Integrated Micro-Mechanical Switches for RF Applications

Jae Y. Park · Geun H. Kim · Ki W. Chung* · Jong U. Bu

Abstract

RF micromachined capapcitive switches are newly designed and fabricated with various structural geometry of transmission line, hinge, and movable plate formed by using electroplating techniques. low temperature processes, and dry releasing techniques. In particular, Strontium Titanate Oxide($SrTiO_3$) with high dielectric constant is investigated for high switching on/off ratio and on capacitance as a dielectric layer of an integrated capacitive switch. Achieved lowest actuation voltage of the fabricated switches is 8 volts. The fabricated switch has low insertion loss of 0. 08 dB at 10 GHz. isolation of 42 dB at 5 GHz, on/off ratio of 600, and on capacitance of 50 pF, respectively.

요 약

다양한 구조의 트랜스미션 라인과 힌지들을 갖는 고주파용 마이크로머신드 용량성 스위치들이 새롭게 디자인되었고 전기도금 기술, 저온 공정기술, 그리고 건식 식각기술들을 이용하여 제작되었다. 특히, 집적화된 용량성 스위치들이 높은 스위칭 on/off ratio와 on 캐패시턴스를 갖도록 하기 위하여 고유전율을 갖는 $SrTiO_3$라는 상유전체를 절연체로 사용하였다. 제작된 스위치들은 8 V의 구동전압, 0.08 dB의 삽입손실, 42 dB의 높은 isolation, 600의 on/off ratio, 그리고 50 pF의 on 캐패시턴스의 특성들을 갖는다.

Ⅰ. INTRODUCTION

Recent development in MEMS technology has made possible the design and fabrication of micro-mechanical switch as a new switching element. The micromechanical switches have low resistive loss, negligible power consumption, good isolation, and high power handling capability compared to the semiconductor switches. The reported micromechanical switches were consisted of sputtered or evaporated thin metal films and silicon nitride or dioxide using cantilever[1] and membrane[2]~[4] topologies. However, most of them have a high actuation voltage and low switching on/off ratio and on capacitance. consumption, and low power handling capability.

In this research, RF micromachined capacitive switches are newly designed and fabricated. Various structural geometry of transmission line, hinge, and movable plate formed by using electroplated Au or Cu are investigated for obtaining low insertion loss and low actuation voltage. Strontium Titanate Oxide with high dielectric constant is investigated for high switching on/off ratio and on capacitance. The proposed switches are fabricated using electroplating techniques, low temperature processes, and dry releasing technique compatible to the MMIC fabrication processes.

Ⅱ. DESIGN CONSIDERATION

Fig. 1. shows a schematic drawing of the proposed RF MEMS capacitive switches. Fig. 1(a)

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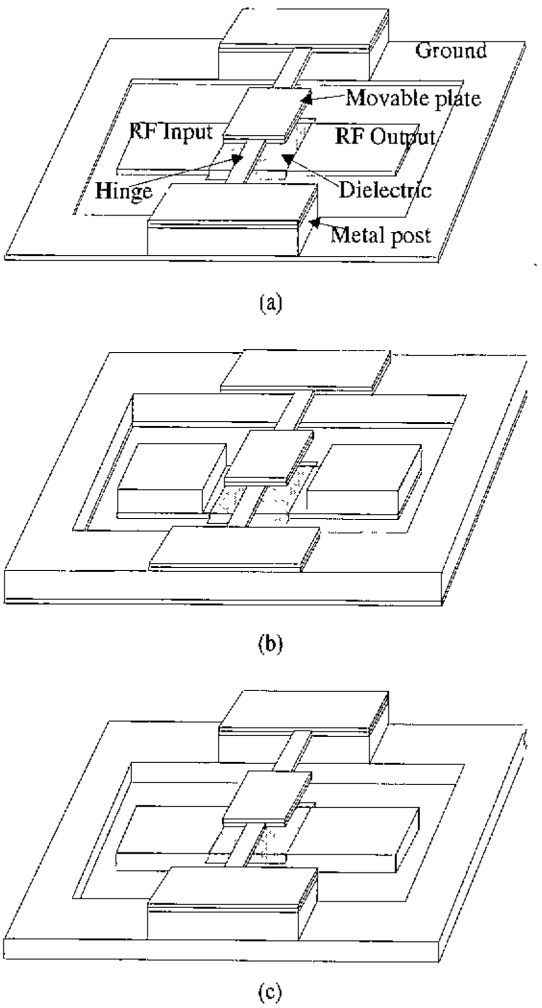

Fig. 1. Schematic drawing of RF MEMS Capacitive Switches: (a) sputtered thin transmission line, (b) partially electroplated tranmission line, and (c) fully electroplated transmission line.

shows a switch with a thin ground plane and a transmission line. Fig. 1(b) shows a switch with a thick ground plane and a partially thick transmission line. Fig. 1(c) shows a switch with a thick ground plane and a thick transmission line.

The thicker the transmission line is, the lower the insertion loss of the capacitive switch is when the switch is off. Capacitive switches control mechanically an electrical current or signal by using the on/off impedance ratio, while resistive switches utilize the mechanical connection of two isolated transmission lines. Thus, high impedance ratio is also desirable for achieving better switching characteristics in the capacitive switches. Silicon nitride or oxide commonly used may not be appropriate for making RF MEMS capacitive switches with small size, high on capacitance, and high on/off ratio due to their small relative dielectric constant. Thus, STO with high dielectric constant is investigated and utilized for fabricating RF MEMS capacitive switches.

When a voltage is applied between the movable plate and the transmission line of the capacitive switches shown in Fig. 1, the electrostatic force pulls the movable plate down onto the dielectric layer. The dielectric layer can reduce stiction and eliminate microwelding between the movable plate and the transmission line. The off/on ratio of the RF MEMS capacitive switch can be approximately calculated by using the following equation:

$$\frac{Z_{off}}{Z_{on}} = \frac{C_{on}}{C_{off}} = \frac{\varepsilon_{dielectric} h_{air} + h_{dielectric}}{h_{dielectric}} \qquad (1)$$

The actuation voltage of the micromechanical switch can be determined by the applied voltage, the hinge geometry, the membrane material properties, and the gap height between the movable plate and dielectric layer on top of the transmission line. A first order solution of the pull-down voltage(V_p) can be calculated by the following equation[5],[6]:

$$V_p = \sqrt{\frac{8K_s g_0^3}{27\varepsilon_0}} \qquad (2)$$

where K_s is the spring constant of the mechanical system, g_0 is the initial gap between the movable plate and the transmission line. Fig. 2 shows a schematic drawing of the hinge structures of the capacitive switch. Various geometries are investigated to obtain low operation voltage by reducing residual stress.

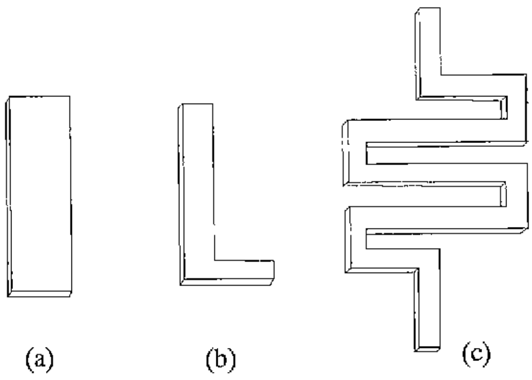

Fig. 2. Schematic drawing of various hinges of RF MEMS switches shown in Fig. 1.

Ⅲ. FABRICATION

3.1 The process started with a GaAs or a Quartz substrate

A ground plane and a transmission line were formed by lift off techniques. STO high dielectric layer was deposited and patterned on top of the formed transmission line by using a RF Sputter. A patterned seed layer was formed. A polyimide or photoresist was then spun on the top of the seed layer to construct electroplating molds for the metal posts and the partially electroplated transmission line.

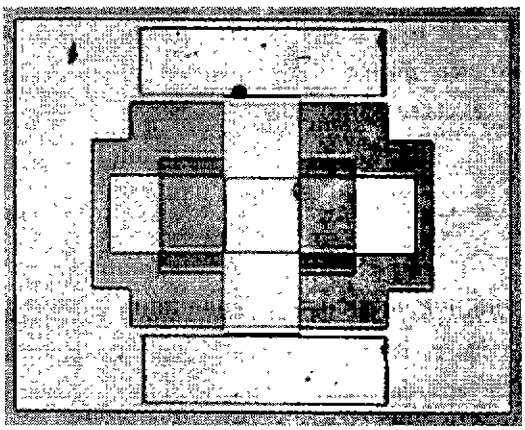

Fig. 3. Photomicrograph of the fabricated RF MEMS capcitive switch with the hinge structure shown in Fig. 2(a).

The molds were filled with electroplated Au or Cu.

After a seed metal was being deposited, a photorsist mold was formed for constructing a hinge and a movable plate. The mold was filled with electroplated Au, Cu, or Ni. A mass was also formed on the top of the formed plate by using photolithography technique and electroplating technique. After removing the photoresist layers and seed metal, the movable plate and hinge were released by etching the sacrificial layer (polyimide or photoresist)

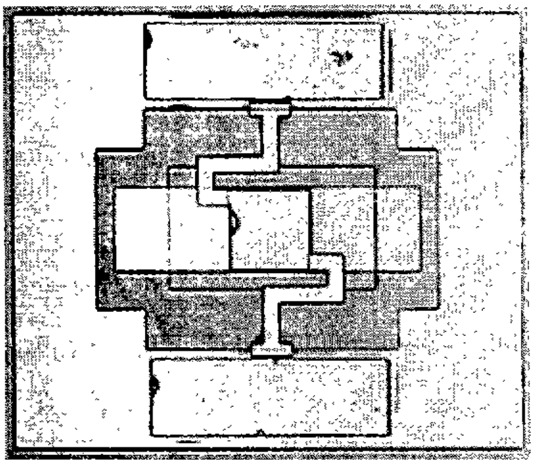

Fig. 4. Photomicrograph of the fabricated RF MEMS capcitive switch with the hinge structure shown in Fig. 2(b).

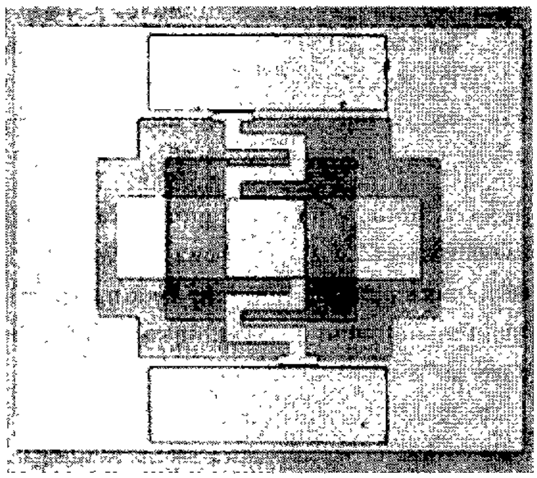

Fig. 5. Photomicrograph of the fabricated RF MEMS capcitive switch with the hinge structure shown in Fig. 2(c).

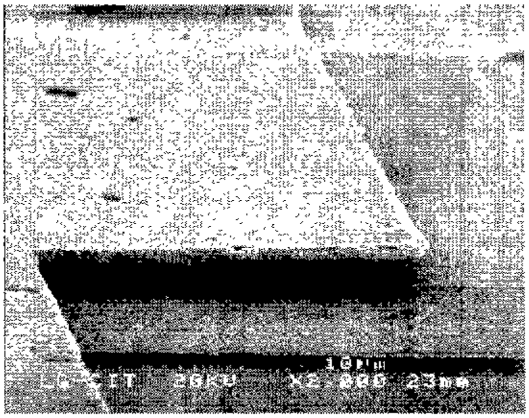

Fig. 6. Close-up view of fully released meander-type hinge and movable plate of the fabricated RF MEMS capacitive switch.

using a barrel plasma etcher. Figs. 3, 4, and 5 show the pictures of the fabricated RF MEMS capacitve switches. Fig. 6 shows a close up view of released movable plate of the fabricated RF MEMS switches.

Ⅳ. EXPERIMENTAL RESULTS

Before fabricating the proposed RF MEMS capacitive switches, dielectric constants of STO materials were measured by fabricating MIM (Metal/Insulator/Metal) capacitor. Table 1 shows the measured dielectric constants of the fabricated STO films. As shown in Table 1, dielectric constant of the STO was increased as the deposition temperature increased and was consistent up to several GHz in frequencies. It has also very low loss tangent (less than 0.02), low leakage current, and high breakdown voltages.

The fabricated switches have structural geometries with switching area of 100×100 μm^2, hinge thickness of 0.6~1.5 μm, and air gap height of 2.5 ~3.5 μm. Transmission line of the switch shown in Fig. 1(a) was approximately 0.15 μm in thickness and comprised of chromium/platinum/gold/platinum. Transmission line of the switch shown in Fig. 1(b) was ranged from 2.4 μm to 3.4 μm in thickness and comprised of chromium/platinum/gold/platinum/gold. Transmission line of the switch shown in Fig. 1(c) was ranged from 3.5 μm to 4.5 μm in thickness and comprised of chromium/platinum/gold/platinum/gold/gold. After fabricating the switches shown in Fig. 1, the insertion losses (switch up) were measured and compared. The switches shown in Figs. 1(a), (b), and (c), have insertion loss of 4.5 dB, 0.15 dB, and 0.07 dB at 20 GHz, respectively. Thus, the geometry shown in Fig. 1(a) is not appropriate for RF MEMS capacitive switch.

Table 1. Relative dielectric constant of fabricated Strontium Titanate Oxide ($SrTiO_3$)films.

	Silicon nitride at 250℃	STO deposited at 200℃	STO deposited at 250℃	STO deposited at 300℃
ε_r	6~8	30~40	60~70	110~120

Although the switch shown in Fig. 1(c) has the lowest insertion loss, the isolation (switch down) characteristics is not good due to the low off/on impedance ratio. Since the movable plate was not intimate contact on dielectric layer due to the surface roughness of the electroplated thick transmission line. The smaller gap is desired to achieve the higher on capacitance. Fig. 7 shows insertion loss (switch

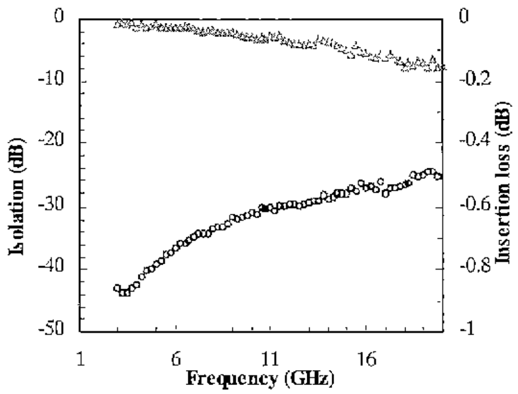

Fig. 7. Insertion loss (up position) and isolation (down position) of the fabricated RF MEMS capacitve switch with a structural geometry shown in Fig. 1 (b) and Fig. 2(a).

up) and isolation (switch down) of the fabricated-switches using a structural geometry shown in Fig. 1 (b) and Fig. 2(a). It has low insertion loss of 0.08dB at 10 GHz, isolation of 42 dB at 5 GHz, on/off ratio of 600, and on capacitance of 50 pF, respectively. Fig. 8 shows comparison of isolation characteristics of the fabricated switches. As shown in Fig. 8, the isolation is dependent on the hinge structures. The switch with meander-type hinge has the lowest isolation characteristics due to the its inductive effect, while it has the lowest actuation voltage, 8 volts. Fig. 9 shows comparison of the actuation voltages of RF switches. The fabricated switch has the lowest actuation voltage compared to the reported switches previously. The pull down-voltage was computed by using a finite 3-D element modeling tool, ANSYS and electroplated gold material properties. The estimated pull-down voltages are approximately 8 to 15 volts. As expected, the computed pull-down voltages are varied by the hinge geometry, hinge material properties, and the initial gap height.

V. CONCLUSION

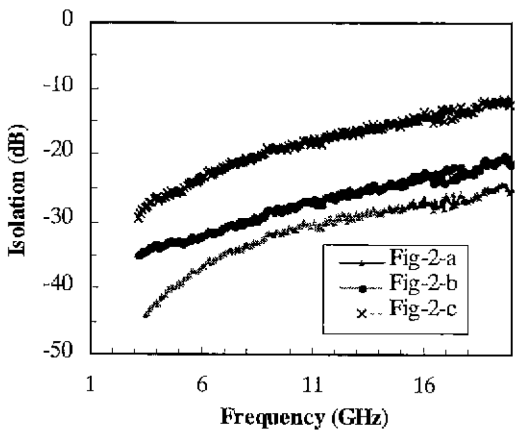

Fig. 8. Comparison of isolation (down position) characteristics of the fabricated RF MEMS capacitive switches with different hinge structures shown in Fig. 2.

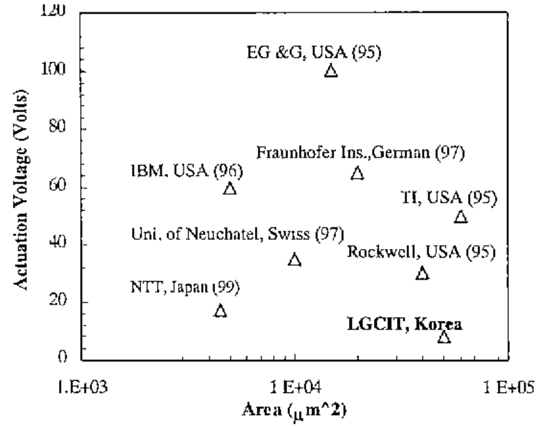

Fig. 9. Comparison of actuation voltages of fabricated RF MEMS capacitive switches and previous mechanical capacitive switches[7].

RF MEMS capacitive switches have been newlydesigned and fabricated using electroplating techniques, low temperature processes, and dry releasing techniques compatible to the MMIC fabrication processes. Various structural geometry have been tested for achieving better performance characteristics of RF MEMS capacitive switches. Achieved lowest actuation voltage of the fabricated switches is 8 volts. The fabricated switch has low insertion loss of 0.08dB at 10 GHz, isolation of 42 dB at 5 GHz, on/off ratio of 600, and on capacitance of 50 pF, respectively. These switches also have high current carry capability due to the use of electroplated gold. The fabricated micromechanical switches can be possibly used for various microwave applications including digitally controlled antenna/ impedance matching circuits, transmitters/ receivers, phase shifters, phased array antennas/ radars, tuning circuits, and so on.

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