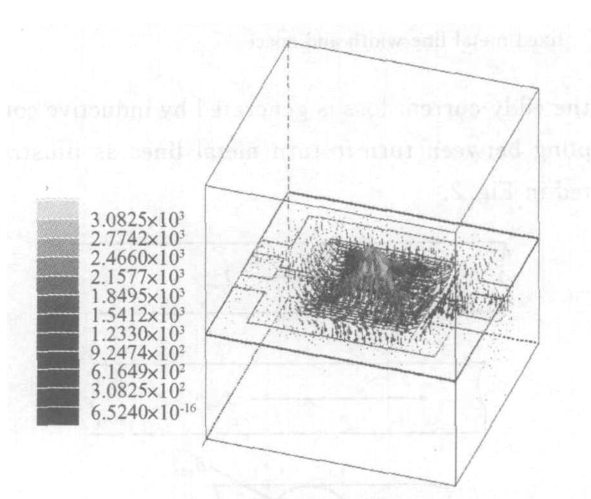

Fig. 3 Vector magnetic field distributing plot of the inductor

Furthermore, the series resistance of the inductor coil R_s is inversely proportional to the metal width W. We can obtain smaller R_s by increasing the metal line width W. But such a structure would increase the area of the inductor that possibly affects the substrate losses and other performance factors. To analyze the performance of the different metal line width and space, we design three spiral inductors with the same layout size (D_{out} = 400μm) and the same number of turns (N = 4.5) on the high-resistivity silicon substrates ($\rho = 10^3 \Omega \cdot cm$). We use HFSS and analyze their electromagnetic field distribution, then extract their S parameters and obtain the spiral inductance (L), the maximal Q factor (Q_{max}), frequency at Q_{max} (f_0) and self-resonant frequency (f_{sr}) of these inductors, which are shown in Table 1.

Table 1 Comparison of conventional inductors with different W and S

	Q_1	Q_2	Q_3
W_n/μm	20	15	10
S_n/μm	10	15	20
L/nH	7.47	7.92	8.48
Q_{max}	13.4	14.2	12.9
f_0/GHz	2.20	2.15	2.20
f_{sr}/GHz	5.1	5.1	4.9

It can be easily seen from Table 1, Q_{max} of Q_1 is not the largest although it has the largest metal line width, which may be caused by the eddy-current effect. Thus, metal line width and space of the inductor should be designed accurately to get better performance.

In the next part, we present a design method of gradually changed metal line width and space on the basis of inductor's metal losses analysis.

3 Performance analysis of the gradually changed inductor

The series resistance R_s of the inductor can be expressed as follows[9].

$$R_s = \sum_{n=1}^{N}\left[\frac{r_s(f)}{W_n} + C g_n^2 f^2 w_n^2\right] l_n \qquad (2)$$

where $r_s(f)$ is the sheet resistance of the metal line, f is the frequency, l_n is the length of the nth of the coil, C is a constant, and g_n is a function dependent on geometrical parameters such as N, l_1, W_n and S_n[9].

According to the metal losses analysis, the eddy-current effect leads to asymmetric current density in the metal line of the coil, which will increase the series resistance R_s[8] and reduce Q factor of the inductor at high frequency.

Moreover, the associated magnetic field B_{coil} has a maximum intensity in the center of the coil. Therefore, the narrow metal lines can decrease losses in the innermost turn while wide metal lines optimize the outer turn where ohmic losses are predominant[9]. A different metal width is used for each turn of the coil. Hence, the width of the metal lines W_n is gradually reduced from outside to inside.

In the other case, the magnetic field generated by neighboring lines will change the current distribution of the metal line. The inter-turn space S_n values should be selected accordingly. When S_n is smaller the magnetic field will become stronger, resulting in a more asymmetric current density in the metal line. In addition, increasing S_n with the inner opening diameter and the metal line width unchanged, the total length of the metal conductor will become longer. These effects will increase the series resistance of the inductor coil R_s and reduce Q factor of the inductor. Therefore, we design a inductor with gradual reduced W_n and S_n from outside to inside in order to improve its Q factor. The gradual changed structure of a planar spiral square inductor is shown in Fig. 4.

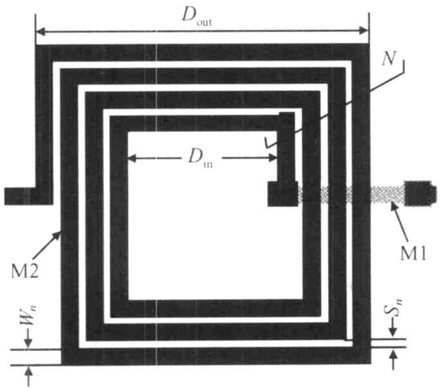

Fig. 4　Top view of a gradual changed spiral inductor

We simulate many inductors by HFSS and analyze their electromagnetic field distribution, then extract their S parameters and obtain Q factors of these inductors.

Table 2 shows a comparison between three groups of conventional and gradual changed inductors with different D_{out}. At first, Q factors of all the gradual changed inductors are higher than those exhibited by correspondent inductors of fixed metal line width and space. For the inductor with 450μm D_{out}, L value of the gradual changed structure is 10.45nH, which is only 3.2% larger than the conventional one. However its Q_{max} reaches 16.95, which is up to 23.7% better than the result of the conventional inductor. In addition, when the value of Q exceeds 10, the range of operation frequency of the gradual changed inductors is wider than that of the conventional inductors of different D_{out}. With the layout size unchanged, the Q factor of the inductor can be effectively improved by using gradually reduced metal line width and space from outside to inside.

Table 2　Comparison of conventional and gradual changed inductors

N	4.5					
D_{out}/μm	350		400		450	
Structure	Fixed	Gradual changed	Fixed	Gradual changed	Fixed	Gradual changed
W_n/μm	15	10～30	15	10～30	15	10～30
S_n/μm	15	8～12	15	8～12	15	8～12
L/nH	5.87	6.19	7.92	8.25	10.13	10.45
Q_{max}	12.85	13.70	14.20	16.40	13.70	16.95
f_0/GHz	2.45	2.55	2.15	2.15	1.85	1.80
f_{sr}/GHz	6.10	6.30	5.10	5.00	4.30	4.20
Range of f @Q>10/GHz	1.10～4.05	1.05～4.35	0.90～3.60	0.78～3.70	0.86～3.00	0.70～3.20

4　Results and discussion

Based on the results of electromagnetic simulation, we fabricated many inductors on the high-resistivity silicon substrate ($\rho = 10^3 \Omega \cdot cm$) according to the following processes. Cr/Au metals approximately 0.5μm are evaporated and patterned to form the underpass of the inductors. A PECVD SiN layer is deposited for electrical isolation; its thickness is approximately 0.3μm. Subsequently, a 2μm-thick-Au layer is evaporated and electroplated for patterning spiral coil.

Q_{A1} and Q_{A2} represent two square inductors with the same number of turns (N = 4.5) and outer opening diameter (D_{out} = 350μm). Q_{B1} and Q_{B2} also represent two square inductors with the same number of turns (N = 3.5) and outer opening diameter (D_{out} = 400μm). However, Q_{A1} and Q_{B1} represent two conventional inductors with fixed metal line width and space. Their metal line widths are separately 20 and 15μm, and their conductor inter-turn space are separately 10 and 15μm. Q_{A2} and Q_{B2} represent two inductors of gradual changed metal line width and space. The structure parameters of Q_{A2} are: W_n of each turn from outside to inside 30, 24, 20, 16, and 10μm; S_n of each turn from outside to inside 12, 11, 9, and 8μm. The structure parameters of Q_{B2} are: W_n of each turn from outside to inside 30, 24, 16, and 10μm; and S_n of each turn from outside to inside 12, 10, and 8μm.

Measurements are carried out at frequencies ranging from 100MHz to 10GHz by a network analyzer (HP8722D) and Cascade on-wafer-probe. Accurate measurements for the inductors alone can be obtained. By measuring S-parameters of both the device under test (DUT), probe pads and ground planes (PAD), and subtracting the effects of PAD from DUT. Subsequently, we obtain characteristic curves of Q factor versus frequency with MATLAB.

The obtained Q factors versus frequency are plotted in Fig. 5 (HFSS simulations) and Fig. 6 (experimental data). Good agreement is observed between measurements and simulations, validating the proposed design method of gradually changed metal line width and space. In Fig. 6, Q_{max} of the gradual changed inductors (Q_{A2} and Q_{B2}) are all higher than those of the conventional inductors in each group. The Q_{max} of Q_{B2} (L = 6nH, Q_{max} = 14.25, f_0 = 2.46GHz, f_{sr} = 6.85GHz) is largest for

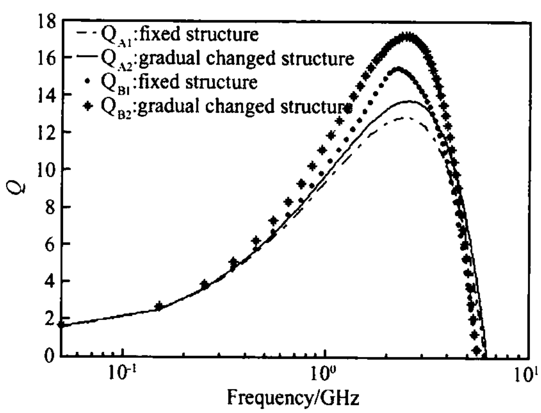

Fig. 5 Simulated Q factors versus frequency for the inductors with gradual changed structure and fixed structure

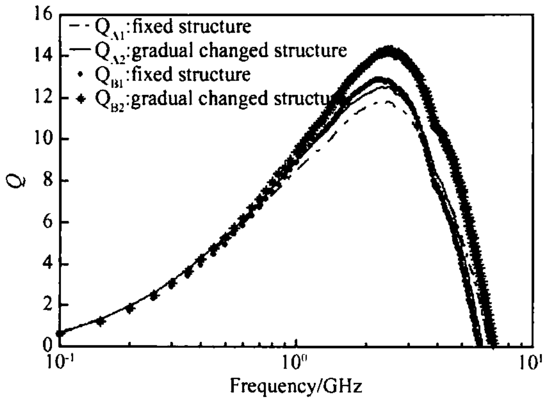

Fig. 6 Experimental Q factors versus frequency for the inductors with gradual changed structure and fixed structure

all the inductors. At the frequency of operation, Q_{max} of the optimized inductor is up to 11.3% than Q_{B1}. So with the layout size unchanged, Q factor of the inductor can be effectively improved by using the inductor of gradual reduced metal line width and space from outside to inside.

5 Conclusion

This work is devoted to the design of RF spiral inductors in silicon technology. The Q factor of the inductor is mainly affected by the substrate losses and the metal losses. After analyzing the eddy-current effect by FEM simulation using HFSS, this paper presents a RF spiral inductor of gradually reduced metal line width and space from outside to inside. Using the gradual changed structure, a Q factor of 14.25 has been obtained for a 6nH inductor at 2.46GHz, which is up to 11.3% better than the result of the conventional inductor. The inductor can be integrated with RF IC's to gain better performance in RF front end of a wireless communication system.

References

[1] Richelli A, Colalongo L, Quarantelli M, et al. A fully integrated inductor-based 1.8-6V step-up converter. IEEE J Solid-State Circuits, 2004, 39(1): 242

[2] Abidi A A. RF CMOS comes of age. IEEE J Solid-State Cir-

cuits ,2004 ,39(4) :549

[3] Li Linan ,Qian He. A new method for optimizing layout parameter of an integrated on-chip inductor in CMOS RF IC 's. Chinese Journal of Semiconductors ,2000 ,21(12) :1157

[4] Chin A ,Chan K T , Huang C H ,et al. RF passive devices on Si with excellent performance close to ideal devices designed by electro-magnetic simulation. IEEE IEDM ,2003 ,15(5) :375

[5] Nam C , Kwon Y. High performance planar inductor on thick porous silicon (OPS) substrate. IEEE Microw Guided Wave Lett ,1997 ,7(8) :236

[6] Yue C P ,Wong S S. On chip spiral inductors with patterned ground shields for Si-based RF IC 's. IEEE J Solid-State Circuits ,1998 ,33(5) :743

[7] Liu Chang ,Chen Xueliang , Yan Jinlong. Novel substrate pn junction isolation for RF integrated inductors on silicon. Chinese Journal of Semiconductors ,2001 ,22(12) :1486

[8] Craninckx J ,Steyaert S J. A 1. 8-GHz low-phase-noise CMOS VCO using optimized hollow spiral inductors. IEEE J Solid-State Circuits ,1997 ,32(5) :736

[9] López-Villegas J M ,Samitier J ,Cané C ,et al. Improvement of the quality factor of RF integrated inductors by layout optimization. IEEE Trans Microw Theory Tech ,2000 ,48(1) :76

金属线宽及线间距渐变的射频螺旋电感 *

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摘要: 为减少射频螺旋电感的金属导体损耗,提出了一种电感金属线宽及金属间距从外到内逐渐变小的新颖结构. 与传统的固定金属线宽和间距的电感相比,该渐变结构电感涡流效应的影响较小,金属导体损耗减小,从而降低其串联电阻,品质因子 Q 值提高. 实验结果确证了所提方法的正确性. 对一个高阻硅衬底上 6nH 电感,优化设计的渐变结构电感 Q 值在 2. 46GHz 处可达到 14. 25,比版图面积相同、固定线宽及间距的传统电感高 11. 3 %. 因此,在无线通信系统的射频前端,采用这种电感与射频集成电路结合,能获得更好的射频电路性能.

关键词: 射频螺旋电感; 品质因子; 涡流效应; 金属损耗
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