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Systematic Analysis and Modeling of On-Chip Spiral Inductors for CMOS RFIC Application

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Abstrct

In this paper, a systematic analysis for on-chip spiral inductors has been developed. With our simplified model, accurate predictions of quality factor curve were presented. Three key parameters, maximum quality factor Q_{max}, frequency at maximum quality factor f_{Qmax} and self-resonance frequency f_{SR} are investigated for inductor's performances. As inductors sizes are scaled, less influence of metal width on Q_{max} but more on f_{Qmax} and f_{SR} was obviously observed.

I Introduction

Due to large demand of achieving compact and cheap system-on-chip (SoC) systems, silicon based on-chip spiral inductors, essential for radio frequency (RF) and monolithic microwave integrated circuits (MMIC), have attracted strong attentions in recent years. A large amount of experiments and their models about spiral inductors based on silicon substrates have been presented [1][2]. Because the quality factor curves are the most significant ways to investigate the inductor's performances, the presented equations about Q mentioned above are a little complicated. In this paper, three key parameters, maximum quality factor Q_{max}, frequency at maximum quality factor f_{Qmax} and self-resonance frequency f_{SR}, where Q is zero, have been taken to approximately characterize the quality factor curves [3][4].

II Experiment

Various dimensions of octagonal stacked inductors, which are metal widths of 6, 9 and 12 um and inner radius of 20, 30, 40, 50, 70 and 90 um are under test in this paper. Of them, metal traces 1 to metal 7 are vertically stacked in series by vias and only one-turn for each metal layer. Three different patterns (OPEN, SHORT, THRU) were used for accurate de-embedding. Agilent 8510 VNA and 4156 with the frequency up to 20 GHz were used for S-parameters measurement. During the measurement, methods of SOLT (Short-Open-Load-Thru) were used for calibration, and under the control of Agilent IC-CAP software.

III. Model Description

For conventional one-port model of spiral on-chip inductors, as shown in Fig. 1(a), the quality factor Q can been derived as follows [5]:

$$Q=\frac{\omega L_s}{R_s}\cdot\frac{R_p}{R_p+\left[\left(\frac{\omega L_s}{R_s}\right)^2+1\right]\cdot R_s}\cdot\left[1-\frac{R_s^2\left(C_s+C_p\right)}{L_s}-\omega^2L_s\left(C_s+C_p\right)\right] \quad (1)$$

$$R_p=\frac{1}{\omega^2C_{ox}^2R_{si}}+R_{si}\left(1+\frac{C_{si}}{C_{ox}}\right)^2 \quad (2)$$

$$C_p=C_{ox}\cdot\frac{1+\omega^2\left(C_{ox}+C_{si}\right)C_{si}R_{si}^2}{1+\omega^2\left(C_{ox}+C_{si}\right)^2R_{si}^2} \quad (3)$$

All parameters are shown as Table I and can be extracted from Micro-Wave Office simulator. The circuit of C_{ox}, C_{si} and R_{si} can been simplified to equivalent circuit of R_p and C_p, as shown in Fig. 1(b). The first term in (1) refers to the stored magnetic energy and the ohmic loss of metal trace above substrates, the second term refers to degradation factor due to substrate loss, and the last term refers to self-resonance degradation factor due to increased electric field. At giga-hertz range, R_p and C_p can been simplified as follows:

$$R_p=R_{si}\left(1+\frac{C_{si}}{C_{ox}}\right)^2 \quad (4)$$

$$C_p=\frac{C_{ox}\cdot C_{si}}{C_{ox}+C_{si}} \quad (5)$$

Because of $\frac{R_s^2\left(C_s+C_p\right)}{L_s}\langle\langle 1$ and $\frac{\omega L_s}{R_s}\rangle\rangle 1$ at giga-hertz range, quality factor can be represented as follows:

$$Q=\frac{\omega L_s R_p}{R_s R_p+\omega^2L_s^2}\cdot\left[1-\omega^2L_s\left(C_s+C_p\right)\right] \quad (6)$$

Let the second term of (6) to zero, self-resonance frequency f_{SR} can be derived as follows:

$$f_{SR}=\frac{1}{2\pi\sqrt{L_s\left(C_s+C_p\right)}} \quad (7)$$

In addition, we can let $\frac{dQ}{d\omega}=0$ to derive Q_{max} and f_{Qmax} as follows:

$$f_{Q\max}=\left.\frac{\omega_{Q\max}}{2\pi}\right|_{\frac{dQ}{d\omega}=0} \quad (8)$$

$$Q_{\max}=\left.Q\right|_{\omega_{Q\max}} \quad (9)$$

IV Result and Discussion

Fig. 2 shows the comparison of quality factor curve between measured and modeled extracted from (6) for inductors with metal width of 6 um, inner radius of 20 um, and metal width of 12 um, inner radius of 90 um. Good prediction is observed for our simplified model. Fig. 3 shows the relation of maximum quality factor Q_{max} versus inner radius (proportional to total metal length) and metal width. Q_{max} decreased with increased inner radius due to increased resistance. For large inner radius, Q_{max} increased with metal width due to the reduced resistance as shown in Fig. 4. But when the inner radius of inductor was scaled, the influence of metal width on Q_{max} becomes less significant. This is due to the little influence of width both on L_s and R_s [6] as shown in Fig. 5 and 6. For deep submicron technology, metal width is the minor consideration factor for scaled inductors design. By the way, good agreements between measured and modeled data are very clear in this work.

The impacts of inner radius and metal width on f_{Qmax} are shown in Fig. 7 and 8, respectively. And the impacts on f_{SR} are shown in Fig. 9 and 10, respectively. As inner radius increases, both f_{Qmax} and f_{SR} decreases due to increased overlap and substrate capacitances, and then tend to become insensitive to inner radius. Opposite to Q_{max} (Fig. 3), the influences of width on f_{Qmax} and f_{SR} happened at large inner radius are trivial, because the variation of width is less significant compared to that of total metal length. Thus in deep submicron technology with very scaled inductor design, metal width must be reduced to increase f_{Qmax} and f_{SR} effectively.

V Conclusion

In this work, we simplified the model of conventional quality factor and investigate the impact of inner radius and metal width on three key parameters, maximum quality factor Q_{max}, frequency at maximum quality factor f_{Qmax} and self-resonance frequency f_{SR}. For deep submicron technology with scaled inductors, less influence of metal width on Q_{max} but more on f_{Qmax} and f_{SR} was obviously observed. Good agreements between measured and modeled data are obtained.

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Table I Model parameter description

Parameter	Description	Model
Rs	**Series resistance**	$R_s = \dfrac{\rho \cdot l}{w \cdot \delta \cdot \left(1 - e^{-t/\delta}\right)}$
Ls	**Series inductance**	$L_s = 2l\left(\ln\dfrac{2l}{w+t} + 0.5 + \dfrac{w+t}{3l}\right)$
Cs	**Series feed-forward capacitance**	$C_s = n \cdot w^2 \cdot \dfrac{\varepsilon_{ox}}{t_{ox}}$
Cox	**Capacitance between metal and substrate**	$C_{ox} = \dfrac{1}{2} l \cdot w \cdot \dfrac{\varepsilon_{ox}}{t_{ox}}$
Csi	**Substrate capacitance**	$C_{si} = \dfrac{1}{2} l \cdot w \cdot C_{sub}$
Rsi	**Substrate resistance**	$R_{si} = \dfrac{2}{l \cdot w \cdot G_{sub}}$

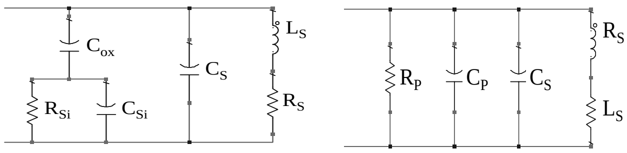

Fig.1 (a) Conventional one-port model for spiral inductors, and (b) its simplified equivalent circuit

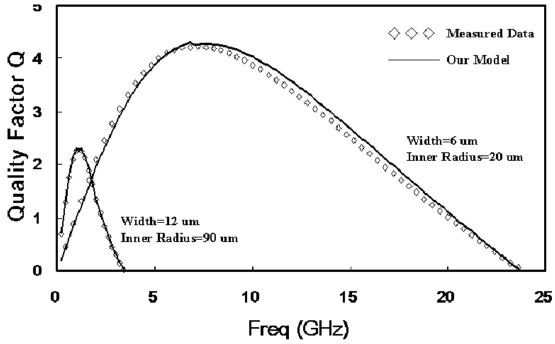

Fig.2 Comparisons of quality factor curve between measured and modeled extracted from (6) for inductors with metal width of 6 um, inner radius of 20 um, and metal width of 12 um, inner radius of 90 um.

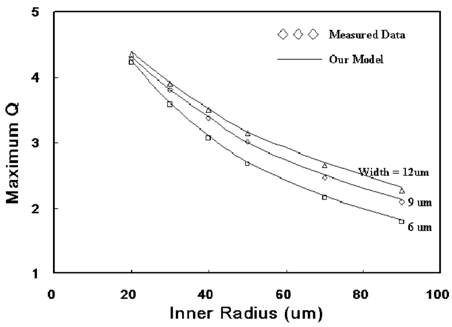

Fig.3 Relations of maximum quality factor Q_{max} versus inner radius.

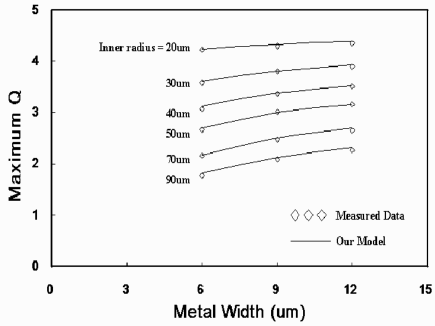

Fig.4 Relations of maximum quality factor Q_{max} versus metal width.

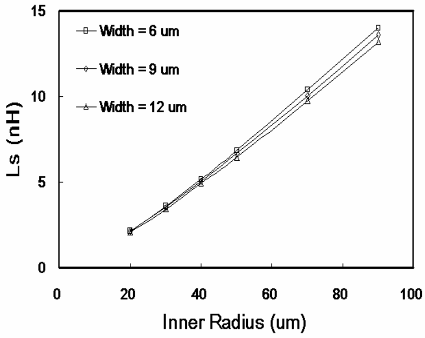

Fig.5 Relations of series inductance versus inner radius.

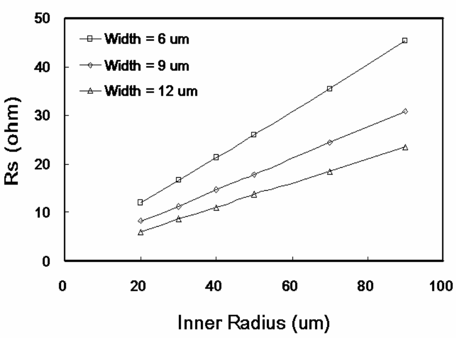

Fig.6 Relations of series resistance versus inner radius.

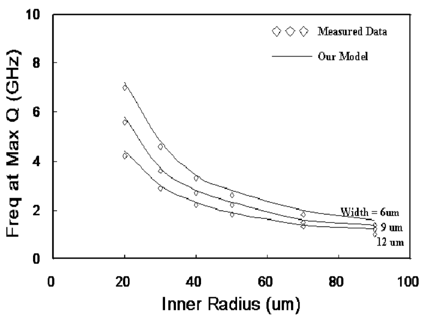

Fig.7 Relations of frequency at maximum quality factor f_{Qmax} versus inner radius.

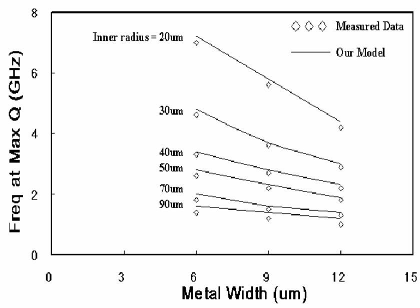

Fig.8 Relations of frequency at maximum quality factor f_{Qmax} versus metal width.

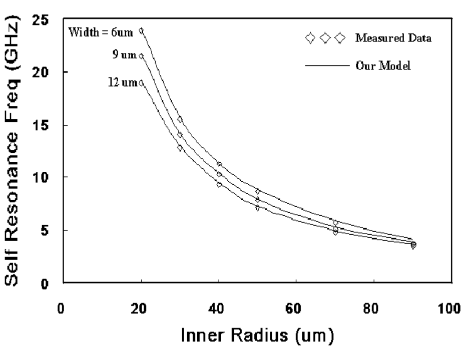

Fig.9 Relations of self-resonance frequency f_{SR} versus inner radius.

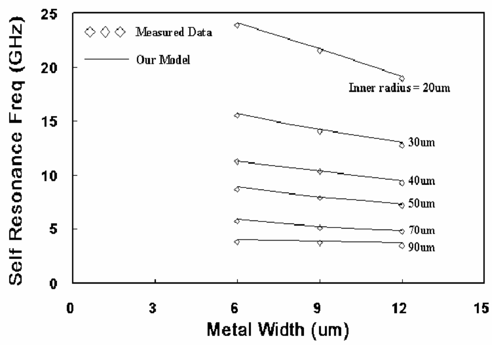

Fig.10 Relations of self-resonance frequency f_{SR} versus metal width.