BROADBAND LOW ACTUATION VOLTAGE RF MEM SWITCHES

Shyh-Chiang Shen, David Caruth, and Milton Feng

Center for Compound Semiconductor Materials and Dept. of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, IL 61801-2355

ABSTRACT -

We demonstrate a sub-10volts RF MEM switch built on a semi-insulating GaAs substrate. The fabrication process is a 7-mask-layer process compatible with GaAs MMIC processes. The insertion loss is less than 0.1 dB and the isolation is better than 25 dB over frequencies up to 40 GHz. The MEM switches will provide a solution as a broadband, low voltage building block for RF communication applications.

I. INTRODUCTION

The low insertion loss, high isolation radio frequency (RF) Microelectromechanical (MEM) switches have been thought of as one of the most attractive devices for space-based reconfigurable antennas and integrated circuit applications[1]. They provide GaAs phase shifters, for example, with reduced insertion loss for switching between different line lengths or between high and low-pass filters[2-4]. As the loss of the phase shifter arrays decreases, fewer amplifiers are required in phase antenna arrays. The cost, weight, and heat dissipation problems can be drastically reduced.

Many RF MEM switch topologies have been reported up to date. Typically, they are categorized as rotary, cantilever, and membrane switches. All of them have showed superior RF characteristics to their semiconductor counterparts. Most of the RF MEM switches, however, require very high actuation voltages (usually 30-50 volts). The high voltage operation mode will make RF MEM devices impractical for many wireless communication applications. Low voltage RF MEM devices have thus become a critical issue of the validation of RF-MEM-based communication systems. Much effort has gone into the search for low voltage RF MEM switches[5-7]. However, most of these low voltage designs require a large area and the improvement on the actuation voltage may be limited. There is a need for an innovative structure to address the drawbacks of known devices in order to realize the low actuation voltage RF MEM switches. At the University of Illinois, we proposed a novel hinged RF MEM switch for low voltage operation[8] and reported a promising low voltage operation of 14V and excellent RF performance over frequencies up to 40GHz[9]. In this paper, we will demonstrate improved low voltage hinged MEM switch performance with a **sub-10** volts operation, an insertion loss of less than 0.1 dB, and an isolation of better than 25 dB over the frequency band of 0.25-40GHz. An RF Model of the MEM switch was also established. We believe the hinged RF MEM switches have the potential to achieve a lower actuation voltage comparable to that of the FET-based switches and will provide a solution to RF-MEMS-based RF systems.

II. DEVICE TOPOLOGY AND FABRICATION PROCESS

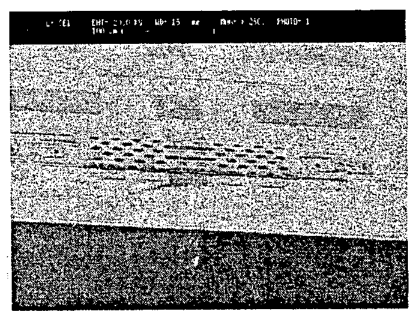


Fig. 1 A SEM photograph of a fabricated RF MEM switch

Shown in Fig. 1 is an SEM picture of a fabricated RF MEM switch on a S.I. GaAs substrate. The RF signal is guided by a coplanar waveguide. The top and bottom electrodes along with a metal pad inserted in between constitute a single-pole-single-throw, dual-electrode hinged MEM switch. The electrodes facilitate the application of the actuation voltages. The actuation voltage provides an electrostatic force to make the conductive pad move up and down. When a voltage is applied on the bottom electrodes, the pad contacts the signal line and ground planes and provides a through path for signals. The input RF signal from one port will short to the ground and no RF signal will flow through to the other port, which corresponds to the switch 'off' state. When a voltage is applied to the top electrodes, the conductive pad is attracted upward. RF signals flow through the output port without much insertion loss. This corresponds to the switch 'on' state. The switching operation can therefore be realized by applying two out-of phase pulses on the top and bottom actuation electrodes.

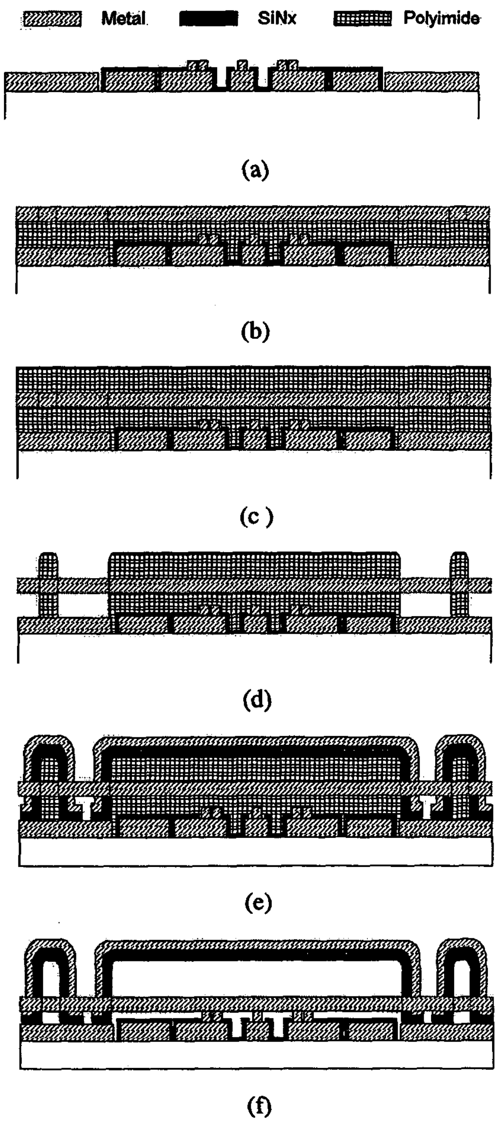


Fig. 2 Hinged RF MEM Switch Process Flow

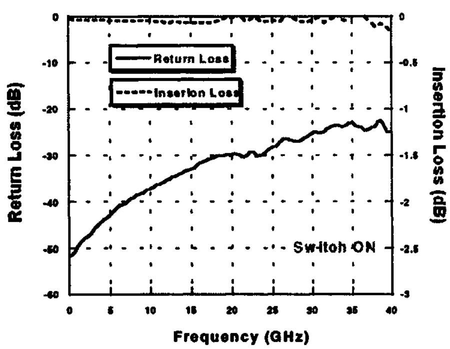
Theoretically, the minimum electrostatic force required for actuation is equal to the sum of the weight and the friction of the conductive pad. The minimum actuation voltage required for the switch operation can be expressed as: $V_{min} = \sqrt{2(mg + F_{friction})/\varepsilon_o A_{pad}}\, d$, where d is the gap between the conductive pad and electrodes, mg is the weight of the conductive pad, $F_{friction}$ is the friction force, A_{pad} is the area of actuation pad, and ε_o is the permitivity of the air. Assuming that the friction force $F_{friction}$ is proportional to metal pad area A_{pad}, the minimum actuation voltage is independent of the metal pad area. The device size can thus be relatively small to enable direct scaling to higher frequency applications. In addition, the metal pad is virtually free of mechanical strain in contrast with cantilever and membrane structures. The high actuation voltage due to mechanical stress can therefore be reduced, and with a proper choice of conducting pad metal, the actuation voltage may be less than three volts.

Shown in Fig. 2 is the hinged RF MEM switch process flow. The device fabrication is a 7 mask-layer process compatible with conventional GaAs MMIC process. First, a 1-μm thick Au layer is evaporated and patterned to form the CPW and the bottom electrodes. A layer of PECVD silicon nitride is deposited, followed by a via-hole etch (Fig. 2a). A Polyimide sacrificial layer is spun on and a 1μm thick Au layer is evaporated to form the conductive pad (Fig. 2b). A second polyimide layer is spun on (Fig. 2c) and is patterned for top electrode support posts (Fig. 2d). A 0.8μm thick low-temperature PECVD silicon nitride layer is deposited followed by a 0.5-μm of Au deposition to form top electrodes. The silicon nitride layer is then etched in an RIE system and the sacrificial layers are removed by wet etch. Finally, the devices are released using a carbon-dioxide supercritical drying technique[10].

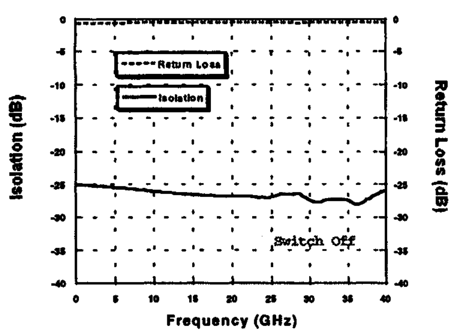
Gold is chosen for the conductive pad metal because of its low material stress. This leads to less warping of the conductive pad, and results in smaller parasitic capacitances in the switch, providing a lower insertion loss when the switch is in the on state. It is worth noting that the growth temperature of the silicon nitride for top electrode support should be low enough to prevent the polyimide underneath from reflowing. A lower temperature PECVD silicon nitride may also prevent voltage-induced charges from building up in the dielectric layer during switching.

III. Results and Discussion

The S-parameters of the devices are measured from 0.25GHz to 40GHz using an HP8510C vector network analyzer and 150 μm pitch RF coplanar probes. An on-wafer calibration scheme is adopted to eliminate pad parasitics. The calibration standards are built on a semi-insulating GaAs substrate with short, open, load, and through (SOLT) patterns. The pads effectively become a part of the measurement system after the on-wafer calibration, and the measured data are the s-parameters of the two-port located between the pads[11].



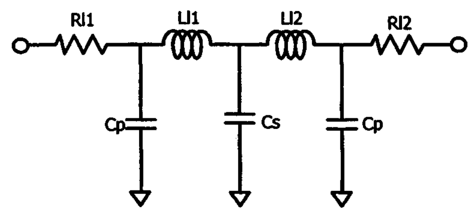
(a)



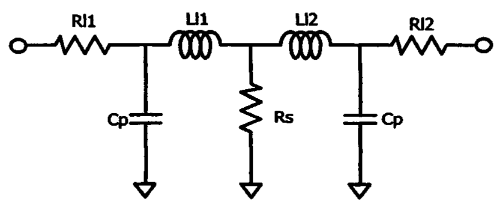
(b)

Fig. 3 Measured data of RF MEM switch for (a) switch-on and (b) switch-off states

The measured data are shown in Fig. 3. For the switch-on state (Fig. 3a), it shows an insertion loss of less than 0.1dB with a return loss of better than 23 dB for frequencies up to 40 GHz. The insertion loss is a collective result of substrate radiation loss and the stray capacitance of the metal pad hanging on top of the CPW section for the switch-on state. For the switch-off state (Fig. 3b), an isolation of higher than 25 dB over the 40 GHz bandwidth is achieved. The flat frequency response for the switch-off state is due to the resistive coupling of RF signals from the center conductor to ground planes, which is unique compared with other capacitively-coupled shunt MEM switches. The extremely broadband frequency response will lessen the complexity of RF circuit design using RF MEM switches. The minimum actuation voltage is 9 volts. The reduced actuation voltage compared with our previous work can be attributed to improved flatness of the conductive pad and utilization of a carbon-dioxide supercritical release procedure. The use of this technique can help reduce the sticking problem during the sacrificial layer release [10].



(a)



(b)

State	Rl1 (Ω)	Ll1 (pH)	Rl2 (Ω)	Ll2 (pH)	Cp (fF)	Cs (fF)	Rs (Ω)
ON	0.26	37	0.26	37	~0	38	0
OFF	0.23	12.5	0.23	12.5	~0	0	1.2

Fig.4 MEM switch equivalent circuit model and extracted device parameters for (a)switch-on and (b)switch-off states

The equivalent circuits and the extracted device parameters are shown in Fig. 4. Rl1, Rl2, Ll1, and Ll2 represent the finite length of transmission line lying in the MEM switch section. Cp accounts for the parasitic capacitance between the metal plate and the coplanar structure due to non-uniform metal contact. Cs and Rs are the on-state capacitance and the off-state shunt resistance, respectively. An off-state resistance of 1.2 Ω and an on-state capacitance of 38 fF are extracted from the model. The parasitic capacitance is negligible, indicating the metal pad flatness is well controlled. A lower off-state resistance results in a higher isolation, and a smaller on-state capacitance indicates a lower insertion loss. The conductive pad size, therefore, becomes a trade-off parameter in hinged RF MEM switch design. The resulting device models show that the MEM switch is a very linear device for frequencies up to at least 40 GHz.

IV. Conclusion

We demonstrate a sub-10volts RF MEM switch built on a semi-insulating GaAs substrate. The 7-mask layer fabrication processes are developed to be compatible with GaAs MMIC processes. The insertion loss is less than 0.1 dB and the isolation is better than 25 dB over the frequency band of 40 GHz. The hinged RF MEM switches will provide a solution for low voltage and highly linear switching methods for the next generation of broadband RF, microwave, and millimeter-wave circuits.

V. Acknowledgement

This paper is supported under the contract of F33615-99-C-1519 on DARPA-RECAP program - Mechanically Conformal and Electrically REConfigurable APerture Using Low Voltage MEMS and Flexible Membrane for Space-Based Radar Application.

References

[1] E. R. Brown, "RF_MEMS switches for recofigurable integrated circuits," *IEEE Trans. Microwave Theory and Tech.*, vol.46, no.11, pp. 1868-1880, Nov. 1998.

[2] B. Pilklans, S. Eshelaman, A. Malczewski, J. Ehmke, and C. Goldsmith, "Ka-Band RF MEMS phase shifters," *IEEE Microwave and Guided Wave Lett.*, Vol. 9, No.12, Dec. 1999,pp. 520-522

[3] A. Malczewski, S. Eshelaman, B. Pilklans, J. Ehmke, and C. Goldsmith, "X-band RF MEMS phase shifters for phased array applications," *IEEE Microwave and Guided Wave Lett.*, Vol. 9, No.12, Dec. 1999,pp. 517-519.

[4] J.S. Hayden and G. M. Rebeiz, "One and two-bit low -loss cascadable MEMS distributed X-band phase shifters," *2000 IEEE MTT-S International Microwave Symposium Digest*, pp. 161-164

[5] S.P. Pacheco, L. P.B. Katehi, and C. T.-C. Nguyen, "Design of low actuation voltage RF MEMS switch," *2000 IEEE MTT-S International Microwave Symposium Digest*, pp. 165-168

[6] D. Hah, E. Yoon, nad S. Hong, "A low voltage actuated micromachined microwave switch using torsion spring and leverage," *2000 IEEE MTT-S International Microwave Symposium Digest*, pp. 157-160

[7] N.S. Barker and G.M. Rebeiz, "Distributed MEMS true-time delay phase shifters and wide-band switches," *IEEE Trans. Microwave Thoery and Tech.*, Vol. 46, No. 11, pp. 1881-1889, Nov. 1998

[8] M. Feng and S.C. Shen, U.S. Patent Pending, August 1998.

[9] S.C. Shen and M. Feng, "Low Actuation Voltage RF MEMS Switches With Signal Frequencies From 0.25GHz to 40GHz," *1999 IEEE International Electron Device Meeting Technical Digest*, Dec. 5-8, 1999, pp.689-692.

[10] C.W. Dyck, J.H. Smith, S.L. Miller, E.M. Russick, C.L.J. Adkins, "Supercritical carbon dioxide solvent extraction from surface-micromachined micromechanical structures," *SPIE Micromachining and Microfabrication*, Oct. 1996

[11] D. C. Caruth, "Large Signal Modeling of MESFETs," *M.S. Thesis, Univ. of Illinois*, 1999