An Equivalent Circuit Model for On-chip Inductors with Gradual Changed Structure

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ABSTRACT: *Inductor with gradual changed metal width and space by good design can get better Q factor than the inductor with fixed metal width and space. In this paper, a simple wide-band inductor model is presented considering both the increase of resistance and the decrease of inductance due to the skin and proximity effects. This model has been verified with simulation and the experimental results of spiral inductors with various geometrical configurations on high-resistivity silicon substrate. Good agreements have been achieved under the self-resonance frequency, which indicates its accuracy. This model has also been proved to be suitable for both the conventional inductor with fixed structure and the inductor with gradual changed structure.*

Categories and Subject Descriptors:
B.3.1 [Semiconductor Memories]

General Terms: Semicondutors, Circuits, Sprial inductors

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1. Introduction

With the rapid development of wireless technology, RF ICs have played a vital role in wireless circuits. On-chip spiral inductors are widely used in RF IC design as system-on-chip solution, such as filters, low-noise amplifiers, and voltage-controlled oscillators. To increase the Q factor, inductors with changed metal width or space structure have been presented [1, 2]. In [1], a single gradually changed structure with fixed space but gradually reduced metal width from outside to inside has been proposed. The Q factor of a 20-nH inductor with this structure is up to 60% better than the result of a single strip-width inductor at 3.5GHz. In [2], the sum of metal width and space of inductor's each coil is fixed while the ratio of the metal width to space is gradually reduced from outside to inside. With this design, the Q factor of a 7-nH inductor on high-resistivity silicon is 23.5% higher than the conventional inductor with fixed metal width and space at 2.1GHz. All of these show that the gradually changed structure inductor is attracting for RF ICs.

Various models of spiral inductors on silicon substrate have been reported in resent years [3-4]. The model in [3] can well modify the eddy-current loss in the silicon substrate, while the T-model in [4] has been proposed to accurately simulate the broadband characteristics of spiral inductors. As mentioned above, gradually changed inductors can gain good performance, but the models of these inductors have not been reported. Therefore, a lumped element model applied to gradually changed inductor is necessary.

Comprehensively considering the achievements of skin and proximity effects and substrate coupling effect, a model of on-chip spiral inductor with gradually changed structure has been discussed. The model in this paper shows the performance of the inductor with gradually changed structure by taking ohmic losses and magnetic field distribution into account. The experimental results show that the model is both suitable for the fixed inductor and the gradually changed inductor. So it's very useful for the on-chip inductor simulation and optimization design.

2. Proposed Inductor Model

In [2], the paper presents a novel gradually changed structure. The sum of the metal width and space is fixed while the ratio of the metal width to space is gradually reduced from outside to inside. It is shown in Figure 1.

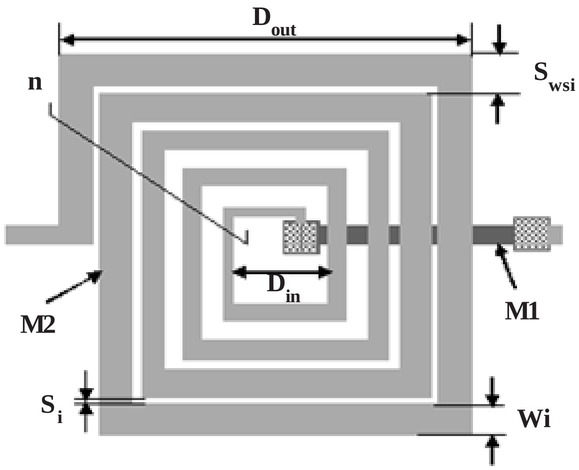


Figure 1. Top View of a Spiral Inductor with Gradually Changed Structure

The Structure parameters of the inductor include number of turns (N), inner opening diameter (D_{in}), outer opening diameter (D_{out}), metal line width of the nth turn (W_n), conductor inter-turn space (S_n) and two metal layers ($M1$ and $M2$).

According to skin and proximity effects, current does not flow uniformly in wiring and resistance increases with increasing frequency. Inductance decreases when the current flowing in wiring becomes less uniform with increasing frequency [5, 6]. So the addition of a combination of resistance Ro and inductor Lo in parallel has been added in the model to simulate the increase in resistance and the decrease in inductance due to the skin and proximity effects [7].

It has been reported that in order to represent the lateral substrate coupling, R_{sub} and C_{sub} are introduced in the inductor model [8]. A parallel combination of R_{sub} and C_{sub} is placed under the silicon dioxide layer, similar to the equivalent-circuit model for substrate coupling [9] and on-chip interconnects [10].

Comprehensively covering the research achievements in inductor models such as the skin and proximity effect and substrate coupling effect, the model for gradually changed spiral inductor is presented in Figure 2. According to this model, the series resistance R_s and the series inductance L_s of equivalent circuit can be extracted as

$$R_s = R_1 + R_0 \frac{\omega^2 L_0^2}{R_0^2 + \omega^2 L_0^2} \quad (1)$$

$$L_s = L_1 + L_0 \frac{R_0^2}{R_0^2 + \omega^2 L_0^2} \quad (2)$$

When $\omega \to 0$. $R_{DC} = R_1$, $L_{DC} = L_1 + L_0$;

When $\omega \to \infty$. $R_{HF} = R_1 + R_0$, $L_{HF} = L_1$.

R_{DC} and L_{DC} are series resistance and inductance in low frequency. R_{HF} and L_{HF} are series resistance and inductance in high frequency. It means that the proposed model can represent the frequency characteristics of spiral inductors. The series resistance R_s will increase and the series inductance L_s will decrease with increasing frequency.

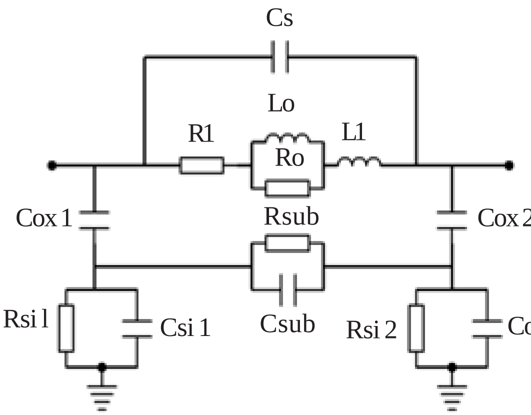


Figure 2. Proposed equivalent circuit model of an inductor based on substrate coupling and skin and proximity effects

Compared with fixed structure inductor with the same outer opening diameter and number of turns, gradually changed structure inductor has wider metal strip in outer turns. Ohmic losses are inversely proportional to the metal strip width and a wide metal strip width is expected to decrease the ohmic losses. So R_s of gradually changed structure inductor is smaller than that of fixed structure inductor. In the other case, magnetically induced losses mainly influence the center of the inductor. Increasing the distance between inner turns can decrease magnetically induced losses. Due to using wider distance in the inner turns, L_s of the gradually changed structure inductor is smaller than that of the fixed structure inductor. Hence, besides validating the model's availability, we also pay much attention on the validity of R_s and L_s in inductors with different geometrical configuration.

3. Model validation and Discussion

To verify the validity and accuracy of the model above, square spiral inductors with various geometrical configuration have been designed first by HFSS and then fabricated on high-resistivity silicon substrate ($\rho = 10^3 \Omega\cdot cm$) in the following processes. Firstly, Ti/Au metals approximately $0.6\mu m$ are electroplated and patterned to form the underpass of the inductors. Secondly, a PECVD SiO_2 layer about $0.8\mu m$ is deposited for isolation. Subsequently, $1.5\mu m$ thick Ti/Au layer is evaporated and electroplated for patterning spiral coil of inductor. The physical dimensions of the inductors are summarized in Table 1. The parameters of the inductor include number of turns (N), outer opening diameter (D_{out}), metal width (W), conductor inter-turn space (S). $Q1$, $Q4$, $Q7$ are the conventional inductor with fixed metal width and space.

$Q2$, $Q5$, $Q8$ are the inductors with fixed space and gradually reduced metal width from outside to inside, we call them single gradually changed inductors. And $Q3$, $Q6$, $Q9$ are gradually changed structure inductors with the sum of metal width and space of each coil fixed while the ratio of the metal width to space is gradually reduced from outside to inside.

Measurements are carried out at frequencies ranging from 100MHz to 10GHz by E8363B network analyzer 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. After inductors have been measured, the equivalent circuit parameters for the proposed model can be extracted.

Each parameter in equivalent circuit model should be extracted accurately by using gradient algorithm in ADS,. R_{si} and C_{si} in two branches should be in the same value. Considering the asymmetry of the two ports, C_{ox1} and C_{ox2} should be different. The Q factor, the equivalent series resistance R_s and the equivalent series inductance L_s are added to the aim function. For the spiral inductor always works under the self-resonance frequency, the equivalent circuit model should meet the practical requirement accurately under the self-resonance frequency. According to the data measured, all parameters in Figure 2 model have been extracted and shown in Table 2.

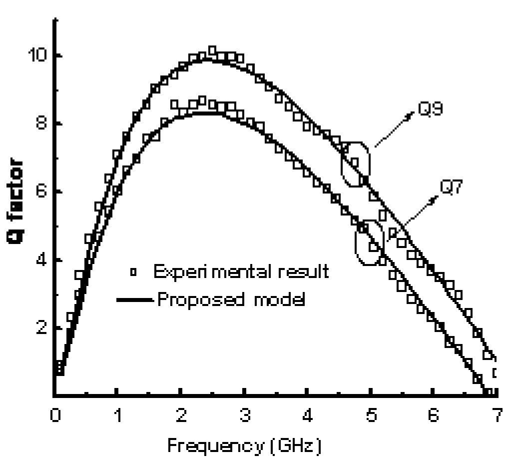
It is shown that the model extracted parameters in Table 2 can be well fitted the inductor parameters and the changes of the extracted parameters are consistent with the change of geometrical configuration. Parts of validated results are listed below.

Figure 3 shows the model validation results for Inductor $Q7$ and $Q9$. Figure 3a gives the Q factor comparison. As being seen, Q factor of the proposed model shows the good agreement with not only the conventional structure $Q7$ but also the gradually changed structure $Q9$. Q factor of Q9 is higher than that of $Q7$, which is also identical with the design. Figure 3b and 3c show the equivalent series resistance R_s and series inductance L_s curves for $Q7$ and $Q9$. In Figure 3b and 3c, R_s and L_s of $Q9$ are smaller than the R_s and L_s of $Q7$, which consists with the analysis above.

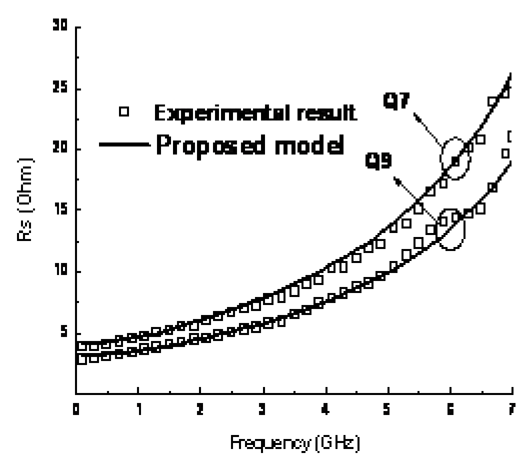
Figure 4 shows the Q factor comparison of experimental results and model simulations for Inductor $Q6$ and $Q9$, $Q6$ with 3.5 turns and $Q9$ with 4.5 turns. It is found that the proposed model shows good agreement with the gradually changed structure of different numbers of turns.

Sample Number	D_{out}(μm)	N	W+S (μm)	W(μm)	S(μm)	Inductor Type
Q1		3.5	30	15	15	conventional
Q2				24.23.20.15	10	single gradually changed
Q3				24,23,20,15	6,7,10,15	gradually changed
Q4		3.5	40	20	20	conventional
Q5	400			32.30.27.20	10	single gradually changed
Q6				32.30.27.20	8.10.13.20	gradually changed
Q7		4.5	30	15	15	conventional
Q8				25.24.23.20.15	10	single gradually changed
Q9				25.24.23.20.15	5.6.7.10.15	gradually changed

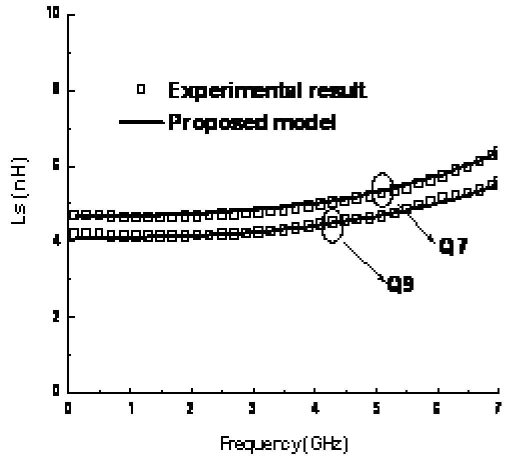
Table 1. Various physical dimensions of the inductors



(a) Q factor comparison



(b) R_s factor comparison



(c) L_s factor comparison

Figure 3. Comparison of experimental results and model simulations for Q7 and Q9

	L_1 (nH)	L_0 (nH)	R_1 (Ω)	R_0 (Ω)	C_{ox1} (fF)	C_{ox2} (fF)	R_{si1} (Ω)	R_{si2} (Ω)	C_{si1} (fF)	C_{si2} (fF)	C_s (fF)	R_{sub} (Ω)	C_{sub} (fF)
Q1	5.83	0.28	5.11	4.27	126.5	128.3	887.1	887.1	183.1	183.1	30.1	753.9	9.77
Q2	5.44	0.23	4.51	3.67	151.4	153.5	864.4	864.4	191.2	191.2	37.2	717.7	15.6
Q3	4.93	0.16	3.71	3.07	134.7	136.9	877.6	877.6	188.6	188.6	35.6	733.9	12.7
Q4	6.13	0.26	5.41	4.17	148.5	149.8	874.3	874.3	173.2	173.2	36.1	736.8	20.8
Q5	5.92	0.23	4.81	3.86	152.8	153.4	854.1	854.1	183.1	183.1	41.6	706.3	30.4
Q6	5.58	0.16	4.38	2.86	142.5	143.8	861.2	861.2	191.0	191.0	53.1	726.4	25.7
Q7	4.43	0.23	4.11	3.86	138.6	139.7	897.8	897.8	173.1	173.1	32.1	683.5	35.7
Q8	4.53	0.18	4.05	3.57	155.8	155.8	879.3	879.3	181.5	181.5	38.4	668.9	41.3
Q9	3.93	0.16	3.15	2.56	136.5	137.1	885.1	885.1	158.2	158.2	36.5	679.2	37.7

Table 2. Model Parameters Extracted from Measurement Data

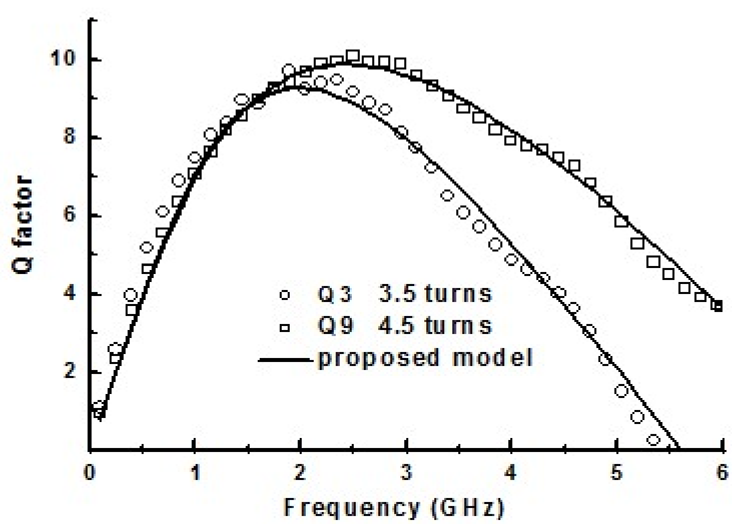


Figure 4. Comparison of Q factor between experimental results and simulations of Q3 and Q9

4. Conclusion

A simple wide-band inductor has been presented considering the skin, proximity effects and substrate coupling. A combination of resistance Ro and inductor Lo in parallel in the proposed model model the skin and proximity effects with increasing frequency. A parallel combination of R_{sub} and C_{sub} captures the substrate coupling. The experimental data indicates that the model can be used in both conventional and gradual changed inductor and the model extracted parameters are consistent with the physical effects in different geometrical configuration. These all show the model's value in inductor design.

5. Acknowledgment

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