A macro model of silicon spiral inductor


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Abstract

A new automatic parameter extraction method for modeling of silicon spiral inductors is presented. The concepts on self-resonance frequency (f sr) and quality factor of a spiral inductor are utilized to develop the concise extraction procedures. In the mean time, the presented extraction procedures are programmed as a macro to execute all the extractions automatically and shorten the extraction time effectively. Without any additional optimization or curve fitting, almost all the patterns of S-parameters between the measured and the simulation of extracted data implemented with the extraction macro are less than 5%. The programmed extraction macro makes it fast and accurate to extract and characterize the behaviors of silicon-based spiral inductors with different structures and substrate resistivities. It provides a concrete foundation for commercial silicon radiofrequency (RF) circuit design to realizing on-chip silicon RF integrated circuits. Furthermore, the directly extracted equivalent model parameters, without any optimization, also provide a rule to fairly, effectively and physically judge the performance of a spiral inductor. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Spiral inductor; Radiofrequency (RF); Programmed extraction macro

1. Introduction

With the dramatic advancement of Si VLSI technologies, the system-on-chip (SOC) silicon radiofrequency (RF) integrated circuit has recently emerged as an attractive candidate to satisfy the rapidly growing wireless communication applications [1–5]. The wireless communication applications based on Si technologies can increase the integration density of RF module, baseband and digital signal processing (DSP) modules, etc. Therefore, both the reliability and production cost of Si-based RF integrated circuits (RFICs) can be improved as compared to those of compound RF circuits. There are many widely used frequency range of personal wireless communication applications just lying in low GHz, such as 0.9 GHz of global system for mobile communication (GSM) system, 1.8 GHz of digital communication system (DCS) system and 2.4 GHz of Bluetooth technology. As a result, the performance of Si RF components in the frequency range of low GHz is a very important issue for realizing on-chip Si RFICs.

Unfortunately, semi-conducting silicon substrate produces substrate loss effect and dramatically degrades the performance of Si components at microwave frequency range [6–12]. Among the Si-based RF components, silicon spiral inductor plays one of important roles. The inductors can be used in many applications of RF circuits, such as impedance matching of low-noise amplifier, on-chip filtering, etc. [1–6]. However, the loss effect of Si substrate makes the performance of inductors
Nomenclature

- $f_{sr}$: self-resonance frequency, Hz
- $\omega_{sr}$: self-resonance angular frequency, rad/s
- $R_s$: series resistance of the inductor, $\Omega$
- $L_s$: series inductance of the inductor, nH
- $C_p$: fringing capacitance of the adjacent metal traces, fF
- $C_{ox1}$ and $C_{ox2}$: the capacitance between spiral metal layers and substrate, fF
- $R_{sub1}$ and $R_{sub2}$: equivalent substrate parasitic resistance, $\Omega$
- $C_{sub1}$ and $C_{sub2}$: equivalent substrate parasitic capacitance, fF
- $\delta$: the deviation between the ideal and real quality factor
- $\pi$: the pi constant
- $f$: the operation frequency, Hz

change tremendously with various operation frequencies. As a result, accurate and convenient equivalent circuit model of silicon inductor, that describes the behavior of inductor at certain frequency, plays a very important role for on-chip silicon RF integrated circuit designs.

To achieve the goal of extracting the equivalent model parameters of silicon inductors and model the inductors' characteristics accurately for RF circuit design, a convenient and fast extraction method, only from the measured $S$-parameters without any additional test structures, is presented in this paper. Besides, the presented extraction procedures are programmed as a powerful macro according to the extraction algorithms to execute all the extraction procedures automatically and shorten the extraction time effectively. In the meantime, the spiral inductors with different structures and different substrate resistivities have also been analyzed to verify the accuracy and convenience of the extraction macro. Furthermore, the extracted equivalent parameters of inductors can be adopted as the initial values of optimization or curve fitting, if necessary, to obtain the user-desired inductor model parameters for RF circuit simulation.

2. Extraction methods of silicon inductor model

The most important issue on designing silicon spiral inductors is to obtain inductors with desired inductance values and high enough quality factors at the same time. To achieve it, the structure and layout geometry of the inductors must be designed well to induce the magnetic coupling between spiral windings, to reduce the series resistance of the inductors' metal spirals and improve the loss effect from substrate. Increasing the metal thickness [9,10], shunting multi-level metals [8,12] or using the metal with lower resistivity [11] all help to reduce the metal series resistance of the inductors. Thicker dielectric layer below the metal spiral [10,13] or utilizing substrates with higher resistivities [9–11,14] both can reduce the loss effect of Si substrate. Besides, the center of the inductors should have considerable space to allow the passing of the magnetic flux [10]. The spacing between adjacent metal lines should be downsized adequately to optimize the magnetic coupling. The introduction of the patterned ground shielding [15] or removing the silicon underneath spiral inductor [5] also improves the loss effect of silicon substrate. The design of silicon spiral inductors is really a state of the art and involves a complex trade-off between the various layout geometry and process parameters.

In the reported literature, the most popular extraction methods of equivalent inductor parameters are utilizing the electromagnetic (EM) simulation [8,10,16,17] or fitting the simulated results to the measured data by circuit simulator or parameter optimization tool [9,14,18,19]. The popular EM simulation tools include momentum and high frequency structure simulator (HFSS) of Agilent-EEsof, etc. Although the EM simulation theoretically can provide the simulation results with considerable accuracy, however, the processing time of EM simulation generally takes several hours or even longer time. Besides, the extracted results by EM simulation often cannot provide sufficient physical meanings, and sometimes even the EM simulation cannot converge to produce reasonable results successfully.

Another kind of widely used methods that utilize curve fitting or parameter optimization by circuit simulator or optimization tool, such as the advanced design system (ADS) circuit simulator or LIBRA of Agilent-EEsof, always require fine-tuning of parameters repeatedly. The procedure of repeated fine-tuning or optimization generally cannot be finished very soon. In the mean time, the finally extracted parameters from parameter tuning or optimization are not unique for the same inductor. That is, we can obtain many sets of inductor parameters that all seem to model the behavior of the same inductor well, even though the extracted parameters are not reasonable. The nonuniqueness of the extracted results implies that the method by curve fitting makes the extracted results own less physical meanings. The methods by curve fitting or parameter optimization
lower the capability of providing systematic rules to characterize the performance of silicon spiral inductors fairly, effectively and physically.

In order to overcome the disadvantage of the EM simulation and curve fitting methods, a programmed extraction macro based on the proposed extraction algorithms is presented to extract equivalent circuit parameters of silicon inductors fast and effectively. The IC-CAP software of Agilent used here provides an environment to build an equivalent inductor model and establish the extraction formulas/macro where the parameter extraction language (PEL) is utilized. The proposed extraction macro can extract one unique set of model parameters with satisfied accuracy for the same inductor. The systematic extraction procedures, unlike the fine-tuning of curve fitting methods, can extract the model parameters with more physically oriented meanings and judge the characteristics of inductors more effectively.

3. Extraction algorithms of the programmed extraction macro

Spiral inductors with different process structures and parameters are fabricated with standard silicon process technology. Table 1 lists the different process parameters of the inductors. The top view of the fabricated spiral inductors for measurement and simulation is shown in Fig. 1. The two-port S-parameters are measured by an Agilent-8510 network analyzer and Cascade Microtech coplanar GSG probes. The parasitic effects of probe pads are de-embedded with an “open”
dummy device. While evaluating the characteristics of a one-port inductor, one terminal of the lumped equivalent model is shorted to ground. The lumped-element model of the spiral inductors used here is the same as that appeared in the literatures [6,19].

Utilizing the equivalent inductor model in Refs. [6,19], a programmed extraction macro that integrates the proposed extraction algorithms is developed to extract equivalent circuit parameters of silicon inductors fast and accurately. The extraction algorithms and the schematic processing flow of the programmed extraction macro are described below and summarized in Fig. 2. After executing the extraction macro, the measured two port $S$-parameters of an inductor are de-embedded with an “open” dummy device to remove the parasitic effects of probe pads. Then, the de-embedded $S$-parameters are converted to one port $Z$-parameters (one port $Z_{in}$) by shorting another terminal to ground, and the plot of the individual real part curves of one port input impedance is displayed as shown in Fig. 3. This figure exhibits the measured real part, imaginary part and the $Y_{11}$ curves of the sample W13 inductor as an example for demonstrating the extraction algorithms. Because $R_{s}$ is nearly independent of frequency at low frequency region, $R_{s}$ can be therefore extracted from the real part of one port $Z_{in}$ at the lowest operation frequency as indicated in Fig. 3. After automatically display the plot of the imaginary part curves of one port input impedance, also as shown in Fig. 3, the one port quality factor (Q-factor) and inductance as a function of frequency are evaluated as $Q$-factor $= \text{Im}(\text{one port } Z_{in}) / \text{Re}(\text{one port } Z_{in})$ and $L = \text{Im}(\text{one port } Z_{in})/(2\pi f)$. The parameter $L_s$ can be ex-

![Fig. 2. The schematic flow chart of the programmed extraction macro.](image-url)
Because the value of \( \frac{1}{2} \), \( C \) the value of \( Z \) value of real part of comes dominant and makes energy transmitted into the lossy silicon substrate be extracted. self-resonance angular frequency of \( \omega_s \), the value of \( R \) thus can be mathematically derived and extracted as: 

\[
C_p = \frac{\omega_s L_s}{\omega_s^2 + \omega_s^2 L_s^2} R_s \]

Therefore, the concept of deviation (\( \delta \)) between the ideal and measured quality factor, as shown in Fig. 4, can be utilized to extract the value of \( C_{ox} \) according to the derived method indicated in Fig. 2. The proposed extraction algorithms for \( R_{sub} \), \( C_{sub} \) and \( C_{ox} \) play the key techniques to program the extraction macro. Through the execution of the programmed extraction macro, all the equivalent model parameters of the silicon spiral inductors can be extracted fast and smoothly.

4. Verification of the extraction macro and discussions

As the inductor operates at higher frequency, the energy begins to transmit into the lossy silicon bulk. Consequently, the quality factors of silicon spiral inductors well described by \((\omega_s L_s/R_s)\) at low frequency are degraded rapidly due to the substrate loss effect. Therefore, the concept of deviation \((\delta)\) between the ideal and measured quality factor, as shown in Fig. 4, can be utilized to extract the value of \( C_{ox} \) according to the derived method indicated in Fig. 2. The proposed extraction algorithms for \( R_{sub} \), \( C_{sub} \) and \( C_{ox} \) play the key techniques to program the extraction macro. Through the execution of the programmed extraction macro, all the equivalent model parameters of the silicon spiral inductors can be extracted fast and smoothly.

As operation frequency increases high enough, energy transmitted into the lossy silicon substrate becomes dominant and makes \( C_{ox} \) approach electrically shorted-circuit. Therefore, the one port input impedance \( Z_n \) is approximately characterized by the combination of \( L_s \), \( R_s \), \( C_p \), \( C_{sub} \) and \( R_{sub} \). The parameter \( C_{sub} \) thus can be mathematically derived and extracted as: 

\[
C_{sub} = L_s/(R_s + \omega_s^2 L_s^2) \]

The maximum value of real part of \( Z_n \) almost occurs at the same angular frequency point, \( \omega_{sr} \). Based on the above results, we could establish the transfer function near the self-resonance frequency as: 

\[
Y_{sr} = X_{sr} j = (1/R_{sub})(1/R_{max}) - (R_s + C_s/L_s) \]

The value of \((R_s + C_s/L_s)\) is small as compared to other two terms, the value of \( R_{sub} \) can be extracted from the maximum value of real part of \( Z_n \). The value of \((R_s + C_s/L_s)/L_s \times 100\% \) could be expressed as an optional extraction error index of \( R_{sub} \) value. The values of \( C_{sub} \) and \( R_{sub} \) are now extracted successfully according to the proposed extraction algorithms. The schematic extraction points of \( C_{sub} \) and \( R_{sub} \) are also indicated in Fig. 3.
Indeed, the devices with (IMD) (W21, W24) have larger Q-factor due to its smaller metal series resistance $R_s$ and smaller substrate loss. These results imply that the directly extracted equivalent model parameters implemented with the

Fig. 4. The deviation ($\delta$) between ideal and measured Q-factor is utilized to extract the $C_{ox}$ value.

Fig. 5. The measured and simulated $S_{11}$ and $S_{21}$ curves of the two port inductor (sample W13).
programmed extraction macro really can physically estimate and respond the characteristics of silicon spiral inductors with different structures and substrate resistivities.

Figs. 5–8 show the measured and simulated (extracted) results of sample W13 as an example for demonstrating the extraction accuracy. Table 2 lists the root mean square (RMS) extraction error of real part and imaginary part of S-parameters for the inductors listed in Table 1. Note that almost all RMS extraction errors between the measured and the simulated results are less than 5%. The discrepancy between the measured and simulated curves in Figs. 5–8 and the RMS errors are all small enough to be accepted and well satisfy the practical requirement of the circuit simulation in the frequency range of personal wireless communication applications, such as 0.9, 1.8 or 2.4 GHz. The processing time for extracting a set of model parameters of an inductor is generally about three minutes. Such a short processing time gives a way to the extraction of high-volume inductors for building a model library of inductors.

The proposed extraction macro that based on the equivalent inductor model in Refs. [6,19] and mathematically derived extraction algorithms can extract one unique set of model parameters for the same inductor.
The unique set of model parameters overcome some drawback of EM simulation or curve fitting methods, that is, many sets of obtained inductor parameters all seem to model the behavior of the same inductor well, even though the extracted parameters are both not reasonable and physically oriented. The systematic extraction procedures, unlike the fine-tuning of curve fitting method, can extract the model parameters and judge the characteristics of inductors effectively. Through the execution of the programmed extraction macro, the dependence of the equivalent circuit parameters on different inductor structures can be reflected reasonably, as shown in Table 1.

The equivalent inductor parameters extracted by the extraction macro are for general purpose, such as the libraries of the mixed-signal devices established by the foundry companies. If the circuit designers need the model parameters utilized on specific narrow-band, slight tuning of the parameters can be easily finished to achieve the specific purpose. That is, the extracted inductor equivalent parameters can be adopted as the initial values of fine-tuning, if necessary, to obtain the user-desired inductor model parameters for RF circuit simulation. In summary, it implies that the proposed extraction macro is accurate and convenient enough to obtain the equivalent inductor circuit model parameters.

5. Conclusion

A programmed macro for extracting equivalent model parameters of silicon spiral inductors automatic
cally is presented. It can extract the equivalent model parameters of silicon spiral inductors with different structures and substrate resistivities fast and accurately. The extracted parameters also can reflect the characteristics of inductors physically and reasonably. The macro program is especially suitable for high-volume parameter extractions of many inductors to reduce the time consumption on parameter extractions effectively.

References