

2 × 2 RF MEMS switch matrix

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Abstract: The authors report on the recent development of a 2 × 2 RF MEMS switch matrix for high power applications. The RF design and modelling of the switch matrix using full-wave electromagnetic (EM) simulations are described. The method of fabrication and experimental setup are presented. Results for the recorded RF performance for on and off states are presented. Power handling characteristics of the switch are also examined. Some challenging issues for the development of this type of device are addressed.

1 Introduction

RF MEMS switches have been the subject of intense investigations as attractive alternatives to p-i-n diodes and FET switches for radar and communications [1, 2] applications at microwave and millimetre wave frequencies (RF) [3, 4]. The near-zero power consumption, low intermodulation products, very high isolation and very low insertion loss have driven these investigations. The two main types of RF MEMS switch are the capacitative bridge [5, 6] and cantilever designs [7–9]. However, the reported RF MEMS switching devices are only capable of handling several hundred milliwatts to a few watts microwave power before device failure. Device failure occurs by either ‘stiction’ (a combination of sticking and friction) whereby surface forces, such as electrostatic and van der Waals, produce a permanent adhesion between the two electrodes, keeping the switch in the closed position, or microwelding, which results when the gap between the two electrodes becomes so small that electrical breakdown of the air occurs and the electrodes become fused together. At higher power levels electromigration [10] can also affect the reliability owing to the increased current densities and dimensions involved. The opportunity for these modes of failure to occur increases significantly with the power handling requirements of the switch. It is anticipated that there are great challenges in developing such high power RF MEMS switches, which, however, are of interest for many applications.

There are different approaches in which high power RF MEMS switches may be developed, such as those based on material improvements [11, 12], power splitting [13–15] reducing self actuation and increasing power handling using thick metal CPW topologies [16].

In this paper we report on recent developments of high power RF MEMS switches using a matrix or array of switching elements as shown in Fig. 1a. By exploring a power splitting/combining concept, an increase in the number of rows of the switch matrix can effectively increase the power handling, while an increase in the number of columns of the switch matrix will improve isolation. This approach allows us to configure the switch matrix to be tailored for different power and isolation requirements while maintaining a low RF power level and low actuation voltage at each individual switching element.

2 Electromagnetic design and modelling

For our demonstration, we have designed a 2 × 2 high power switch matrix of this type, which is illustrated in Fig. 1b. This high power switch consists of two pairs of bridge beams for a good stress balance. The bridges comprise four cantilever switching elements, pairs of which are joined head-to-head as shown. Each of the cantilever switching elements is 600 μm by 150 μm, and the whole high power switch chip, including a built-in DC bias circuit, is 1.05 mm by 1.75 mm on a 250 μm-thick high resistivity,
silicon wafer. The switch dimensions including the bias electrode and RF transmission lines are illustrated in Fig. 2. The switch is designed for operation at X-band. In order to minimise dimensions a simple power splitting method is implemented. The 50Ω line is split into two higher impedance lines which are separated by a 50µm gap. The use of other splitter types that utilise λ/4 transformer sections would have resulted in a less compact chip design. As the microstrip line forks the current splits along the outside edges of both lines. As these lines are in close proximity some cancelling of the field between the lines occurs resulting in lower currents on the inside of the branch pair. This coupling can be reduced by increasing the line spacing although this requires building a longer bridge between the switches adding to the fabrication complexity.

Figure 3 shows the full-wave EM simulated performance of the switch design. When all the switching elements are pulled down, by applying an actuation voltage, the switch is in the RF 'On' state. The frequency responses in the off-state are shown in Fig. 3b, where we can see that a high isolation (>30 dB) is achieved over the band.

Figure 4 shows the simulated wideband performance of the quadruple switch. As can be seen the switch was optimised to operate from 8 to 12GHz. The current distribution of the switch at the on state is illustrated in Fig. 5, where one can see that the input power has actually divided into four main current tracks and then combined at the output so that higher power handling can be expected. In the off state shown in Fig. 6 the power is reflected back from the incident port and the output port remains isolated owing to the isolation of two switches on series.

Figure 3  Full-wave EM simulated performances
a On-state
b Off-state

3 Micromachining fabrication

The fabrication processes for the proposed RF MEMS switch that was developed used a seven layer mask set

![Fig. 2](image)  SiN cantilever beam and DC electrodes and RF lines

- a Dimensions (all in millimetres) of SiN cantilever beam
- b DC electrodes and RF lines

![Fig. 3](image)  Full-wave EM simulated performances

- a On-state
- b Off-state

![Fig. 4](image)  EM simulated wideband performance of the designed quadruple RF MEMS switch
illustrated in Fig. 7 to produce a sandwiched or balanced bridge structure of dielectric-metal-dielectric. The mechanical nature of the balanced structure counteracts stresses in the beam, which are process induced or due to the inherent differences in the material properties of the dielectric and metal. The substrate chosen was 250μm FZ-silicon with 10kΩ/cm resistively. The first stage involved initially depositing SiO₂ as an insulating layer followed by patterning the resist (mask 1), then 5 nm of Cr was deposited followed by 2μm Au. Then the resist was removed using a lift-off process.

The second stage involved raising the height level of the pillar and RF contact to be above that of the DC electrode to provide increased switch contact force. To achieve this, a layer of resist was deposited followed by approximately 1μm of Au being added to the pillar and RF lower contact region (mask 2) this was followed by another lift-off stage.

Next a sacrificial layer was deposited and the top contact metal Au was defined (mask 3). A thin Al layer was deposited on the front side surface as an etch stop layer and a gold layer was deposited on the backside of wafer as a ground plane. The fourth stage defined the post hole by etching this in the sacrificial layer (mask 4). The photoreist and Al layer were then removed, followed by 0.5μm deposition of SiN. In the next stage photoreist was patterned (mask 5) and then the SiN layer was dry etched by reactive ion etch to provide the through hole to the electrode layer. The resist was then removed and approximately 1μm Au was deposited for the top electrode (mask

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Fig. 5  Current distribution at on-state for a 10 W RF input at 10 GHz
   a Bottom RF circuitry
   b Top RF contacts

Fig. 6  Charge distribution at off-state for a 10 W RF input at 10 GHz
   a Bottom RF circuitry
   b Top RF contacts

Fig. 7  Fabrication process

Fig. 8  Images of water following release
   a Optical image
   b SEM image (horizontal)
   c SEM (vertical)
   d Surface scan image
6). Finally another 0.5 µm layer of SiN was deposited and defined (mask 7) after this the sacrificial layer was removed by plasma etching thus released the cantilever structure.

After release the wafer was inspected using SEM and surface scan inspections, these are highlighted in Fig. 8. The prototype devices were then diced into 10 mm by 9 mm chips as shown in Fig. 9 and assembled onto a brass carrier to protect the switch and provide heat sinking in addition to facilitating the RF and DC connections. The die was epoxy bonded using Ablefilm™ 5025E onto the brass housing. A Teflon piston applied pressure from a weight assembly shown in Fig. 10 to the die during the curing cycle. A recess in the piston face ensured protection of the switches during this process. The RF connections were made using Huber Suhner SMA connectors with 0.2 mm centre pins. These were directly epoxy bonded to the microstrip feed lines. The DC connections were made using coaxial feed-throughs which were bent slightly and then rotated into position to effect a sprung contact upon the DC actuation pads.

4 DC observations and results

The DC actuation of the switch was observed using an Olympus SZ40 microscope. The DC voltage was switched between 0 and positive 70 V. Actuation was observed to occur at 35.8 V for one for the four switching elements. A second switch element actuates at 50 V and all four can be observed to actuate at 70 V. The differing voltages can be attributed to residual stresses in the cantilever beams affecting the switch electrode heights. The recorded actuation voltage for the first switch agrees with the theory presented from the electromechanical simulations from Intellisuite illustrated in Fig. 11, where the result is given for three initial beam heights.

5 Power measurement set-up and results

The experimental characterisation of the switches at microwave frequency was achieved using the measurement set-up illustrated in Fig. 12. All testing was done with a continuous wave signal at 10 GHz as this is the intended operating frequency for the switch. The microwave power was generated by a synthesised source operating at X-band. The CW signal from the source passed through a variable 0–20 dB attenuator the output signal was then amplified by a Varian travelling-wave tube (TWT) amplifier. The output signal was from the TWT was fed into a 20 dB directional coupler which drew off a signal on the attenuated port for the input power measurement. The through port was coupled to the device under test (DUT) through a coaxial to waveguide transition. After the DUT end-to-end coaxial to waveguide transitions were used to provide DC voltage blocking to the power sensors for the through power measurement.

The measurement set-up was calibrated using a straight through connected measurement combined with a THRU switch equivalent with the DC contacts in place in order to eliminate the effects of the RF and DC feed connections. Once this reference was established the effect of the switch could then be extracted. The power was measured initially for the switch in the OFF position without a DC voltage. The power out as a result of the power in is presented in Fig. 13a. The isolation presented by the open switch was a result of the difference of power out and power in and is presented in Fig. 13b. The input power was increased until 35 dBm without any noticeable change in the isolation of the switch across this range. The isolation remained at approximately –30 dB although this became lower with time owing to slight drift in the gain of the TWT.

The power was then measured for the switch on the ON position with a DC voltage being applied. A voltage of 65 V was used to actuate the switch into the closed position. The power out as a result of the power in was recorded for each step increase in voltage and is presented in Fig. 14a. The
switch insertion loss is a result of the difference between the power out and the power in and is shown in Fig. 14b. After removal of the calibration measurement, the switch insertion loss was measured to be in the range $-1 \text{ dB}$ to $-0.5 \text{ dB}$.

The drift in the TWT amplifier gain resulted in the lowering loss trend recorded. The device under test cold switched a power of 2.3 W without damage occurring. In this instance the switch has not been tested to its maximum limit which remains to be investigated later.

6 S-parameter results

The following results were recorded for the $2 \times 2$ switch design. All measurements were recorded using a HP 870B network analyser. The S-parameter measurements were calibrated using standard SOLT calibration references. The effects of the die housing and connectors was removed using a THRU calibration piece comprising of a switch die with straight microstrip line replacing the switch gaps. Initially the S-parameters for the OFF state were recorded. In this condition all the beams were in the unactuated position, which is approximately 3 mm away from the RF transmission line on the wafer.

The recorded frequency responses for $S_{21}$ and $S_{11}$ in the OFF state are shown in Fig. 15a for $S_{21}$ and Fig. 15c for $S_{11}$. For $S_{22}$ a high isolation (>30 dB) is achieved across the band 8–10 GHz with this result deteriorating to (<20 dB) from 10–12 GHz. In the case of $S_{11}$ a loss was incurred owing to attenuation present in the microstrip line that feeds the switch.

When all the switching elements were actuated to the down position by applying the actuation voltage of 50 V the switch was considered in the ON state and the RF measurements were taken. As can be seen from Fig. 15b and d the switch has a low midband insertion loss of approximately 0.7 dB and a midband return loss isolation (>10 dB). The poorer high frequency results were a result of unwanted cross coupling present in the DC feed networks as this was found to affect the measured switch performance.

The Si/SiO$_2$ combination was found to add significant loss to the $S_{21}$ measurements before calibration, although both high resistive 10 kΩ/cm Si and SiO$_2$ possess low loss. On further investigation it was discovered that when these materials are combined the Si/SiO$_2$ junction can produce an attenuation mechanism at high frequencies [17]. In order to address this problem a suitable alternative dielectric to Si/SiO$_2$ will be required to provide adequate DC isolation. In recent literature the dielectric material benzocyclobutene (BCB) has been successfully used in the fabrication of low loss high frequency applications [18].

7 Conclusion

We have described recent investigations into a $2 \times 2$ power split RF MEMS switch suitable for high power applications, including the RF design, modelling and fabrication processes. The preliminary RF performance recorded shows good agreement with the simulated results. High power performance was recorded with a forward carried power of 33.7 dBm without damage and a reflected power of 35 dBm without self actuation. Further testing of these devices is required to ascertain the full power handling potential and testing of the switching speed performance of the double switch combination is also required. A number of interesting challenges remain in particular within the manufacturing process the reduction of material stresses and improvement of yield shall be addressed. Alternative power splitting designs utilising the same concept presented here are currently being manufactured and further increases in the power handling capability are expected.
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9 References

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Fig. 15 Measured performances

a $S_{21}$ OFF-state
b $S_{21}$ ON-state
c $S_{11}$ OFF-state
d $S_{11}$ ON-state