A Simplified Approach to Model an IC Inductor on Si-Substrate

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Abstract:

In this paper, an attempt is made for the first time to model an inductor in the radio frequency (RF) integrated circuit (IC) technology using Fuzzy Logic. This model is used to calculate and compute the effective inductance of a single spiral ring taking the substrate resistivity and oxide thickness as input parameters. The effective inductance has also been calculated analytically using a physics-based equivalent circuit of the inductor on Si substrate. The results from the model using Fuzzy logic have then been compared with those obtained analytically using the equivalent circuit and a reasonably good agreement has been found.

1. INTRODUCTION:

With the emergence of communication technologies, an inductor on silicon has established itself as a standard passive component [1-4]. In conventional IC technologies, inductor is not considered as a standard component like transistor, resistor, or capacitor, whose equivalent circuit models are usually included in the process description. However the situation rapidly changes as the demand for IC's continues to grow. The design of such an inductor as a component for an integrated circuit in RF silicon technology requires a fast but good model. Various approaches for modeling inductors on silicon chips have been reported [5-7]. Most of these models are based on numerical techniques, curve fitting, or empirical formula, and therefore are relatively inaccurate or not scalable over a wide range of layout dimensions and process parameters For inductor design insights and optimization, a compact, physical model is required. The difficulty of physical modeling stems from the complexity of high–frequency phenomena such as the eddy current effect in the interconnect layers and the substrate loss in the silicon. The lack of an accurate model for on-chip inductors presents one of the most challenging problem for silicon–based radio-frequency integrated circuits (RF IC's) designers [8]. The conventional way to model the inductor is by calculating the effective inductance from the physics-based equivalent circuit, which takes into account the effect of various parameters including parasitic effect. This technique depends on the accuracy of the equivalent circuit and requires cumbersome calculation to obtain an analytical expression for the inductor.

The use of Fuzzy Logic may be an alternative solution, which is based mainly on the expert knowledge and does not depend on the complicated analytical expressions [9,10]. Thus, the approach leads to a simple and easy process. Because of this, the use of Fuzzy Logic is spreading rapidly in the realm of consumer products, e.g Air conditioner, Refrigerator, Washing machine and so on. But, these applications are mainly in the control field. To the knowledge of the authors, there is no report on the modeling of semiconductor devices or elements using Fuzzy Logic. In this paper, an attempt is made for the first time to model an inductor in the radio frequency (RF) integrated circuit (IC) technology using Fuzzy Logic. Here, we will mainly concentrate on a single spiral ring inductor to simplify the computation. The remaining sections of this paper are organized as follows. In section 2, the structure and the equivalent circuit of the inductor on Si is described. The Fuzzy Logic model for this inductor is described in section 3. In section 4, the results and discussion are given. Finally, a conclusion is given in section 5.

2. STRUCTURE AND EQUIVALENT CIRCUIT:

As mentioned earlier, a spiral inductor will be considered in the present analysis. A schematic structure of the spiral IC inductor is shown in Fig.1 [3]. In this structure, the approach has been chosen in substituting a circular spiral coil by a set of concentric rings. On a Si-substarte, oxide layer is grown and then Al metal layers are used to fabricate the rings of the inductor.

The equivalent circuit of the on-chip inductor is shown in Fig.2 [3]. The electrical characteristics of the spiral coil itself are represented by the inductance L_s, the series resistance R_s, and the inter wire capacitance C_p. The resistance R_s is frequency dependent due to the skin effect and current crowding. The skin effect can be neglected in

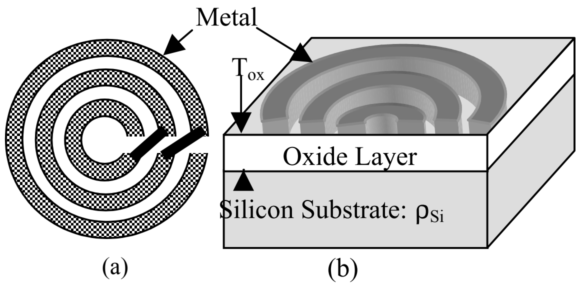


Fig.1 (a) Typical concentric circular-ring model, and (b) Schematic layer structure of an IC inductor.

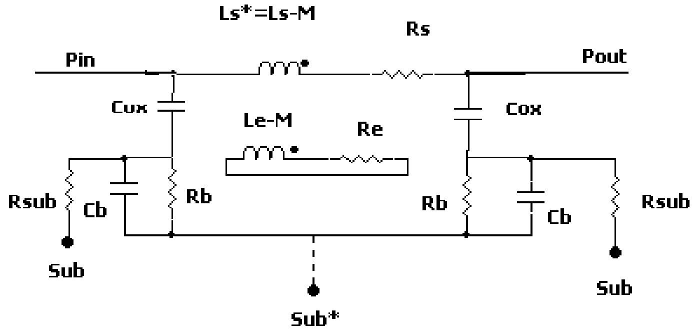


Fig.2 Equivalent circuit of the inductor.

thin metal layers at low frequencies. High frequency leakage current through the silicon substrate is modeled by the oxide capacitance C_{ox}, the substrate resistance R_b and the silicon capacitance C_b. Eddy current in the substrate are illustrated by the loop circuit with L_e-M and R_e. If the silicon resistivity is low (<0.1 ohm-cm), eddy currents in the silicon cause a magnetic field to weaken the primary field of the metal coil. This leads to a reduced inductance L_s*=L_s-M.

3. THE MODEL:

The modeling technique of the IC inductor on silicon to be presented here is based on "FUZZY LOGIC". Fuzzy Logic based modeling requires knowledge of the effect of various input parameters on the system/device performance. So, the effect of different parameters such as ring radius (R_1), frequency (f), substrate resistivity (ρ_{si}), oxide thickness (T_{ox}) and substrate thickness, etc. on the effective inductance value should be understood. We first discuss here the effect of various parameters on the effective inductance.

If the inductor radius (R_1) is increased, the self inductance value will be increased. But it cannot be increased much as the metal coil radius is limited by the optimum value of chip area. If the frequency is increased from the low value to high value, the inductance value initially remains constant and then decreases rapidly at high frequency. At high frequency, the skin effect and current crowding effect increases the series resistance of the metal strip, and the eddy current in the substrate increases. The increase of eddy currents decreases the effective inductance of the metal coil.

The effective inductance of a spiral inductor can vary depending on the substrate resistivity, which is determined by three modes of operation: 1) inductor mode 2) resonator mode 3) eddy current mode. At silicon resistivities beyond 10 Ω.cm, one encounters the regime where the silicon substrate behaves as a dielectric represented by the substrate capacitance C_b. The substrate resistance R_b is large enough to suppress resonance through the relatively large oxide capacitance C_{ox}. Instead the inductor resonates mainly through the dielectric(C_b) and inter winding (C_p) capacitance. This is called the inductor mode. Bellow 10 Ω.cm, the silicon substrate starts to behave as a semiconductor and one observes a drastic drop of resonance frequency, indicating that now resonance starts to occur through substrate resistance R_b via the large oxide capacitance $C_{ox.}$

If the substrate thickness (T_{sub}) is increased, the substrate resistance (R_b) increases while the substrate capacitance (C_b) decreases. The maximum value of substrate thickness is, however, limited by the optimum thickness of the chip. Increase in the thickness of the oxide layer (T_{ox}), leads to decrease in the oxide layer capacitance (C_{ox}) with the consequent increase in the resonant frequency. The mutual inductance between the metal coil and substrate decreases with increase in thickness of the oxide layer resulting in increase of the effective inductance. But, the maximum oxide layer thickness (T_{ox}) is limited by mechanical stress constraints in Si process technology and by the optimum thickness of the chip.

Though many variables are considered in the above discussion, to simplify the analysis, we have considered mainly the effect of two parameters, ρ_{si} and T_{ox}, for two different frequencies while keeping other parameters constant at their nominal values(metal width,W=10μm, metal thickness,d=2 μm, R_1=120 μm, T_{sub}=100 μm). It must be mentioned here that the input parameters should not violate their practical feasibility.

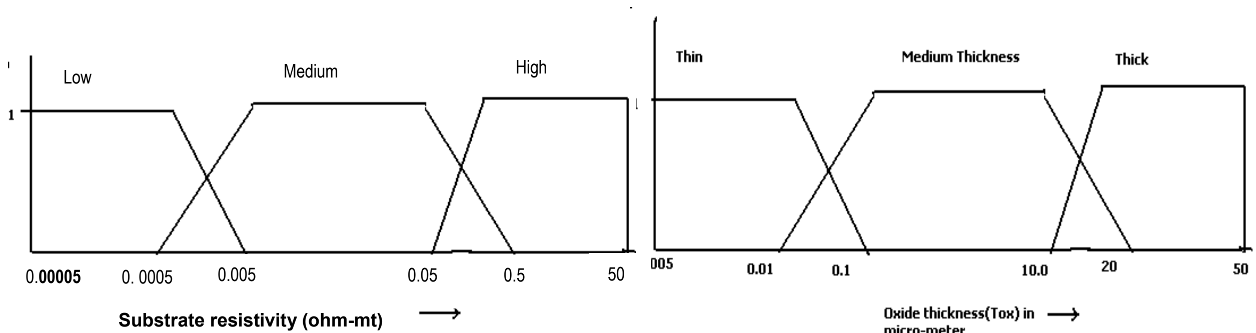
We consider three membership functions of trapezoidal shape for each input variables and the output variable. The 'low', 'medium' and 'high' values of the input variables are shown by the respective membership functions shown in Fig. 2. For example, the linguistic variables for the input substrate resistivity are defined as ‘low’ for $0.00005< \rho_{si}<0.005$, ‘medium’ for $0.0005< \rho_{si}<0.5$, ‘high’ for $0.05 <\rho_{si}<50$ with membership functions shown in the figure 2(a). Similarly, the membership function for the T_{ox} is shown in Fig. 2(b).

Now, next step is to construct the rule base by the knowledge of the dependence of inductance on substrate resistivity and oxide thickness. As the analysis will be done for two difference frequencies, the dependence of the rule-base on the frequency are also to be considered. Thus, using three parameters as input, the rule-base is to be shown. To show in a two-dimensional table, we have used a new variable OPij(i,j=1,2,3) to denote the various combinations of ρ_{Si} and T_{ox} [Table 1 (a)]. Then, the rule base is finally shown in Table 1(b).

4. RESULTS AND DISCUSSION

We take the variation of substrate resistivity from 0.00005 ohm-meter to 50 ohm-meter, variation of oxide-thickness from 0.005 μm to 50 μm, and frequencies of 5GHz and 50GHz. When we enter the certain value of the variable parameters within the given range, we get the membership functions of the low inductor, medium inductor, high inductor from the rule base. This is the FUZZY value of the inductor. Defuzzyfication is done to get the crisp value of the inductor. It is done in different ways such as max-min defuzzyfication, centroid defuzzyfication etc. In our work, we have used the centroid defuzzyfication technique with the help of membership function from the rule base table.

The inductance as obtained from the model is shown in Fig. 3 as a function of substrate resistivity for two different values of the frequency (a) 5GHz and (b) 50 GHz. The model results are also compared with the results obtained from the equivalent circuit analysis. A reasonably good agreement is shown. Similarly, the variation of inductance with oxide thickness is shown in Fig. 4. It can be seen that these results are also in agreement except some deviation for the high frequency values. From the results it is seen that our model works for the lower values of frequency (below the resonant frequency ~ few GHz). But the exact value of L(Fuzzy) and L(calculated) differ from each other by small factor although the order is the same which dictates that some correction is necessary for modeling which can be done by some trial and error method or using the feedback control mechanism employing tools such as neural networks.



(a) (b)

Fig. 2 Membership functions for the linguistic variables of substrate resistivity (ρ_{Si}) and oxide thickness (T_{ox}).

Table-1: (a) Symbolized ρ_{si} and T_{ox} combination (a) Rule-base for the inputs ρ_{si}, T_{ox} and frequency. Med. L means Medium Inductance, HI L means high inductance, N. A. means not applicable and so on.

(a)

T_{ox} / ρ_{si}	Thin	Med. Thick.	Thick
Low	OP11	OP12	OP13
Medium	OP21	OP22	OP23
High	OP31	OP32	OP33

(b)

T_{ox}/ρ_{si} f	OP11	OP12	OP13	OP21	OP22	OP23	OP31	OP32	OP33
Low Freq.	Med. L	Med. L	Med. L	HI L	Med. L	HI L	HI L	HI L	HI L
Med.Freq.	N.A.	Low L	Low L	N.A.	Low L	Med. L	N.A.	Med. L	HI L
High Freq.	N.A.	Low L	Low L	N.A.	N.A.	Low L	N.A.	N.A.	HI L

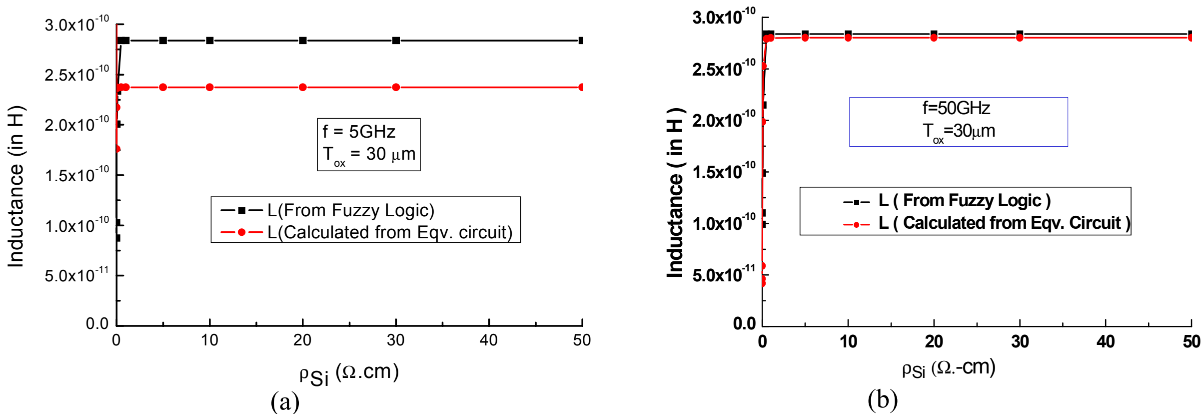


Fig. 3 Inductance (L) vs silicon resistivity for T_{ox}=30 μm at (a) 5GHz, (b) 50GHz.

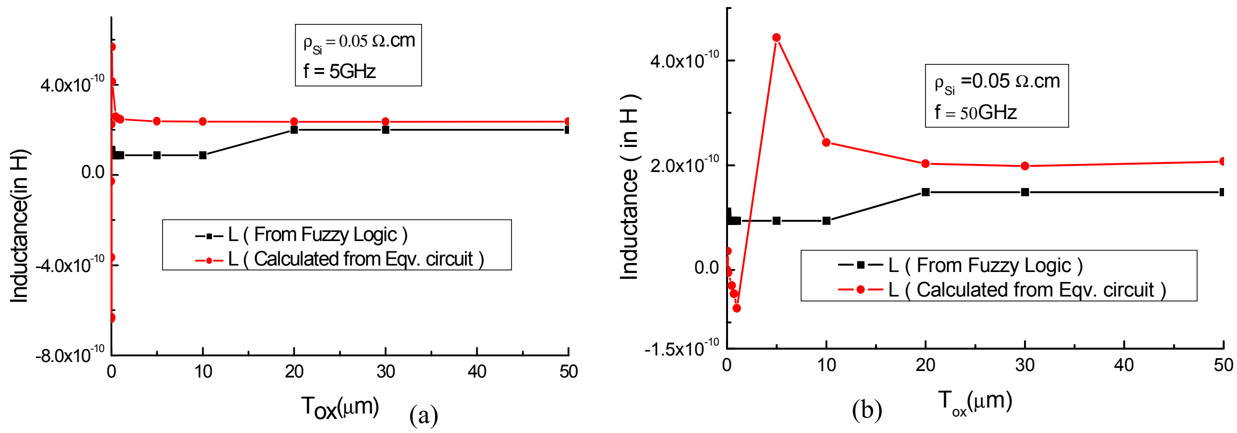


Fig.4 Inductance vs T_{ox} with ρ_{si}=0.05Ω.cm at Frequency (a) 5GHz, (b) 50GHz.

5. CONCLUSION:

In this paper, we have suggested for the first time a model for an IC inductor on Si chip using fuzzy logic. A single spiral ring has been considered in the present study. The effect of various design parameters of the fabricated inductor on the inductance value has been discussed in brief, and a rule base has been constructed. The results are shown for inductance as functions of substrate resistivity and oxide thickness for two different frequencies. The model results are compared with the values obtained from an equivalent circuit analysis, and a reasonably good agreement has been found. Better results can be obtained by employing an optimization technique.

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