Solenoid Type 3-D Passives(Inductors and Transformers) For Advanced Mobile Telecommunication Systems

Jae Y. Park and Jong U. Bu

***Abstract*—In this paper, solenoid-type 3-D passives (inductors and transformers) have been designed, fabricated, and characterized by using electroplating techniques, wire bonding techniques, multi-layer thick photoresist, and low temperature processes which are compatible with semiconductor circuitry fabrication. Two different fabrication approaches are performed to develop the solenoid-type 3-D passives and relationship of performance characteristics and geometry is also deeply investigated such as windings, cross-sectional area of core, spacing between windings, and turn ratio. Fully integrated inductor has a quality factor of 31 at 6 GHz, an inductance of 2.7 nH, and a self resonant frequency of 15.8 GHz. Bonded wire inductor has a quality factor of 120, an inductance of 20 nH, and a self resonant frequency of 8 GHz. Integrated transformers with turn ratios of 1:1 and n:1 have the minimum insertion loss of about 0.6 dB and the wide bandwidth of a few GHz.**

***Index Terms*—3-D passives, inductors, transformers, mobile telecommunications, coupling, multi-layer thick photoresist processes, electroplating, wire bonding, low temperature processes**

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I. INTRODUCTION

On chip inductors and transformers with good performance characteristics are demanded for realizing single chip VCOs, LNAs, filters, and single chip RF transceivers/modules. In particular, on chip transformers are utilized for achieving maximum power transfer and DC isolation between the integrated electronic circuits. Thus, much research efforts have been performed to fabricate the on chip inductors and transformers with high quality factor, wide frequency bandwidth, and high magnetic coupling coefficient.

A large suspended integrated spiral type inductor on silicon for RF amplifier applications was fabricated in [1]; the deleterious effects of the silicon substrate were reduced by selectively etching out the silicon under the fabricated inductor. Electroplated solenoid-type integrated inductors have also been fabricated by using surface micromachining technique and multi-layer of polymeric materials that are suspended approximately 20 μm above the substrate; such devices have reported Q-factors ranging from 30~50 [2]. Large suspended spiral-type inductors with high Q ranging from 40 to 60 were also fabricated by using the surface micromachining techniques [3]. Monolithically integrated spiral transformers have been implemented, but it has high ohmic loss due to thin metallization and high parasitic effects due to the large substrate-contact area [4-5]. Although the performance characteristics of these integrated 3-D inductors and transformers have been improved, they still require the complex fabrication processes resulting in the high production cost and the low yield efficiency.

In this paper, two different fabrication approaches are performed to develop on chip RF inductors and transformers with low-cost, better reliability, high Q factor, and high magnetic coupling coefficient. First, integrated solenoid type 3-D inductors and transformers are proposed by using electroplating techniques and multi-layer of thick photoresist processes which can easily be removed after fabrication. Second, large suspended bonded wire solenoid type 3-D inductors are proposed by using electroplating techniques and wire bonding techniques to avoid the complex fabrication processes, to increase the cross-sectional core area, and to reduce high ohmic contact resistance.

II. DESIGN AND FABRICATION

The Integrated 3-D RF inductors and transformers were fabricated as shown in Fig. 1. A seed metal layer was deposited on top of the substrate and then thick photoresist was spun on. Thick photoresist molds were formed for constructing bottom conductor lines. Electroplated copper was filled into the molds and another thick photoresist was coated and soft baked on top of the electroplated bottom conductor lines. Via molds were formed by using UV photolithography and filled with electroplated copper. Top seed metal layer

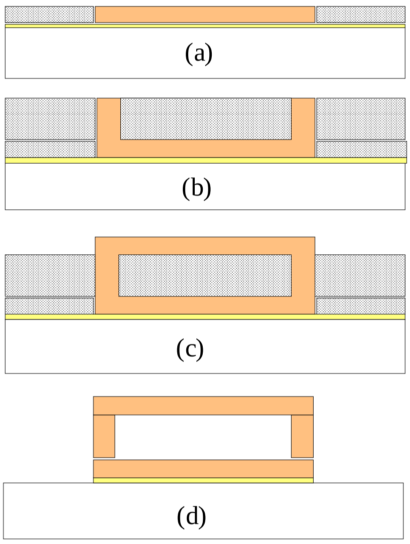


Fig. 1. Fabrication sequence of the integrated solenoid type 3-D inductors and transformers.

was deposited and another thick photoresist was spun on. Thick photoresist molds were formed for top conductor lines and filled with electroplated copper metals. The top

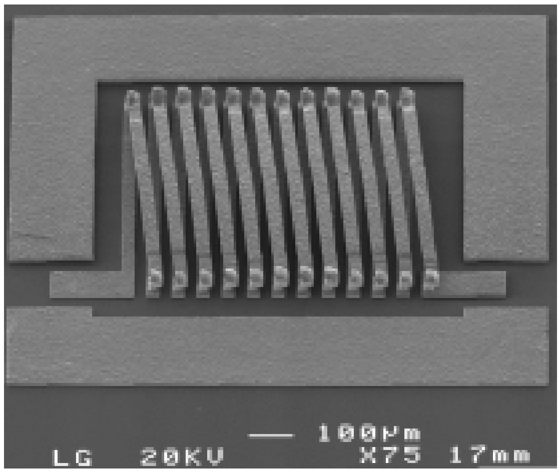
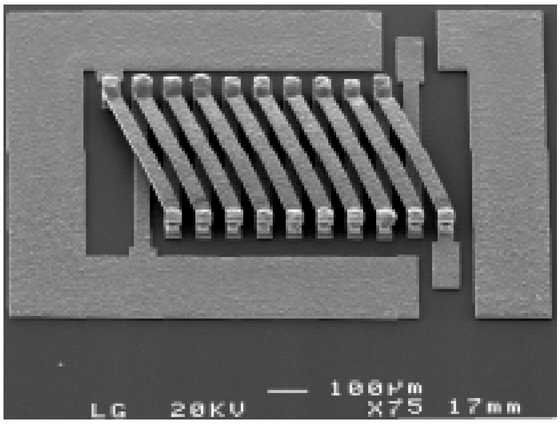
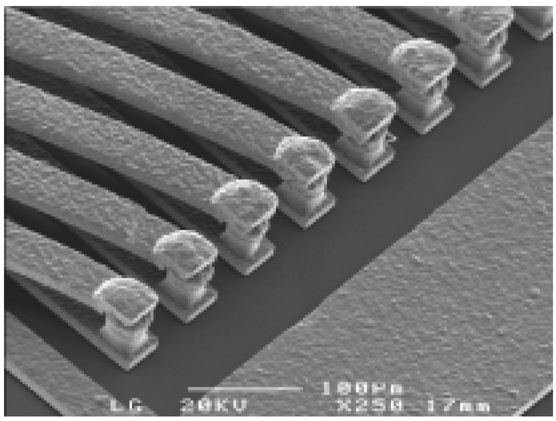


Fig. 2. SEM picture of the integrated solenoid type inductor.



(a)



(b)

Fig. 3. SEM pictures of the integrated RF solenoid type transformer with a turn ratio of 1:1((b) is a close up view of (a)).

and bottom seed metal layers were finally wet-etched after removing the multi-layer of thick photoresist layers by using acetone. Fig. 2 shows a SEM picture of the integrated RF solenoid type inductor with an air core. Figs. 3 and 4 show SEM pictures of the integrated RF solenoid type transformers with various turn ratio of 1:1 and n:1, respectively.

Large suspended bond-wire inductors have been fabricated on a Quartz substrate as follows. Thick metallic bonding pads of 100 μm x 100 μm were formed on a substrate by using an electroplating technique. The formed bonding pads were comprised of thick copper (10um in thickness), nickel (1um in thickness), and gold (0.5um in thickness) metals to reduce metallic losses to increase a quality factor. Suspended lower and bottom conductor lines were formed on top of the fabricated bonding pads by using 1 mil bond-wire and the wedge

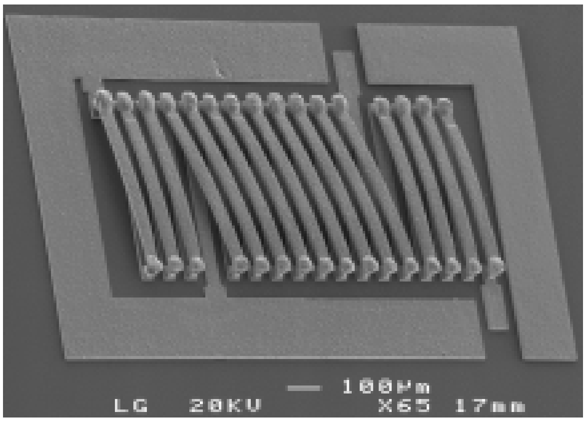


Fig. 4. SEM picture of the integrated RF solenoid type transformer with a turn ratio of n:1.

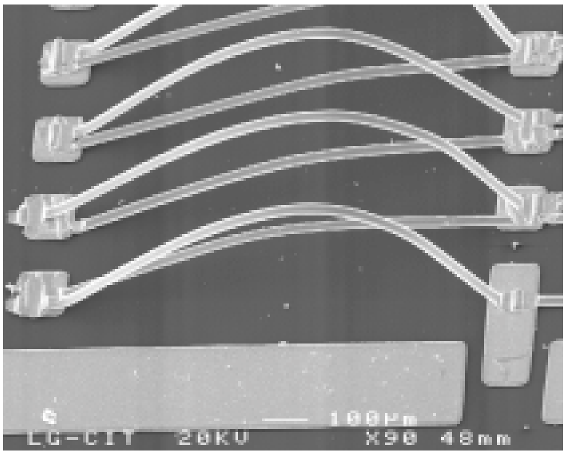


Fig. 5. SEM picture of the fabricated large suspended bond-wire solenoid type inductor.

bonding technique. The average loop heights of the upper and lower bond-wire conductor lines are 350μm and 50μm, respectively. Fig. 5 shows a scanning electron micrograph of the large suspended bond-wire solenoid type inductor.

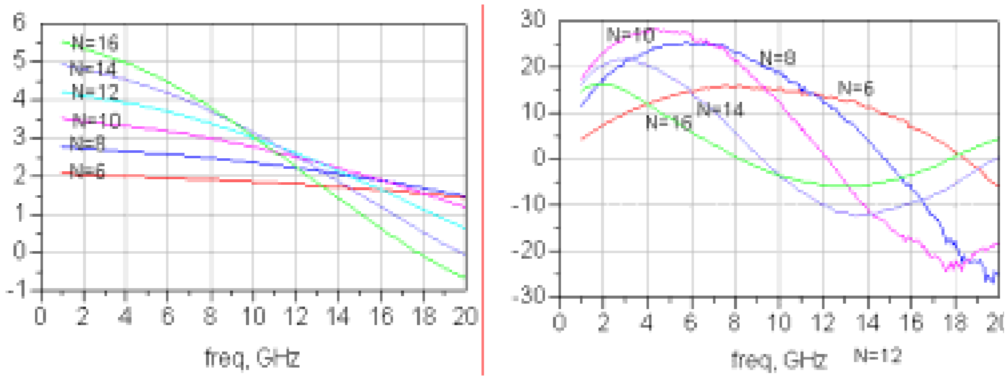
III. EXPERIMENTAL RESULTS AND DISCUSSIONS

The experimental setup was an HP 8510C Network Analyzer, and CASCADE MICROTECH ground-signal-ground high frequency coplanar probes with a pitch size of 150 μm. After calibration on open, short, and 50 ohm resistor standards, the measurement was performed. In this measurement, the parasitics of the probing pads were not de-embedded. The measured two-port S-parameters were transformed into one-port S-parameters by terminating one of the ports with ground at a HP ADS Microwave and RF Design System. A reflection coefficient, S11 of the transformed one-port S parameters was translated into an input impedance, Zin for evaluating inductance and quality factor of the fabricated inductors using the ADS tool. The unloaded Q-factor was determined by dividing the imaginary part of the input impedance, Zin by the real part (dissipated energy).

1. *Integrated Solenoid type 3-D inductors and transformers*

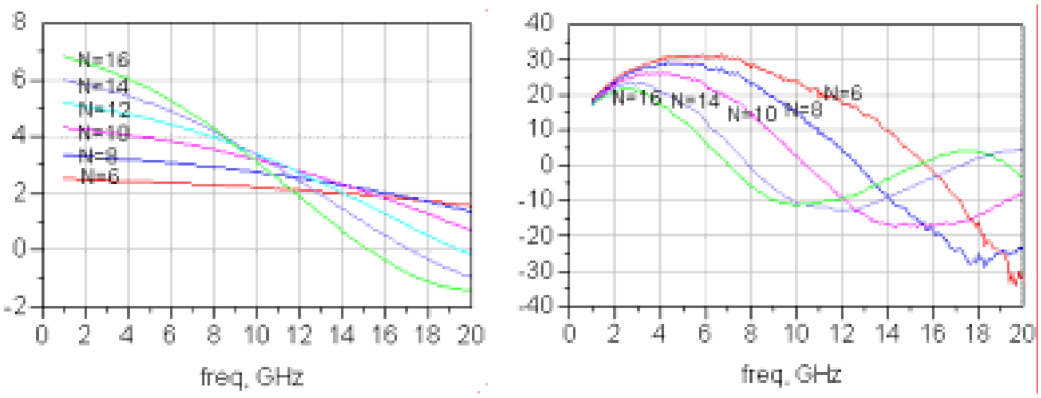
Figs. 6 and 7 show inductance and quality factor of the integrated solenoid type inductors with cross-sectional core area of 0.5 mm and 0.6 mm in width and 0.04 mm in height, respectively. As shown in Figs. 6 and 7, as a number of windings are increased, the total inductance is increased, the self-resonant frequency is decreased, and the quality factor is decreased. As shown in Fig. 8, the quality factor is increased and the inductance is decreased as the cross-sectional area is decreased.

Fig. 9 shows comparison of measured S21 parameters of the integrated solenoid type transformers with turn ratio of 1:1 between primary and secondary windings. The most important figure of merit in the RF transformers is to achieve the minimum insertion loss that is represented by the S21 parameter in the scattering



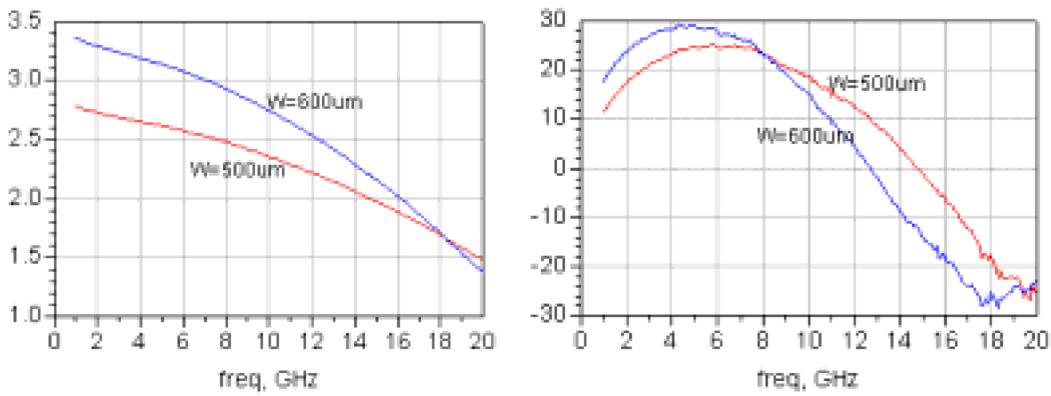
(a) (b)

Fig. 6. Comparison of (a) measured inductance (nH) and (b) quality factor of the integrated solenoid type inductors (electroplated copper conductor: 40 um x 20 um and cross-sectional core area : width 0.5mm x height 40 um).



(a) (b)

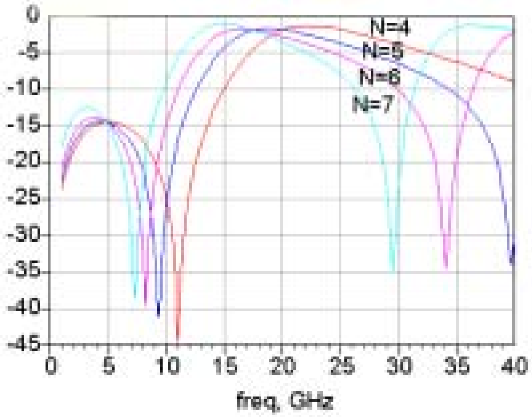
Fig. 7. Comparison of (a) measured inductance (nH) and (b) quality factor of the integrated solenoid type inductors (electroplated copper conductor: 40 um x 20 um and cross-sectional air core area : width of 0.6mm x heignt of 40 um).



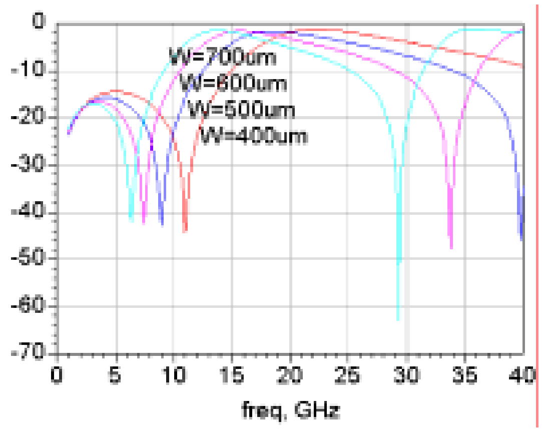
(a) (b)

Fig. 8. Comparison of (a) measured inductance (nH) and (b) quality factor of the integrated solenoid type inductors with 6 windings (electroplated copper conductor: 40 um x 20 um and cross-sectional air core area : width x heignt of 40 um).

matrix. The lower insertion loss means the higher magnetic coupling coefficient between the primary and secondary windings in the transformers. As shown in Fig. 9, the integrated transformers have good performance characteristics and wide band width which can be utilized in various applications. The larger cross-sectional area of core and the smaller windings produce the better performance characteristics in the higher frequency regime. The sharp null is caused by the parasitic capacitance between the windings. Fig. 10



(a)



(b)

Fig. 9. Comparison of measured S21 parameters (insrtion loss) of the integrated 1:1 solenoid type transformers with various of number of windings (N) ((a) cross-sectional air core area : width of 0.4mm x height of 40 um and (b) a number of windings: 4).

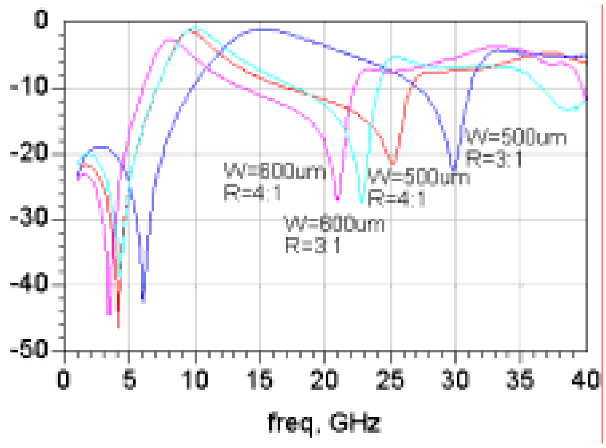


Fig. 10. Measured S21 parameters of the integrated n:1 solenoid type transformers with various turn ratios (R) (copper conductor: 40 um x 20 um and cross-sectional air core area : width x height of 40 um).

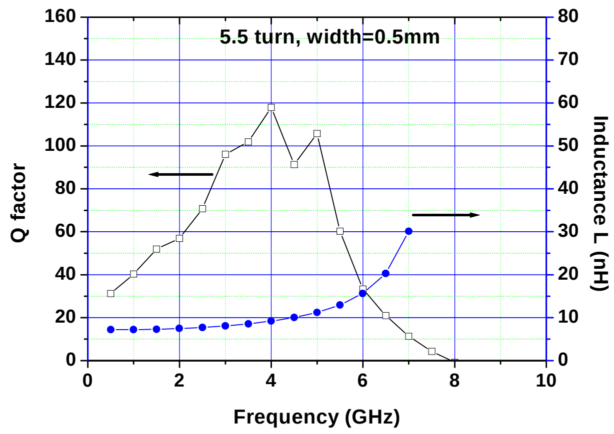


Fig. 11. Inductancce and quality factor of the fabricated large suspended bond-wire solenoid type inductor (1mil bondwire, cross-sectional core area with width of 0.5mm and height of 0.3mm).

shows the measured S21 parameters of the fabricated micro-transformers with various turn ratios. As shown in Fig. 10, the transformer with 500 um in width has better performance characteristics in the high frequency regime than the transformer with 600 um in width, since it has the lower resistive loss and smaller parasitic capacitance. The turn ratio is decreased and the insertion loss is also decreased.

2. *Large Suspended Bonded Wire Solenoid type 3-D inductors*

Fig. 11 shows the measured inductance and quality factor of the fabricated large suspended bond-wire solenoid type inductor with 5.5 turns and a core cross-sectional area of 0.5 mm in width and 0.3 mm in height. As shown in Figure 11, the inductor has a quality factor of 120 at 4 GHz, an inductance of 20 nH, and a self resonant frequency of 8 GHz. Figure 12 shows performance characteristics of the fabricated inductor is dependent on a number of windings. As a number of windings are increased, the total inductance is increased, the self-resonant frequency is decreased, and the quality factor is decreased, since the increased resistance and parasitic capacitance reduce the Q-factor and the self resonant frequency. Figure 13 shows the performance dependency of the fabricated inductor on a size of cross-sectional core area. As shown in Figure 13, the quality factor is increased and the inductance is decreased, as the cross-sectional area of the core is decreased.

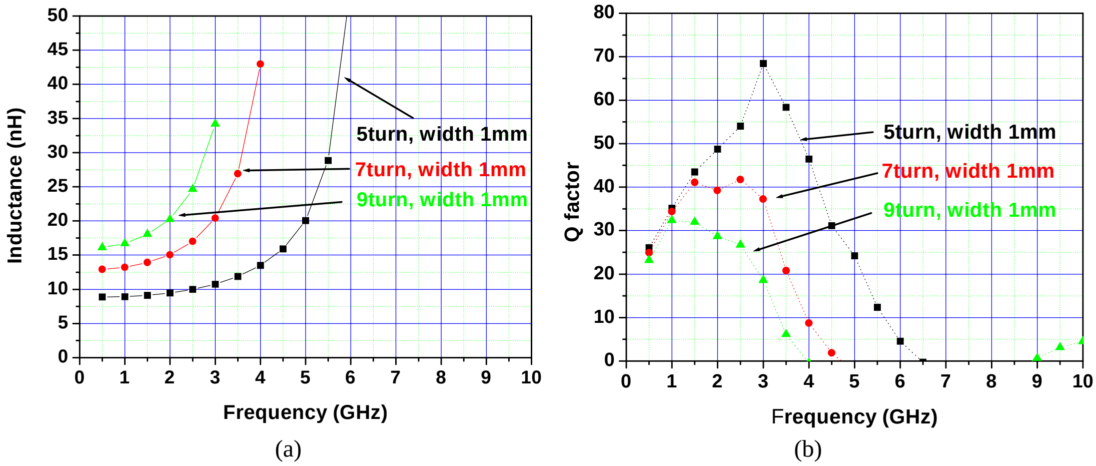


Fig. 12. Comparison of (a) measured inductance and (b) quality factor of the fabricated large suspended bond-wire solenoid type inductors (1mil bond-wire, cross-sectional core area with width of 1mm and height of 0.3mm).

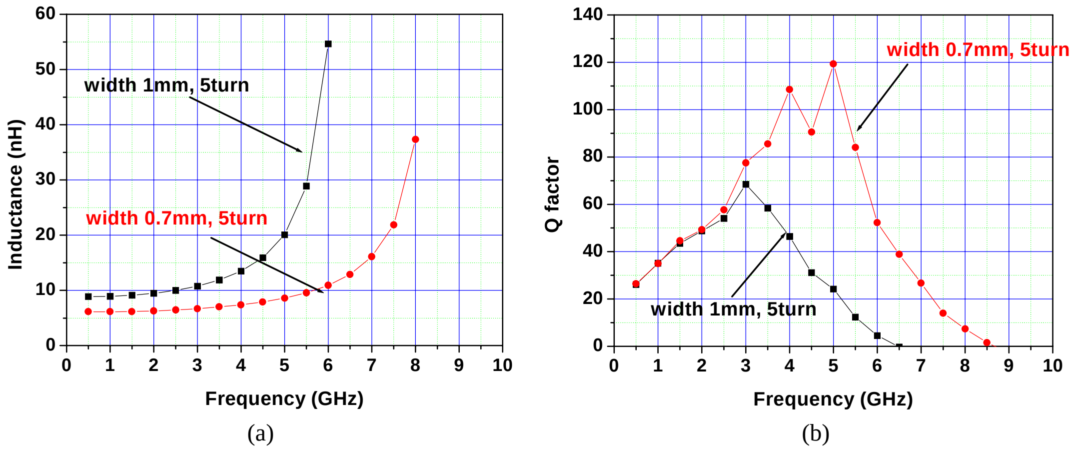


Fig. 13. Comparison of (a) measured inductance and (b) quality factor of the fabricated large suspended bond-wire solenoid type inductors (1mil bond-wire, 5 turns).

IV. Conclusion

Integrated 3-D solenoid type inductors/transformers with air core and large suspended bonded wire 3-D solenoid type inductors for RF/wireless applications have been designed, fabricated, and characterized. Multi-layer of thick photoresist process was developed for fabricating the integrated 3-D inductors/transformers that allow to be easily integrated with CMOS, RFIC, and MMIC circuitry. The integrated solenoid type inductor has a quality factors of 31, an inductance of 2.7 nH, and a self resonant frequency of 15.8 GHz. The integrated solenoid type transformers have low insertion loss, high magnetic coupling coefficient, wide bandwidth, and good performance characteristics at high frequency regime, respectively.

50 ~ 70 μm air gaps were introduced between lower conductor lines and the substrate to achieve higher Q-value and self resonant frequency by reducing substrate loss and the parasitic capacitance from the substrate which is dominant in the total parasitic capacitance. The fabricated large suspended bond-wire on-chip inductor has a quality factor of 120, an inductance of 20 nH, and a self resonant frequency of 8 GHz. The fabricated 3-D passives (inductors and transformers) are promising components for developing the low cost, miniaturized on-chip wireless modules/systems due to their excellent performance characteristics and processing integration with RF active circuitry.

V. ACKNOWLEDGEMENT

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