ELECTROPLATED RF MEMS CAPACITIVE SWITCHES

Jae Y. Park, Geun H. Kim, Ki W. Chung*, and Jong U. Bu
Microsystem Team and RF Team*
Materials and Devices Laboratory
LG Corporate Institute of Technology
16 Woomyeon-Dong, Seocho-Gu, Seoul, 137-724, Korea

ABSTRACT

RF microswitches 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 a micromechanical capacitive switch. 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 Au or Cu.

INTRODUCTION

Recently, many researches have been performed to develop micromechanical switches for mechanically switching microwave signals. So far, semiconductor switches such as FETs or PIN diodes are widely used in millimeter wave integrated circuits (MMICs) and microwave circuits. However, these semiconductor switches have large insertion loss and poor isolation in the 'ON' state and 'OFF' state. The semiconductor switches have also large resistive loss, power consumption, and low power handling capability. Accordingly, new switching elements have been demanded for substituting these semiconductor switches.

Recent development in MEMS technology has made possible the design and fabrication of micromechanical 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.

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. Two different structural geometry for capacitive switching are also investigated such as metal to dielectric contact and metal to metal contact during the switch operation. The proposed switches are fabricated using electroplating techniques, low temperature processes, and dry releasing technique compatible to the MMIC fabrication processes.

DESIGN CONSIDERATION

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

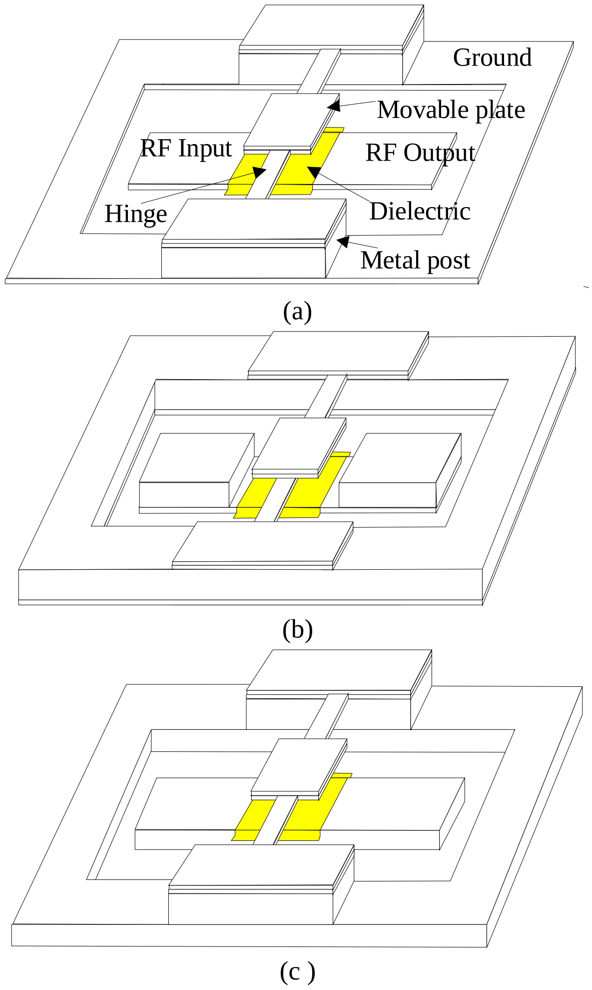

Figure 1: Schematic drawing of RF MEMS Cpapcitive Switches: (a) sputtered thin transmission line, (b) partially electroplated tranmission line, and (c) fully electroplated transmission line

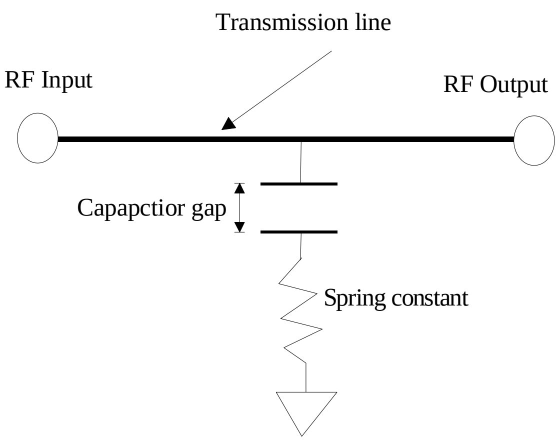

Figure 2: Lumped model of RF MEMS capacitive switch

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. When the switch is off or unactuated, the off capacitance can be calculated by using the following equation:

$$C_{off} = \frac{1}{\frac{h_{dielectric}}{\varepsilon_{dielectric}\varepsilon_0 A} + \frac{h_{air}}{\varepsilon_0 A}} \qquad (1)$$

When the switch is on or actuated, the on capacitance can be obtained by using the following equation:

$$C_{on} = \frac{\varepsilon_{dielectric}\varepsilon_0 A}{h_{dielectric}} \qquad (2)$$

Thus, the off/on ratio of the RF MEMS capacitive switch can be approximately calculated by using the following equation:

$$\frac{Z_{off}}{Z_{on}} = \frac{C_{on}}{C_{off}} = \frac{\varepsilon_{dielectric} h_{air} + h_{dielectric}}{h_{dielectric}} \qquad (3)$$

The theoritical cutoff frequency of the capacitive switch can be calculated by using the following equation where the ratio of off and on impedance degrades to unity:

$$f_{cutoff} = \frac{1}{2\pi R_{on} C_{off}} \qquad (4)$$

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. Fig. 2 shows lumped model of the RF MEMS capacitive switch. A first order solution of the pull-down voltage(V_p) can be calculated by the following equation [5-6]:

$$V_p = \sqrt{\frac{8K_s g_0^3}{27\varepsilon_0}} \qquad (5)$$

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. 3 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. 4 shows two different structural geometry of the capacitive switches. Fig. 4 (a) shows the movable plate contacts with dielectric layer when switch is on and Fig. 4 (b) shows it contacts with the metal electrode on top of dielectric layer. In switches with structural geometry shown in Fig. 4(a), the surface roughness of dielectric or the residue left after release etch may cause bad contact between movable plate and dielectric. But in case of Fig.4 (b), although there are the surface roughness, the residue left, and the bent movable plate due to the occurred tensile or compressive stress during fabrication process, high on capacitance is achievable since the movable plate contacts the upper electrode of the already formed MIM capacitor.

The proposed switches in this research were designed to minimize the insertion loss and maximize the on/off ratio, to minimize the effective on resistance, to maximize the high current capability, and to minimize the operation voltage.

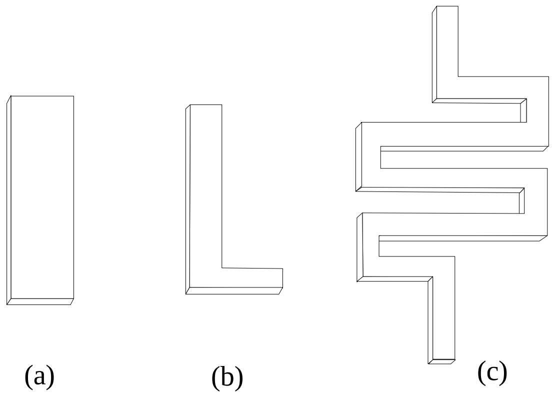

Figure 3: Schematic drawing of various hinges of RF MEMS switches shown in Fig.1

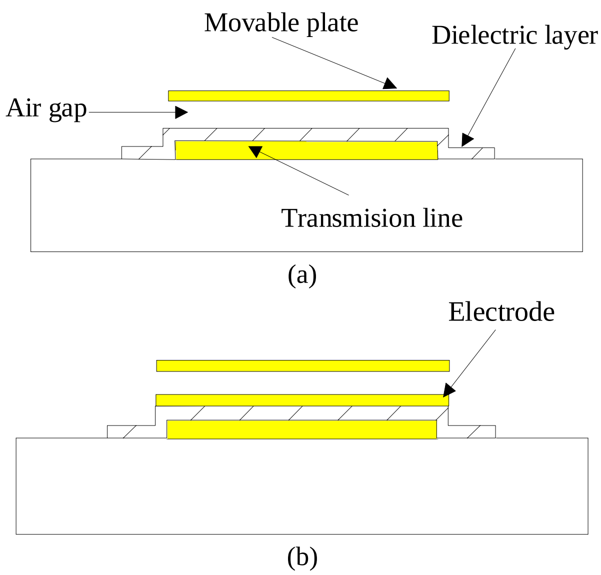

Figure 4: Cross-sectional view of movable plate, dielectric layer, and transmission line of RF MEMS capacitive switches: (a) without and (b) with electrode on top of dielectric layer

FABRICATION

A brief fabrication sequence for the RF MEMS switches described in Fig. 1(a) and (b) is shown in Fig. 5. The process started with a GaAs or a Quartz substrate. A ground plane and a transmission line were formed by lift off techniques. These were comprised of chromium (100 Å), platinum (100Å), gold (1000 Å), and platinum (300 Å). STO high dielectric layer (1900Å) was deposited and patterned on top of the formed transmission line. STO dielectric material was deposited at the condition of 10mTorr in pressure, 27sccm in argon, 3sccm in oxygen, and 320W in RF power for 2 hours by using a RF Sputter. A patterned seed layer was formed for electroplating the metal posts. 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. 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) using a barrel plasma etcher.

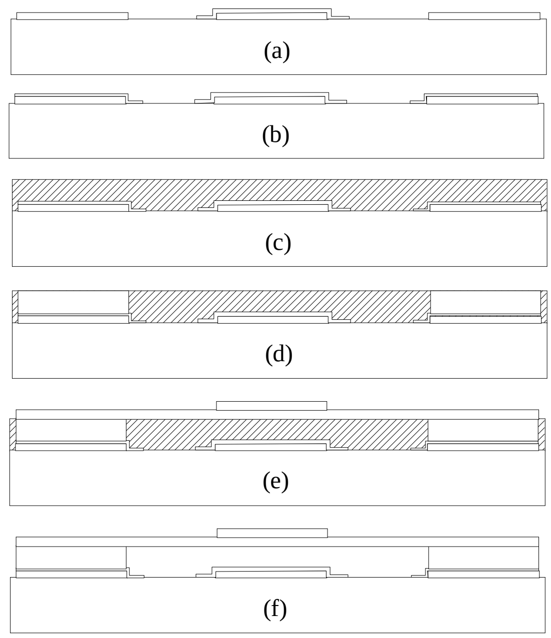

Figure 5: Fabrication sequences of RF MEMS capacitve switches shown in Fig. 1 (a) and Fig. 1(b)

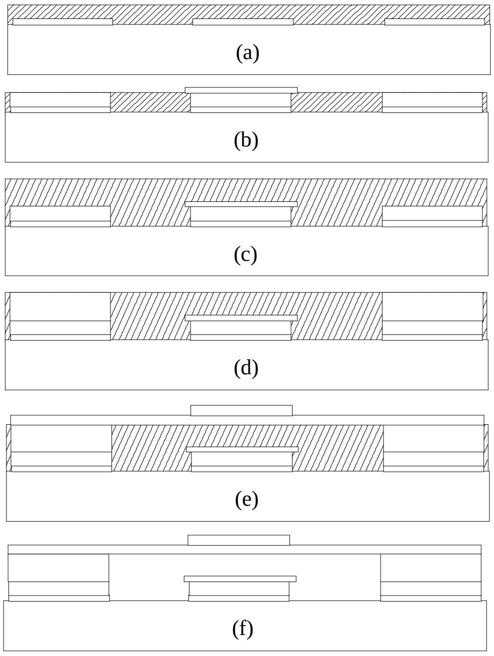

Figure 6: Fabrication sequences of RF MEMS capacitive switches shown in Fig. 1 (c)

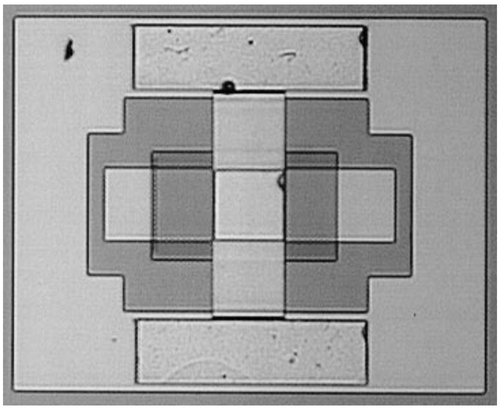

Figure 7. Photomicrograph of the fabricated RF MEMS capcitive switch with the hinge structure shown in Fig.3-(a)

Fig. 6 shows a brief fabrication process for the RF MEMS switches depicted in Fig. 1(c). The process also started with a GaAs or a Quartz substrate. A seed metal layers were deposited and patterned to form a conductive network to be removed after being served as the seed layer for plating a ground plane and a transmission line. A polyimide was then spun on top of the seed layer to construct electroplating molds and filled with gold or copper. Chromium/ platinum was deposited and patterned to deposit STO dielectric on top of the formed transmission line by using lift off techniques. STO high dielectric layer was deposited and patterned on the top of the patterned chromium/ platinum metal layer. Fabrication processes to form metal posts, hinge, and movable plate are same as the processes described in the above. Figs. 7, 8, and 9 show the pictures of the fabricated RF MEMS capacitve switches. Figs. 10 shows a close up view of released meander-type hinge and movable plate of the fabricated RF MEMS switches.

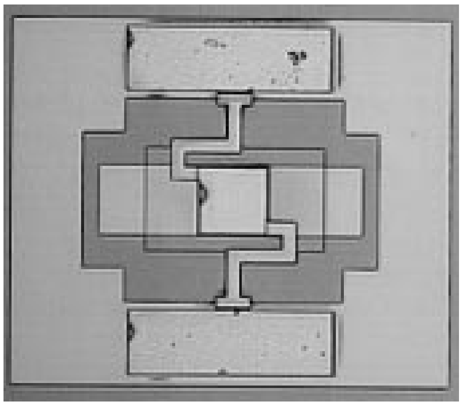

Figure 8. Photomicrograph of the fabricated RF MEMS capcitive switch with the hinge structure shown in Fig.3-(b)

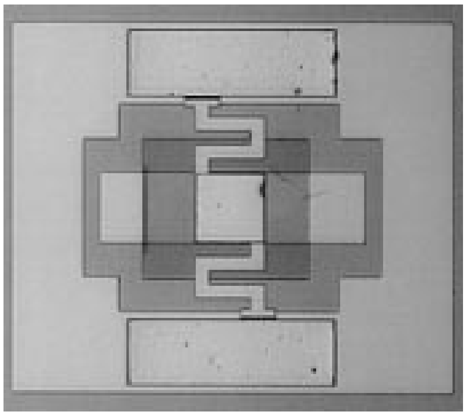

Figure 9. Photomicrograph of the fabricated RF MEMS capcitive switch with the hinge structure shown in Fig.3-(c)

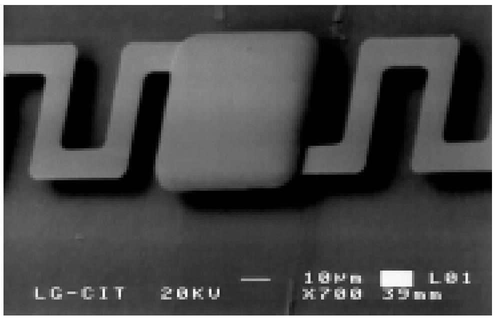

Figure 10. Close-up view of fully released meander-type hinge and movable plate of the fabricated RF MEMS capacitive switch

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

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

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. Thus, the STO dielectric material is useful for fabricating RF MEMS capacitive switches.

Table 2 shows geometries of the fabricated RF MEMS capacitive switches shown in Fig.1. 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 2. Structural parameters of the fabricated RF MEMS capacitive switches

Geometry parameters	Switches shown in Fig. 1
Length of transmission line (μm)	400
Switching area(capacitor area) (μm^2)	100 x 100
Thickness of hinge (μm)	0.6 ~ 1.5
Gap (μm)	2.5 ~ 3.5

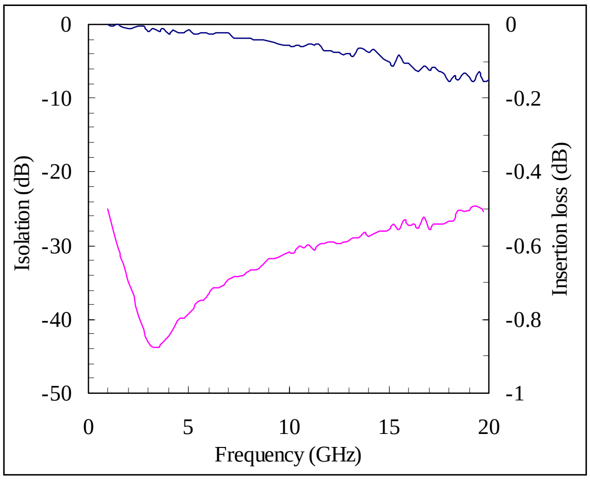

Figure 11. Insertion loss (up position) and isolation (down position) of the fabricated RF MEMS capacitve switch with a structural geometry shown in Fig. 1 (b) and Fig. 3(a)

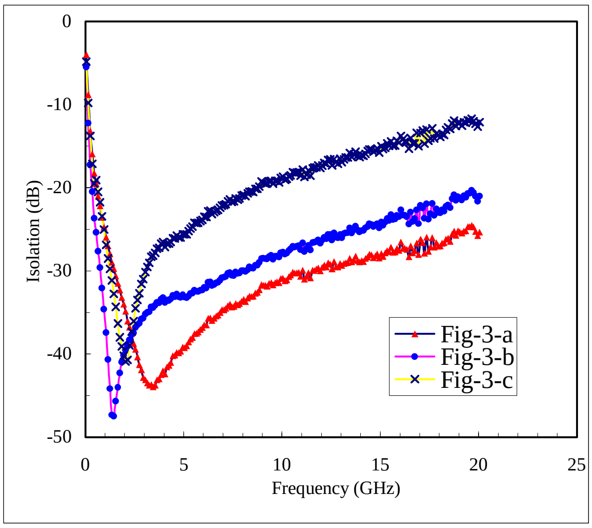

Figure 12. Comparison of isolation (down position) characteristics of the fabricated RF MEMS capacitive switches with different hinge structures shown in Fig. 3

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. 11 shows insertion loss (switch up) and isolation (switch down) of the fabricated switches using a structural geometry shown in Fig. 1 (b) and Fig. 3(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. 12 shows comparison of isolation characteristics of the fabricated switches. As shown in Fig. 12, 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. 13 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. The fabricated switches with Fig. 4(b) topology have the higher actuation voltages than the switches with Fig. 4(a) topology. However, on/off impedance ratio of the switch was improved.

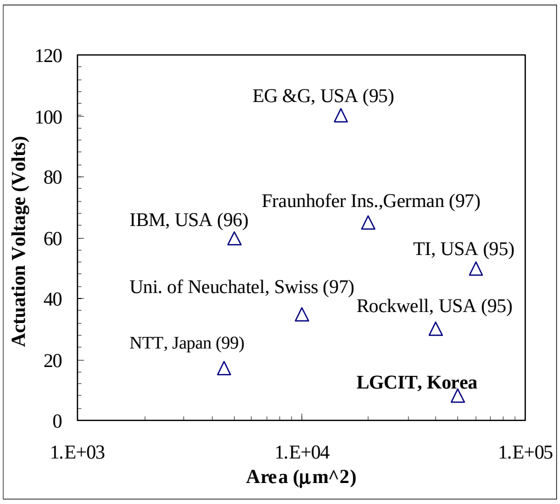

Figure 13. Comparison of actuation voltages of fabricated RF MEMS capacitive switches and previous mechanical capacitive switches [7]

4

CONCLUSION

RF MEMS capacitive switches have been newly designed 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.

ACKNOWLEDGMENTS

This work is supported by Ministry of the Commerce, Industry & Energy, and Ministry of Science & Technology under Government National Project. Fabrication was carried out at the LG Corporate Institute of Technology. The authors would like to thank Microsystem Team and RF (Radio Frequency) Team of the LG Corporate Institute of Technology. Mr. Dong C. Kim is also appreciated for assisting the deposition of STO dielectric material.

REFERENCES

[1] J. J. Yao and M. F. Chang, “A surface micromachined miniature switch for telecommunications applications with single frequences form DC up to 4GHz,” Digest of Technical Papers, Transducers 95, vol. 2, pp. 384 ~ 387, Stockholm, Sweden, June 25 ~ 29, 1995

[2] C. Goldsmith, T. H. Lin, B. Powers, W. R. Wu, and B. Norvell, “Micromechnaical membrane switches for microwave applications,” Proceedings of the 1995 IEEE MTT-S International Microwave Symposium, vol. 1, pp. 91 ~ 94, Orlando, Fl, May 16 ~ 20, 1995

[3] J. N. Randall, C. Goldsmith, D. Denniston, and T. H. Lin, “Fabrication of Micromechnaical switches for routing radio frequency signals,” Journal of vacuum Science and Technology, vol. B14, no. 6, pp. 3692 ~ 3696, Nov./Dec. 1996

[4] Z. J. Yao, S. Chen, S. Eshelman, D. Denniston, and C. Goldsmith, “Micromachined low-loss microwave switches,” IEEE Journal of Microelectromechnaical Systems, vol. 8, no. 2, June, 1999

[5] C. Goldsmith, J. Randall, S. Eshelman, T. H. Lin, S. Chen, and B. Norvell, “Characteristics of Micromachined Switches at Microwave Frequencies,” Proceedings of the 1996 IEEE MTT-S International Microwave Symposium, pp. 1141 ~ 1145, May 16 ~ 20, 1996

[6] P. Osterberg, H. Yie, X. Cai, J. White, and S. Senturia, “Self-consistent Simulation and Modeling of Electrostatically Deformed Diaphragms,” Proceedings of the 1994 IEEE Micro Electro Mechanical Systems Technical Digest, Osio, Japan, pp. 28 ~ 32, Jan. 28 ~ 32, 1994

[7] A. Hirata, K. Machida, H. Kyuragi, and M. Maeda, “A Micromechnical Switches as The Logic Elements For Circuits in Multichip Module on Si (MCM-Si),” Proceedings of the 1999 IEEE Micro Electro Mechanical Systems Technical Digest, Orlando, Fl, pp. 582 ~ 587, Jan. 17 ~ 21, 1999