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Thermal Effects and RF Power Handling of DC~ 5GHz MEMS Switch

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Abstract: A DC to 5GHz series MEMS switch is designed and fabricated for wireless communication applications, and thermal effect and power handling of the series switch are discussed. The switch is made on glass substrate, and gold-platinum contact is used to get a stable and little insert loss. From DC to 5GHz, 0.6dB insertion loss, 30dB isolation, and 30μs delay are demonstrated. Thermal effect of the switch is tested in 85℃ and − 55℃ atmosphere separately. From DC to 4GHz, the insert loss of the switch increases 0.2dB in 85℃ and 0.4dB in − 55℃, while the isolation holds the same value as that in room temperature. To measure the power handling capability of the switch, we applied a continuous RF power increasing from 10dBm to 35.1dBm with the step of 1.0dBm across the switch at 4GHz. The switch keeps working and shows a decrease of the insert loss for 0.1~ 0.6dB. The maximum continuous power handling (35.1dBm, about 3.24W) is higer than the reported value of shunt switch (about 420mW), which implies series switches have much better power handling capability.

Key words: RF MEMS switches; thermal effects; power handling capability
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1 Introduction

MEMS technology provides a new chance to the fabrication of RF devices for super performance and low cost. These devices have low loss, broad band and negligible current consumption[1,2], which have been exploited to fabricate phase shifters with very low loss[3,4]. They have also been used to develop a new class of MEMS tuned LC filters which operate at frequencies up through 3GHz[5]. The use of microelectromechanical systems (MEMS) brings several advantages to applications including the design of phased antenna arrays and broadband receivers at microwave and millimeter-wave frequencies[6,7].

The switch is arguably the paradigm RF-MEMS device. The switches can be categorized by the following three characteristics: (1) RF circuit configuration; (2) mechanical structure; (3) form of contact. Each type of switch has certain advantages or drawbacks in performance, but two types stand out because of their continued pursuit by several different research groups: (1) the cantilever- or spring-actuated switch having a metal beam on the free end of the cantilever that forms an series-configured metal-to-metal contact[8] and (2) the self-actuated bridge switch that forms an parallel-configured metal-insulator-metal contact[9].

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Significant effort is underway to optimize the fabrication and packaging processes associated with the manufacture of MEMS switches. Process advancements via formation through thick silicon substrates and wafer level packaging are in work[10]. Signification effort is also underway to reduce manufacturing variability within the fabrication processes to improve the lifetime of switches[11]. Recent improvements in processing have enabled orders of magnitude improvement in switch lifetime.

In commercial viewpoint, shorter range, modest RF power, and smaller distributed systems are used widely, especially in cellular wireless network like individual terminals or nodes of the network. The popular digital cellular and personal communications service (PCS) bands around 0.9 to 2.4GHz, and in the nearly future, to 5.6GHz. Therefore, switches banding around 0.9 to 5.6GHz are possess of the significant market merits.

In these applications, RF power may be applied to the switch. These RF power levels and their effect on the switch need to be explored to decide what applications the switch can be used effectively. Pillans *et al.*[12] had measured the power handling capability of shunt switch at 10GHz. As the results, the power handing of a continuous wave applications was 510mW. If the switch was operated in a pulsed RF power mode, the power handling was up to 4W. Pillans *et al.* also found that the failure mechanism is self-actuation in high RF power level. Thiel *et al.*[13] presented another failure mechanism. High RF power to the switch produces an increase of temperature, which leads to redistribution of mechanical stress of the switch. This redistribution results in a constant increase of actuated voltage during switch operation. But there are little research reports about the power handling of less than 10GHz, series MEMS switch.

It is important to set up the environment´s effect on the switch in real applications, but there are little papers about this subject. Because the MEMS switch depends on mechanical movement to control the microwave signal, and the mechanical parts distort with temperature change, the performance of the switch that we proposed will shift with the surrounding temperature.

We designed, fabricated, and packaged a series-configured, metal-to-metal contact switch banding around DC to 5GHz and the performance of the switch was tested. The switch was put into an oven set in 85℃ and −55℃ separately, and the microwave performance of the switch was tested again. Following a continuous microwave power was applied across the switch, the insert loss was measured in different power level. At last, the switch was fetched out from its package and observed under micrograph after power testing.

2 Design consideration

A sketch diagram of the switch is shown in Fig. 1. A transmission line is separated by a gap, a metal strap is suspended several micron above the gap and the metal strap is attached to the cantilever.

The switch in the state of isolation is shown in Fig. 1. When actuation voltage is applied between the upper and bottom electrodes, the cantilever is bended down by electrostatic force and the metal strip contacts with the two parts of the transmission line. Here the switch is in the "on" state.

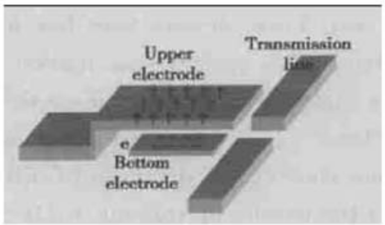

Fig. 1 Sketch diagram of the structure of the switch

Insert loss, isolation, actuation voltage, and switching delay are four important characteristics of the switch. In the design of the switch, we need to derive the relations between these characteristics from the structural parameters. Generally, the resonance theory is used to treat the mechanical feature of the switch, and the microwave performance of the switch accords to Maxwell equation. We use finite element analysis (FEA) in the design of the switch because the physical parameters are not uniform in the whole structure.

The actuation voltage and switching speed of the switch can be simulated by mechanical simulation. We would not introduce the methods in details since it had been discussed thoroughly in previous paper[14]. Correspondingly, the microwave performance of this kind of switch is never proposed, here we would give a detailed description on the methods and results of the microwave simulation.

We use HFSS, a kind of electromagnetic field analysis software, to simulate the S parameters in "on" and "off" states. The model is shown in Fig. 2. The results of the electromagnetic field simulation is shown in Fig. 3. From 1GHz to 5GHz, the insert loss of the switch is lower than 0.6dB, and the isolation is higher than 30dB.

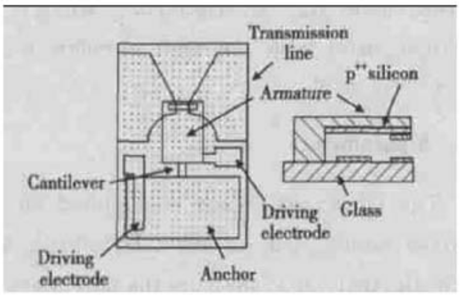

Fig. 2　Model of the switch for electromagnetic field simulation

3　Fabrication

The switch was fabricated on the dissolved silicon process. The flow chart of the process is illustrated as Fig. 4. The switch was fabricated first by heavy boron diffusion to induce a self-stop layer in silicon wafer (Fig. 4(a)). Lithograph and dry etching was used to prepare the anchor (Fig. 4(b)). Silicon dioxide was then deposited. Following, aluminum sacrificial layer and gold were deposited and

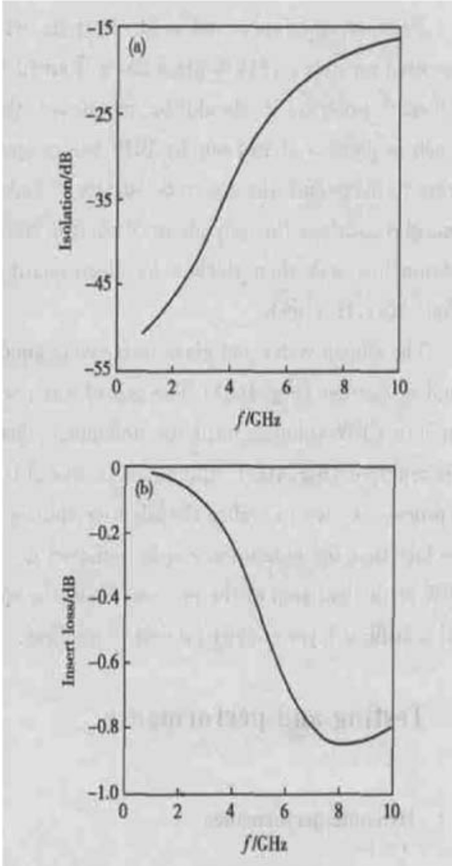

Fig. 3　Simulation results of the switch　(a) Isolation; (b) Insert loss

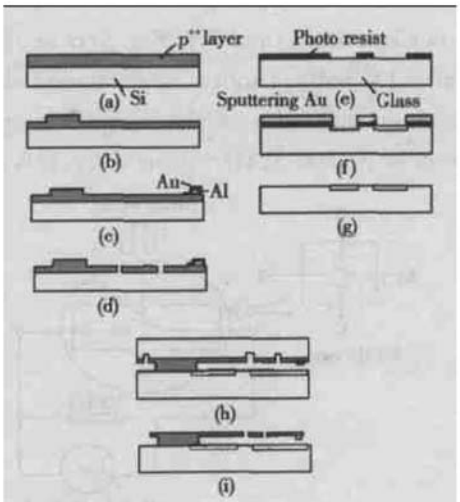

Fig. 4　Silicon dissolved process flow for the fabrication of the switch　The adaptive contact is prepared by aluminum sacrificial layer process.

patterned (Fig. 4(c)). The armature and the cantilever of the switch were formed by another lithograph and the following ICP etching (Fig. 4(d)).

Titanium, platinum, and gold electrode were deposited on Pyrex 7740# glass and patterned by "lift-off" process. It should be mentioned that trench in glass is etched out by BHF before sputtering to make sure the electrode surface is higher than glass surface for only about 50nm, the transmission line was then thicken by electroplating. (Figs. 4(e), (f), (g)).

The silicon wafer and glass wafer were anodic bonded together (Fig. 4(h)). The pair of wafer was put into EPW solution until the undopped silicon was removed (Fig. 4(i)). Aluminum sacrificial layer process is used to realize the adaptive contact in the fact that the aluminum can be removed in the EPW at the last step of the process. Thus, the special sacrificial layer etching process is needless.

4 Testing and performance

4.1 Dynamic performance

The diagram of the dynamic testing circuit of the switch is shown in Fig. 5. A square wave signal was applied to the driving electrode of the switch (across electrodes D and G in Fig. 5); a serial resistor and a DC voltage source were connected across the contact electrodes of the switch's signal line (electrodes S1 and S2); an Agilent 54622A oscilloscope was used to observe both the driving signal and the voltage drop on the resistor.

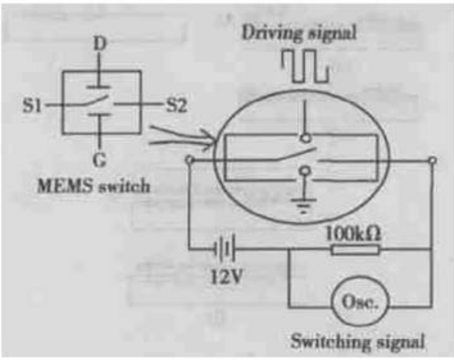

Fig. 5 Sketch diagram of MEMS switch and the testing circuit S1 and S2 are the two terminals of switch, D is the driving electrode, G is the ground of driving circuit. A driving signal is applied on the D electrode of the switch, and the voltage drop across a series resistor is monitored by an oscilloscope.

The dynamic performance of the switch is shown in Fig. 6. The driving voltage is about 22V; the turn-on time delay is about 15μs and the turn-off time delay is less than 10μs.

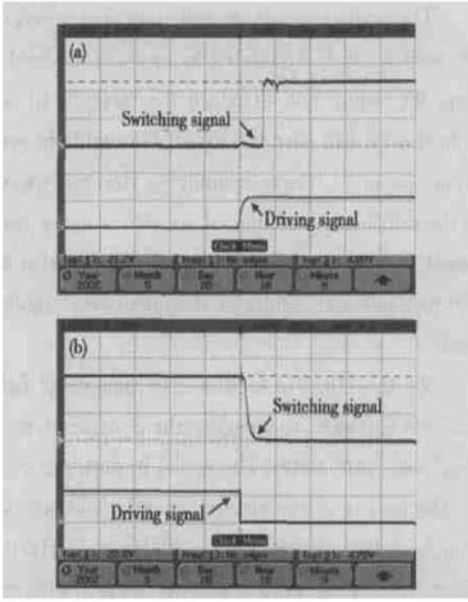

Fig. 6 Performance of the MEMS switch (a) Turn-on; (b) Turn-off The below waveform is the driving signal while the upper waveform is the switching signal.

4.2 *S* parameters

The fabricated switch is mounted on a microwave carrier, and we use a HP 8510A Vector Network Analyzer to measure the microwave *S* parameters of the switch. The bias of the switch is provided by a tunable DC source. The isolation of the switch is shown in Fig. 7, the insert loss at actuation voltage of 32V is given in Fig. 8.

The tested isolation of the switch agrees with HFSS simulation well, but the insert loss is worse than simulated result. There appears a peak at about 2.3GHz. We propose a part of microwave entering the drive circuit through the dielectric between the electroplated gold membrane and the heavily diffused silicon. As next work, we would try to etch a shallow isolating trench in the armature to block the leaked microwave signal.

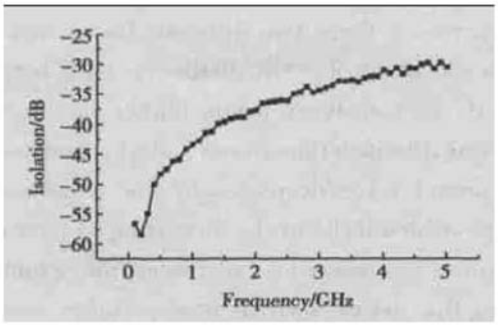

Fig. 7 Isolation of the switch

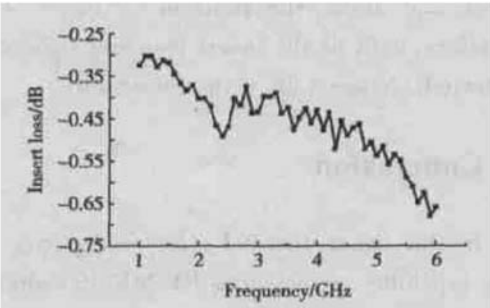

Fig. 8 Insert loss of the switch

4.3 Thermal effect

The switch was packaged and kept in 85℃ for 24h, we fetched the switch out and tested with HP 8510A Vector Network Analyzer immediately. After almost 24h storage in room temperature, the switch was put in − 55℃ for 4h, we also tested the *S* parameters with HP 8510A at once. The change of insert loss and isolation of the switch after high and low temperature storage is shown separately in Fig. 9 and Fig. 10.

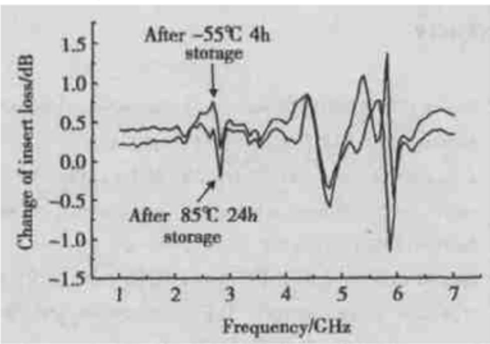

Fig. 9 Change of insert loss of the switch after high and low temperature storage

There are two interesting phenomenons in Figs. 9 and 10. First, the isolation of the switch

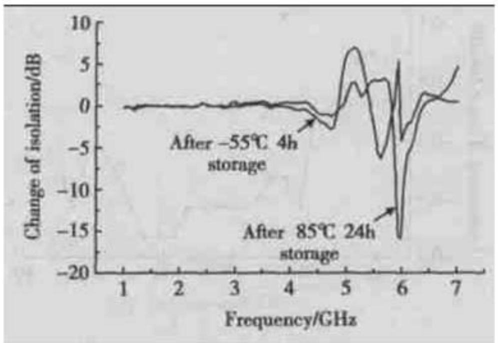

Fig. 10 Change of isolation of the switch after high and low temperature storage

shows little change and the insert loss increases for 0.2dB at 85℃ and about 0.4dB at − 55℃ from 1 to 4GHz. Next, the performance of the switch varies severely with temperature from 4 to 7GHz and the locations of these peaks are similar. For example, there are two peaks at 4.8GHz and 6.0GHz in both Figs. 9 and 10.

4.4 Power handling capability

We used a microwave source (SMP04) and a linear power amplifier to adjust the power across the switch and measure the insert loss by a microwave power meter (HP438B). The diagram of testing circuit is shown in Fig. 11 while the relation of the insert loss increment to the power level are shown in Fig. 12.

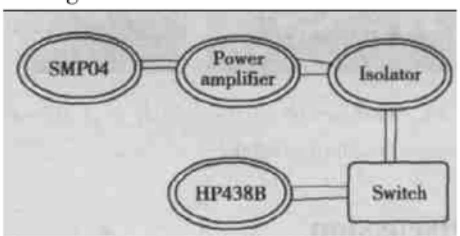

Fig. 11 Diagram of measuring circuit for power capability of the switch

The insert loss decreases with the power level, which agrees with the contact resistance of the switch, which decreases with the DC current load. The switch can operate till the power lever increases to 35.1dB but the turn off delay of the switch increases with power level. 24h after the test, *S* parameters of the switch were measured again, but

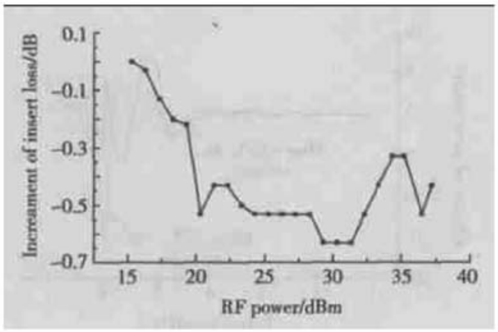

Fig. 12 Relation of the insert loss increment to power level of the switch

the switch was in "off" stage.

We opened the package of the switch and found one of the contact regions of the switch was burned out, even the silicon was melt. The photograph of the melted point is shown in Fig. 13. There exists a melted circle whose radius is about 40μm around one of the contact points of the switch. Half the melted circle locates on the silicon and the other part is on transmission line. The straight consideration of the formation of the melted circle is that there exists a heat source at this contact point.

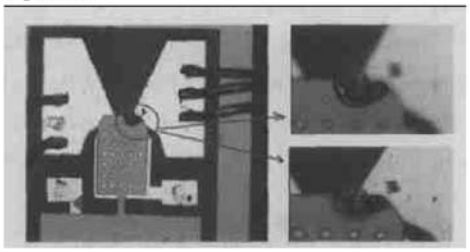

Fig. 13 Photograph of the switch after the testing of power handling capability

5 Discussion

The continuous wave power handling of the switch is tested up to 35.1dBm, and the insert loss decreases with the increasing power level. We propose that the contact material softens with the increasing power and the contact region increases, which leads to the decrease of contact resistance and lowers the insert loss.

From DC to 4GHz, the isolation keeps constant after 85℃ or − 55℃ storage, while the insert loss increases. Since two different layers make the cantilever, we propose it distorting with temperature. If the cantilever bends higher up the glass substrate, the isolation shows a slight increase. But the contact force decreases by the same actuate voltage, which leads to the increasing contact resistance, and the insert loss increases, too. From 4 to 7GHz, the series switch posses some resonant peaks, the thermal shock alters the shape of cantilever, and shifts the position of these peaks. Therefore, both of the insert loss and isolation of the switch change a lot with temperature.

6 Conclusion

In this paper, thermal effect and power handling capability of the series RF MEMS switch are reported at the first time. From DC to 4GHz, compared with the value at room temperature, the insert loss of the switch increases 0.2dB in 85℃ and 0.4dB in − 55℃, while the isolation holds constant. In 4~ 7GHz, the performance of the switch varies acutely, which is proposed to due to the shift of resonant peaks. The continuous wave power handling of the switch is demonstrated up to 35.1dBm, which is higher than the corresponding value of shunt switches. Next, we will try to find the principle of thermal effects, and the failure mechanism of the switch in high power level.

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一种DC~ 5GHz 串联微波开关的温度特性和功率处理能力的测试与分析

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摘要: 描述了一种串联微波MEMS开关的设计、制造过程, 它制作在玻璃衬底上, 采用金铂触点, 在DC~ 5GHz, 插损小于0.6dB, 隔离度大于30dB, 开关时间小于30μs. 对这种微波开关的温度特性和功率处理能力进行了测试, 在DC~ 4GHz, 85℃下的插损增加了0.2dB, - 55℃下的插损增加了0.4dB, 而隔离度基本保持不变. 在开关中流过的连续波功率从10dBm上升到35.1dBm, 开关的插损下降了0.1~ 0.6dB, 并且在35.1dBm(3.24W)下开关还能工作. 和所报道的并联开关最大处理功率(420mW)相比, 该结果说明串联开关具有较大的功率处理能力.

关键词: RF MEMS开关; 温度特性; 功率处理能力

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