DEVELOPMENT OF BROADBAND LOW-VOLTAGE RF MEM SWITCHES

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Abstract

We present novel RF switches using micro-electro-mechanical (MEM) technology. These MEM switches are built on GaAs substrates using GaAs MESFET MMIC-compatible processes. The fabricated shunt switches showed an insertion loss of less than 0.2dB and an isolation of greater than 20dB up to 40GHz. The switching speed is 47µS. The broadband MEM switches are promising building blocks for wideband circuits and reconfigurable antenna applications.

INTRODUCTION

FET-based switches are common components in today's microwave subsystems. Present agile-filter and phased-array antennas use III-V-based FETs circuit or *pin* diodes to perform diverse switching functionality. However, the high insertion loss of these switches ranging from 1dB to several decibels at millimeter wave frequencies will be a serious issue for upcoming 20-40Gb/s applications. There is a crucial need for new switch technologies to address the loss issue for next generation communication systems.

The emerging MEMS technology has been attracting a lot of interests in microwave community due to their excellent RF performance. Many RF MEM switch topologies have been reported and they all showed superior RF characteristics compared with their semiconductor-based counterparts [1]. The low insertion loss, high isolation MEM switches have been thought as one of the most attractive devices for reconfigurable antennas and integrated circuit applications. These switches provide GaAs circuits with reduced insertion loss for switching between different line lengths or between high and low-pass filters [2-4]. With the reduction in loss in switching components, fewer amplifiers are required in communication systems. The cost, weight, and heat dissipation problems can be greatly reduced.

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. At the University of Illinois, we are devoted to the development of low-actuation-voltage RF MEM switches. We proposed a novel hinged switch for low voltage operation [5] and reported a promising low voltage operation of 9V and excellent RF performance over the frequency band up to 40GHz[6-7].

In this paper, we demonstrate the potentially manufacturable low-operation-voltage MEM switches that are capable of direct MMIC integration. The 5-mask-layer MEM switch fabrication process is compatible with standard GaAs MESFET MMIC processes developed at the University of Illinois. Fabricated switches on S.I. GaAs substrates show an insertion loss of less than 0.2 dB and an isolation of better than 20 dB over the frequency band of 0.25-40GHz. The minimum operation voltage is 9.5 volts. The measured switching speed is 47µs. We believe these switches will provide a solution to low voltage and highly linear switching methods for the next generation of broadband RF, microwave, and millimeter-wave circuits.

DEVICE STRUCTURE

In this work, MEM switches using a cantilever topology will be discussed. Cantilever beams are the most commonly used structure for MEMS components. The deflected beams provide moving parts of MEMS components with a restoring force when it is de-activated. Cantilever RF switches have been reported by a few groups [1], [9-11]. Most of them require very high operation voltage. Shown in Fig. 1 is a schematic drawing of a shunt cantilever switch developed at the University of Illinois. The RF signals are guided by a coplanar waveguide (CPW) structure. The metal pad is the moving part of the switch and is supported by cantilever beams. When the metal pad is pulled down by electrostatic force, RF signals are shorted to the ground. This corresponds to the switch-off state. The pad bounces back to its up position when the actuation voltage is removed, which corresponds to the switch-on state.

In contrast with other cantilever switches, the actuation voltage is applied on a separated bottom electrode instead of the cantilever beams. This design scheme offers some advantages. First, the cantilever beams are electrically connected to the ground plane, separating the actuation signal from the RF signal. The intermodulation between actuation voltages and RF signals can be alleviated. This also leads to an extremely broadband RF characteristic. Second, the fabrication of cantilever beams is equivalent to an air bridge in already-established MMIC fabrication processes.

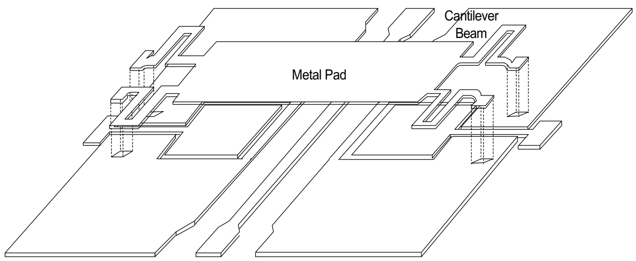


Figure 1. A schematic drawing of RF MEM cantilever switch

As a thumb of rule, the minimum actuation voltage of a cantilever switch can be expressed as [10]

$$V_p = \sqrt{\frac{8Kg^3}{27\varepsilon_o A}}$$

where K is the spring constant of the cantilever beams, g is the gap between the metal pad and bottom electrodes, ε_0 is the permittivity of air, and A is the area of the bottom electrode. In order to get lower voltage operation, we need to effectively decrease the spring constant K. This can be achieved by selecting a low K material and by utilizing a serpentine cantilever beam structure. The effective spring constant of a serpentine cantilever beam can be estimated as [11]:

$$K = \frac{Ew\left(\frac{t}{L_c}\right)^3}{N\left(1+\frac{L_s}{L_c}\left(\left(\frac{L_s}{L_c}\right)^2+12\frac{1+v}{1+\left(\frac{w}{t}\right)^2}\right)\right)}$$

where E and v are the Young's modulus and Poisson's ratio of the cantilever beam; w and t are the width and thickness of the cantilever beam, respectively; L_s is the length of the cantilever beam in each turn, and L_c is the spacing between adjacent turns. N is the total turns of the serpentine beam. With a proper design of beam geometry and the use of low Young's modulus materials, a lower actuation voltage can be achieved.

FABRICATION PROCESSES

The device fabrication is a 5 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 bottom electrodes. A layer of PECVD silicon nitride is deposited, followed by a via-hole etch. A second layer of metal is deposited for metal bump formation. The metal bumps are meant to reduce the physical contact area of the metal pad and CPW structure at switch-off state so that any sticking problems can be alleviated. A polyimide sacrificial layer is spun on and a thick Au layer is evaporated to form the metal pad as well as the cantilever beams. The sacrificial layer is then removed by wet etch. Finally, the devices are released using a carbon-dioxide supercritical drying technique.

DEVICE PERFORMANCE AND DISCUSSION

The fabricated switch is shown in Fig. 2. The metal pad along with four meandered cantilevers is made of a 1–μm thick e-beam evaporated gold. Each cantilever has a dimension of 250μm in total length and 8μm in width. The metal pad size is 80x160 μm^2 and the bottom electrode size is 80x85 μm^2 on each side of the center conductor of a CPW. The switch has a minimum switching voltage of 13volts. The relatively low actuation voltage is a result of the serpentine cantilever structure and reduced material stress by using gold as the pad metal.

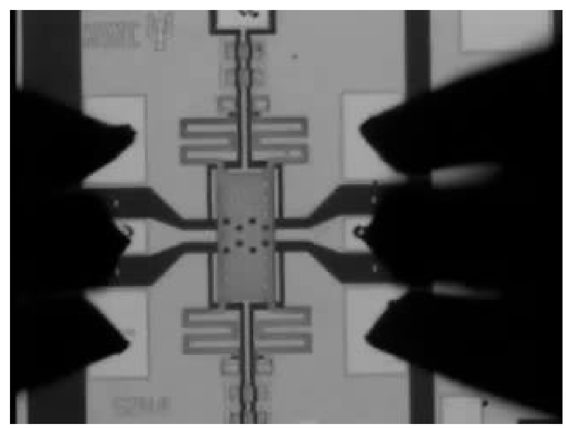
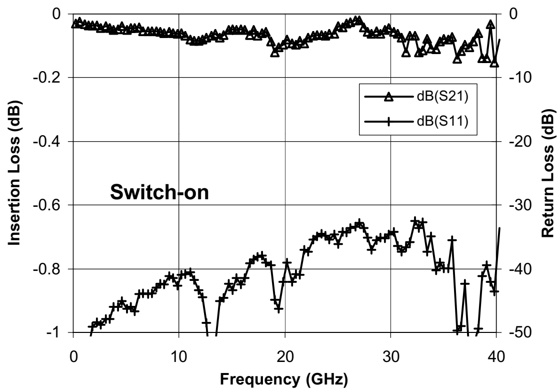
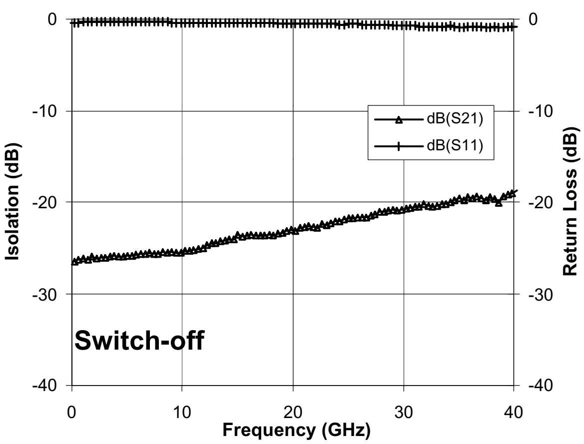


Figure 2. A microscope picture of a cantilever switch

The RF performance is characterized by a S-parameter measurement using an HP8510C vector network analyzer. 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. The measured RF performance of the switch is shown in Fig. 3. For the switch-on state, the switch has an insertion loss of less than 0.2dB with a return loss of less than 30dB at 40GHz. For the switch off state, the switch shows an isolation of 23dB at 20GHz and of 19dB at 40GHz. The relatively flat frequency response for the switch-off state is due to the resistive coupling of RF signals from the center conductor to ground planes



(a)



(b)

Figure 3. The measured RF performance of cantilever switches for (a) switch-on and (b) switch-off states

W_p (μm)	L_p (μm)	L_c (μm)	W_c (μm)	Voltage (V)	Isolation (dB)	Insertion Loss (dB)
80	85	360	8	9.5	17	0.2
80	85	250	8	13	19.5	0.2
100	85	150	10	23	23	0.1
100	85	360	10	19.5	20	0.05

Table 1. A summary of measured results for different device dimensions. W_p and L_p are the width and the length of the pad, respectively, L_c is the total length of the cantilever beam; and W_c is the width of the cantilever beams. Every device has a 4-beam configuration as shown in Fig. 3. The RF data are measured at 40GHz.

Table 1 shows a summary of measurement results for switches with various device dimensions. The results indicate that the beam width and the total length of cantilever beams are two dominant factors for the actuation voltage with similar electrode size. To reduce the actuation voltage, it might be helpful to make a narrower beam and to stretch the beam length. The data show that a minimum actuation voltage of 9.5 volts is achieved for devices with L_c of 360μm and W_c of 8μm with an isolation of 17dB at 40GHz. The relatively low isolation is attributed to the series inductance of the meandered serpentine beams at the switch-off state. The best RF results show an insertion loss of than 0.05 dB and an isolation of 23 dB at 40 GHz can be achieved for the MEM switches.

The measured switching speed is shown in Fig.4. The top trace of the oscilloscope shows the control signal of 5KHz square waves. The corresponding drive signal is a square wave of 15volts and is out of phase with the control signal. The modulated 1MHz HF signal is shown at the bottom trace. The modulated signal shows a time delay of 47μS from the switching-on to the switching-off state. This time delay is defined as the switching speed of a switch. It accounts for the time needed for the metal pad to move from “switch-up” position to “switch-down” position. The experiment results show that cantilever switch is capable of sub-10 volts operation. However, the reduced spring constant will undermine the switching speed as well. As a consequence, a faster switching speed is compromised by the decrease in operation voltage for cantilever switches.

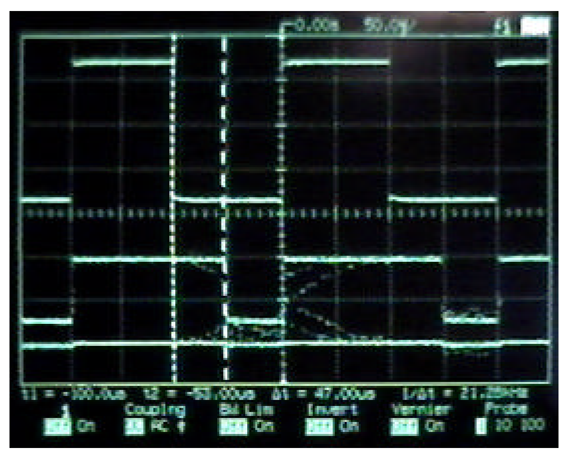


Figure 4. A switching speed measurement of a cantilever switch. The control signal is shown at the top trace and the modulated HF signal is shown at the bottom trace.

A generic lumped-circuit model for RF MEM switch was developed for device performance analysis and circuit design purposes [6]. The lumped circuit model simulates the finite length transmission line embedded in the device and the core portion of a shunt switch. The core portion of the switch is essentially a reactance $R_s + j\omega L_s$ for the switch off state and a capacitance C_s for the switch on state. L_s accounts for the inductance of the suspended metal pad. A smith chart of the modeled parameter versus the measured data is shown in Fig. 5. The lumped model can accurately interpret the behavior of the MEM switch for both on and off states, suggesting the RF MEM switches are very linear devices up to at least 40GHz.

The extracted parameters show an off-state resistance of 1.3Ω series with an inductance of 10pH and an on-state capacitance of 25fF.

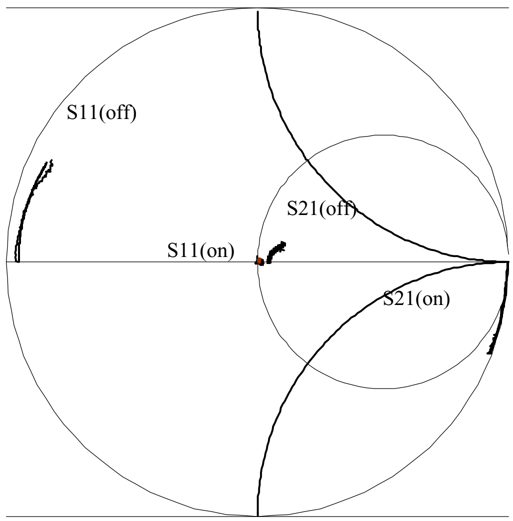


Figure 5. A smith chart showing the measured S-parameters of a switch for both on and off states. The simulated curves are shown in dashed lines and the measured data are shown in solid lines.

CONCLUSIONS

In summary, we have demonstrated state-of-the-art sub-10volts MEM switches. The switch fabrication process is compatible with conventional GaAs MESFET MMIC fabrication processes. It will potentially enable monolithic integration of RFMEMS and MMIC technologies. The fabricated shunt switches show an insertion loss of less than 0.2dB and an isolation of greater than 20dB up to 40GHz. The switching speed is 47µS and the minimum operation voltage is 9.5V. The broadband RF MEM switches are promising building blocks for wideband circuits and reconfigurable antenna applications.

ACKNOWLEDGEMENTS

This work is supported under the contract of DARPA-RECAP program: Mechanically Conformal and Electrically Reconfigurable APertureUsing Low Voltage MEMS and Flexible Membrane for Space Based Radar Applications – Contract No. F33615-99-C-1519

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