AFRL-SN-WP-TP-2006-101

A LATCHING CAPACITIVE RF MEMS SWITCH IN A THIN FILM PACKAGE (PREPRINT)

John L. Ebel, Rebecca Cortez, Kevin D. Leedy,
and Richard E. Strawser

DECEMBER 2005

Approved for public release; distribution is unlimited.

STINFO FINAL REPORT

This work has been submitted to IEEE for publication in 2006 IEEE International Microwave Symposium Conference Proceedings. If this work is published, it is considered a work of the U.S. Government and is not subject to copyright in the United States.

SENSORS DIRECTORATE
AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7320

NOTICE

This report was cleared for public release by the Air Force Research Laboratory Wright Site (AFRL/WS) Public Affairs Office (PAO) and is releasable to the National Technical Information Service (NTIS). It will be available to the general public, including foreign nationals.

PAO Case Number: AFRL/WS-06-0132, 13 Jan 2006.

THIS TECHNICAL REPORT IS APPROVED FOR PUBLICATION.

/s/

JOHN L. EBEL
Electron Devices Branch
Aerospace Components Division

/s /

KENICHI NAKANO, Chief
Electron Devices Branch
Aerospace Components Division

/s/

TODD A. KASTLE, Chief
Aerospace Components Division
Sensors Directorate

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE ***(DD-MM-YY)***	**2. REPORT TYPE**	**3. DATES COVERED** ***(From - To)***
December 2005	Conference Paper Preprint	06/01/2005 – 12/01/05

4. TITLE AND SUBTITLE
A LATCHING CAPACITIVE RF MEMS SWITCH IN A THIN FILM PACKAGE (PREPRINT)

5a. CONTRACT NUMBER
In-house

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62204F

6. AUTHOR(S)
John L. Ebel, Rebecca Cortez, Kevin D. Leedy, and Richard E. Strawser

5d. PROJECT NUMBER
2002

5e. TASK NUMBER
IH

5f. WORK UNIT NUMBER
01

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Electron Devices Branch (AFRL/SNDD)
Aerospace Components Division
Sensors Directorate
Air Force Research Laboratory, Air Force Materiel Command
WPAFB, OH 45433-7320

8. PERFORMING ORGANIZATION REPORT NUMBER
AFRL-SN-WP-TP-2006-101

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Sensors Directorate
Air Force Research Laboratory
Air Force Materiel Command
Wright-Patterson AFB, OH 45433-7320

10. SPONSORING/MONITORING AGENCY ACRONYM(S)
AFRL/SNDD

11. SPONSORING/MONITORING AGENCY REPORT NUMBER(S)
AFRL-SN-WP-TP-2006-101

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
This work has been submitted to IEEE for publication in 2006 IEEE International Microwave Symposium Conference Proceedings. If this work is published, it is considered a work of the U.S. Government and is not subject to copyright in the United States.

Conference paper preprint to be presented at the 2006 IEEE International Microwave Symposium and submitted to the 2006 IEEE IMS Conference Proceedings.

14. ABSTRACT
A latching capacitive RF MEMS switch has been successfully designed, fabricated and tested. The switch uses a long thin metal cantilever which is electrostatically held to an upper electrode at the free end and to a lower electrode at the beam root end forming an S-shaped actuator. The upper electrode sits on top of a thin dielectric shell which also serves as part of the package for the device. Slight dielectric charging holds the cantilever in either the on- or off-state between switching pulses. In the latched states with no bias, insertion loss is 0.2 dB at 10 GHz and isolation is >20 dB in a narrow band around 10 GHz. Repeatable switching has been demonstrated for actuation voltages below 20 V. Hot-switched power handling has been tested up to 6 W at 10 GHz without failure.

15. SUBJECT TERMS
Microelectromechanical Systems (MEMS), Radio Frequency (RF), Microwave Devices

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT:**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** (Monitor)
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			John L. Ebel
Unclassified	Unclassified	Unclassified	SAR	10	**19b. TELEPHONE NUMBER** *(Include Area Code)* (937) 255-1874 x3462

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39-18

A Latching Capacitive RF MEMS Switch in a Thin Film Package

John L. Ebel, Rebecca Cortez, Kevin D. Leedy, Richard E. Strawser

Air Force Research Laboratory, Sensors Directorate,
2241 Avionics Circle, Wright Patterson AFB OH 45433

***Abstract* — A latching capacitive RF MEMS switch has been successfully designed, fabricated and tested. The switch uses a long thin metal cantilever which is electrostatically held to an upper electrode at the free end and to a lower electrode at the beam root end forming an S-shaped actuator. The upper electrode sits on top of a thin dielectric shell which also serves as part of the package for the device. Slight dielectric charging holds the cantilever in either the on- or off-state between switching pulses. In the latched states with no bias, insertion loss is 0.2 dB at 10 GHz and isolation is >20 dB in a narrow band around 10 GHz. Repeatable switching has been demonstrated for actuation voltages below 20 V. Hot-switched power handling has been tested up to 6 W at 10 GHz without failure.**

***Index Terms* — RF MEMS, microwave devices, microwave switches, microelectromechanical devices.**

I. INTRODUCTION

The current generation of RF MEMS capacitive switches has demonstrated excellent RF performance and reliability under controlled conditions[1][2]. However, there is still some room for improvement in the areas of power handling, temperature stability, switching speed, capacitance ratio, and integration-friendly packaging. The devices described in this work offer the potential for improved performance in all of these areas.

In a spring-force restored switch, the ability to hot-switch RF power is limited by RF latching of the device. RF latching occurs when the holding force created by the RF voltage exceeds the restoring spring-force of the beam. For typical capacitive switches, RF hot-switching power is realistically limited to less than about 1 W. Even at such moderate power, the lifetime of the switch will likely be reduced, because the presence of the RF voltage reduces the amount of dielectric charging that the switch can sustain before failure. Although many system applications do not require hot-switching, allowing hot switching can simplify the system design.

Operation over wide temperature ranges is another concern for RF MEMS switches. In devices using a metal bridge, a significant fraction of the spring constant typically arises from tension in the beam. If the thermal expansion coefficients of the beam and substrate are not well matched, the spring constant will vary significantly with temperature. This temperature-induced variation in spring constant reduces the safe operating margins of the device because the device must be stiff enough to operate at high temperature, but not so stiff that the operating voltage is too high at low temperature.

Switching speed of the RF MEMS switch is determined by the net actuator force, the mass of the moving structure, the distance the structure moves, and the damping of the atmosphere surrounding the moving structure. The increased force from zip-mode[3] or touch-mode[4] actuators compared to parallel-plate actuators is well understood, and the net actuator force can be further increased by removing the opposing spring force of the moving beam. Optimization of the switching speed can be completed by making the moving beam less massive, and by removing the damping atmosphere. Unfortunately, for most spring-force restored devices, their relatively high mechanical Q-factors result in many milliseconds of ringing upon opening when operating in even moderate vacuum.

For parallel-plate actuated spring-force restored devices, there is a critical trade-off between operating voltage, restoring force, and capacitance ratio. For devices operating at the same voltage, the restoring force of the device can be increased by decreasing the open-state gap and increasing the beam spring constant. As a result, the increased restoring force required for reliable operation is achieved by reducing the on-state to off-state capacitance ratio of the device.

Finally, the packaging scheme for the RF MEMS switch should be compatible with a monolithic microwave integrated circuit approach for applications such as phase shifters, switchable filters, and signal routing networks. Ideally, the packaging approach should have low RF losses, should be implemented with standard fabrication processes, and should protect the device from the environment before the device leaves the clean fabrication area. A thin-film packaging approach meets all of these goals. In addition, a device that can operate in a low-pressure environment allows sealing of the thin-film package by a wider range of vacuum deposition techniques than would be available for devices requiring gas damping.

Non-RF devices using S-shaped actuators have been previously demonstrated by Shikida et. al. [5]. A gold-contact RF switch using an S-shaped actuator was previously built by Oberhammer et. al. [6], and achieved an insertion loss of 2.8 dB and an isolation of 30 dB at 15 GHz. In both of these cases, the S-shaped actuator was formed by a wafer-bonding process. While the S-shaped actuator may offer advantages in a contact switch through increased contact force and increased opening force, the advantages of the S-shaped actuator for capacitive switches seam more clear cut. This work reports a low-loss capacitive RF MEMS switch with an S-shaped actuator formed by an integrated fabrication process in a thin-film package.

II. DESCRIPTION OF THE DEVICE

The devices are fabricated on sapphire substrates by the following sequence: (1) evaporate and liftoff Ti / Au (20 nm / 280 nm) transmission lines, (2) sputter and liftoff resistor (>500 ohms/sq), (3) deposit and etch PECVD Si_3N_4 (250 nm), (4) coat and pattern first resist sacrificial layer (1-3 um), (5) evaporate and liftoff Au (500-750 nm) bridge metal, (6) coat and pattern second resist sacrificial layer (1-3 um), (7) sputter Si_3N_4 (1.7 um) cap, (8) evaporate and liftoff Ti / Au (20 nm / 280 nm) top electrode, (9) pattern and dry etch Si_3N_4 cap, (10) wet etch sacrificial resist layers, and (11) dry in supercritical CO2 dryer.

An optical microscope image of the device after release is shown in Fig. 1. The root end of the cantilever can be seen through the Si_3N_4 cap in the left side of the image. Two rows of release holes in the cap run along either side of the cantilever.

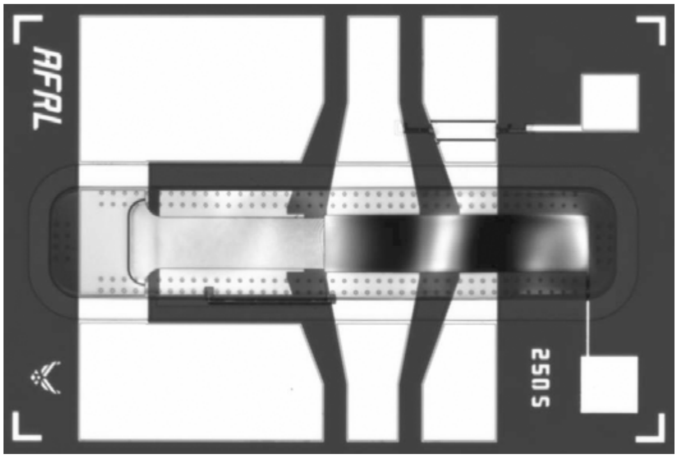

Fig. 1. Optical Microscope image of device after release.

A schematic cross-section of the device in the on-state and off-state is shown in Fig. 2. The bottom holding electrode is 250 um in length and is connected to RF signal line through a 20k-ohm resistor. The cantilever is 90 um x 800 um, and the signal line is 160 um wide where the cantilever crosses. The S-shaped actuator is formed by pulling the free end of the cantilever up to the top holding electrode, and pulling the root end down to the bottom holding electrode after release. Slight dielectric charging holds the cantilever in either the on- or off-state between switching pulses.

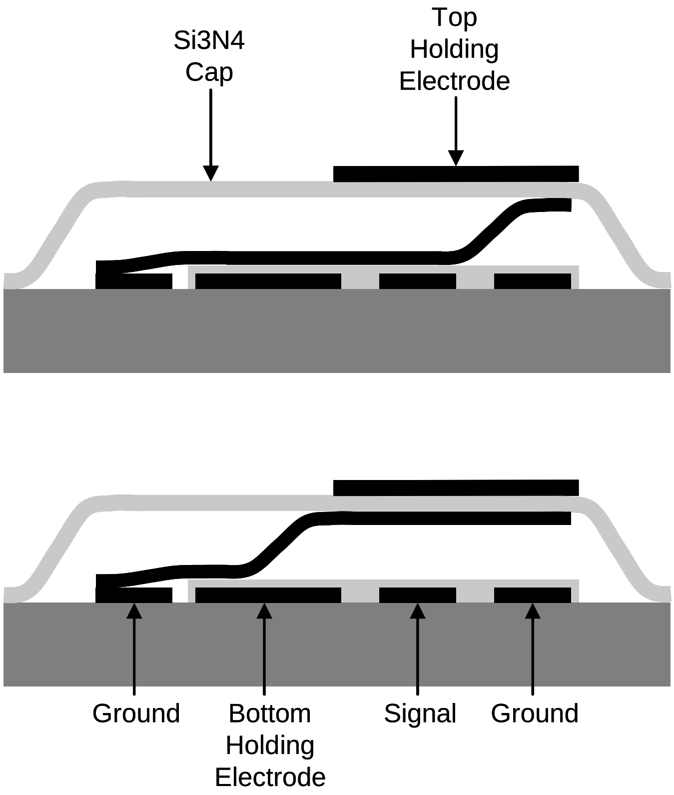

Fig. 2. Schematic cross-section of the device in the off-state (top) and on-state (bottom).

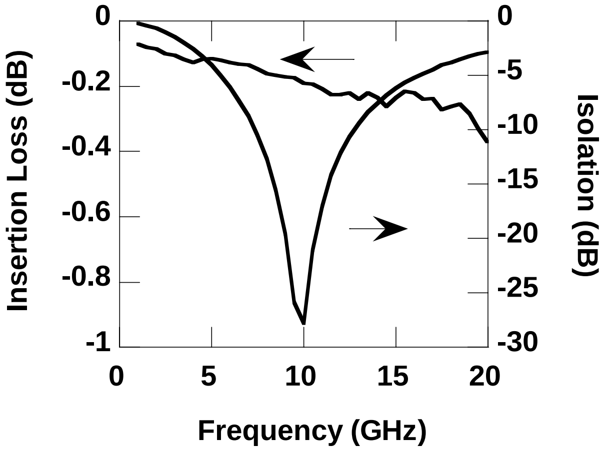

Fig. 3. S-parameter measurements of the device while latched in the on-state and off-state.

III. RF MEASUREMENTS

S-parameter measurements were taken of a device while latched in the on-state and off-state. The measurements shown in Fig. 3 were taken with no bias applied, and the time between latching the device into a particular state and making the s-parameter measurement was greater than half an hour. In the latched states with no bias, insertion loss is 0.2 dB at 10 GHz and isolation is >20 dB in a narrow band around 10 GHz. The resonance in the isolation state is caused by the series combination of the cantilever inductance and the shunting capacitance in the path to ground.

The dynamic latching behavior of the device is shown in Fig. 4 and Fig 5. The measurements were made with RF power of 20 dBm at the device.

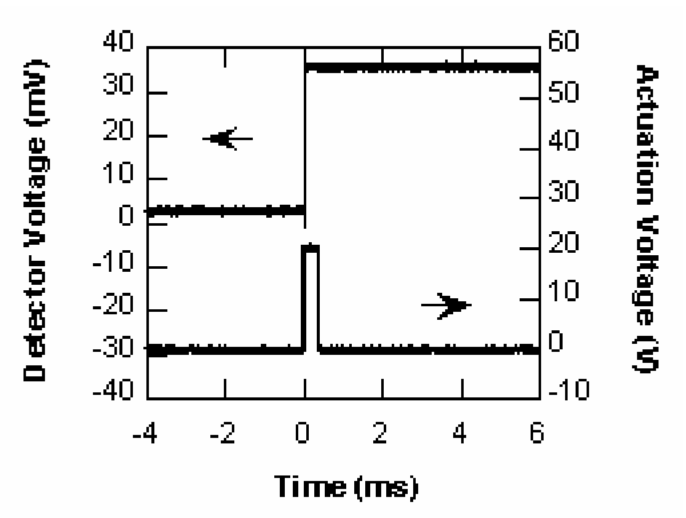

Fig. 4. Turn-on and latching.

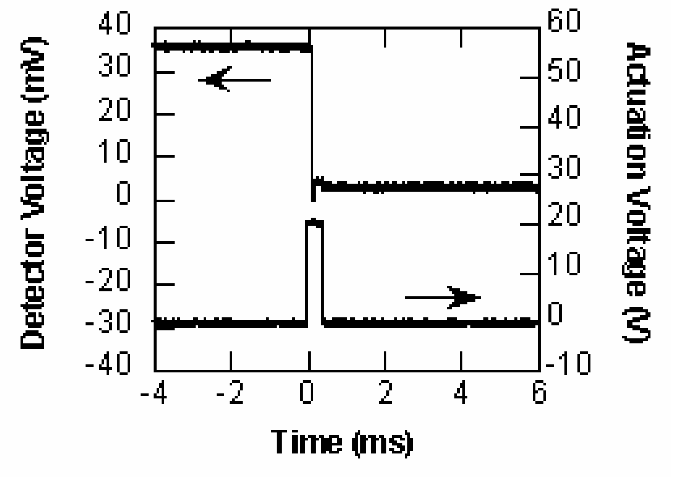

Fig. 5. Turn-off and latching .

Turn-on voltage of the device was measured as a function of RF power up to 38 dBm. As expected, the turn-on voltage increases as the RF power is increased. Fig 6 shows the measured results for turn-on voltage vs. RF power. The turn-off voltage does not increase as the RF power increases. Increasing the turn-on voltage of the device should not greatly accelerate dielectric charging since the upper dielectric layer is substantially thicker than the lower dielectric layer covering the RF signal line and lower holding electrode (1.7 um vs. 250 nm).

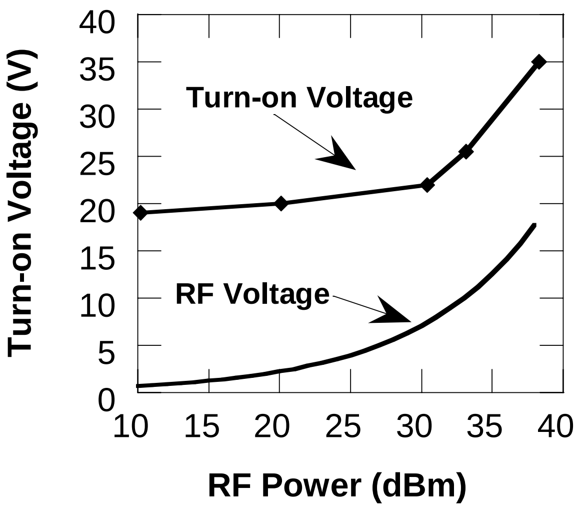

Fig. 6. Turn-on voltage as a function of RF power.

IV. CONCLUSIONS

An integrated process for forming a latching capacitive RF MEMS switch with an S-shaped actuator in a thin-film package has been developed and demonstrated. The power handling and latching characteristics of the initial devices have been measured. Other device characteristics such as temperature stability, switching speed, and lifetime are yet to be measured, but there are clear reasons to expect this type of device to perform well in these areas.

The shape and switching dynamics of the S-shaped actuator are significantly more complicated to model than parallel-plate actuators. Optimization of the device for switching speed and lifetime depends on development of these models. Many alternate RF configurations are possible using this type of actuator, and improved broad-band performance can be designed into the device once a more complete model for the S-shaped actuator is developed.

REFERENCES

[1] C. Goldsmith, J. Ehmke, A. Malczewski, B. Pillans, S. Eshelman, Z. Yao, J. Brank, and M. Eberly, "Lifetime characterization of capacitive RF MEMS switches," *IEEE MTT-S Dig.*, 2001, pp. 227-230.

[2] J. B. Muldavin, C. O. Bozler, J. Vian, S. Targonski, C. L. Keast, M. A. Gouker, “Reliability Testing and Enhancement of RF MEMS Capacitive Switches,” *2004 IEEE MTT-S IMS Workshop*.

[3] G. V. Ionis, A. Dec, k. Suyama, “A zipper-action differential micromechanical tunable capacitor,” *2001 MEMS Conference Digest*, August 2001.

[4] C. Cabuz, E.I. Cabuz, T.R. Ohnstein, J. Neus, R. Maboudian, “Factors enhancing the reliability of touch-mode electrostatic actuators,” Sensors and Actuators (79), 2000 pp. 245–250.

[5] M. Shikida, K. Sato, and T. Harada, "Fabrication of an Electrostatic Micro actuator with an S-shaped Film, *Proc. of Transducers 1995*, pp. 426-429.

[6] J. Oberhammer, B. Lindmark, G. Stemme, “RF Characterization of Low-Voltage High-Isolation MEMS Series Switch Based on a S-shaped Film Actuator,” *Proceedings SBMO/IEEE MTT-S iMOC 2003*, pp. 537-540.