A Capacitive RF MEMS Shunt Switch

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Abstract - A brief overview of RF MEMS devices with static displacement is presented. As an example of RF devices, a capacitive MEMS switch for millimeter-wave has been proposed. The movable electrode is capacitively connected to the ground. The actuator is separated from the signal path and the movable electrode is pulled upward by electrostatic force. The insertion loss is 0.77 dB, and the isolation is well over 30 dB at 76.5 GHz.

Index Terms - MEMS, capacitive switch, millimeter-wave, electrostatic force.

. INTRODUCTION

The application of micro electro mechanical systems (MEMS) is expanding. Such devices as ink-jet printer heads, automotive sensors (sensing of pressure, acceleration, rotation, etc), and mirror array for a projector are examples of the well-known MEMS devices.

Remarkable advances are also found in the research and development of RF devices by MEMS technology. Some reviews have already been published on RF MEMS devices [1]-[5]. MEMS technology is expected in the application to RF devices because it can fabricate 3-dimensional structure which is difficult to attain by conventional semiconductor processes. The following features can be listed when we think of the application of MEMS technology to RF devices.

1) Tunable devices can be realized using mechanical displacement of some part of the device.
2) Movable structure can be formed which can be oscillated resonantly.
3) Simple structure separated from the materials which degrades RF characteristics can be fabricated.

The examples of the devices with the above first feature are switches [6]-[15] and variable capacitors [16]-[19]. Switches are actively investigated and some of them are already commercialized. The movable antenna [20] is also an example of this type of devices. The devices with the above second feature are mechanical resonator [21]-[22], and mechanical filter with the mechanical resonator. Film Bulk Acoustic Resonator (FBAR) [23] is also classified into this type.

The advantages or expected features of this type of devices are as follows.
1) Low loss: It is easy to make low-resistivity electrode, so the conductor loss can be reduced. Since the gap between the electrodes are mainly air, dielectric loss can also be reduced easily.
2) High isolation: The flexibility in design of the device structure is high in comparison with semiconductor devices such as diodes or transistors. In addition air gap is easily introduced around the device. So isolation can be higher than semiconductor devices.
3) Low distortion of signal (High linearity): In the case of switches, the position of movable parts are defined by direct contact of fixed and movable part, so the movable electrode is not moved by electrostatic field of signal. Since the RF characteristics is determined by the mechanical position of the movable parts, distortion of signal can be quite low.
4) Low power consumption: In principle, electrostatic actuation does not consume power after displacement.
So actual power consumption can be less than that of FET.

5) Integration and size reduction: Monolithic integration with circuit is possible for some type of switches and variable capacitors. Wafer level package can be employed in some cases, which is favorable for size reduction.

The expected level of the above features depends on the application, and the suitable matching of the device and the application is more important than in the case of semiconductor devices.

Ⅴ. A CAPACITIVE SHUNT SWITCH

As an example of RF MEMS devices, we propose a capacitive shunt switch for millimeter-wave application.

Two types of switches have been proposed: capacitive type [6]-[12] and metal-to-metal type[12]-[15]. In general discussion as mentioned above, MEMS switches are superior in insertion loss and isolation when compared with diodes or transistors. But serious limitations such as switching speed and high driving voltage always impose some restriction on application. The reliability of mechanical actuation or mechanical contact is one of the serious concerns and must be clarified for many potential applications. Thus, MEMS switch can be applied where such advantages are essential as low insertion loss, high isolation, low signal distortion, low power consumption, etc.

Capacitive switches have 'metal-to-dielectric' contact and their reliability can be higher than that of metal-to-metal ohmic contact switches. But difficulty does exist when we try to apply the capacitive switches to relatively lower frequency. As for capacitive switches, large capacitance is inevitable for resonance at relatively low-frequency range of below 10GHz, because extremely large inductance is difficult to attain with simple fabrication process. But the difficulty in the absolute value of C and L is eased when the frequency range is higher. For some application in millimeter-wave range, tuning ratio can be relatively low value of less than 10, which makes easier the actual application of capacitive switch to millimeter-wave. On the other hand, steady advance in application can be found in various fields such as automotive radar, high-speed data transfer, etc.

In our previous reports [18]-[19], a prototype MEMS variable capacitor was proposed. We used the electromagnetic force to smoothly actuate the movable electrode for wide tuning range. But for reducing the size of devices, electrostatic force is preferable, as is often pointed out.

In this report, we will propose a MEMS capacitive switch for millimeter-wave range which is fabricated by bulk micromachining technology.

A. Basic design of capacitive switch

Figure 1 shows the schematic view of the capacitive shunt switch of single pole single throw (SPST) type. The coplanar waveguide (CPW) is along B-B’ in Fig.1(a). The movable metal electrode is on the silicon plate which is actuated by electrostatic force between the silicon plate and the electrode above the plate.
Unlike most of capacitive switches, the actuator is separated from the signal path. By separating the actuator electrode from the signal electrode, the design of electrodes can be more flexible, because the actuation electrodes do not have to meet the requirements for keeping RF characteristics.

With zero actuation voltage, the movable electrode is on the CPW through insulating stopper layer (Fig.1 (b),(d)). Elastic force by silicon spring presses the movable electrode on the CPW. RF signal is shunted to the ground because electromagnetic resonance occurs under this configuration. When the actuation voltage is applied to the actuator, the movable electrode is pulled up (Fig.1(c)). The resonance condition is no more fulfilled, and the signal goes through, which makes on-state. In this structure, movable electrode is capacitively connected to the ground. Even if the movable electrode is not resistively connected to the ground electrode, shunt switch can be realized by capacitive connection.

Figure 2 shows the basic layout of electrodes and the corresponding equivalent circuit. In Fig.2(a), only the symbols for capacitors (C1,C2,C3) are drawn. The upper equivalent circuits in Fig.2(b) corresponds to the physical layout, and it can be reduced to the lower one in the figure.

In order to confirm the switching behavior by the separate movable electrode, we performed three-dimensional simulation by HFSS (Ansoft corp.). Figure 3(a) shows the layout of the model for simulation and the simulated distribution of electromagnetic field is shown in Fig.3(b) for on-state and in (c) for off-state; all of the figures are for half model. The movable electrode is 60µm long along CPW (53/80/53-µm, characteristic impedance of 50Ω), and 500µm wide. The gap between the CPW and the movable electrode is set to be 3µm and 0.3µm for on- and off-states, respectively. The gap is totally air in this simulation. The input signal (76.5GHz) from the left port is clearly switched by the movable rectangular electrode.

Two types of movable electrodes were employed for confirmation of the effect of matching circuits. Figure 4 shows the layout of both electrodes. As for single electrode (Fig.4(a)), movable electrode is rectangle in shape and fine meander pattern is for adjusting inductance Ls. Another is tuned one (Fig.4(b)) consisting of two electrodes and a matching circuit between them [7],[10]. The two electrodes have the same dimension with the single electrode, and they are separated by a matching circuit about 250µm long.
B. Structure and fabrication process

Prototype switches were fabricated by bulk micromachining technology. Figure 5 schematically shows fabrication process. (i) The glass lid with drive electrode is processed. The glass is Pyrex glass, and the electrode is Pt/Ti for this switch. A layer of SiO$_2$ is deposited on the electrode for insulation. (ii) The cavity of about 3µm depth is formed, which defines the stroke of movable part. (iii) The glass lid and the silicon for movable part are anodically bonded with each other. Some part of metal electrode is pressed to silicon for making electrical contact for the actuator. Then the silicon is thinned to 50µm by mechanical polishing. (iv) The movable electrode (Au/Pt/Ti) is deposited and the fixed-fixed beam is made by deep RIE. (v) The CPW electrode and stopper layer (SiO$_2$) are formed on a silicon substrate. High-resistivity silicon (over 10Ω·m) is used because low-resistivity silicon deteriorate RF performance. (vi) The movable part and the CPW part are bonded with polyimide. As for sealing, polyimide may be insufficient for keeping the reliability of mechanical movement of the switch. Further research is inevitable mainly for preventing humidity.

After finishing wafer process, the glass on the edge of the CPW was removed by the first dicing, and each chip was separated by final dicing. Figure 6 shows the photo of the movable part and CPW, and the bonded chip on an evaluation board. Though all the fabrication process is in wafer-level, these photos are for chips diced for specific evaluation.

C. RF characteristics

The S-parameters were measured by network analyzer (8510XF of Agilent Technologies) for the frequency range of 50 to 100 GHz. The switch chip was placed on the evaluation board. No electromagnetic seal was installed around the chip, and no obvious resonance due to the substrate was observed. The probes were put on the edge of CPW, and the length of CPW is 2.8mm. The driving voltage of about 50V was also applied from the pad on the CPW substrate.

The insertion loss is shown in Fig.7 together with calculated result by HFSS. The measured insertion losses are 1.06dB for the single electrode and 0.77dB for the tuned electrode at 76.5GHz. At least around this frequency, the measured values agree well with calculated ones (1.19dB for single electrode and 0.68dB for tuned electrode). The loss for tuned electrode is lower than that of single electrode as
expected. As far as we know, it is quite difficult to attain the same level of performance by PIN diode or FET.

The measured isolations were 15.6dB for the single electrode and 36.8dB for the tuned electrode. The latter value of isolation is available for many applications. The measured return losses were 15.1dB for the single electrode and 23.3dB for the tuned electrode at 76.5GHz. Return loss should be controlled in many applications, and that of 20dB or better is important for them.

D. Discussion

The prototype MEMS switch shows a good performance for millimeter-wave range and it can be available for some applications if the conditions are fulfilled such as reliability, cost, size, etc.

In designing the switch, the separate actuation mechanism can ease the restriction on the shape of electrode. If the CPW is used as actuation electrode, the size of movable electrode is determined so that the both conditions for mechanical force and RF performance can be fulfilled. So the enlargement of electrode for increasing force, for example, is not necessarily possible when RF condition is not fulfilled. For the present structure, pull-up force is partly determined by the areas of the movable silicon plate and the upper electrode on the lid, and they can be much larger than the movable electrode.

The MEMS switches are superior to PIN diode or FET in insertion loss, isolation, and return loss. The equivalent circuits shows the parameters which determines the RF characteristics. When the resonance occurs, the loss is determined by the equivalent resistance Rs. The Rs is mostly determined by the resistivity of the movable electrode, so the conductivity of the electrode metal must be high enough. By bulk micromachining, flexible condition can be employed for deposition and after-treatment, because restriction is less than surface micromachining process where movable electrode is made after the CPW is finished.

Performance improvement by the tuned electrode can be significant. As shown in Fig.4, tuned electrodes are on the same silicon plate, and they are actuated by one actuator, so only a slight increase in size is necessary for improvement by matching circuit. This is one of the advantages of the present switch.

It is desirable to extend the application frequency to such lower range as 2 to 5GHz. In principle, if we can make much larger capacitance and much higher on/off ratio, the structure of the present switch can be available. It is a challenge and some breakthrough will be necessary in design and fabrication process.

Ⅴ. PERSPECTIVE OF RF MEMS DEVICES

A. Monolithic integration with circuit

The above switch is fabricated by bulk-micromachining technology, which is mainly used for discrete MEMS devices. But many reports have already been made about RF MEMS devices based on surface-micromachining technology which is suitable for integration with circuit. The surface-micromachining technology utilize deposition of base materials such as polysilicon, and it is very similar to usual IC fabrication process. Obviously the monolithic integration of RF MEMS devices with circuit is very attractive. One of the most attractive advantages is to be able to use the well defined process technology. Some companies are already developing the IC for wireless communication which integrates MEMS devices. If the one-chip or System-on-Chip (SoC) solution is available, significant reduction of size and cost can be expected.

But there are many issues to overcome for achieving this kind of integration. As for process, when the MEMS devices are fabricated after finishing circuit, severe restriction is sometimes forced in order not to damage the circuit. Another issue is that the base material is limited to silicon with resistivity suitable for circuit. If high-resistivity silicon is necessary as in the above MEMS shunt switch, special processes such as epitaxial deposition is inevitable, which leads to higher cost and degrade the advantage of integration.

The packaging is also an important issue for integrated MEMS devices with movable parts in it. The low-price package such as plastic mold cannot be applied and the more expensive package such as ceramic package is necessary. The area of the integrated device is larger than discrete one, so the relative cost of package can be higher if the circuit area is dominant.

At present, monolithic integration is not so easy, and many approaches are made for discrete devices and researches about System-in-Package (SiP) solution is active [5]. A variety of technology for SiP have been proposed to improve the flexibility of packaging procedure.

B. Development of RF MEMS devices

Several issues remain for the application of the RF MEMS devices. As for the devices with static displacement like switches, the following issues should be considered.

1. High driving voltage: For electrostatic actuation, relatively high voltage of around 10 to 60V is necessary for stable actuation of moving part. Though the supply current is very small, the circuit for power supply is costly.
2. Low speed: Since the mechanical displacement is necessary, operation time of less than 1µs is difficult. Typical operation time is 1 to 100µs, which limits the application of the device.

3. Relatively low reliability: The mechanical movable and the fixed parts have the possibility of sticking to each other. The mechanical strength of the movable part is generally less than that of solid devices such as diodes or transistors. So relative reliability of MEMS device is less than that of the conventional devices.

4. Packaging complexity: The package must not degrade the mechanical movement of the movable part. So the ambient material must be gas or vacuum, and corresponding package is necessary. In most cases, hermetic sealing is necessary for avoiding stiction. The cost reduction is more difficult than usual integrated circuits.

The seriousness of the above issues depend on the device or the application. The MEMS devices show the some superior RF characteristics to that of the solid devices, but many issues must be resolved to meet the requirements for certain applications. The reliability must be guaranteed for its application, and the cost reduction is one of the most important issues.

The suitable selection or creation of the application is essential for the expansion of the application.

\section{Conclusion}

As an example of MEMS devices, a capacitive MEMS switch was proposed. The actuator is separated from the signal path and the movable electrode is pulled upward by electrostatic force. Though the movable electrode is only capacitively connected to the CPW, the switching is made properly. The RF characteristics such as insertion loss, isolation, and return loss are good and the switch can be applied to some application of millimeter-wave range. For further extension of application, such issues must be overcome as reliable wafer-level packaging, enhancement of on/off ratio, etc.

The main advantages and disadvantages of RF MEMS devices with static displacement are listed. Many of the present RF MEMS devices have several issues to overcome before actual application. The reliability of mechanical part and the fabrication cost are main issues. The applications which strongly require low loss, high isolation, high linearity, and low power consumption should be found or created for future development.

\section{References}


