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New Modeling Technology for Spiral Inductors for Ultra Wideband Applications

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***Abstract*—Spiral Inductor is becoming a crucial element for the increasing demands of the emerging wireless communication designs. Yet, the challenges of modeling spiral inductors for narrow-band applications are increasing along with emerging Ultra-Wideband (UWB) wireless applications. The challenge is to get an accurate model for UWB applications. A characterization using simulation offers more flexibility during the design process of the spirals. This approach also avoids the need for a specific test wafer dedicated to the spirals, a process parameter characterization suffices. As simulation adds predictive nature in the design process, changes can be made more easily to optimize and fine-tune the layout of the spiral for an optimal inductance value and quality factor. This optimization process can even be automated. Parameter studies can reveal sensitivities and insight on how to improve the behavior of the spiral. A simulation-based approach requires an accurate, computationally efficient and user-friendly tool. This paper discusses integrated spiral inductor metrics, key physical design challenges, and current modeling approaches and limitations. It introduced a new EM solver for introduces a new spiral inductor modeling methodology and application example that is well suited to UWB wireless applications.**

***Index Terms*—UWB, EM Solver, Quality Factor, Test wafer.**

I. INTRODUCTION

The rising demand for low-cost radio frequency integrated circuits (RF-IC's) has generated tremendous interest in on-chip passive components. Currently, there are several integrated resistor and capacitor options and most of these implementations are easy to model. Considerable effort has also gone into the design and modeling of inductor implementations, of which the only practical options are bond wires and planar spiral geometries. Although bond wires permit a high quality factor (Q) to be achieved, with typical in the 20–50 range, their inductance values are constrained and can be rather sensitive to production fluctuations [6]. On the other hand, planar spiral inductors have limited, but have inductances that are well defined over a broad range of process variations. Thus, planar spiral inductors have become essential elements of communication circuit blocks such as voltage controlled oscillators (VCO's), low-noise amplifiers (LNA's), mixers, and intermediate frequency filters (IFF's).

The technologies we are using earlier are not very accurate for modeling of a spiral inductor. The narrow band models of spiral inductors are not applicable to current and future process technology. Also, the narrow band inductor models can produce inaccurate results in time domain simulations, which are necessary in the circuit level characterization and design of RF circuits. Wideband inductor models provide frequency independent circuit elements level characterization and design of RF circuits Fig 1.Wideband inductor models provide frequency independent circuit elements. To efficiently break down the modeling tasks into more understandable and manageable parts, we will look at the key inductor metrics that designers look for. Three key metrics accompany integrated inductors- Self and mutual inductance, quality factor (Q), and self-resonance frequency (SRF).To have the accurate and efficient inductor design space exploration, optimization and synthesis, systematic wideband inductor modeling techniques that model substrate eddy currents and other frequency dependent effects without resorting to technology specific parameters are specified.

II. PARAMTERS OF SPIRAL INDUCTORS

A spiral inductor can be built on a silicon substrate by using the multilevel interconnects that is routinely provided with today's mainstream silicon fabrication processes. A minimum of two metal layers is needed to build the basic spiral coil M3 in Fig. 1 and an underpass contact M2 in Fig.1 to return the inner terminal of the coil to the outside [1]. The lateral structure of an inductor is defined by the number of turns, the wire width and space, and the total area covered, as shown in Fig. 2.

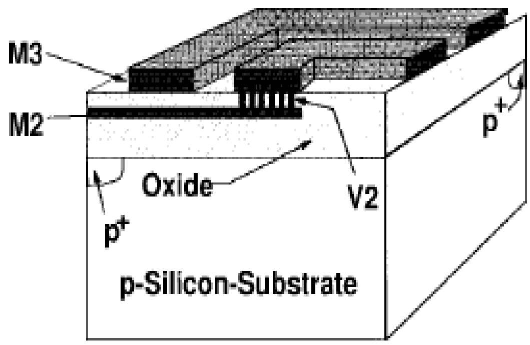

Fig. 1 Cross sectional view of Spiral Inductor

The key to accurate physical modeling is the ability to identify the relevant parasitics and their effects. Since an inductor is intended for storing magnetic energy only, the inevitable resistance and capacitance in a real inductor are counter-productive and thus are considered parasitics. The parasitic resistances dissipate energy through ohmic loss while the parasitic capacitances store electric energy. The

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physical model of a spiral inductor on silicon is shown in Fig.1and 3. The series inductance Ls, and the series resistance Rs represent the inductance and resistance of the spiral and underpass respectively. The overlap between the spiral and the underpass allows direct capacitive coupling between the two terminals of the inductor. This feed-through path is modeled by the series capacitance Cs. Cox models the oxide capacitance between the spiral and the silicon substrate. The capacitance and resistance of the silicon substrate are modeled by the Csi and Rsi [4], [7].

Inductors are used in circuit design as storage bins for magnetic energy, in contrast to capacitors, which are used as storage bins for electric energy. The inductance value is composed of self and mutual inductance. The self-inductance is a measure of the magnetic field-generated by a time-varying current- external to the wire, and is more dependent on the length of the wire than on its cross-section. Mutual inductance is the measure of mutually coupled magnetic fields of adjacent wires with current flowing in the same direction. With spiral inductors, mutual inductance tends to be the dominant portion of the inductor's overall inductance value, and its value is more dependent on the spiral wire's pitch than the wires spacing.

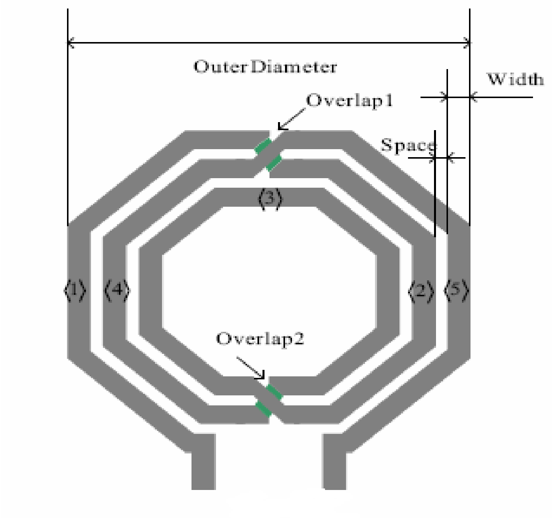

Fig.2 Layout of Spiral Inductor

The next important parameter concerning the integrated inductor is the quality factor, or Q. Q is a measure of how good an inductor you have. The simple definition of Q is the amount of energy stored over the energy loss in one cycle .In terms of inductors, Q becomes the ratio of peak magnetic energy minus peak electric energy (an unwanted side effect observed in the spiral inductor's parasitic capacitance) over energy loss in one cycle[1,3]

The third inductor design metric is known as the self-resonance frequency (SRF). At this frequency, the inductor stops behaving like an inductor and starts to resemble a poor capacitor. This is best illustrated in Fig.3. Simply, at high enough frequency, the spiral inductor associated electric field increases to a point beyond the oxide layer(s) and capacitively couples through the semi-conducting substrate to the low potential point, whether it is a backside ground or a package ground. Designers often choose a frequency operating range that is safe enough from the SRF (within 65 - 75% of the inductor's frequency band)[4].

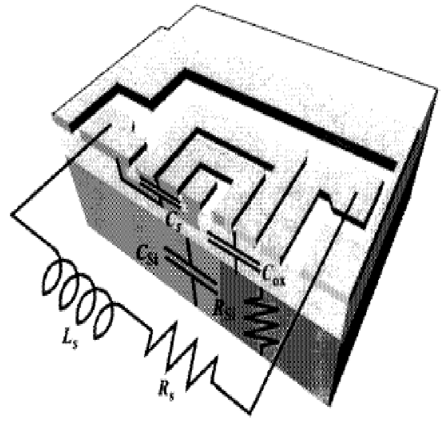

Fig.3 A cross-section of a typical spiral inductor with its associated parasitic capacitance and resistance.

III. Design Issues For Spiral Inductors

For integrated spiral inductors, there are some key physical designs issues include accurate substrate modeling and analysis, spiral-to-substrate interaction, and spiral conductor physical properties.

Substrate modeling and analysis is an important step in successful inductor modeling. When it comes to Si-based designs, the importance of accurately modeling the substrate effects is further enhanced. This is due to the semi-conducting of Si. The substrate effects depend on the doping level of the Si substrate. This is a great challenge for spiral inductor designers, where controlling energy coupling from the spiral inductor to the substrate is an important and challenging task. Substrate coupling effect is a function of frequency, and as shown in Fig. 4, this phenomenon dominates spiral inductor losses, affecting inductor Q around the 5 GHz region and above. [2, 5]

The electric field generated due to the inductor's magnetic flux is confined within the oxide layers at low frequencies. However, at higher frequencies, the electric field becomes large enough that it capacitively couples through the oxide layer(s) to the substrate. And, at even higher frequency, the electric field breaks thru the substrate capacitor and shorts to the low potential point, whether it is a backside ground or a package ground. This is the self-resonance frequency (SRF) of the spiral inductor described earlier as shown in Fig 4.

Another key physical effect associated with spiral inductors are the so-called substrate currents. Substrate currents are mainly composed of two parts: displacement currents from spiral traces to the substrate thru the oxide capacitance, and eddy currents in the substrate. Displacement currents are a product of the time varying electric field thru the oxide capacitance, and increase with higher frequencies as described earlier. Eddy currents, often associated with transformer applications, are a product of the spiral inductor time-varying magnetic field penetrating the conductive substrate.

The induced currents in the conductive substrate flow in opposite direction to the current flow of spiral inductor, producing a negative effect on the performance of the integrated inductor. [4]

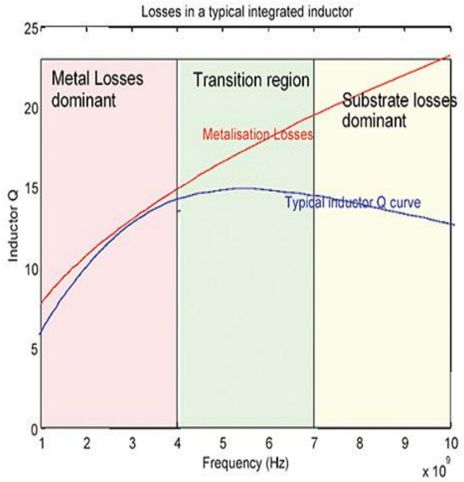

Fig 4 Metal and substrate losses typical of spiral inductors on silicon

At low frequencies, current flow distribution inside a wire tends to be evenly distributed. However, at high frequencies, current flow distribution becomes non-uniform and affected by eddy currents. As described earlier, eddy currents are a product of time-varying magnetic fields and adhere to Faraday's law. The effects of eddy currents can be observed in proximity effects, as discussed earlier regarding substrate currents, and as skin effects. Skin effects are essentially a measure of field penetration into nearby metal inducing eddy currents inside the metal, which in turn produce fields running in opposite direction to the impinging fields- and affecting the current distribution inside the metal conductor. Skin effects are measured by the so-called skin depth and are a function of frequency [2, 6]

IV. Parameter Effects

Effects of various layout parameters like, number of windings, metallization width, separation distance, etc., on Q and L have been discussed as follows;

A. Variation on the Number of Windings (N)

As expected, the inductance value increases when the spiral has more turns [7]. However 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-resonance frequency (where the inductance value goes through a zero and capacitive effects start to dominate the behavior of the spiral) decreases significantly for each new winding added because of the increased capacitive coupling between the windings and the increased capacitive coupling to the substrate.

The maximum quality factor also decreases significantly with increasing N because the increased metal loss.

B. Variation on the Separation Distance (SI)

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-resonance frequency. The maximum of the quality factor is not so sensitive to the separation distance [7].

C. Variation on the Width of the Metalization (W)

As the width of the metalization (W) is increased, the inductance value decreases as the loop area of the inner windings decreases with increasing width, but the self resonance decreases because of the larger capacitive coupling of the spiral metalization to 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 factor 2, only increases the maximum quality factor from 4.2 to 5.5.

D. Variation on the Thickness of Oxide Layer Underneath Spiral (h)

The last parameter that is varied is the thickness of the oxide underneath the substrate metalization. As expected, the inductance value at the lower frequencies is not affected by the substrate thickness. However because of the 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 material.

V. Modeling Of Spiral Inductor

Although the EM approach to spiral inductors modeling has many benefits, it also has some limitations, mainly because the EM model is often a snapshot of a given set of parameter and process specifications. In other words, if the user requires a different mix of component parameters or a slightly modified layer stack, a new model is needed. This may be manageable when working on a single inductor at a time, but when working with bigger circuits, this can be painful [6, 8]

Over the years, many have come out with clever techniques to make this iterative process more efficient with well-designed database management and interpolation techniques. However, these attempts, as worthy as they may be, still do not deliver what circuit designers of emerging wireless applications need a parameterized, broadband, EM-accurate model that simulates at very fast speeds that are comparable to those of standard analytical models, without compromising accuracy or speed.

The Synthesis of spiral inductors is the inverse operation of the modeling work, where the geometric dimensions (sizes) of an inductor is to be determined so that a list of resulting electrical characteristics can meet the predefined specifications. It is also called a sizing problem.

Though synthesis is independent of what kind of evaluation method is adopted to calculate those characteristics, a fast one is preferred to be included within the iteration loop because there may be a large number of iterations during the optimization. Three levels of evaluation methods are possible, which are:

(i) Analytical Design Equation methods are possible, which are quite efficient, but the accuracy is normally poor.

(ii) Scalable Circuit model with a SPICE simulator, which has acceptable accuracy and speed.

(iii) A numerical EM field solver, which is the most accurate. Tightly integrated with the Virtuoso platform, Virtuoso Spectre RF complements the SPICE-level analog simulation capabilities of the Virtuoso Spectre Circuit Simulator with world-class RF simulation and analysis technologies. Virtuoso Spectre RF is the only RF simulator that addresses the needs of the entire RF design spectrum. It offers a frequency-domain harmonic balance engine for faster and accurate simulation of high dynamic-range weakly non-linear RF circuits, and it uses a patented time domain shooting algorithm optimized for highly non-linear circuits.

A. Virtuoso Passive Component Designer

The Virtuoso Passive Component Designer is a built-in feature in Virtuoso Spectre RF for the synthesis, electromagnetic analysis, and modeling of spiral inductors and transformers. Synthesis of spiral inductors, transformers and BALUNs, producing a complete PDK component with symbol, schematic, layout, and simulation model (Fig.5).Synthesis is just the inverse of modeling. Accurate passive component verification and coupling analysis based on full wave and quasi-static electromagnetic solvers. Generation of inductor and transformer equivalent circuits from simulated and measured S-Parameter data capability. The flow diagram is as shown in Fig.5

B. Bounds and Initial Values of Sizes

For designing and modeling of an inductor, all the parameters with respect to it the synthesis variables are sizes (geometric dimensions) of an inductor (n, r, s, and w, i.e., number of turns, inner radius, spacing and width); these four unknowns need to be determined during synthesis. The lower and upper bound of sizes are set according to the design rules. The sheet resistances are technology dependent parameters.

A scalable industry-oriented, 24-element "2-π" compact circuit model for on-chip RF CMOS spiral inductors is presented (Fig.3). It has a good accuracy up to self-resonant frequency (SRF). The solver which includes the scalable model and a SPICE simulator as the evaluation method within the iteration loop [7, 8]

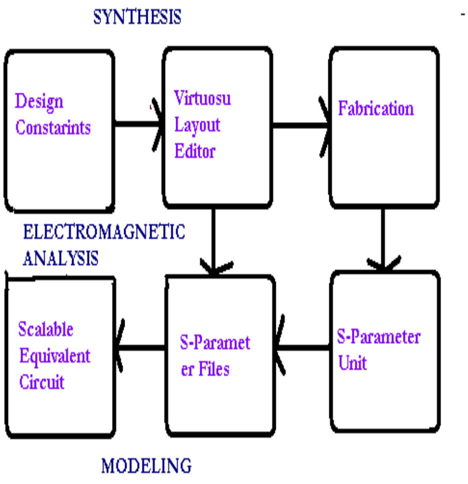

Fig.5 Virtuoso Passive Component Designer

VI. Conclusion

In this paper we talked about the VPCD (Virtuoso Passive component Designer) which is is need of the current technology requirements for Ultra Wideband Applications. As the Virtuoso Passive Component Designer is now optimized even for 65nm, so by using 90nm or 65nm technology we can synthesize a scalable 2-π model. The 2-π model has higher accuracy and is a distributed model. But still there are not simple equations to derive the values of 24 elements in this 2-π model. The RF Analysis is also possible as the built-in modeling capability converts S-parameter files into physical lumped element models, ready for RF analysis which is very helpful for RF ICs designer and it leads to optimization of the performance of RF ICs.

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