MMIC Compatible High Performance Lateral Deflection RF MEMS Switches

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Abstract

A metal-to-metal contact, lateral deflection (LD) RF MEMS switch has demonstrated excellent RF performance and superior switching speed. The switch operates from DC to 50GHz with an average switching speed of less than 2µs under normal operation, and less than 1µs under "push-pull" operation. Insertion loss of less than 0.2dB and isolation of greater than 33dB at 10GHz have been demonstrated for X-band operation. For higher frequencies, insertion loss of less than 1dB and isolation of greater than 25dB have been demonstrated at 50GHz. The LD switches are fabricated in NGST's 100mm MMIC production line with a RF functional yield of greater than 90%.

INTRODUCTION

RF MEMS switches offer superior performance compared to solid-state switches, especially for low power high frequency applications. Electrostatically acutated MEMS switches, for example, have negligible power consumption, lower insertion loss, better isolation and higher linearity than the solid-state switches. In this paper, we report a Lateral Deflection (LD) RF MEMS switch [1] [2] developed at NGST for broadband, low power applications. This LD switch is a metal-to-metal contact switch, and it has several unique features making it very attractive for systems that require a large number of switches. Unlike most of the MEMS switches reported to date, the motion of the LD switch is parallel to the substrate rather than perpendicular to it. Due to this lateral configuration, the LD switch is inherently a SPDT switch, and can replace two SPST switches in design. This SPDT feature can significantly reduce the number of switches required in a system without changing system design or comprising system performance. In addition, it also reduces chip real estate required for fabrication, making it suitable for large array applications.

The basic lateral switch is a suspended metal beam in a double-clamped configuration, as shown in Figure 1. The switch is actuated electrostatically by applying voltages to the electrodes on either side of the center beam, which is grounded through thin-film resistors. When the LD switch is actuated, the center beam flexes laterally towards the electrode. The center region of the switch was designed to have the smallest lateral separation between the beam and the RF output contact area to ensure that physical contact is made first in this region during switch operation. There are mechanical stops located along both side of the center beam to prevent it from over-traveling. Over-traveling of the beam will cause a short between the beam and the electrodes, eliminating the potential required between the two for electrostatic actuation. The beam stop locations were designed to maximize the contact force in the center region of the switch while preventing the beam from physically touching one of the electrodes during operation.

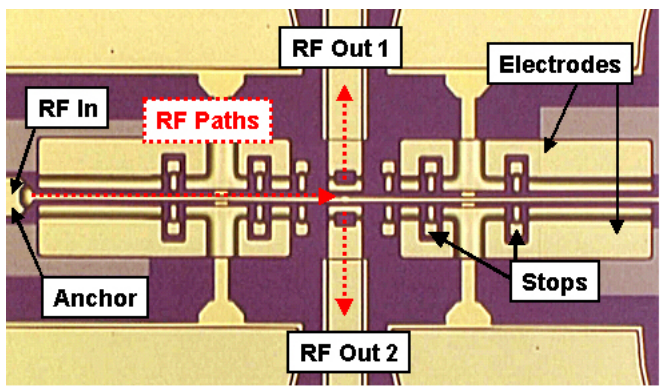

***Figure 1:** Optical photograph of a lateral deflection RF MEMS switch showing its key features.*

In this lateral configuration, the RF input signal is applied through one of the beam anchors, and the RF signal can be routed to either RF Output 1 or RF Output 2 by applying a DC voltage to the appropriate electrode. The two RF paths are illustrated in Figure 1 by the dotted arrows. This lateral switch is bi-directionally powered, hence, it does not rely on spring restoring force of the center beam alone to break contact. This unique feature also enables "push-pull" mode of operation, which further enhances its switching speed. The details of this "push-pull" mode of operation will be discussed in the Switching Speed Section.

SWITCH FABRICATION

NGST's LD RF MEMS switches are fabricated using a simple four-mask surface-micromachining process. Fabrication begins with a blanket nitride deposition for substrate passivation. Next, the thin-film resistor (TFR) layer is patterned and deposited to form the resistors located between the beam anchors and ground, and between the electrodes and DC voltage inputs. These resistors have no functional impact on the switch, they are fabricated as on wafer protection for high frequency test equipment should a short between the beam and the electrodes occur during testing.

After the TFR resistors are fabricated, the first interconnect layer is patterned and deposited followed by the patterning of the sacrificial layer. The sacrificial layer is simply a layer of hard-baked photoresist that forms the elevated region of the LD switch. The photoresist is hard-baked to smooth the transition between the anchored and the elevated portions of the center beam anchors, the electrodes and the stops. Selection of the photoresist and its baking parameters are essential for obtaining the desired profile of the elevated region of the switch. The ideal photoresist profile for this lateral switch is a very flat top surface with smooth edge transition. The flat surface ensures that the maximum electrostatic force can be achieved between the center beam and the electrodes by aligning the two on the same vertical plane. The rounded photoresist edge profile provides smooth transition between the anchored and elevated areas to ensure conformal deposition of the structural metal is achieved.

After the sacrificial photoresist is baked, the structural metal is patterned and deposited to form the key features of the switch. Finally, the switch is released by stripping the hard baked photoresist followed by a supercritical CO_2 treatment. Figure 2 is a scanning electron micrograph showing the center region of the switch after the sacrificial layer has been removed. As shown in Figure 2, the center beam is suspended approximately 1µm above the substrate as defined by the thickness of the sacrificial photoresist. The width of the center beam is 2µm with the exception of the center contact region, which is 3µm wide. The suspended beam is approximately 2µm thick as defined by the structural layer thickness, and the beam length is typically 300µm between the beam anchors depending on switch design. The distance between the RF contact region and the center of the beam is 1µm, and it is 2µm between the electrode and the rest of the beam for electrostatic actuation.

Each of these switch fabrication steps described above is performed at low temperatures, making these MEMS switches compatible with MMIC fabrication. In addition, the fabrication process requires only 4 masks, involves relatively simple processing steps, and can share many layers with standard MMIC processes. This switch fabrication process adds very little fabrication overhead for an integrated MMIC-MEMS process. The described fabrication process is also substrate independent, and LD switches fabricated on GaAs, Quartz, and glass substrates have been demonstrated at NGST.

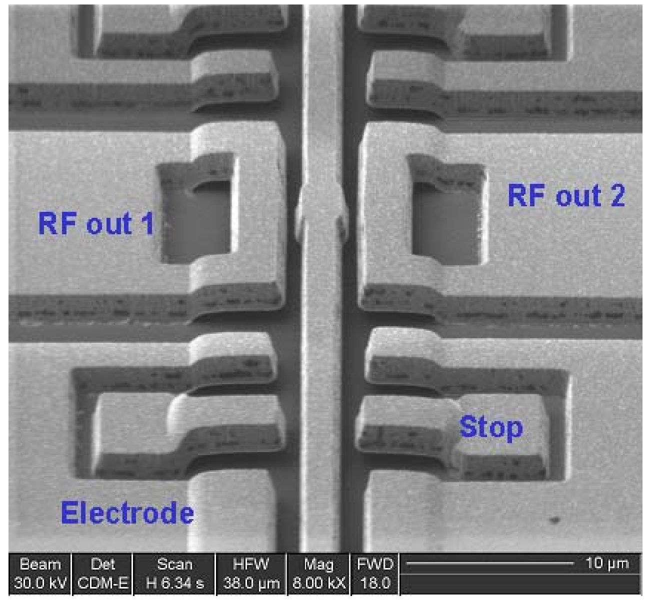

Figure 2: *A scanning electron micrograph showing the center region of the LD switch.*

RF PERFORMANCE

The LD RF switches are suitable for broadband operation from DC to above 50GHz. The lateral switch displays excellent RF performance as shown in Figures 3 and 4. Insertion loss of less than 0.2dB and isolation of greater than 33dB at 10GHz have been demonstrated for X-band operation. At higher frequencies, insertion loss of less than 1dB and isolation of greater than 25dB have been obtained at 50GHz. Switch simulations were performed using HFSS, and ideal condition of zero contact resistance when the switch is actuated was assumed. As shown, the RF response of the switch is also very flat across the entire band (up to 50GHz), and the measured data is in good agreement with simulations.

SWITCHING SPEED

In addition to its excellent RF characteristics at high frequencies, the LD switches also exhibit fast switching speed. There is no squeeze film damping effect observed during switch operation, this is primarily due to the lateral beam motion and the relatively small travel distance required for switch contact. Typical switching speed of a

LD switch is less than 2µs under normal operation. Figure 5 shows the typical closing speed of the LD switch. Under normal operation, the switch has three different positions: the unactuated position in the center (as shown in Figure 2) and the two actuated positions to either side of the RF output contacts. In this case, when the switch is actuated, the beam travels from its central resting position to the appropriate RF output contact, and when the switch is turned off, the switch opens by the beam's spring restoring force back to the center position.

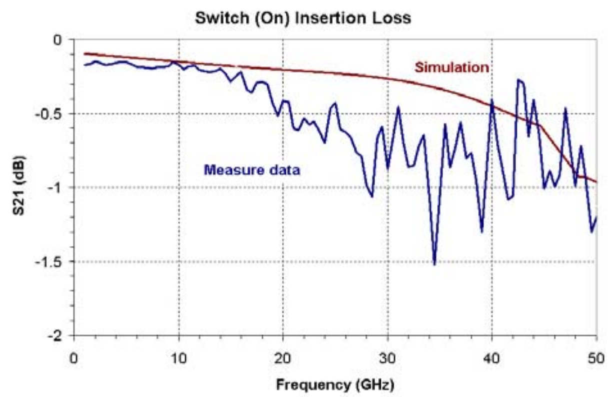

Figure 3: *RF performance of the LD switch: IL of 0.2dB at 10GHz, and 1dB at 50GHz.*

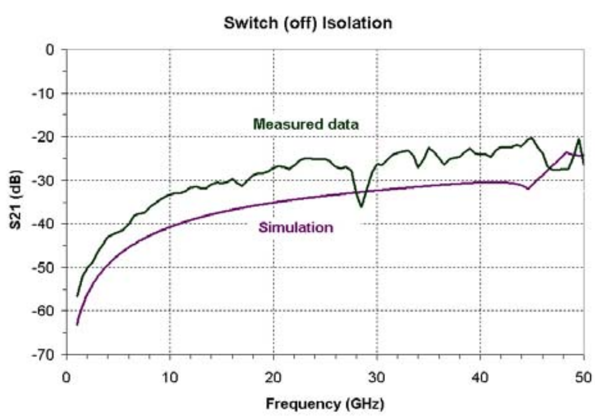

Figure 4: *RF performance of the LD switch, Isolation of greater than 33dB at 10GHz, and 25dB at 50GHz.*

When the switch is operated in "push-pull" mode, the switching speed is further enhanced. In this mode, the switch is bi-directionally powered, and it operates like a SPST switch. To toggle the switch under "push-pull" operation, a voltage is applied to one of the electrodes before the voltage applied the opposite side is turned off. In this case, the switch beam travels from one RF contact to the other, and the suspended beam does not rest in the center unbiased position. As illustrated in Figure 6, the control voltage of the desired contact side (V1) is turned on before the voltage on the opposite side (V2) is turned off, and sub-microsecond switching speed of the LD switch can be achieved with this "push-pull" operation. It is also possible to operate the switch in the normal SPDT mode with power-assisted operation by applying proper voltage waveforms.

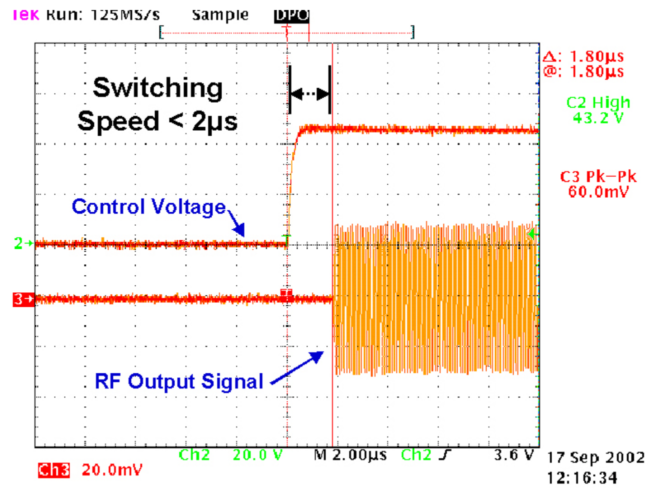

Figure 5: *Switching speed of NGST's LD MEMS switch is less than 2µm seconds under normal operation.*

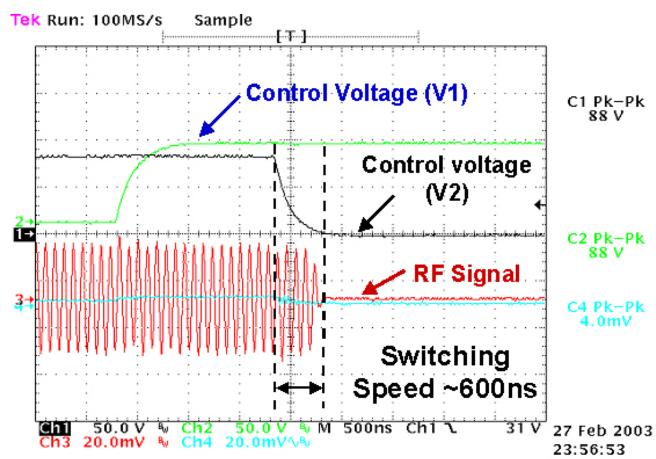

Figure 6*: Sub-microsecond switching speed of the LD switch was demonstrated with "push-pull" operation.*

YIELD AND PROCESS UNIFORMITY

Recently, the MEMS fabrication process was transferred to NGST's 100mm Hi-Rel MMIC production line. Utilizing NGST's production facility with i-line steppers and production-controlled processes, average RF functional yield of the LD switch is greater than 90%. The device testing was performed at NGST's production testing facility with automated testing and data collection. The

MEMS switches are fabricated on the entire 100mm GaAs wafer, from edge to edge. A representative data set obtained from 100% device testing is shown in Figure 7. Figure 8 is the corresponding actuation voltage map obtained from the same wafer. As illustrated in Figure 8, most of the functional rejects are from devices near the edge of the wafer.

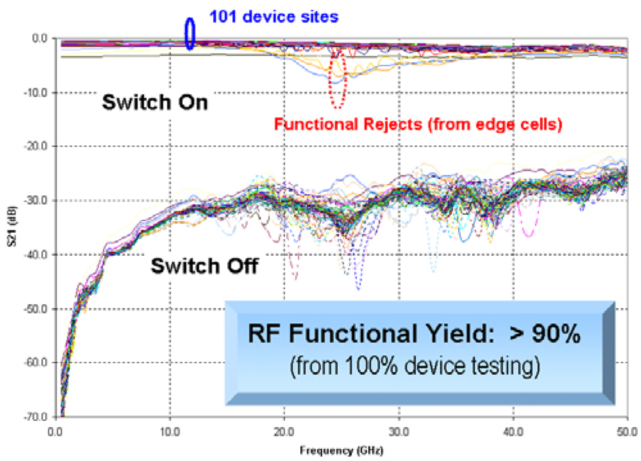

Figure 7: *Representative RF data set from switches fabricated on a 100mm GaAs substrate showing excellent RF functional yield of the LD switches.*

Due to the unique lateral geometry of the switch, the critical dimension, which is the separation distance between the central beam and the electrode, is defined by photolithography. The required electrostatic actuation voltage, V, is a function of this separation distance, d, and d is defined by the photoresist linewidth of the structural layer. Hence, process uniformity can be evaluated by monitoring the actuation voltage of the LD switches across the wafer. As shown in Figure 8, average actuation voltage of this particular type of LD switch is approximately 70V, with a standard deviation of 2.5V across the wafer. With this excellent process uniformity, it is possible to control a large array of switches by one control voltage, which adds flexibility in circuit designs as well as robustness in switch performance.

Conclusions

The Lateral Deflection (LD) RF MEMS switch developed at NGST has demonstrated excellent RF performance at high frequencies, superior switching speed, and high functional yield with good process uniformity. Its compact lateral SPDT design and the dual-powered feature make it suitable for front-end communication and large array systems. In addition, switch fabrication is simple and MMIC compatible, making LD switches a good candidate for circuit integration to further enhance system performance.

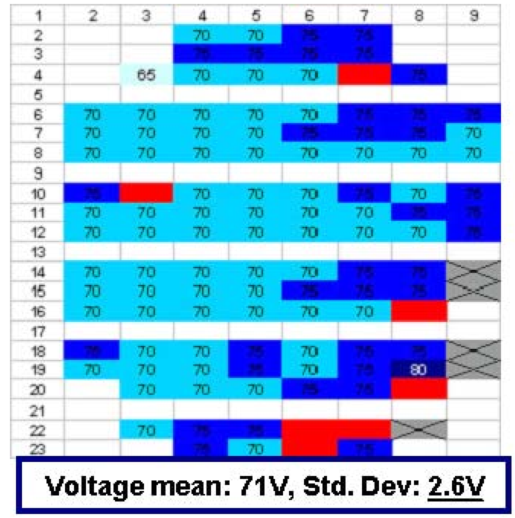

Figure 8: *Actuation voltage map obtained from 100% testing of a 100mm GaAs wafer. The empty rows, (row 5, 9..etc) contain no switch devices, they are test cells with process monitoring structures. The cells with a cross denote incomplete cells in which the particular switch design under test is off the wafer edge.*

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[2] R. B. Stokes, A. M. Kong, J.P. Trieu, and R. U. Bhorania, "Lateral Deflection RF MEMS Switch", *Government Microcircuit Application Conference* (GOMAC), Apr. 2003, paper 16-6.

Acronyms

NGST: Northrop Grumman Space Technology
RF: Radio Frequency
MEMS: Micro Electro Mechanical Systems
LD: Lateral Deflection
SPDT: Single Pole Double Throw
SPST: Singe Pole Single Throw
TFR: Thin-Film Resistor