Monolithically Integrable RF MEMS Passives

Eun-Chul Park, Yun-Seok Choi, Jun-Bo Yoon, and Euisik Yoon

Abstract— **This paper presents high performance MEMS passives using fully CMOS compatible, monolithically integrable 3-D RF MEMS processes for RF and microwave applications. The 3-D RF MEMS technology has been developed and investigated as a viable technological option, which can break the limit of the conventional IC technology. We have demonstrated the versatility of the technology by fabricating various 3-D thick-metal microstructures for RF and microwave applications, such as spiral/solenoid inductors, transformers, and transmission lines, with a vertical dimension of up to 100 μm. To the best of our knowledge, we report that we are the first to construct a fully integrated VCO with MEMS inductors, which has achieved a low phase noise of –124 dBc/Hz at 300 kHz offset from a center frequency of 1 GHz.**

Index Terms — **RF MEMS, surface micromachining, inductor, transformer, transmission line, VCO.**

I. INTRODUCTION

Modern RF communication systems require stringent specifications for RF components. Despite much work, which has been done on the integration of RF systems into a single chip, many components remain off-chip. This is because the RF passives with the required performance are not available in the standard silicon process. Many recent studies have shown that two aspects are extremely important in order to obtain high-performance integrated passive components when the signal frequency is in the GHz range. One is the metal thickness and the other is how far the device is isolated from the lossy substrate. For these two reasons, research has been performed to investigate other technological options among available fabrication processes.

With this in mind, various micromachining technologies, which have been developed for implementing microelectromechanical systems (MEMS), have been investigated and applied to RF and microwave applications [1-3]. In this paper, we provide a surface micromachining technique aimed at the monolithic integration of free 3-D microstructures, which are beneficial to RF and microwave applications. We also present the performances of inductors, transformers, and transmission lines, which have been fabricated using the 3-D MEMS process. Finally, we demonstrate fully integrated voltage controlled oscillators (VCOs) which have been fabricated using a conventional 0.18 μm CMOS process for the actives and integrating high-Q inductors on top of the circuit as a post IC process utilizing the 3-D MEMS process developed in this work.

II. FABRICATION TECHNIQUE

A. *Fabrication Process*

The fabrication process is very simple: first, make a 3-D photoresist mold having arbitrarily-shaped upper recess regions; second, fill both the lower and upper recess regions with metal; and finally remove the photoresist molds.

The process flow is shown in Fig. 1, starting with a

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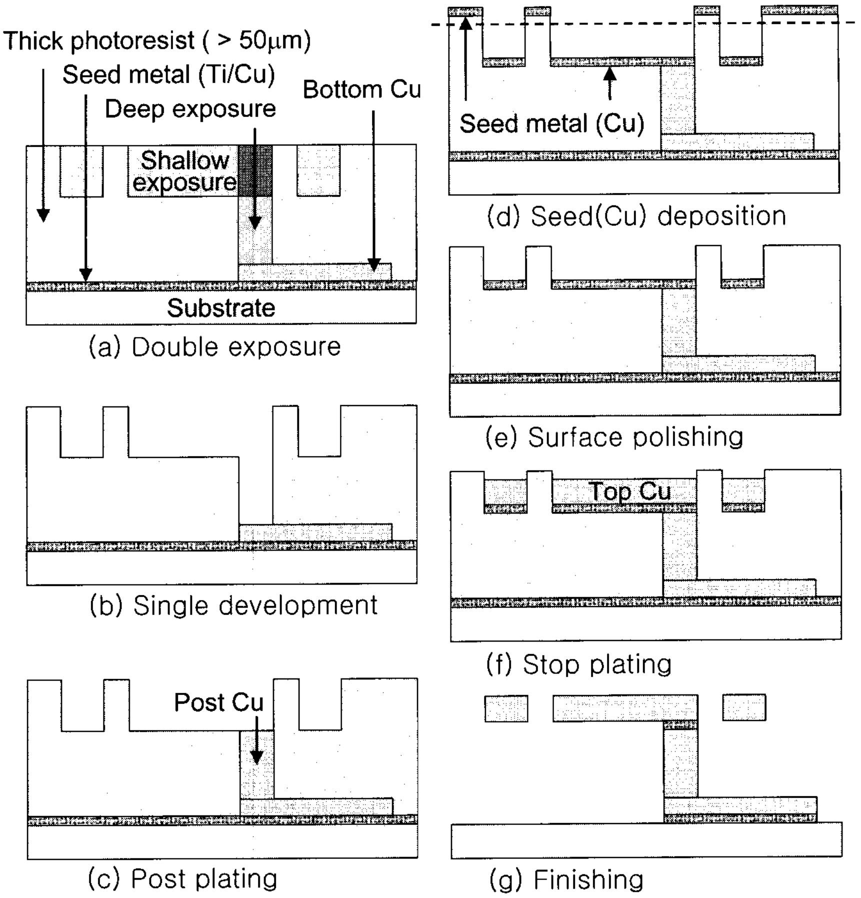
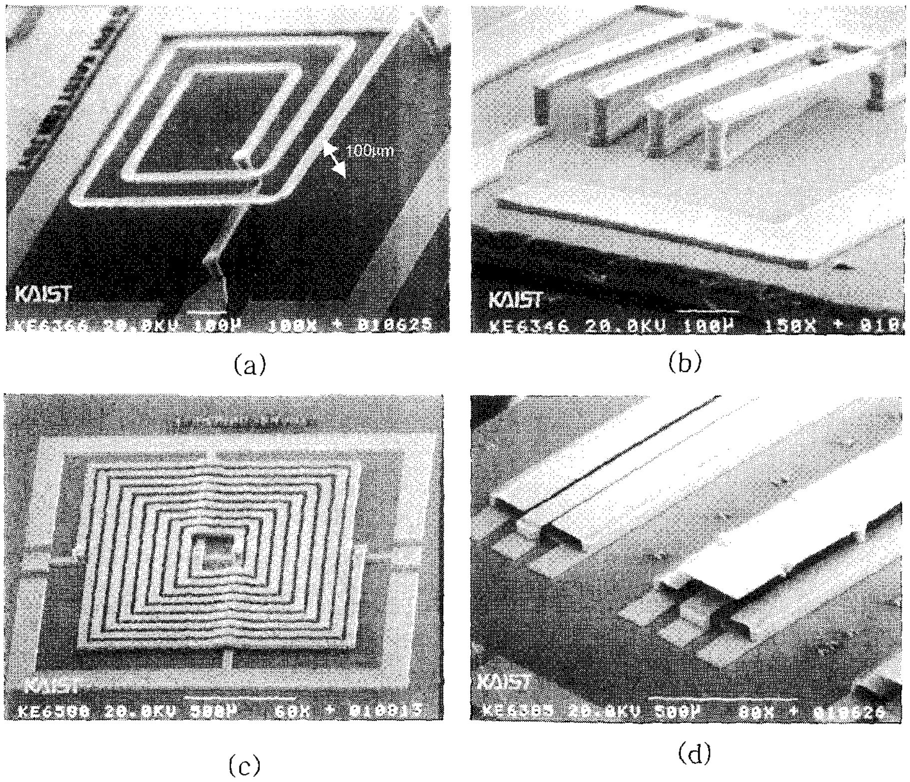


Fig. 1. Proposed fabrication process flow

substrate on which the bottom seed metal (Ti/Cu) is deposited. The bottom Cu electrode is then formed using conventional lithography with a thick photoresist followed by electroplating. After removing the photoresist, another thick photoresist (usually over 50 μm in thickness) is spun onto the wafer, as shown in Fig. 1.(a). A two-step UV exposure follows with two different photomasks and exposure times. A single step development reveals the 3-D photoresist mold as shown in Fig. 1.(b). The typical MESD process conditions can be found in [4]. Once the 3-D photoresist mold is fabricated, the lower recess region is filled with the electroplated metal to form the posts in Fig. 1.(c). The Cu electroplating solution used in this work is defined in [4]. Since the post's electroplating is done filling upward from the bottom of the lower recess region, we can obtain fully-filled, robust posts. After the post electroplating, the surface is covered with another seed metal (Cu) as shown in Fig. 1.(d). To make sure that the next electroplating occurs only in the upper recess regions, as shown in Fig. 1.(f), the topmost seed metal is removed as shown in Fig. 1.(e). The dashed line shown in Fig. 1.(d) indicates the boundary to which the mechanical polishing is done. Next, another electroplating is performed to fill the upper recess regions with metal as shown in Fig. 1.(f). Since all the second seed metal in the upper recess regions are electrically connected to the bottom seed metal through the metal posts, all the upper recess regions are simultaneously filled during the electroplating process. This makes it possible to obtain longer and arbitrarily shaped, suspended structures. Finally, the sacrificial 3-D photoresist mold is removed with acetone and the bottom seed metal is etched for electrical isolation between devices. The final suspended microstructure is shown in Fig. 1.(g).



(a) (b)

(c) (d)

Fig. 2. SEM view of fabricated 3-D passives

B. Fabricated RF MEMS Passives

Fig. 2 shows the SEM photographs of the spiral inductor, solenoid inductor, 1:1 transformer and transmission line fabricated using the proposed technology. From the structures in Fig. 2, one can see that they have been easily shaped in many variations and are suspended flat, due to the excellent planarization capability of the sacrificial photoresist mold. The flat suspended lines also indicate no internal stress gradient residing in the electroplated metal structures. In Fig. 2, we have demonstrated a spiral inductor suspended 100 μm over the substrate, a solenoid inductor, a transformer, and a coplanar waveguide suspended 50 μm over the substrate. All these multi-level microstructures have been made using the fundamental process shown in Fig. 1 and described above. This demonstrates that our technology is versatile enough to construct multi-level, fairly- complicated microstructures.

III. HIGH-Q MEMS INDUCTORS

As the operating frequency of recent silicon RF IC's move into the multi-GHz frequency range, it becomes difficult to achieve affordable Q-factors (>15) from on-chip inductors fabricated using conventional thin-film, planar IC processes. Recently, we have reported a new MEMS fabrication process developed for RF and microwave applications [5]. This process allows us to fabricate arbitrary shaped, highly suspended metal microstructures, which are fully CMOS-compatible, can be manufactured in a stable process and exhibit structural robustness. In this chapter, we report on the RF performance of the suspended spiral inductors fabricated using our new fabrication technology based on the standard silicon substrate (1~30Ω·cm).

Fig. 3 shows the SEM microphotograph of the fabricated inductor, which clearly reveals the flat and smooth surface of the suspended inductor together with robust post structures [6]. We measured the on-wafer RF from 0.2 GHz to 20 GHz using an HP 8510C network analyzer. Fig. 4 shows the characteristics of the fabricated inductors along with the definition of inductance (L) and Q-factor (Q) used in this work. We have achieved a peak Q-factor of 70 at 6 GHz, an inductance of 1.38 nH (at 1 GHz) and a self-resonant frequency over 20GHz using the standard silicon substrate. As we increase inductance, the Q-factor decreases for a given frequency. This is because capacitive coupling increases between the substrate and the longer suspended metal lines, ultimately degrading both the peak Q value and peak-Q frequency. All the inductors exhibited a fairly flat inductance and high Q-factor (>20) up to 5GHz, which is a desirable characteristic required in today's multi-GHz silicon RF IC's.

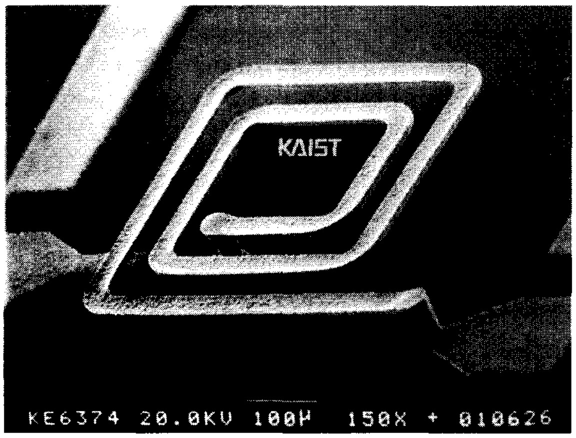


Fig. 3. SEM view of fabricated 3-D inductor

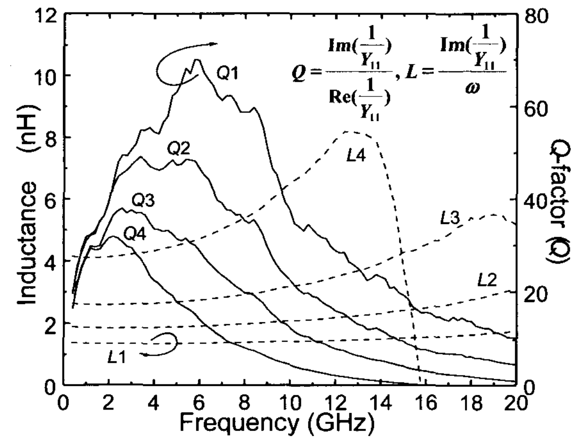


Fig. 4. Measured inductance and Q-factor of the fabricated inductors

IV. HIGH-PERFORMANCE MEMS TRANSFORMERS

Recently, transformers have been required in many RF IC applications for impedance matching/transforming, signal coupling, phase splitting (balun), etc [7,8]. However, on-chip transformers acquired from the conventional silicon IC technologies do not meet the required performance of circuit designers. In order to address this issue, non-standard substrates such as high-resistivity silicon or insulating substrates [8], or sometimes substrates with insulation layers [7] have been used to reduce the substrate loss. In addition, special processes using thick Al or Cu metallization have been used to reduce ohmic loss.

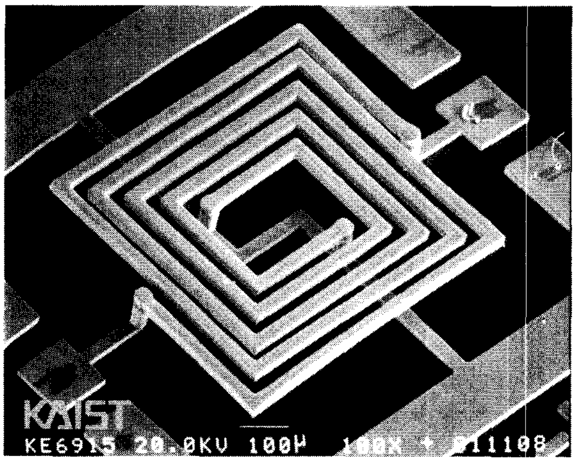


Fig. 5. Fabricated 1:1 MEMS transformer

We have achieved significant improvement in transformer performance by employing the metal surface micromachining process previously reported by our group [9,10]. This process provides an air-gap in the micromachined transformers to significantly reduce the substrate coupling loss and utilizes thick metal layers (>10 μm) to reduce ohmic loss. We have also achieved a high magnetic coupling factor (<0.81) in the fabricated spiral-type transformers as shown in Fig. 5. Fig. 6 shows the measured and modeled characteristics of the spiral type transformer in the frequency range from 0.05 to 10GHz, presenting the minimal insertion loss (S21) of 1.9dB at 1GHz. The S21 in Fig. 6 has a sharp null around 7GHz. This results from coupling capacitance between the primary and secondary coils [7],[11].

V. FULLY-INTEGRATED VCO USING MEMS INDUCTORS

Generally, planar transmission line structures are used in monolithic microwave integrated circuits for flexibility and simplicity. It is important to develop low loss transmission lines to be used as resonators or filters when operating at microwave frequencies. In conventional silicon IC technologies, planar transmission lines suffer from metal and substrate loss [12]. To reduce metal resistance wide metal lines have to be used, however, this causes large substrate coupling losses. Therefore, thicker metal with less substrate coupling is key in obtaining lower loss transmission lines.

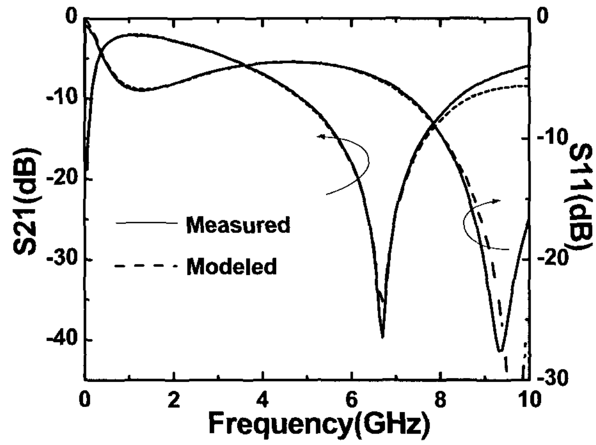


Fig. 6. Measured and modeled S-parameters of fabricated MEMS transformer

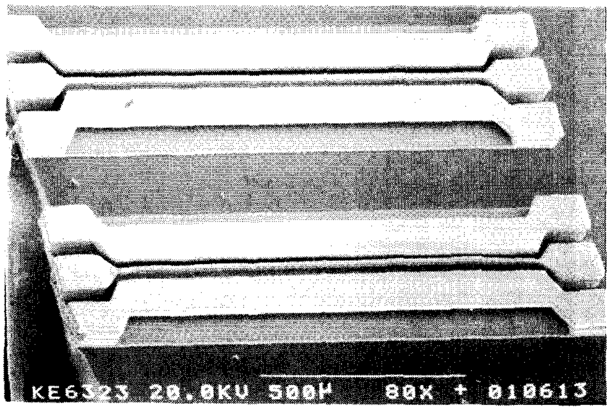


Fig. 7. Fabricated coplanar waveguide type MEMS transmission line

We have designed and developed MEMS transmission lines using numerical analysis and a 3-D MEMS process. The fabricated coplanar waveguide, which we developed, is shown in Fig. 7. The signal line thickness is 15 μm, it has a width of 25 μm, a gap to the ground line of 10 μm, and a gap to the substrate of 40 μm. Fig. 8 shows the measured characteristics of the spiral type transformer in the frequency range from 0.5 to 18 GHz. Measured insertion loss (S21) is less than 0.1 dB/mm and the phase discrepancy between the measured and simulated result is less than 1° at 18 GHz.

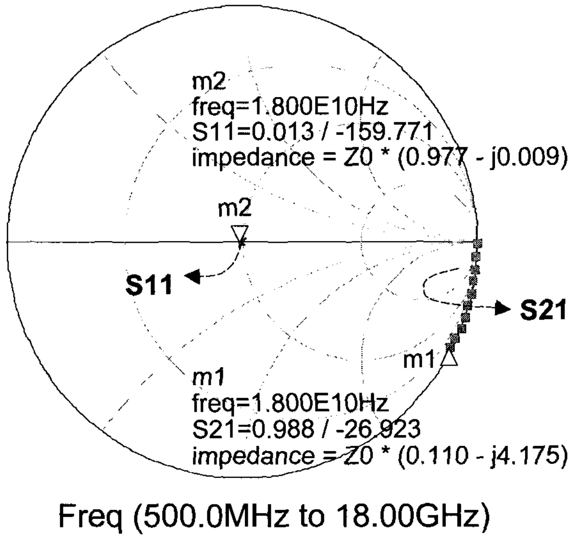


Fig. 8. Measured Smith chart plot of the MEMS transmission line

VI. FULLY-INTEGRATED VCO USING MEMS INDUCTORS

Voltage controlled oscillator (VCO) is one component which remains external to chips due to its stringent phase noise requirements. Phase noise is a measure of the signal purity of an oscillator and it decreases inversely proportional to square of the quality factor of the resonator. It is difficult to achieve a high quality factor in resonators, because, inductors with high quality factors are not available in the standard silicon process. 3-D MEMS inductors could overcome the high phase noise level in the standard process and give an integrated solution.

A fully integrated VCO, operating at 1 GHz and 2.6 GHz, has now been realized in a 0.18 μm TSMC and post-CMOS MEMS process. The active chip has been integrated with a MEMS inductor using the 3-D MEMS process. The integrated VCOs are shown in Fig. 9. The phase noise of the VCO has been measured, as shown in Fig. 10, using an HP8564E spectrum analyzer. The VCOs consume 15 mW from a 3 V power supply in the VCO core. The VCO tuning was measured by varying

Table 1. Measurement results of MEMS VCOs

Type	Free running frequency	Output power (dBm)	Phase noise (dBc/Hz) @300kHz	Harmonics (dB)	Power consumution (mW)	Tuning range
1 GHz VCO	1.08GHz	-4.83	-124	<-18	15	1.08-1.83 GHz
2.6 GHz VCO	2.62GHz	0	-117	<-17	15	2.62~4.22 GHz

the control voltage of varactor from 0 to 3 V. Measured results are summarized in Table 1.

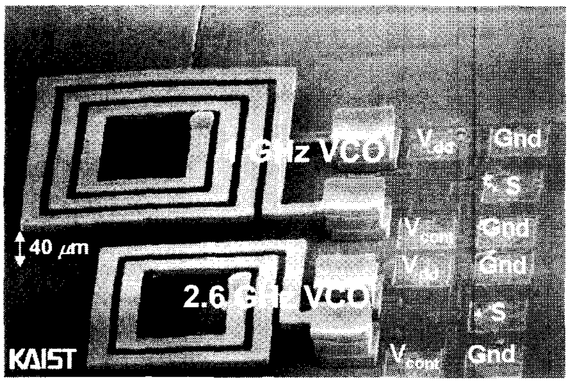


Fig. 9. *SEM photo of fully integrated MEMS VCOs*

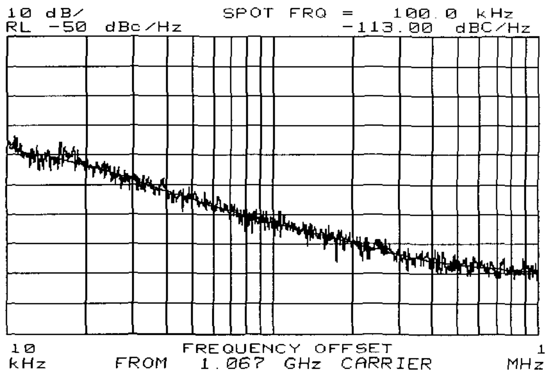


Fig. 10. Measured phase noise plot of 1 GHz MEMS VCO.

VII. CONCLUSIONS

A CMOS-compatible 3-D micromachining process has been developed, which represents a technological breakthrough in integrated high-performance passive components for RF and microwave applications. The proposed MEMS process is believed to extend the boundaries of current planar IC technology and enhance the performance of integrated RF IC inductors, transformers and transmission lines. The fabricated inductors on standard silicon substrates show high Q-factors of up to 70 when operating in the multi-GHz frequency range. The fabricated transformers on the standard silicon substrate show the minimal insertion loss of 1.9 dB at 1 GHz. The insertion loss of fabricated transmission lines was less than 0.1 dB/mm at 18 GHz. We have demonstrated that the proposed MEMS process can give a fully integration solution by developing MEMS integrated VCOs.

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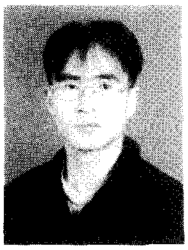

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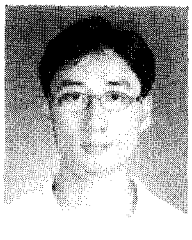

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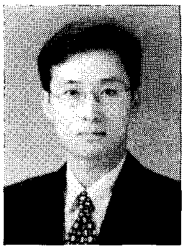

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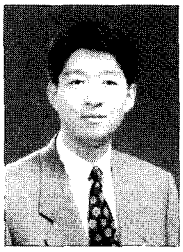

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