Ultra Broadband MEMS Switch on Silicon and GaAs Substrates

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Abstract

This paper reports on the performance of highly reliable dc to 110GHz low-voltage millimeter wave MEMS switches on GaAs and Si. The switch has demonstrated insertion loss less than 6dB and isolation better than 15dB up to 110GHz and a cold switching lifetime greater than 6.9×10^9 cycles. The design and fabrication methods used to achieve ultra broadband performance and high reliability are presented.

INTRODUCTION

The potential for low loss, wide bandwidth operation makes RF MEMS switches highly desirable for use in reconfigurable integrated circuits. However, the widespread use of MEMS switches is presently hindered by poor reliability. Stiction or static friction is a well-known failure for RF MEMS that limits reliability. We have reported the reliability of an RF MEMS switch with rf performance up to 40 GHz [1]. This paper will discuss the use of separation posts, which eliminates stiction and improves the RF isolation performance. The results show that carefully engineered separation posts have resulted in the first MEMS switch with low operation voltage, improved lifetime, excellent rf performance from dc to 110GHz on both Si and S.I. GaAs substrates.

DEVICE DESCRIPTION

The University of Illinois millimeter wave MEMS switch [2, 3] is a shunt design with metal-to-metal contact. The switch is supported at four corners by serpentine cantilevers, as shown in the SEM image in Fig. 1. The shunt configuration is preferable over a series configuration because, in the up state, the CPW transmission line is continuous, resulting in fewer parasitic effects. In addition, in the down state, the isolation of the series switch design is limited by the capacitive coupling between the two open conductors. The fabrication process is designed to be compatible with established back-end MMIC processing techniques. The device includes a metal bridge made entirely of gold that spans a CPW transmission line. In the up state, the switch is suspended approximately 3 μm above the signal line. In the down state, the switch is pulled into direct metal-to-metal contact with the signal line creating a short circuit from signal to ground. The electrostatic force to pull the switch down is provided by a dc voltage applied to the actuation pads beneath the bridge and the restoring force that pulls the switch back into its up position is provided by the mechanical strength of the cantilevers. In our original design [1], silicon nitride covers the top of the actuation electrodes to prevent a short circuit between the switch and actuation pad. In our new design, raised separation posts near the actuation area prevent the switch's failure due to charging effects.

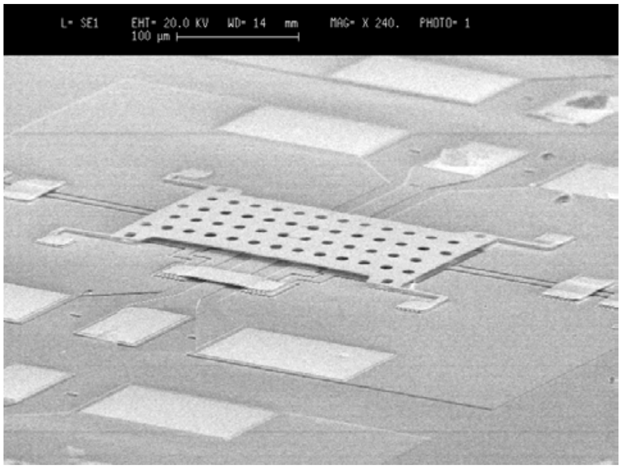

Fig. (1) Fabricated MEMS switch

FABRICATION PROCESS

The UIUC MEMS switch fabrication process is a six-mask-layer process as shown in Fig. (2). The Metal 1 process forms the CPW and dc actuation electrodes on the substrate. Silicon Nitride (SiNx) is used to prevent the shorting of the actuation electrodes to the grounded air bridge. The via hole etching process step creates the electrical contact from the air bridge metal to the signal line in the down state. The contact bumps are then placed in

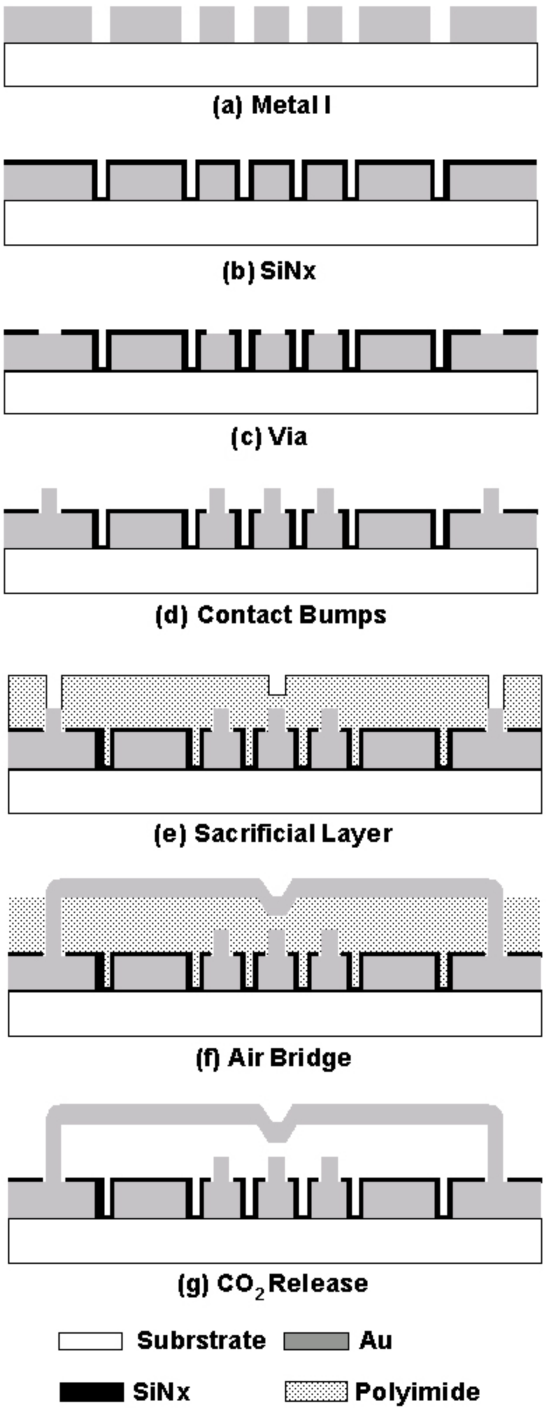

Fig. (2) RF MEMS switch process flow

via holes the using electron beam evaporation. In our MEMS switch process, titanium (Ti) and gold (Au) are used because of the metal adhesion properties of Ti, and the low resistivity and low material stress properties of Au. The total thickness for the coplanar waveguide is 1 µm. After the contact metal process is completed, a photosensitive polymer is used to form the sacrificial layer upon which the bridge will be deposited. A dimple is formed along the signal line which is on top of the sacrificial layer to create the good contact from bridge to the signal line. Without this dimple on the bridge, good isolation is difficult to achieve, and variable capacitor like performance of the switch is observed. Two metal depositions are used for the air bridge formation. A carbon-dioxide supercritical drying technique is utilized in the final processing step preventing sticking during the removal of the sacrificial layer.

POST DESIGN AND RESULTS

Our original design implements the silicon nitride as a barrier for the electrical short. From measured results, the switch tends to stick to silicon nitride in its down state. When the switch is actuated, the greatest amount of contact and highest fields occur between the metal bridge and bottom actuation pad. Therefore charge accumulation is most likely to occur where the bridge contacts the dielectric layer directly above the bottom actuation pads. By positioning separation posts at each corner and within the actuation pad, contact between the suspended metal pad and dielectric is eliminated. Fig. 3 and 4 illustrate the position of the separation posts.

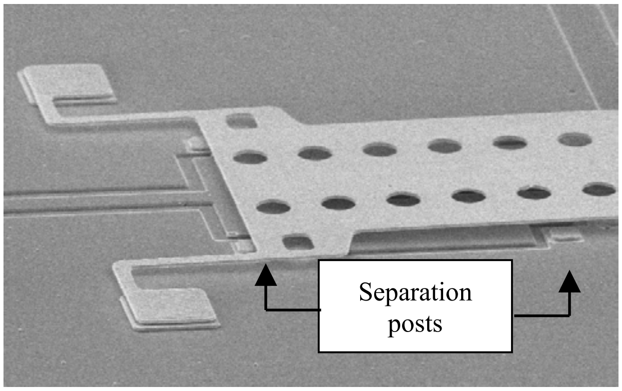

Fig.(3) Separation post to avoid stiction issue

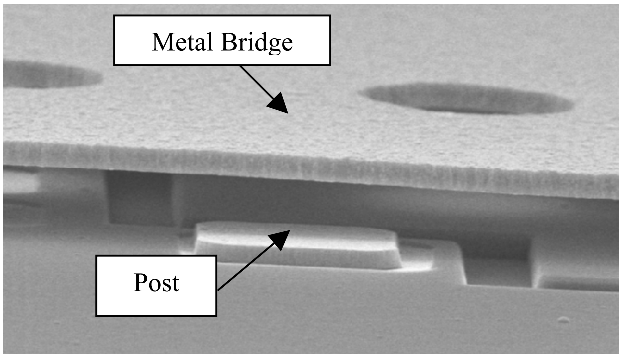

Fig (4) A close view of the post

In our experiment, we fabricated the switches with separation posts on both GaAs and Si. For the Si substrate with a resistivity of 4000 Ohm-cm, we added an additional dielectric layer underneath the CPW to prevent substrate conductivity at high frequency. Devices are tested from 0.25 to 110 GHz in the up and down states on an HP 8510C Vector Network Analyzer to obtain the data in Fig. 4, 5 and 6. S-parameters are measured in three different bands: 0.25-50 GHz (Lowband), 50-75 GHz (V-band), and 75-110 GHz (W-band) using on-wafer SOLT calibrations. The on-wafer SOLT calibration structures place the measurement reference planes 100 μm from the edges of the top metal plate, removing the phase and loss of the CPW pads and transmission line feeds from the measured data.

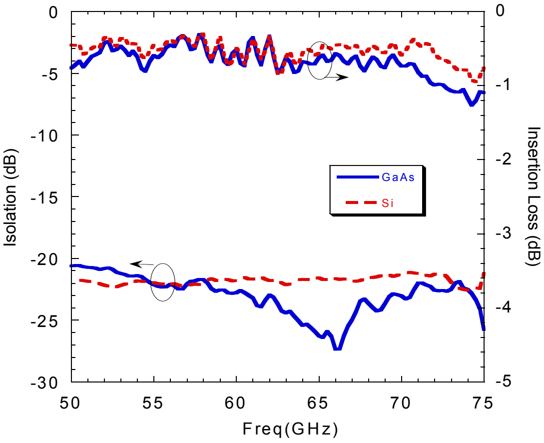

Fig. (4) Insertion loss and isolation for V-band

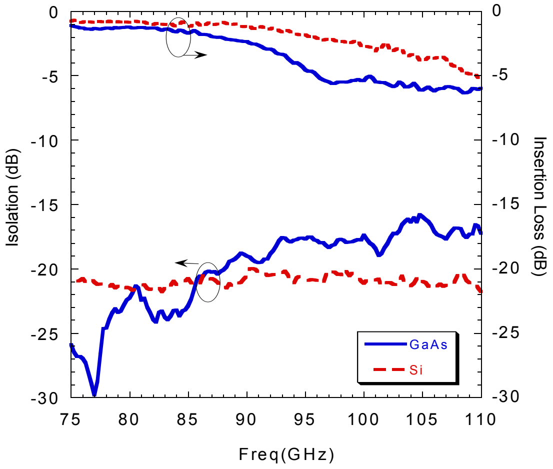

Fig. (5) Insertion loss and isolation for W-band

The best isolation of UIUC cantilever switches without posts is 22dB at 40GHz [1]. However, the isolation usually reduces at higher frequency ranges. The separation posts in our design not only prevents the dielectric-charging problem, it also helps for the device isolation at high frequency. For V-band (50 to 75GHz), the insertion loss is less than 1dB with isolation better than 22 dB for both substrates as shown in Fig 4. For W-band (75 to 110GHz), the insertion loss is less than 6dB for both substrates but the isolation of switches on silicon differ. The isolation of the Si sample is >20dB and the isolation of the GaAs sample is >15dB. The switches on GaAs show increased substrate loss for frequencies higher than 75GHz. To our knowledge, this is the first ever-reported broadband MEMS switch, which can be operated over the frequency range of dc to 110GHz (Fig. 6).

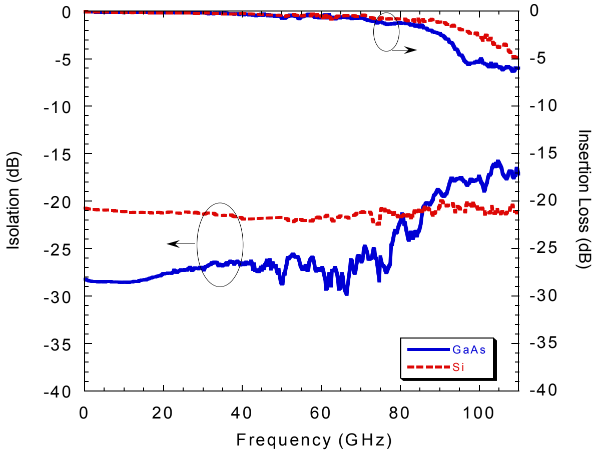

Fig. (6) Insertion loss and isolation for 0.25 to 110GHz

The tradeoff of using post is the increase in actuation voltage. Our future goal for the MEMS switch design is to achieve reliable switching with low actuation voltages. For low voltage operation, the separation post area must be minimized to allow for the largest possible actuation pad area. To examine the effects of the separation posts on actuation voltage, the average actuation voltage was calculated for switches with and without separation posts. The average actuation voltage of 260 switches without separation posts is 13.5 V with a standard deviation of 4.7 V. The average actuation voltage of 438 switches with separation posts is 15.2 V with a standard of deviation of 4 V. These averages include devices that vary in bridge pad, cantilever, and separation post geometries. Therefore, it was possible to accumulate much larger sample pools for the actuation voltage calculations. These averages show that by including posts in the design, low voltage operation is still possible for all of our switch geometries.

The addition of separation posts in our switch design improves the switching lifetime. Table I shows the lifetime summary of switches with and without separation posts. Both best and highest lifetimes have been achieved for the samples with separation posts. Fig. 8 shows our switches' lifetime performance compared with other reported data [4-6].

TABLE I

Lifetime results for switches with and without separation posts

Mechanical Reliability	***Separation Posts***	***No Separation Posts***
Greatest	6.97×10^9	1.62×10^7
Average	3.99×10^8	$\sim 3 \times 10^2$
Standard	2.92×10^8	Not Calculated

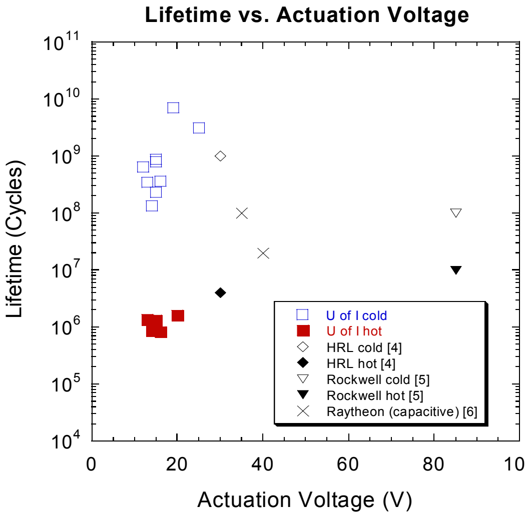

Fig (8) Lifetime comparison of various switches

CONCLUSIONS

We have developed a high performance of broadband MEMS switch, which can be used from dc to 110GHz. Our MEMS switch process is compatible with MMIC processing technique, and can be fabricated on any substrate. Insertion loss of <6dB and isolation >16dB of the switch is measured at 110GHz on S.I. GaAs substrate. Also, insertion loss of <5dB and isolation >20dB is measured on high-resistivity silicon substrate. Separation posts used in the switch design improve both switching lifetime and high-frequency isolation performances.

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ACRONYMS

RF: Radio Frequency
MEMS: Microelectromechanical Systems
S.I.: Semi-Insulating
SEM: Scanning Electron Microscope
MMIC: Monolithic Microwave Integrated Circuit
CPW: Coplanar Waveguide
UIUC: University of Illinois at Urbana-Champaign