第26卷 第11期 半 导 体 学 报 Vol.26 No.11
2005年11月 CHINESE JOURNAL OF SEMICONDUCTORS Nov.,2005

Lumped Equivalent Circuit of Planar Spiral Inductor for CMOS RFIC Application *

Zhao Jixiang

(Department of Electronic Engineering, China Jiliang University, Hangzhou 310018, China)

Abstract: A lumped π-type equivalent circuit of planar spiral inductor for CMOS RFIC application is developed by the domain decomposition method for conformal modules (DDM-CM). Closed form expressions of lumped parameters for a square spiral inductor on a Si-SiO_2 substrate are obtained and verified with the previously published experimental results.

Key words: planar spiral inductors; equivalent circuit; inductance; quality factor; DDM-CM
EEACC: 2140
CLC number: TN303 **Document code:** A **Article ID:** 0253-4177(2005)11-2058-04

1 Introduction

Spiral inductors have gained much application in the design of integrated RF transmitters and receivers. For this reason, much research work has been done in past years with analysis and optimization of spiral inductors[1~5]. However, for spiral inductors on single or multiplayer-substrates, an accurate closed form expression for inductance is not available so far. Time-consuming numerical methods and inaccurate empirical formulae have to be used to get the inductance and quality factor. In this paper the domain decomposition method for conformal modules (DDM-CM) is used to get a simple lumped equivalent circuit of planar spiral inductors on a multilayer substrate. The DDM-CM was introduced by Papamichael and Stylianopoulos[6]. With the DDM-CM, a planar spiral inductor on a multi-layer substrate can be transformed to an elongated microstrip line[5], which can be finished with general microstrip line theory. Compared with the published spiral inductor models, the main advantage of the microstrip line model comes from the fact that the complicated computation of mutual parameters (such as mutual inductance) is omitted. A corresponding lumped equivalent circuit has been modeled, and closed form expressions for the quality factor and inductance of a square spiral inductor on Si-SiO_2 substrate are obtained and verified with the experimental results in Ref. [1], showing that the model is simple, accurate, and scalable.

2 Equivalent circuit

Considering a spiral inductor on multi-layer substrates, which is depicted in Fig. 1, according to Refs. [6,7], we rewrite the approximated total module of the square spiral inductor from Ref. [5], which are given as follows.

$$m = [N]^{+}\left(\frac{2d_{in}+2w}{w}-\frac{4}{\pi}\ln 2\right)+\frac{[N]^{+}([N]^{+}-1)}{2}\times\frac{4w+4s}{w}+[N]^{-}\left(\frac{2d_{in}+3w+s}{w}-\frac{4}{\pi}\ln 2\right)+\frac{[N]^{-}([N]^{-}-1)}{2}\times\frac{4w+4s}{w} \quad (1)$$

$$d_{in} = d_{out} - (2[N]^{+}-1)(w+s) \quad (2)$$

---

* Project supported by the Science Foundution for Outstanding Youth of Zhejiang Province

Zhao Jixiang PhD, associate professor. His research interest is in characterization of microwave and RF circuit devices.

Received 28 March 2005, revised manuscript received 15 July 2005

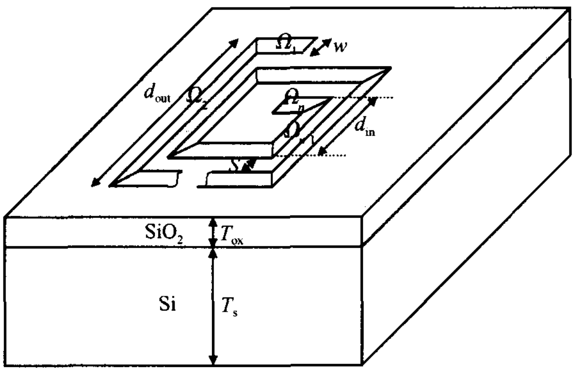

Fig. 1　A square spiral inductor on Si-SiO_2 substrate

where w is the conductor width, s the turn separation, N the number of turns that is a multiple of 0.5, $[N]^{\pm}$ denotes the N to the nearest integer towards infinity and zero, respectively, and d_{in}/d_{out} the inner/outer diameter. When the microstrip line length is equal to the inductor length l, then the conductor equivalent width is $w_{eq} = l/m$. The other geometrical parameters, such as the thickness of the conductor and thickness of each layer of the substrate keep constant during the transformation by DDM-CM, so the lumped equivalent circuit of the microstrip line can be modeled as a two-port network, shown in Fig. 2.

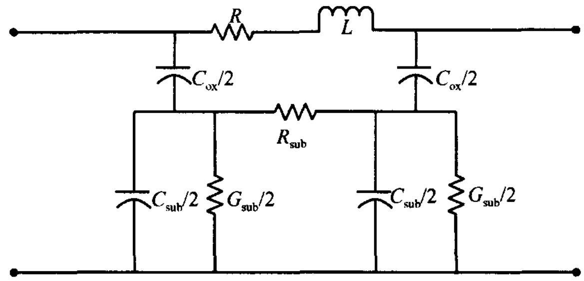

Fig. 2　Lumped π-type equivalent circuit of microstrip line

The element Y_{11} of its admittance matrix $[Y]$ can be obtained:

$$Y_{11} = \frac{1}{R + SL} + \frac{1}{\dfrac{2}{SC_{ox}} + \dfrac{R_{sub} + \dfrac{2}{G + S(C_{ox} + C_{sub})}}{0.5(G + SC_{sub})\left(R_{sub} + \dfrac{2}{G + SC_{sub}} + \dfrac{2}{G + S(C_{ox} + C_{sub})}\right)}} \quad (3)$$

in which $S = j\omega$, ω the is the angular-frequency and other parameters are given by the resistance of the microstrip[8].

$$R = \sqrt{R_{dc}^2 + (kR_{hf})^2},\ R_{dc} = \frac{l}{\sigma w T},\ R_{hf} = \frac{l}{2\sigma\delta(w + T)} \quad (4)$$

the modified factor $k = \max\{1 + \min(\delta, T)/T, 1.2\}$, and T, w is the thickness and width of microstrip line, respectively. The inductance of the microstrip[9] is

$$L \approx \frac{l\mu_0}{2\pi}\ln\left(\frac{2\pi}{P}\right),\quad P = 2\frac{w_{eq} + T}{h} \quad (5)$$

where $h = t_{ox} + t_{Si}$. The oxide-layer capacitance C_{ox}, the substrate shunt admittance G, capacitance C_{sub} and lateral substrate resistance R_{sub} are listed as follows[10]:

$$C_{ox} = \varepsilon_{ox}\varepsilon_0[w/t_{ox} + 0.77 + 1.66(w/t_{ox})^{0.25} + 1.06(T/t_{ox})^{0.5}]l \quad (6)$$

$$G = \frac{t_{ox}\sigma_{sub}}{t_{sub}\varepsilon_0\varepsilon_{ox}C_{ox}} \quad (7)$$

$$C_{sub} = \frac{\varepsilon_0\varepsilon_{sub}}{\sigma_{sub}}G \quad (8)$$

$$R_{sub} = \frac{l}{w\,t_{sub}\sigma_{sub}} \quad (9)$$

in the above formulas, σ_m is the microstrip conductor conductivity, δ_m the skin depth, σ_{sub} the substrate conductivity, ε_{ox} and ε_{sub} are the oxide-layer and substrate permittivity, respectively. The quality factor and inductance of the spiral inductor can be obtained.

$$Q_{inductor} = \frac{\mathrm{Imag}(1/Y_{11})}{\mathrm{Real}(1/Y_{11})} \quad (10)$$

$$L_{inductor} = \frac{\mathrm{Imag}(1/Y_{11})}{2\pi f} \quad (11)$$

3　Results and discussion

The validity and accuracy of the transmission line model by DDM-CM for parameters extraction of the spiral inductor is evaluated through an example by comparison with the experimental results. A square spiral copper inductor with $N = 3$ turns, width $w = 18\mu m$, and spacing between spires

$s = 18\mu m$, outer dimension $d_{out} = 226\mu m$, the spiral metal thickness value, $T = 2.7\mu m$, is fabricated on a silicon substrate with resistivity $\rho = 10\Omega \cdot cm$, thickness $t_{Si} = 500\mu m$. The thickness of the SiO_2 film is $t_{ox} = 6.3\mu m$. The quality factor and inductance of the square spiral inductor as a function of frequency is shown in Fig. 3 and compared with the experiment results in Reference [1, the type LB2 (Cu1)].

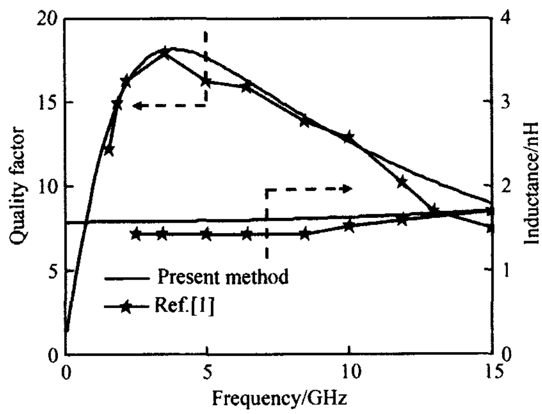

Fig. 3 Inductance and quality factor of the square inductor versus frequency

This method can be extended to an arbitrary spiral inductor, which is only has single connectivity. The closed form expressions are available for the quality factor and inductance. The lumped π type equivalent circuit is expected to be efficient for analysis and optimization of RF circuits.

References

[1] Burghartz J N, Edelstein D C, Jenkins K A, et al. Spiral inductors and transmission lines in sillion technology using copper-damascene interconnects and low-loss substrates. IEEE Trans Microw Theory Tech, 1997, 45(10): 1961

[2] Yue C P, Wong S S. Physical modeling of spiral inductors on silicon. IEEE Trans Electron Devices, 2000, 47(3): 560

[3] Pieters P, Vaesen K, Brebels S, et al. Accurate modeling of high-Q spiral inductors in thin film multiplayer technology for wireless telecommunication applications. IEEE Trans Microw Theory Tech, 2001, 49(4): 589

[4] Jenei S, Nauwelaers Bart K J C, Decoutere S. Physics-based closed-form inductance expression for compact modeling of integrated spiral inductors. IEEE J Solid-State Circuits, 2002, 37(1): 77

[5] Zhao Jixiang, Mao Junfa. Parameters extraction and modeling for planar spiral inductor on Si-SiO_2 substrates by DDM for conformal modules. IEEE Trans Microw Theory Tech, 2003, 51(6): 1763

[6] Papamichael N, Stylianopoulos N S. On the theory and application of a domain decomposition method for computing conformal modules. J Comput Appl Math, 1994, 50: 33

[7] Bowman F. Introduction to elliptic functions. London: English Univ Press, 1953

[8] Dana R F, Chow Y. Edge condition of the field and a.c. resistance of a rectangular strip conductor. IEEE Proceedings Pt H, 1990, 137(2): 133

[9] Sellberg F. Simple determination of all capacitances for a set of parallel microstrip lines. IEEE Trans Microw Theory Tech, 1998, 46(2): 195

[10] Valkodai A, Manku T. Modeling and designing silicon thin-film inductors and transformers using HSPICE for RFIC applications. Integration, 1997, 24: 159

CMOS RFIC 平面螺旋电感的集总等效电路*

赵吉祥

(中国计量学院电子工程系，杭州　310018)

摘要：基于 DDM-CM 理论，建立了 CMOS 工艺下射频集成电路中广泛使用的平面螺旋电感器的π型集总等效电路．获得了 Si-SiO_2 结构衬底上解析、封闭的集总参数的表达式，并和已经发表了的实验数据进行了比较，验证了所得结果的准确性．

关键词：平面螺旋电感器；等效电路；集总电感；品质因子；DDM-CM

EEACC：2140

中图分类号：TN303　**文献标识码**：A　**文章编号**：0253-4177(2005)11-2058-04

*浙江省人才培养自然科学基金资助项目

赵吉祥　博士，副教授，主要研究兴趣为射频与微波集成电路的分析和建模．

2005-03-28 收到，2005-07-15 定稿