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Conference Paper

Cantilever Beam Metal-Contact MEMS Switch

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We present a new design of a miniature RF microelectromechanical system (MEMS) metal-contact switch and investigate various aspects associated with lowering the pull-down voltage and overcoming the stiction problem. Lowering the pull-down voltage in this design is based on reducing the spring constant by changing the cantilever beam geometry of the RF MEMS switch, and the stiction problem is overcome by a simple integrated method using two tiny posts located on the substrate at the free end of the cantilever beam.

1. Introduction

With the increased demand for faster, smaller, highly tunable, and cheaper communication systems that consume less power and have wider bandwidths, micromachining techniques and MEMS devices found a new field of applications. RF MEMS switches have been introduced as a prime candidate to replace the conventional solid-state switches, since they offer high isolation, very low insertion loss, high linearity, and an actuator that does not require any special epitaxial layers as in the case of diodes [1, 2].

The RF MEMS switch is a switching device that is fabricated using the micromachining technology, where the on/off switching is achieved via mechanical movement of a freely moving structure. Actuation mechanisms for forces required for mechanical movement include thermal, electrostatic, magnetic, and piezoelectric. Each method has its own problems; high power requirements and slow switching speed in using thermal; high voltages in case of electrostatic which may lead to difficulty of integration; high complexity, cost, and power requirements for magnetic actuation; and integrating piezoelectric materials for piezoelectric actuation is problematic, because films are difficult to pattern and the processing involves high crystallization temperature [1–4]. Among these actuation mechanisms, MEMS switches that operate electrostatically are most commonly used in RF circuits, as they are the simplest, the most compact, and the lower in power consumption. MEMS switches also have the advantage that they do not involve any special processing steps which are not supported by normal MMICs processes [1, 3].

In this paper, the cantilever beam metal-contact switches are selected since they utilize direct physical contact between metals with a low contact resistance to achieve low insertion losses when actuated. They can, therefore, be operated at higher frequencies, low loss, and an isolation defined by the coupling capacitance between electrodes when the switch is open. Further, a cantilever switch offers the important advantage of reduced pull-down voltage, when compared to that required by the air-bridge switch [1, 5].

Even though cantilever beam RF MEMS switches show very good performance, current implementations still suffer from a high pull-down voltage and the stiction problem restricting their integration with RF circuits.

In order to lower the actuation voltage of the MEMS switch, three different routes can be followed: (a) increasing the actuation area; (b) diminishing the gap between the cantilever and bottom electrode; (c) designing a structure with a low spring constant. In the first case, the area can only be increased by so much before compactness becomes a prevailing issue. In the second case, the isolation (parasitic parallel plate capacitance) associated with the RF signal restricts the value of the gap. The third route is the most flexible, since the design of the springs does not considerably impact the size, weight, and the RF performance of circuits [6, 7].

With low pull-down voltage switches, still stiction (adhesion) problem in cantilever beam MEMS switch with metal to metal can be a serious problem within operation, which occurs when the cantilever beam touches the contact pad, where the contact surfaces become stuck in the form of strong a adhesion. These surfaces may be unable to separate even if the applied voltage is removed [8, 9]. Figure 1 shows the stiction phenomenon in the cantilever MEMS switch.

In order to overcome the adhesion forces generated at the contact interface, many techniques have been reported to reduce stiction. This can be achieved by (a) selecting contact materials with less adhesion; (b) adding a thin dielectric layer to separate two conducting electrodes when actuated between the electrodes; (c) applying chemical surface treatment; (d) eliminating contamination with plasma cleaning; and (e) increasing the equivalent spring constant by increasing the cantilever thickness and shortening the cantilever length. Although these techniques can increase restoring forces, the pull-down voltage and insertion loss will increase significantly as a result. This can reduce the device efficiency [8–11].

As explained, the design of a cantilever beam MEMS switches with low pull-down voltage, which are compatible with RF circuit and that can overcome the stiction problem is still a challenging task. This paper addresses these design challenges in the case of electrostatically actuated cantilever beam metal-contact RF MEMS switches.

2. Switch Design

In managing the trade-offs between the switch parameters in this design, the pull-down voltage and stiction problem are given the highest priority, followed by the insertion loss and the electrical isolation. To reduce the spring constant of the cantilever beam (to obtain a low pull-down voltage), there are three parameters that can be changed, namely, cantilever beam material, thickness, and cantilever beam geometry. Of these parameters, only changing the beam geometry does not require any fabrication changes and providing high cross-axis sensitivity between vertical and lateral dimensions in compact area.

By analysis of the performance of RF MEMS switch configurations, it is clearly seen that the cantilever beam is the most crucial part of an RF MEMS switch. Not only it determines the pull-down voltage and operation frequency but also is the source of most the dominant failure mechanisms in the switch. The cantilever beam must be strong enough so that the restoring force can overcome the stiction to ensure proper operation of the switch. One should note that while we aim at maximizing the restoring force, there are several constraints that must be considered such as the resonant frequency; the pull-down voltage, which must be in a reasonable range; the gap between cantilever contact and bottom pad contact, which must be above a minimum height to ensure proper isolation; and the switch size that must be reasonable in order to ensure compatibility with RF circuits.

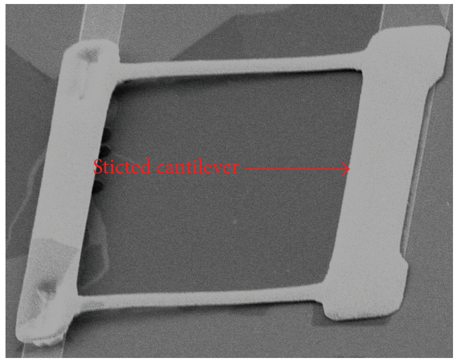


Figure 1: Stiction phenomenon in the cantilever MEMS switch.

The cantilever beam FR MEMS switch with non-meandered suspension shown in Figure 2 is the solution for integration with RF circuits, since it can be operated at high frequencies.

The proposed MEMS switch structure has a movable top cantilever beam which consists of a contact pad and two non-meandered suspensions connected with two supporting posts from one side at the input signal line. The other side is elevated above the bottom output signal line. The contact pad connects RF signal lines and enables actuation when a DC voltage is applied. The area of contact pad is a more limited variable than others because even though the larger the contact pad, the lower the insertion loss is, but also the poorer the off-state electrical isolation is because of the increased capacitive coupling between the contacts pads. This capacitance can be reduced by increasing the air gap, but this increase in the gap also increases the pull-down voltage since the same gap distance also determines the actuation capacitance. Furthermore, the increase in the pad area increases the overall mass of the cantilever beam, and thus the switching time of the MEMS switch. Many switches with different contacts pad areas have been fabricated, and their electrical and mechanical performances were tested. The switch with 3175 μm^2 contact pad area was chosen. It is large enough to provide lower pull-down voltages, good isolation, and a minimum contact resistance—avoiding any ohmic heating due to passing a large DC or RF signal; hence, the cantilever beam with 2 μm thickness of gold was used. When there is no DC voltage applied, the cantilever beam will be in the up position where the contact pad does not allow the RF signal to directly pass through the switch. The cantilever beam can be pulled down to the bottom contact by applying a DC voltage creating a short circuit that allows the RF signal to pass through the switch. If the DC voltage is then reduced, the cantilever beam releases backup (typically at a lower voltage than the actuation voltage).

The geometry of cantilever beam in this design was chosen to produce the lowest possible pull-down voltage. Also, the gold was chosen as a switch material since it provides a

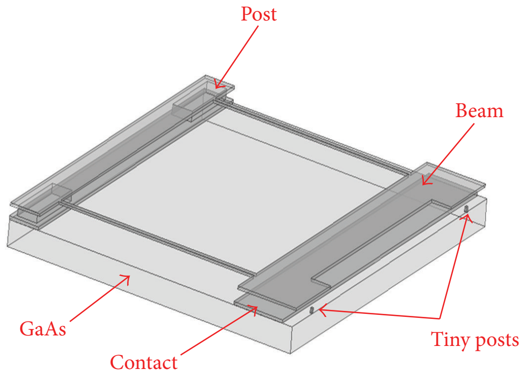


FIGURE 2: Structure of cantilever beam MEMS switch.

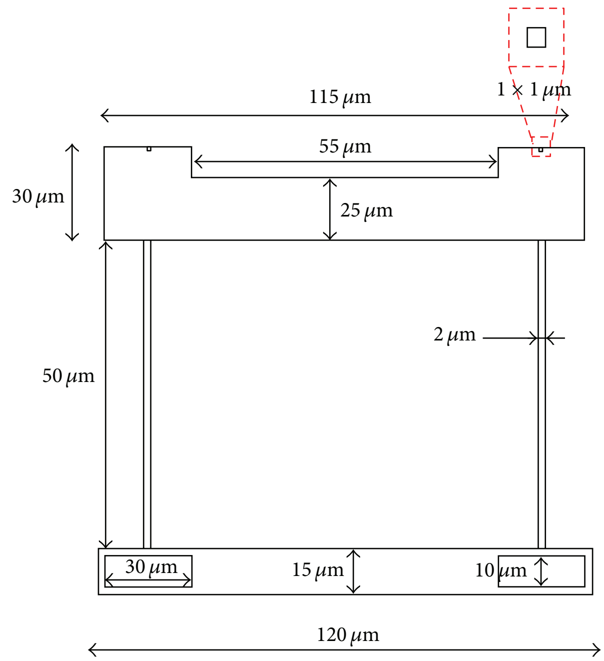
low Young's modulus of 57 GPa. However, reduction of the spring constant might cause more stiction problems during operation. Therefore, in this design, we propose a simple integrated way to prevent the stiction problem using two tiny posts located on the substrate at the free end of the cantilever beam. These tiny posts will limit the downward motion of the contact pad and maximize the mechanical restoring force without significant effect on pull-down voltage. This solution should be effective no matter what the actual cause of stiction is. To calculate pull-down voltage and compare it with the designed values, the cantilever beam dimensions were measured using a scanning electron microscope S4700. Dimensions are given in Figure 3.

The calculated pull-down voltage was 14.8 volt. This agrees well with the measured value of 12.5 volt with an actuation current of about 1 mA. This makes the power consumption to be 12.5 mw. Our design requires zero power to maintain the switch in either the off-state due to the nature of the electrostatic actuation. Figure 4 shows I-V measurements of the proposed switch. Measurement was done using an on-wafer DC probe station. The switch off-state capacitance and contact resistance have been calculated based on the measured dimensions and were approximately 9.54 pF and 0.615 Ω, respectively. This results in a high electrical isolation of −32.4 dB and a low insertion loss of 0.053 dB at 200 GHz.

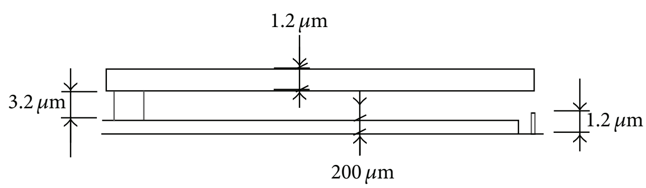
3. Fabrication

The cantilever beam MEMS switch fabrication is based on elevated micromachined structures technology. The switches were fabricated on a GaAS substrate with a substrate thickness of 630 μm and a dielectric constant of 12.9. The most common materials that could be used for the fabrication of the RF MEMS switches are copper, aluminum, or gold. Examining the trade-offs of each one of them, gold was a logical choice as the switch material for our design, since it has a good conductivity (0.452/cm$\mu\Omega$), a smaller Young's modulus, a low propensity to form alien surface films, high melting point, is easily deposited, and is corrosion resistant.

The first two layers (dc switch pads, tiny posts) are built with the same process using E-beam lithography and evaporation and a liftoff of 30 nm/250 μm thickness for the switch pads and 50 nm/1.2 μm thickness for the tiny posts of nichrome/gold layer. This was the stage where accurate pattern transfer was most important as the e-beam markers must be accurately reproduced to ensure that the alignment of subsequent layers is correct. The second stage was to build the cantilever beam using an air-bridge process. This stage started with defining the supporting posts in AZ4562 photoresist followed by exposure and development. The thickness of



(a) Top view



(b) Side view

FIGURE 3: Dimensions of cantilever beam MEMS switch.

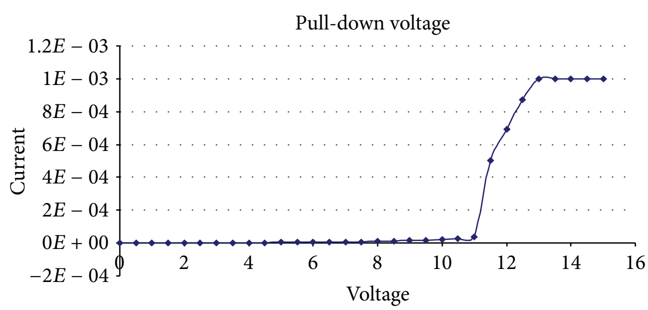


FIGURE 4: I-V measured characteristics of the fabricated cantilever MEMS switch.

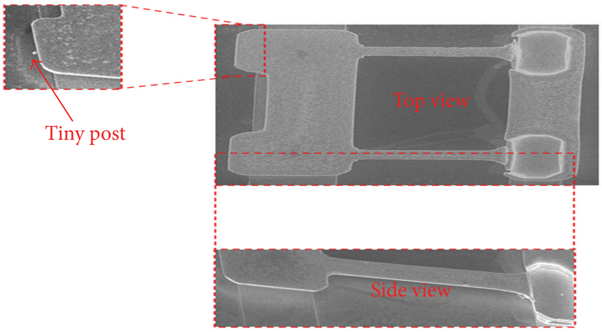


Figure 5: SEM photo of cantilever beam MEMS switch.

photoresist determines the height of the cantilever. The thickness can be varied as required by using different spinning speeds. A 50 nm/10 nm thickness nichrome/gold seed layer was deposited using the Plassys MEB Electron Beam Evaporator. The titanium (Ti) layer provides adhesion for the posts contact, and the 10 nm Au layer prevents the Ti layer from oxidizing. A 40 nm layer of Au was then sputtered to provide the electrical contact for the subsequent electroplating. Next, the switch cantilever beams were formed in 2 μm thick S1818 photoresist followed by electroplating of 2 μm thickness of gold. The top layer of 1818 photoresist was removed by flood exposure and development. The seed layer was then etched away in gold etching to remove the Au followed by Ti etch in 4 : 1 buffered HF. Finally, the bottom layer of AZ4562 was removed by flood exposure and development. Figure 5 shows the SEM photo of cantilever beam MEMS switch.

4. Conclusion

In conclusion, it can be seen that the proposed RF MEMS switch configurations described in this paper offer a new method to design and fabricate RF MEMS switches. The proposed switches utilize physical contact of metal with low contact resistance to achieve low insertion loss when actuated, so it can be operated at the G-band frequencies with an isolation defined by the coupling capacitance of the electrodes when the switch is open. The fabrication scheme offers a new method for monolithic integration with active MMIC transceiver circuitry.

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