A High Performance Solenoid-Type MEMS Inductor

Seonho Seok, Chul Nam, Wonseo Choi, and Kukjin Chun

Abstract— **A solenoid-type MEMS inductor with a quality factor over 10 at 2 GHz has been developed using an electroplating technique. The integrated spiral inductor has a low Q factor due to substrate loss and skin effects. It also occupies a large area compared to the solenoid-type inductor. The direction of flux of the solenoid-type inductor is parallel to the substrate, which can lower the substrate loss and other interference with integrated passive components. To estimate the characteristics of the proposed inductor over a high frequency range, the 3D FEM (Finite Element Method) simulation is used by using the HFSS at the Ansoft corporation. The electroplated solenoid-type inductor is fabricated on a glass substrate step by step by using photolithography and copper electroplating. The fabrication process to improve the quality factor of the inductor is also developed. The achieved inductance varies within a range from 0.5 nH to 2.8 nH, and the maximum Q factor is over 10.**

Index Terms — **solenoid, inductor, electroplating, MEMs, integration**

I. INTRODUCTION

The MEMS technology is the enabling technology to a variety of area. Conventionally, surface micromachined accelerometer and gyroscope are mainly researched and the actuator such as the x-y stage for the data storage has been also presented[1]. Recently, the RF MEMS[2] and optics[3] applications grow as a new area.

With the ever-growing market of mobile communication, the PLL frequency synthesizer is imposed tighter specifications on phase noise to lower channel interference. Stability is important of the oscillator signals to follow these specifications. Oscillator frequencies must be stable against variations in temperature, against aging, and against any phenomena such as noise or microphotonics. The low phase noise VCO consists of a passive LC tank and a negative gm active circuit. The most important parameter that determines the stability of the VCOs is the Q-factor of the frequency setting part such as LC tank.

Many researches have focused on integrated passive components composing the LC tank with high quality factors. Most integrated inductors are of the spiral–type [4]. For silicon-based CMOS RF IC's, the inductor quality factor (Q) is degraded at high frequencies due to both the skin effect and substrate loss. There are some approaches concerning substrates, such as the use of high–resistivity substrates(150-200Ω ·cm) [5], and etching a pit in the silicon substrate under the inductors [6]. However, these methods add extra processing cost and are not compatible with standard CMOS processes. For the skin effect, which means high frequency current flows on the metal surface, thick gold metallization [4], multiple metal layers in parallel [7], and copper metallization [8] have been reported. Even though these methods are compatible with standard CMOS processes, the inductor quality factor is still lower than 10. While the on-chip bondwire inductor [9] shows superior performance compared to the spiral inductor, its repeatability and robustness make it less applicable on RF passive components.

Recently, solenoid-type MEMS inductors have been reported for wireless communication applications [10]. A superior high Q inductor is obtained from high conductive copper material and high aspect-ratio thick photoresist.

Manuscript received August 5, 2001; revised September 6, 2001.

The authors is with School of Electrical Engineering Seoul National University
(e-mail : ssh@mintlab.snu.ac.kr)
Tel : +82-2-880-5449 Fax : 82-2-887-6575

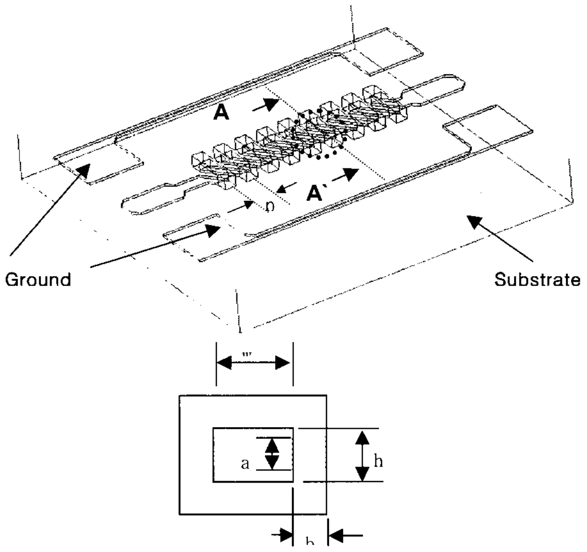


Fig. 1. The proposed MEMS Solenoid-type inductor structure.

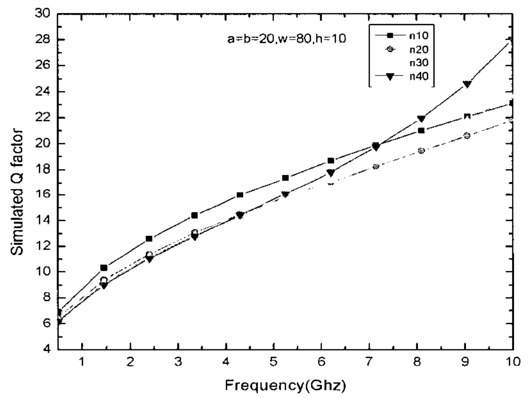


Fig. 2. Simulated Q factor. vs. number of turn.

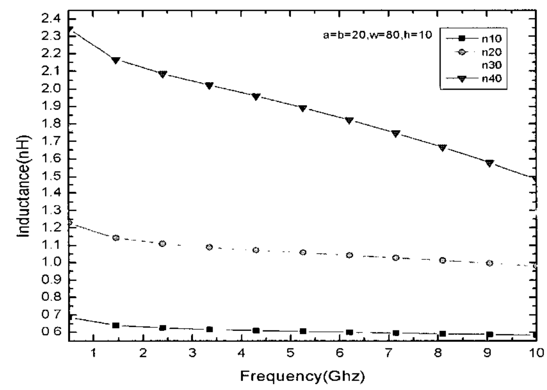


Fig. 3. Inductance value. vs. number of turn.

In this work, we have fabricated the solenoid-type MEMS inductor occupying small area compared with others by copper electroplating and photolithography. The fabricated solenoid-type inductor shows the inductance between 0.5 nH and 2.8 nH and the maximum Q factor of over 10.

II. DESIGN

For a solenoid-type inductor, the inductance L can be represented with a simple equation (1), neglecting substrate and fringing effects.

$$L = \frac{4\pi \times 10^{-7} \times n^2 \times A}{n \times p} \tag{1}$$

where n is the number of coil turns, A is the cross-sectional area, and p is the pitch between turns. This analytical equation for the inductor is not adequate for high frequency application, because high frequency current flows on the conductor surface by the skin effect. In order to well understand all electromagnetic effects on the inductor with high frequency, specific simulations are necessary because the problem is too complex to be solved analytically. The only way to fully simulate all of the effects is a full three-dimensional (3-D) finite-element simulation. The simulation is done to obtain insight into which structural dimension parameters are

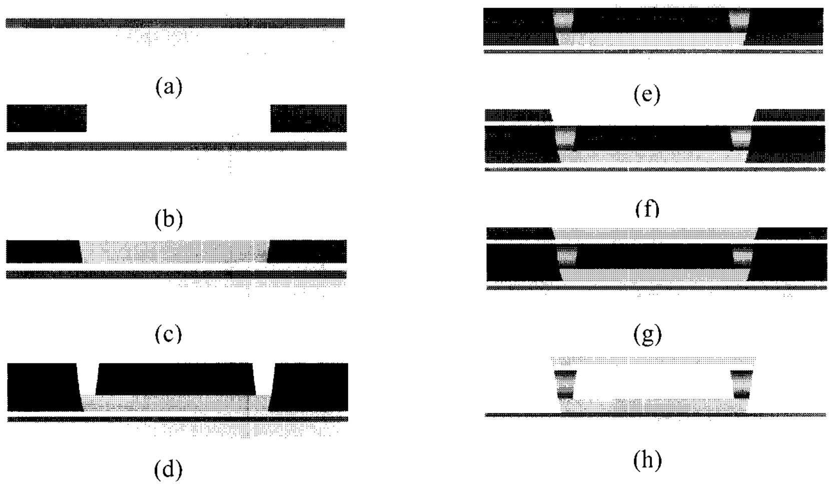
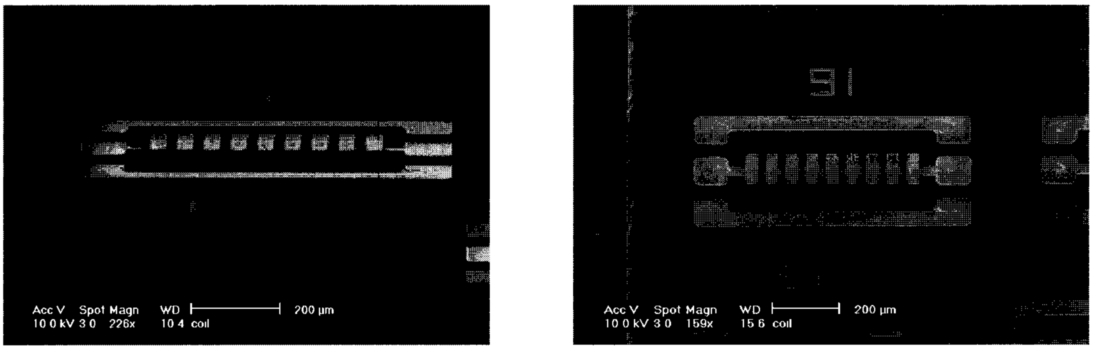


Fig. 4. The Fabrication process sequences : (a) Cr 200 Å/Au 2000 Å seed deposition (b) Photolithography for electroplating base mold using first mask (c) copper plating (d) post(via)pattern photolithography using second mask (e) temperature curing and seed layer evaporation (2000Å Au) (f) Air bridge pattern photolithography using third mask (g) Air bridge copper plating (h) PR and seed layer removal



(a) (b)

Fig. 5. The SEM photograph of 9 turns, copper plated solenoid inductor.

dependent on inductance.

The inductor has a rectangular cross-sectional shape. The simulated structure (Fig. 1) is the same as the fabricated one. A ground-signal-ground probe pattern is also included in the simulation. A copper plated structure is constructed on a glass wafer. The simulations are performed with a = b = 20 um, w = 80 um, h = 10 um, and n = 10, 20, 30, and 40 respectively with commercially available software, Ansoft HFSS [11]. It takes several hours and a large amount of virtual memory to simulate all frequencies, so we choose ten frequency points. This is enough to estimate the inductance and quality factor. As seen from Fig. 2 and Fig. 3, the inductance value is linearly dependent on the number of turns, but as frequency increases, the inductance is no more dependent on it proportionally. The simulation results show that the quality factor is over 10 at 2 GHz, and the inductance value is between 0.5 nH and 2.8 nH.

III. FABRICATION

Fig. 4 shows the fabrication process sequence of the solenoid-type inductor. A pyrex 7740 glass wafer is used as a substrate to reduce the substrate loss, onto which a seed layer of Cr (200 Å) / Au (2000 Å) is evaporated consecutively. AZ4620 positive photoresists are used to produce a 5 um thick base and air bridge, and a 10 um thick post (via) electroplating mold. After base mold photolithography, 5 um thick base copper is electroplated from the gold seed layer.

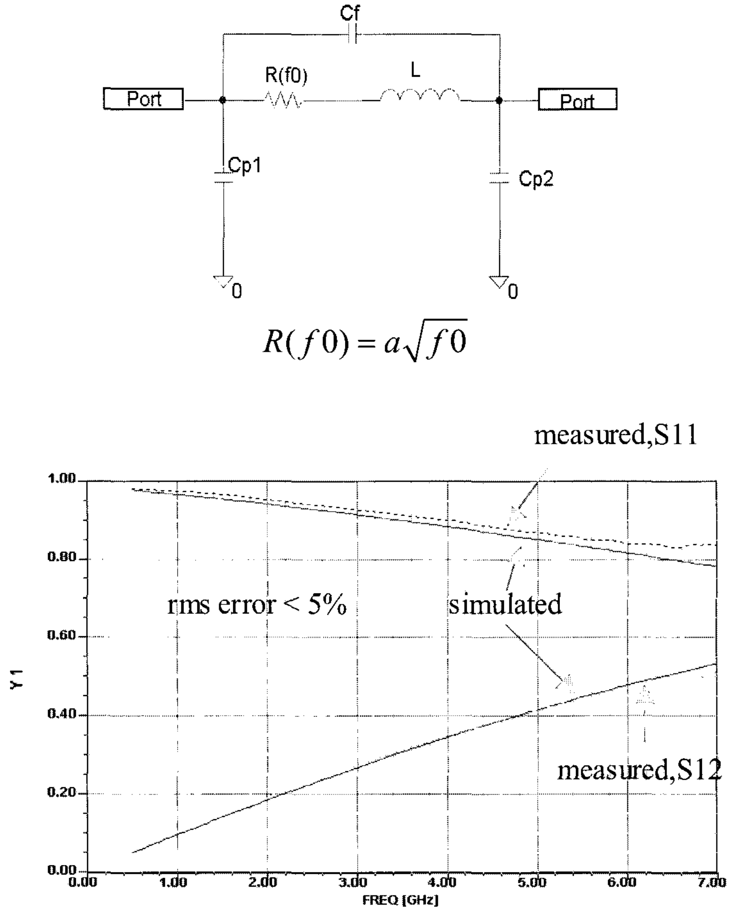


Fig. 6. The Lumped equivalent model (a) electrical model for the solenoid inductor (b) optimization results of the ansoft serenade™.

The electroplating is achieved by a commercially available plater machine, CW-3. This machine was modified from a bump plater controlled by software. Given the plating area and current density, the target plating thickness can be achieved by software timing control. After post (via) plating, two consequent photoresist layers are cured in an oven to dehydrate. Then, a gold seed layer is deposited to implement the air bridge. In the MESD method [12], the air bridge is formed by overplating without the additional photolithography. The air-bridge patterning by photolithography gives the inductor as the designed dimensions which results in a high quality factor.

Following air-bridge plating, the photoresist is stripped with acetone, and the seed layer is removed by a commercial gold etchant. The photoresist residue on the seed layer is removed using O_2 Plasma. By this same method, the base and post (via) mold are removed. Fig 5 shows the SEM picture of the fabricated solenoid inductor.

IV. MEASUREMENT

The inductors are measured using a HP8510B network analyzer and a cascode mircotech RF probe. The 2 ports S-parameter measurements are performed from 500 MHz to 10 GHz. The open pad is also measured in order to de-embed pad capacitance and resistance to extract the exact inductance value. With the lumped equivalent model shown in Fig. 6, the parameter of the model is extracted from the measured S-parameter using the Ansoft Serenade™. The extracted value whose error is

Table I. Extracted parameter of lumped equivalent model for the solenoid inductor.

Device	L(nH)	a	C_f(fF)	C_{p1}(fF)	C_{p2}(fF)
L37	1.546	3.156	4.362	0.236	0.234
L38	1.991	4.435	5.942	0.236	0.265
L39	1.315	2.483	1.156	0.236	0.234
L40	2.255	4.297	1.289	0.236	0.236
L41	1.171	1.856	4.172	2.342	2.257
L42	0.4993	1.503	4.172	0.072	0.054

L37 : a = b = 30 um, w = 80 um, n = 30
L39 : a = b = 15 um, w = 80 um, n = 20
L41 : a = b = 8 um, w = 80 um, n = 20
L38 : a = b = 20 um, w = 80 um, n = 40
L40 : a = b = 15 um, w = 80 um, n = 40
L42 : a = b = 20 um, w = 80 um, n = 20

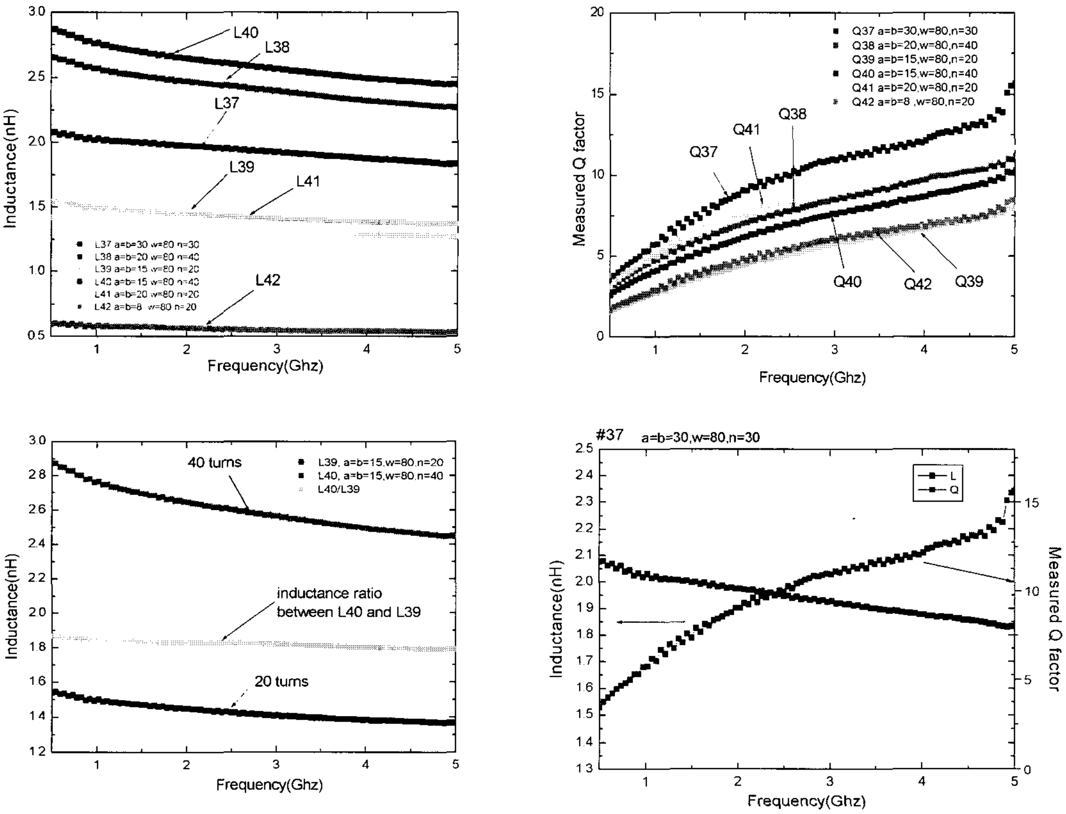
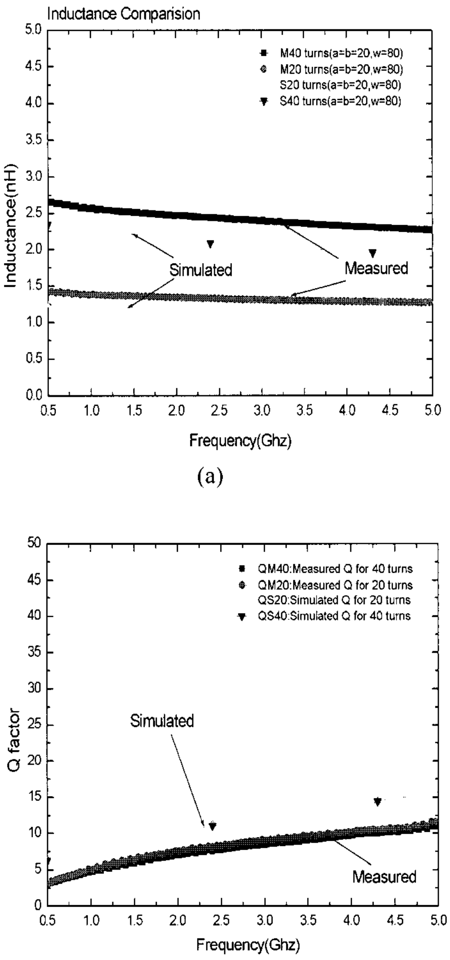


Fig. 7. The measurement results (a) Inductance for various dimension (b) measured Q factors (c) inductance ratio for two different number of turns (L39 and L40) (d) inductance and Q factor for a = b = 30um w = 80 um with 30 turns.

less than 5 % is shown in Table I. In the proposed model, C_{p1} and C_{p2} are the capacitance between the base and the substrate. C_f is the coupling capacitance between the base patterns. The series resistance R and the line inductance are extracted from the Y-parameter using equation (2) below.

$$R = real(\frac{1}{Y_{12}}), L = \frac{1}{\omega} imag(\frac{1}{Y_{12}}) \qquad (2)$$

As shown in Fig. 7(a) and Fig. 7(b), the inductance value is linearly decreased by the number of turns as in L39 and L40, and L41 and L38, and the Q factor is more than 5 at 2 GHz. Fig. 7(c) shows the detailed plot about inductance. It shows that the inductance increasing factor is 1.85 as the number of turns of the inductor is increased twice. Figure 7(d) shows that the inductor with a = b = 30 um, w = 80, and n = 30, has inductance 1.95 nH and Q factor 9.7 at 2.4 GHz. The inductor has a self-resonance frequency over 7 GHz.



(a)

(b)

Fig. 8. Comparison between measurement and simulation (a) Inductance (b) Q factor.

In Fig. 8, the measured inductance is about 20 % higher than the simulated results. This is partly due to the fabrication variation such as post (via) height or bridge width. For a lower quality factor, the CuO is blamed that increases contact resistance when the G-S-G RF probe probes on the pad.

5. CONCLUSION

Solenoid-type inductors are simulated and realized by electroplating and photolithography. The conventional analytical equation of inductance is not adequate for solenoid-type inductors mainly used in high frequency application, so we choose the commercial available FEM software, HFSS which can help get the exact analysis of a three-dimensional structure. Based on the extracted S-parameter from HFSS simulation, we simulate the RF CMOS VCO circuit.

The fabricated solenoid inductance value ranges from 0.5 nH to 2.8 nH. The occupied area is 120 um × 780 um for 1.5 nH. Through the post-CMOS process, the solenoid-type inductor will be integrated through pad opening. Now that the solenoid type inductor has a higher Q factor over the spiral inductor, the solenoid inductor integrated VCO has a very low phase noise and meets the strict requirements in communication transceiver. As copper metallization has been focused on as the next candidate in ULSI technology, the fabrication process for the copper plated solenoid inductor will be adapted as standard CMOS process of the future.

ACKNOWLEDGEMENT

The authors would like to thank all staffs of ISRC and Mtec. This work was supported by the KETI(Korea Electronics Technology Institute) G7 project under the Ministry of Commerce, Industry and Energy on grant ISRC 2000-X-6119. This work was also partly funded through BK21(Brain Korea 21) by the Ministry of Education.

REFERENCE

[1] J.Choi, H.Park, K. Kim and J. Jeon,"Electromagnetic micro x-y stage for probe-based data storage:, Journal of semiconductor technology and science, vol.1, No. 1, March 2001, pp.84 – 93.

[2] J. Park, J. Bu and J. Lee,"RF MEMS Devices for wireless application", Journal of semiconductor technology and science, vol.1, No. 1, March 2001, pp.70 – 83.

[3] K. Lee and Y. Kim,"Uniform improvement of micromirror array for reliable working performance as an optical modualtor in the maskless photolithography system", Journal of semiconductor technology and science, vol.1, No. 2, Jun 2001, pp.132 – 139.

[4] M.Yamaguchi,M Matsumoto,H. Ohzeki and K.I. Arai,

" Analysis of the inductance and the stray capacitance of the dry-etched mirco inductors", IEEE Trans. Magnetics,vol.27. No 6, Nov 1991,pp. 5274 – 5276.

[5] K.B.Ashby,I.A.Koullias,W.C.Finley,J.J.Bastek,and S.Moinian,"High Q inductor for wireless applications in a complementary silicon bipolar process,"IEEE J. Solid-State Circuits,vol 31,Jan 1996,pp. 4-9.

[6] J.Y-C.Chang,A.A.Abidi, and M.Gaian,"Large suspended indutors on silicon and their use in a 2mm CMOS RF amplifier," IEEE Electron Device Lett, vol. 14., May 1993,pp. 246-248.

[7] J.N.Burghartz, M.Soyuer,K.A.Jenkins,and M. D. Hulvey," High-Q inductors in standard silicon interconnect technology and its application to an integrated RF power amplifer."in IEDM Tech.Dig., 1995,pp. 1015-1017.

[8] J.B.Burghartz,D.C. Edelstein,K.A. Jenkins, C.Jahnes, C. Uzoh, E.J.O'Sullivan, K.K.Chan,M.Soyuer, P.Roper, and S,Cordes,"Monolithic spiral inductos fabricated using a VLSI Cu-damascene interconnect technology and low-loss substrates,"In IEDM Tech,Dig.,1996,pp. 99-102.

[9] J.Cranincks and M.Steyaert."A 1.8-Ghz CMOS Low-phase Noise Voltage-controlled Oscillator with prescaler", IEEE Journal of Solid-State Circuits, Vol.30. No.12, December 1995, pp. 1474-1482.

[10] D.J.Young,V.Malba,J-J.Ou,A.F.Berbhardt, and B. E. Boser,"Monolithic high-performance three-dimensional coil inductors for wireless communication applications," In IEDM Tech.Dig.,1997,pp. 67-70.

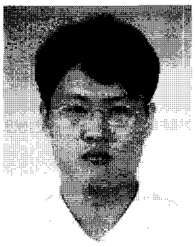
[11] Ansoft HF Maxwell HFSS/ Ensemble Basic course.

[12] J. B. Yoon, B.K.Kim,C.H.Han,Euisik Yoon,K.R.Lee and C.K.Kim."High-performance electroplated solenoid-type integrated inductor (SI^2)for RF Applications using simple 3D surface micromachining technology",In IEDM 1998,pp. 544-547.

[13] Pietro andreani and Sven mattisson,"A 2.4 GHz CMOS Monolithic VCO based on an MOS Varactor",Circuit and systems,1999.ISCAS '99. Proceedings of the 1999 IEEE international symposium ,vol 2, pp. 557-560.

[14] Jan Cranincks, Student member,IEEE and Michiel S.J. Steyart,"A 1.8Ghz Low Phase-Noise CMOS VCO Using optimized hollow spiral inductors", IEEE Journal of solid-state circuits,vol 32,No 5,May,1997, pp. 736-744.

Kukjin Chun He received the B. S. degree in electronics engineering from Seoul National University in 1977 and the M.S. and Ph.D. degrees in electrical engineering from the University of Michigan in 1981 and 1986, respectively. He was an Assistant Professor in the Department of Electrical and Computer Engineering at Washington State University from 1986 to 1989. He joined the faculty of Seoul NationalUniversity in 1989, where he is currrently an Professor in the School of Electrical Engineering and director for Microsystem Technology center since 1997. His research interests include semiconductor devices and processes, as well as semiconductor sensors and actuators.



Chul Nam He received the B.S degree from division of electrical engineering at KAIST,Deajon, in 1991. From 1991 to 1997, he worked as an engineer with ASIC design center of Samsung electronic company. From 1997 to 1998, he worked as an engineer manager with ALL MEDICUS company.Now, he is a graduate member in MINT Lab. He is also technical assistant on an ebeam lithography system in ISRC of SNU. His current research interests include an integrated RF MEMS system and micro-electroplated technology.

Seonho Seok He received the B.S in electrical engineering from the Kyung pook National University and the M.S from the Seoul National University, Korea, in 1997 and 1999, respectively. He is in the Ph.D candidate in Seoul National University, researching in the areas of the RF MEMS devices.

Wonseo Choi He received the B.S in school of electrical engineering from the Seoul National University, Korea in 2000. He is in the M.S cadidate in Seoul National University, Korea. His major interest is RF MEMS devices.