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AlN Based RF MEMS Tunable Capacitor with Air-Suspended Electrode with Two Stages

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Abstract—**In this paper, a MEMS tunable capacitor was successfully designed and fabricated using an aluminum nitride film and a gold suspended membrane with two air gap structure for commercial RF applications. Unlike conventional two-parallel-plate tunable capacitors, the proposed tunable capacitor consists of one air suspended top electrode and two fixed bottom electrodes. One fixed and the top movable electrodes form a variable capacitor, while the other one provides necessary electrostatic actuation. The fabricated tunable capacitor exhibited a capacitance tuning range of 375% at 2 GHz, exceeding the theoretical limit of conventional two-parallel-plate tunable capacitors. In case of the contact state, the maximal quality factor was approximately 25 at 1.5 GHz. The developed fabrication process is also compatible with the existing standard IC (integrated circuit) technology, which makes it suitable for on chip intelligent transceivers and radios.**

Index Terms—**Tunable capacitor, RF MEMS, aluminum nitride, air-gap, wide tuning range, capacitance**

I. INTRODUCTION

A Micro electro mechanical systems (MEMS) technology enabling the batch fabrication of miniaturized mechanical structures, devices, and systems has been originated from the Integrated circuit (IC) technology [1]. The MEMS technology has become more important for the development of radio frequency (RF) and microwave communication systems since it can be used to implement the free-standing or movable three-dimensional (3-D) microstructures and hence achieve higher quality-factor (Q-factor) than many conventional IC devices. RF MEMS components that are currently under development in laboratories and industries around the world include switches, tunable capacitors, MEMS inductor with high Q factor [2], film bulk acoustic resonators (FBARs), and MEMS resonators and filters [3-5].

For instance, various MEMS based tunable capacitors have been applied in the RF front-end building blocks of the modern RF/microwave communication systems, such as voltage controlled oscillators (VCOs) [6-8], tunable filters [9-13], and impedance matching networks [14]. These MEMS tunable capacitors should have wide-tuning range [15], high Q-factor [16] and low driving voltage [17] for being successfully commercialized. Among all the micromachined tunable capacitors developed to date, the parallel-plate configuration using electrostatic actuation is most commonly used. The parallel-plate capacitor can be fabricated using surface micromachining processes established well. However, the tuning range of such capacitors is limited to 50% by the pull-in effect. The pull-in instability, due to which only 33% of the gap between plates could be covered smoothly, greatly reduces the useful dynamic range of MEMS tunable capacitors.

In this paper, a RF MEMS tunable capacitor is newly designed and fabricated by using aluminum nitride

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dielectric film and a movable electrode with two different air gap structures. This design keeps the simplicity of conventional two-parallel-plate configuration, while overcoming its low tuning range. In addition, an aluminum nitride film is used as a high dielectric layer in order to increase a tuning range, decrease an operating voltage, and be integrated with FBAR (Film Bulk Acoustic Resonator) device for on chip tunable filters and intelligent radios.

II. DESIGN

Fig. 1 shows a 3-dimensional geometrical structure of the proposed MEMS tunable capacitor. The proposed tunable capacitor has the structure of 2-port network using a shunt capacitor with air-suspended metal and fixed signal electrodes. As shown in Fig. 2, the conventional parallel-plate variable capacitor with single gap-spacing, that is g_1 or g_2, and its maximum tuning range is theoretically limited to 50%. To substantially enhance the maximum tuning range of the tunable

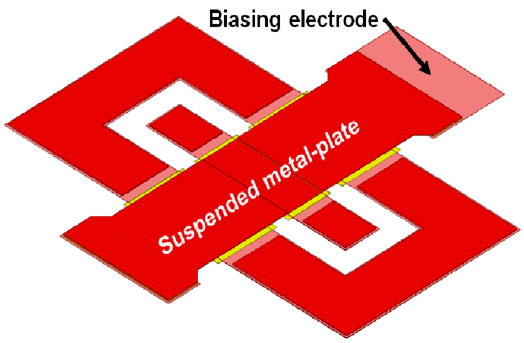


Fig. 1. 3-D geometrical structure of the proposed tunable RF MEMS capacitor with an air-suspended movable electrode with two stages.

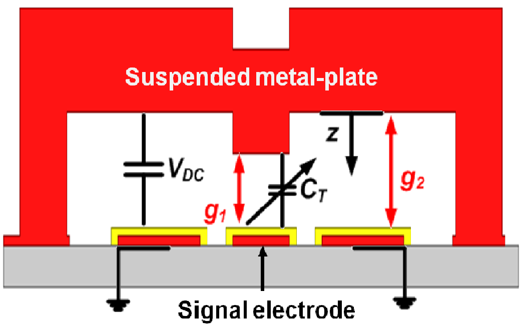


Fig. 2. A cross-sectional drawing of the proposed tunable capacitor with an air-suspended movable electrode with two different stages.

capacitor, two air gap structure was adopted with one-to-three ratio of the g_1 ranging from 1 to 2 μm and g_2 with 3 μm. The structure with two air gap was simply implemented using the double exposure process of photolithography and electroplating technique. At first, the area of air-suspended metal electrode with the distance of g_1 was contacted onto the fixed signal electrode due to the electrostatic force by V_{DC}. Moreover, in this case, the capacitance of the proposed tunable capacitor was smoothly increased, because the height of g_1 was lower than a third height of g2, which is the height by pull-in voltage.

In an initial state, the capacitance could be obtained by using an effective dielectric constant, ε_{eff} [14]

$$\sqrt{\varepsilon_{eff}} = \left[1 + \left(a_1 - b_1 \ln\left(\frac{w}{b}\right)\right)\left(\frac{1}{\sqrt{\varepsilon_r}} - 1\right)\right]^{-1} \quad (1)$$

where w is the width of the conductor line and ε_r is the relative dielectric constant of the aluminum nitride film in the designed MEMS tunable capacitor. The coefficients a_1 and b_1 are calculated by the relationship between a of the thickness of silicon substrate and b of the air gap. The coefficients a_1 and b_1 are specified by

$$a_1 = 0.155 + 0.505\left(\frac{a}{b}\right) \quad (2)$$

$$b_1 = 0.023 + 0.1863\left(\frac{a}{b}\right) - 0.194\left(\frac{a}{b}\right)^2 \quad (3)$$

In the initial state, the calculated capacitance of the designed MEMS tunable capacitor was 0.217 pF by using the above equations. In the contact state, the calculated capacitance was 0.593 pF by using the measured relative dielectric constant of 8.2.

Fig. 3 shows the 3-D EM simulated capacitance results of the proposed tunable capacitor at an initial and a contact states. As shown in Fig. 3, the proposed tunable capacitor without any bias voltages had the capacitance about 0.278 pF. After being contacted by applying the operation voltage, the tunable capacitor exhibited the capacitance of approximately 0.78 pF due to the fringing capacitance occurred between two electrodes.

Another important characteristic parameter of the MEMS tunable capacitor is the Q-factor. For the

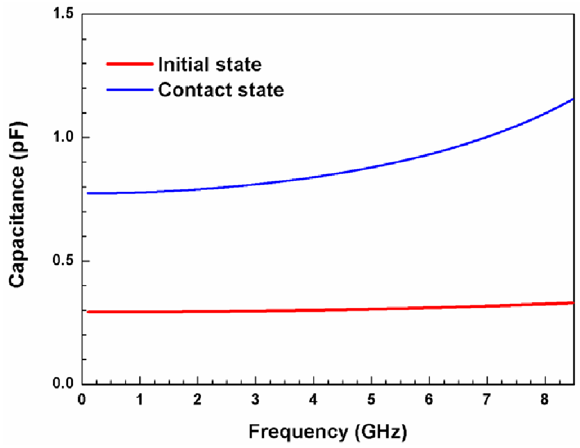


Fig. 3. 3-D EM simulated capacitances vs. frequency of the proposed RF MEMS tunable capacitor at initial and contact states.

improvement of the *Q*-factor, this study adopted a high resistivity silicon substrate (2 k to 10 k Ω-cm) to reduce effectively the RF loss occurred form the substrate.

III. FABRICATION

Fig. 4 shows the detailed fabrication sequences of the proposed RF MEMS tunable capacitor with an air-suspended movable electrode with two stages. The proposed MEMS tunable capacitor was fabricated on high resistivity silicon substrate (2- to 10-kΩ-cm) of 525 μm in thickness for reducing the substrate loss. After depositing silicon oxide film as an insulator on the substrate, bottom electrodes of platinum and aluminum nitride film were deposited and patterned in sequence with the thickness of 0.35 μm and 0.2 μm, respectively. As shown in Fig. 4(c), AZ7220 photoresist with the thickness of 3 μm was then double-coated and patterned as a sacrificial layer for forming the air-suspended movable electrode by double expose etch technique. A gold material with the thickness of 0.2 μm for seed layer and a Ti material with the thickness of 500 Å for adhesion layer were then sputtered on the top of the patterned sacrificial layer. After forming the thick photoresist molds for electroplating process, Au was electroplated to form thick air-suspended movable electrode with the thickness of 4 μm for improvement of reliability of RF MEMS tunable capacitors. Finally, after making etch holes on the thin gold seed layer, the sacrificial layer was finally removed by using acetone

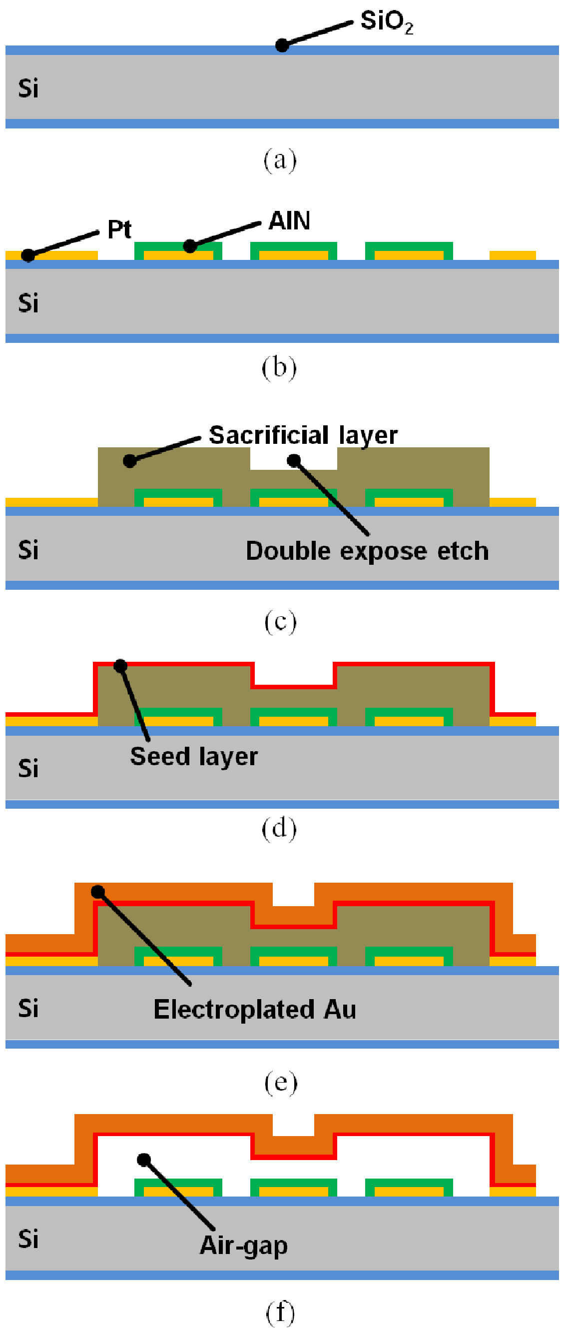
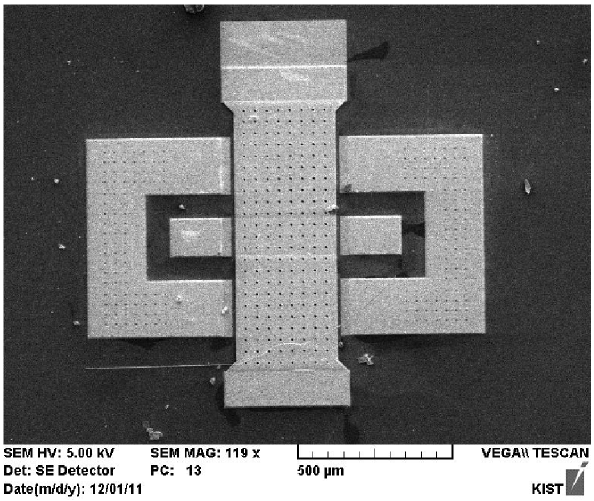


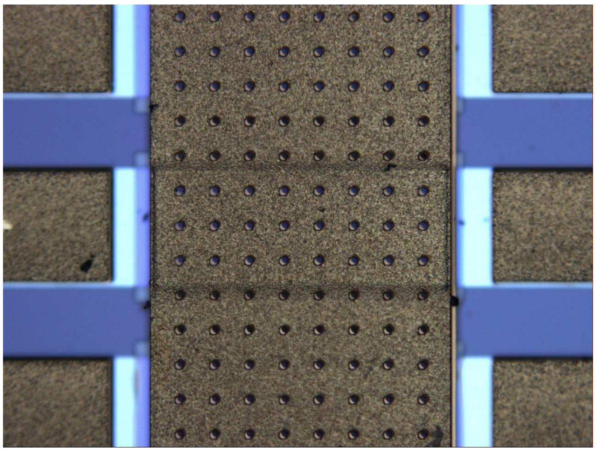
Fig. 4. Fabrication sequences of the proposed RF MEMS tunable capacitor with an air-suspended movable electrode with two stages.

and critical point dryer (CPD) process.

Fig. 5(a) and (b) shows a scanning electron microscope (SEM) photograph and a close-up view of the fabricated RF MEMS tunable capacitor. The formed height between SiO_2 layer and movable metal-plate was approximately 3 μm. Moreover, the formed height between AlN dielectric material and movable metal-plate



(a)



(b)

Fig. 5. A SEM photograph (a) and its close-up view, (b) of the fabricated RF MEMS tunable capacitor with an air-suspended movable electrode with two stages.

by double-exposed etching was approximately 1.95 µm. Its size was 1.2 mm × 1.2 mm. The contact area between the air-suspended movable electrode and the fixed signal electrode was 120 µm × 300 µm. Moreover, each bias area between the movable electrode and the fixed ground plane was 180 µm × 300 µm.

IV. Measurement Results

The fabricated MEMS tunable capacitor was measured and characterized by using an Agilent E5071 network analyzer and PICOPROBE GSG with 250 µm pitch size. A short-open-load-through (SOLT) has been adopted to calibrate the characteristics of the measurement equipment before measuring the fabricated capacitors. The measured frequencies were ranged from 1 to 8 GHz for commercial RF and microwave applications. The applied actuation voltage was ranging from 0 to 75 V.

Before fabricating the proposed tunable capacitor, the MIM capacitors with the aluminum nitride film were first fabricated, measured, and characterized. Fig. 6 shows the capacitance and the quality factor behaviors of the capacitor with the area of 80 µm × 80 µm at commercial radio frequencies. The maximal quality factor was higher than 30 and the capacitance density was 270 pF/mm^2. The measured dielectric constant and dielectric loss of the fabricated aluminum nitride were 8.2 and 0.01, respectively.

Fig. 7 shows the measured capacitances of the fabricated MEMS tunable capacitor at the frequency of 2 GHz. When the operation voltage was not applied, the fabricated capacitor had the capacitance of 0.317 pF, as

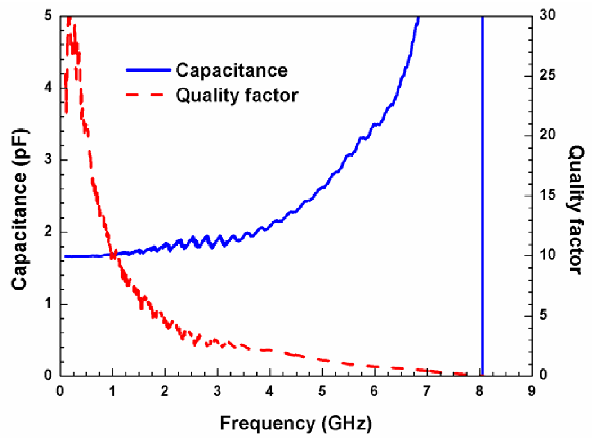


Fig. 6. Measured capacitance and quality factor of the fabricated AlN based MIM capacitor.

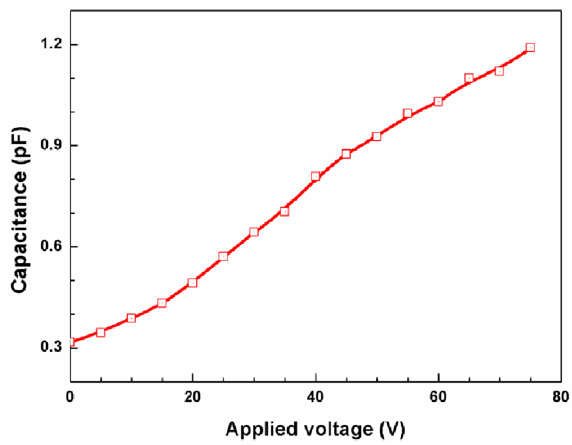


Fig. 7. Measured capacitances of the fabricated RF MEMS tunable capacitor at various applied voltages.

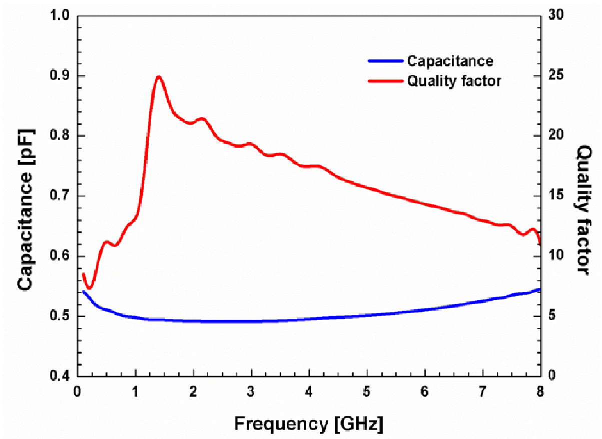


Fig. 8. Measured capacitance and quality factor of the fabricated RF MEMS tunable capacitor at the applied voltage of 30 V.

expected through the EM simulation. In the contact state, the capacitance was approximately 0.62 pF. The air-suspended movable electrode was contacted on the fixed signal electrode at the applied voltage of 30 V. It was slightly lower than the EM simulated capacitance of 0.78 pF. This discrepancy might be caused by the enlarged etch holes compared with the designed values. As shown in Fig. 7, the capacitance was linearly increased at the applied voltages higher than 30 V due to the zipping effects. The tunable capacitor exhibited a capacitance of 1.19 pF and a capacitance tuning range of 375% at the applied voltage of 75 V, which make it suitable for tunable filter and antenna applications. Fig. 8 shows the measured capacitance and quality factor of the MEMS tunable capacitor. In the contact state, the maximal quality factor of 25 was obtained at 1.5 GHz.

V. CONCLUSIONS

In this paper, a MEMS tunable capacitor with wide tuning range was successfully designed and fabricated by using aluminum nitride film and a gold suspended membrane with two air gap structures for commercial RF applications. The utilized high dielectric aluminum nitride film and two air gap structured membrane were effective to achieve a wide-tuning range and high capacitance density of the MEMS tunable capacitor, as expected. In addition, the developed fabrication sequence was simplified and compatible with the aluminum nitride based FBAR devices resulting in on chip tunable filters and radios with high performances and small size/volumes.

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