Accurate Modeling of Spiral Inductors on Silicon for Wireless RFIC Designs

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ABOUT THE AUTHOR

Jan Van Hese was born in 1965 in Sint-Niklaas, Belgium. He obtained his degree as an electrical engineer in 1988 at the University of Gent, Belgium and obtained a Ph.D. on the topic of electromagnetic modeling of passive interconnect structures in 1993 at the same university. Since 1993, he has been working for Hewlett-Packard, and later for Agilent Technologies, initially as a software development engineer working on electromagnetic simulation. In 1998 he became a project manager responsible for physical electromagnetic modeling.

To achieve higher levels of integration for wireless systems, it is desirable to integrate spiral inductors on silicon RF chips (RFICs). However, the quality of inductors fabricated on silicon is usually low. With the resistive loss in the spiral-coil metallization, the resistivity of the silicon substrate, and capacitive coupling effects to the substrate, inductors on silicon behave quite differently than ideal inductive components.

Successful design and simulation of wireless ICs relies on accurate characterization of the electrical behavior of these spiral inductors. With their generally poor performance, the spirals are usually designed for a maximum quality factor (Q) at the desired operating frequency, in combination with the desired inductance value and available substrate floor space. This article discusses the major issues that must be considered in the development of accurate models of spiral inductors on silicon.

Designers have traditionally characterized spirals on silicon using measurements, where a test wafer with a large number of spirals is designed, fabricated and measured. Since this approach does not allow predictive design, a large number of spirals are characterized and only a small number of those spirals are used in practical designs. Basically, the best-performing spirals are selected using criteria such as desired inductance value, maximum Q at a specified operating frequency, and the
area occupied by the spiral. Spirals are also used as-is, which means that no improvements are made to obtain better behavior. Using measured data, a lumped element model is derived for the selected spirals for use within the IC design process.

Characterization of the spirals using simulation permits more flexibility during the design process. This approach also avoids the need for a specific test wafer, relying instead on a process-parameter characterization. Because simulation adds predictive nature to the design process, changes can be made more easily to optimize and fine-tune the layout of the spiral to get the desired inductance value and best available Q. You can even automate this optimization process.

Parameter studies can reveal sensitivities and insight on how to improve the behavior of the spiral. To achieve the potential of the simulation-based approach, the simulator must be accurate, computationally efficient, and user-friendly. Whether you characterize the spirals using measurements, simulation, or a combined approach, it is important to have an accurate model that you can efficiently use in the RFIC design process.

The first section of this article compares the spiral design and characterization processes based on measurements and simulation. Since the choice of the simulation software is important in terms of the desired accuracy, efficiency and use model, we will give background information on the simulation technology that will be used in this paper, Advanced Design System 2001’s planar EM simulator, Momentum, from Agilent EEsof EDA. We will then look at a practical complex-spiral-inductor design and compare simulation and measurement results for this example. Based on the simulation results, we will derive lumped element models that describe its electrical behavior. Finally, the article will study the changes in behavior for a typical spiral when parameters such as conductor width, conductor separation, and oxide-layer thickness are varied, and show how this type of analysis can help in the design process.

Design and Characterization Methodologies for Silicon Spirals

The design process for spiral inductors or transformers on silicon usually begins with the choice of a basic spiral layout type (such as, rectangular, octagonal, or circular). Several spiral layout types are in use today, with some of the typical setups shown in Figure 1.
The metallization levels you need to create the spiral have to be mapped to the silicon process. To reduce inductor loss and improve the Q, the metallization layer with the lowest loss must be chosen for the spiral. To reduce eddy current losses in the substrate and to reduce the capacitive coupling to the substrate, this metallization layer should be as far as possible from the silicon substrate.

Once you choose the spiral layout, you have to determine the physical parameters, including number of turns, conductor width, and separation distance. Simple analytical equations, analytical models, and previous experience can help the designer obtain initial values for the desired inductance value and Q. For these starting parameters, one can use an estimate of the substrate characteristics and loss effects. After this first step in the design process, the designer can use different methodologies to analyze and optimize inductor performance.

A measurement-based methodology starts with the design and fabrication of a test wafer with a large number of spiral layouts, which include variations on the basic parameters of number of turns, width, and separation distances. After fabrication, all the spirals are measured (usually S-parameters) and basic quantities such as inductance and Q values, which are functions of frequency, are derived from the measured data. Once all inductors are characterized, they are categorized in terms of electrical behavior and occupied area.

A selection of usable spirals is added to a library, for selection later in the RFIC design process. If needed, a new test wafer is designed, fabricated, and measured with additional variations of the best spirals to get closer to the desired optimal electrical behavior. Often, lumped-element models are also determined from the measured data, since time-domain circuit simulators such as Spice are more efficient when using lumped element models.

The biggest disadvantages of the measurement-based approach is the need for a test wafer or multiple test wafers, which is expensive and time consuming. Also, you can only reliably use the selected spirals in the actual IC design process, even if the best fitting spiral does not meet all the
requirements. It is then necessary to make adjustments elsewhere in the design. The measurement approach also requires highly accurate measurements that require, in particular, special care in the calibration procedure.

An attractive alternative for the trial and error measurement methodology uses electromagnetic (EM) simulation software that allows predictive design. This is a process where the behavior of the spiral inductors can be predicted without the need for expensive and time-consuming fabrication or measurements. Simulation allows a designer to characterize a virtual spiral, which is defined in a layout drawing environment. Due to the needs for accurate and broadband models up to 5 or 10 GHz (or even higher), designers need EM-simulation software. Most EM-simulation software produces frequency dependent S-parameter data, resulting in virtual equivalence to a measurement-based technique. The choice of the simulation software is very important to obtain accurate results with the minimum setup and computation time.

Advantages of the simulation-based approach include more flexibility for the designer to try variations of the spiral layouts or optimize them for a desired behavior, and a much shorter design cycle that is independent of wafer runs. A typical spiral simulation, including setup and interpretation of the results, should not take more than half an hour. With this type of simulation, you can quickly explore alternative setups to obtain better performance. To obtain reliable results, simulation software requires an accurate setup of the process parameters, including substrate and metallization characteristics. A process characterization step is also advised.

EM-Simulation Techniques
Several commercial electromagnetic simulation software packages are available, based on different electromagnetic-simulation technologies, including finite-difference, time-domain, finite-element, or method-of-moments technologies. For simulating spirals on silicon, the method-of-moments-based simulation offers significant advantages over the other techniques. The primary advantage of this simulation is reduced simulation time and computer requirements, since only field quantities on metal surfaces are introduced as unknowns in the computations. In general, the method-of-moments technique starts from an integral formulation of Maxwell’s equations with the currents flowing on the metallization as unknowns. This integral equation is solved by discretizing the currents on the metallization surfaces. The technique uses the concept of Green’s functions to characterize the behavior of the substrate, including the electromagnetic effects in the silicon material. Capacitive coupling to the silicon substrate and magnetically-induced eddy currents are also taken into account in this manner.

In this article, we will use a method-of-moments simulator, Momentum, which produces frequency-dependent S-parameters. The method-of-moments discretization and solution process for planar structures is shown in Figure 2. The planar structure is decomposed into a substrate layer stack of infinite lateral extent and finite metallization patterns. The metallization patterns are meshed (Figure 2a) using elementary rectangular, triangular, or general polygonal cells. Maxwell’s equations are translated into integral equations by imposing the boundary conditions on the planar structures. The surface currents on the planar metallization structure are modeled using rooftop basis functions defined over the cells in the mesh (Figure 2b). Applying the Galerkin testing procedure imposes the boundary conditions. This results in a method-of-moments interaction or impedance-matrix equation as indicated in Figure 2d.
You can give an interesting interpretation to this impedance-matrix equation in terms of an equivalent network model\(^1\), as shown in Figure 2c. In this network, the nodes correspond to the cells in the mesh and hold the cell charges. Each cell corresponds to a capacitor to ground representing the electric self-coupling of the associated charge basis function. All nodes are connected with branches, which carry the current flowing through the edges of the cells. Each branch has an inductor representing the magnetic self-coupling of the associated current basis function and a resistor representing the conductor loss due to the current basis function.

Specifically, we will use the Momentum's RF mode, which has a number of features that directly benefit the simulation of spirals on silicon. Momentum RF uses a quasi-static approximation of Green's functions, which offers a significant speed improvement in the simulations compared to the full-wave EM variant. Since the silicon spirals are always small compared to the wavelength at the maximum frequency of interest, it is easy to validate the quasi-static approximation. The simulation in Momentum RF uses general polygonal cells to mesh the surfaces of the metallization, which results in faster simulation times compared to a mesh that uses only rectangles and triangles.\(^1\) Since Momentum RF uses the so-called star-loop basis functions to represent the currents on metallization, the simulations are accurate at all frequencies, including the lower frequency ranges.

Simulation and Measurement Results for an Octagonal Spiral Inductor
In this section we will characterize a four-turn octagonal spiral inductor. A top view of the spiral layout is shown in Figure 3. Inductor width is 25 µm and the separation between the different windings is 5 µm. The inductor is put on a 500 µm 15 W-cm substrate. The thickness of the SiO\(_2\) layer underneath the inductor is 8 µm. The metallization layer for the spiral has an equivalent surface impedance of 9.2 mW/sq., which is a low value and is a consequence of the combination of the different metallization levels. Surrounding the inductor is a metallization ring (halo), which acts as the path for the return current in the structure. The metallization ring is also connected to the silicon substrate with several vias.

Figure 3: Layout of the octagonal spiral inductor with ground ring
In the simulation setup using Momentum, two internal ports are inserted, one on each side of the inductor. Two additional ground reference ports are added close to the internal ports and connected to the ground ring to ensure that the return current follows this path in the simulation. The finite thickness of the inductor metal is taken into account in the simulation using two metallization layers, modeling the top of the metal and the bottom of the metal respectively. Both are connected using vertical metallization planes (vias).

We measured and simulated the spiral over the between 0 to 40 GHz. In this frequency range, the structure is electrically small, which justifies the use of the Momentum RF engine. The mesh, consisting of rectangles, triangles and general polygonal cells, is shown in Figure 3. The two-port S-parameters from the Momentum simulation results are plotted in Figure 4 and, compared to measured data, shows excellent agreement over the entire frequency band, especially in the 0 to 25 GHz range. The wide-band simulation (0 to 40 GHz) took less than 20 minutes of CPU time on an 800 MHz Pentium III PC, requiring less than 40 MB of RAM. We used Momentum's highest accuracy mode for the simulation, with edge mesh and frequency-dependent skin-effect-loss modeling in the metallization.

Spiral Inductor Models
You can use the S-parameter model, obtained directly from measurements or simulations, during further design steps of the RFIC. However, in many cases it is more efficient to use a derived model and you can choose between several types of models.

**Frequency-Dependent Inductance and Quality-Factor Model**
Once you measure and simulate the spiral inductor in terms of S-parameters, it is useful to examine a number of derived quantities. The most important ones are inductance value and Q, both of which are frequency dependent. The easiest method for determining these quantities is based on the simple equivalent lumped-element model of Figure 5, consisting of an inductor and a resistor.

![Figure 5: Simple equivalent model for a spiral inductor](image)

Applying the simulated and measured S-parameter data to the model in Figure 5 (by identifying the input impedance when Port 2 is shorted to ground) allows you to plot the inductance (L) and resistance (R) values as a function of frequency. You can then use these values to obtain the quality factor Q:

\[ Q = \frac{\omega L}{R} \]

where \( \omega \) is the angular frequency.
The plots for L and Q as a function of frequency are shown in **Figure 6** for the octagonal spiral example. The inductance and Q determined from the measured and simulated data correspond well and are plotted from 0 to 15 GHz. Note that above 11.5 GHz, the inductance value in the model, along with Q, becomes negative. This indicates that capacitive effects are dominating the behavior of the spiral at these frequencies and that the simple model of **Figure 5** is no longer meaningful. The Q reaches a maximum of 9.5 at 2.2 GHz. This low Q value indicates that the loss effects in the inductor metallization and in the silicon substrate, along with the parasitic capacitive-coupling effects, have seriously deteriorated the electrical behavior of the spiral.

**Higher Accuracy Lumped-Element Model**

A more detailed model that is often used to represent the behavior of the silicon spiral is shown in **Figure 7**. Although the spiral inductor is not symmetrical with respect to the two ports, the equivalent model is usually assumed to be symmetrical for simplicity. The various components in the model of **Figure 7** all have physical meanings. The shunt elements $L_s$ and $R_s$ represent the series inductance and resistance of the inductor. The capacitor $C_p$ represents the capacitive coupling between the windings of the spiral inductor. The substrate effects are taken into account with the capacitance to the silicon substrate, which is represented using the $C_{ox}$ capacitance and the parallel $C_{sub}/R_{sub}$ combination, which models the effects in the silicon substrate. Note that the ground symbol can refer to the substrate node, which may or may not be connected to the absolute ground. The spiral will behave slightly differently with different substrate node-grounding configurations. This equivalent model has the advantage of compactness and is physically meaningful. To obtain the element values, you can use either a special extraction software program or a global optimization capability to obtain the set of element values for an optimal fit to the S-parameters.

![Figure 7: A more detailed lumped-element model for a spiral inductor](image)

**Figure 7:** A more detailed lumped-element model for a spiral inductor

Usually, the lumped element model cannot be used over very broad frequency band. For the octagonal spiral results in **Figure 4**, it is not possible to find one adequate fit over the entire 0 to 40 GHz range using the model of **Figure 7** (assuming frequency-independent components). Using the general optimization capabilities in the Advanced Design System, we can fit element values in the frequency band from 0 to 5 GHz, which results in the following element values:

- $L_s = 3.08 \text{ nH}$
- $R_s = 2.28 \text{ W}$
- $C_p = 0.02 \text{ pF}$
The comparison of the S-parameters for this model with the simulated data we used to obtain the model parameters shows that, although the model of Figure 7 captures most of the spiral's behavior, it is not perfect (Figure 8).

Instead of finding one global fit covering a certain frequency range, you can also fit the lumped-element values of the model in Figure 7 at different discrete frequencies and examine the frequency dependency of the element values. In Figure 9, the frequency variations of the Ls and Rs elements are shown for the 0 to 5 GHz frequency range.

Figure 9: Frequency-dependent inductance (Ls) and resistance (Rs) values (0 to 5 GHz), fit at discrete frequencies

Parameter Variation Study
One clear advantage of the simulation-based methodology is the ease at which parameter changes can be made to the spiral design in order to optimize the electrical behavior or test the parameter sensitivity. To illustrate capability, we will examine the effects of changing some of the basic spiral parameters have on the frequency-dependent inductance and Q. The spiral geometry we will use is the rectangular spiral of Figure 1c. The spiral is fabricated on a 600 µm substrate with a resistivity of 10 W-cm. The top metallization of the spiral is separated from the silicon substrate by a 7 µm (=H) oxide layer. The metallization has a surface impedance of 35 mW/sq. The layout has the following parameters: width of the metallization (W), outer dimension (OD), length of the feedlines (L), separation between the metal winding (S1), distance between the feedlines (D), and number of
windings (N). We derived the following simulation results using one metallization level in the simulation setup, requiring less than 2 minutes of simulation time on a 800 MHz Pentium III PC for each of the frequency sweeps. We will start with the following nominal values for these parameters and then vary some of the parameters to examine the effects on inductance and Q.

N=3
W = 10 µm
OD = 250 µm
L = 20 µm
S1 = 3 µm
D = 30 µm

**Variation of Number of Windings (N)**
The first obvious parameter to vary is the number of windings of the spiral (N). The inductance and quality factor for five values of N (2, 3, 4, 5, and 6) are shown in **Figure 10**. As expected, the inductance value increases when the spiral has more turns. However, from **Figure 10** we can deduce that the inductance value does not increase linearly with the number of windings, as the area of the inner windings (loop area) is smaller compared to the outer windings, since the outer size of the spiral is kept constant. The self-resonant frequency decreases significantly for each added winding because of the increased capacitive coupling between the windings and the increased capacitive coupling to the substrate, as well as the increased inductance. The maximum Q also decreases significantly with increasing N because of the increased metal loss.

**Variation of Separation Distance (S1)**
**Figure 11** shows the effects of varying the separation distance between the windings, S1, from 2 to 6 µm. The inductance value decreases with increasing S1, as the loop area of the inner-spiral windings decreases with increasing separation distance. Smaller separation distances result in higher capacitive coupling between the windings and therefore a lower self-resonant frequency. The maximum of the quality factor is not as sensitive to the separation distance as is the inductance.

**Variation of Metallization Width (W)**
To obtain the data shown in **Figure 12**, the width of the metallization (W) was varied from 6 to 12 µm. The inductance value decreases, since the loop area of the inner windings decreases with increasing width. The self-resonant frequency also decreases because of the larger capacitive coupling between the spiral metallization and the substrate. Since the series loss decreases with increasing width, the quality factor increases, but not linearly; in fact, doubling the width, which decreases the DC resistance by a factor 2, only increases the maximum quality factor from 4.2 to 5.5.

**Variation of Oxide-Layer Thickness Underneath the Spiral (h)**
The last parameter to be varied is the thickness of the oxide underneath the substrate metallization (**Figure 13**). As expected, the inductance value at the lower frequencies is not affected by substrate thickness. However, because of capacitive-coupling effects and the increased losses in the silicon substrate, the quality factor as well as the self-resonance decrease as the oxide thickness decreases, illustrating the need to put the spiral as far away as possible from the silicon.
Summary
This article reviewed the requirements for spiral-inductor modeling. This discussion covered the traditional measurement-based design and characterization process for spiral inductors and demonstrated the advantages of a simulation-based approach. The choice of the simulator you use is important in terms of the accuracy and efficiency requirements. Only EM-based simulation can provide the required accuracy in the models. To illustrate the accuracy of the simulation, comparisons were made for an octagonal spiral. Finally, to illustrate another advantage of the simulation approach, several parameter variation studies were made on a standard rectangular spiral to show the effects of varying different physical parameters on performance.

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