Numerical Simulation of Liquid Metal RF MEMS Switch Based on EWOD

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Abstract. Conventional RF MEMS switches rely on metal-to-dielectric or metal-to-metal contacts. Some problems in the “solid-solid” contact, such as contact degradation, signal bounce and poor reliability, can be solved by using “liquid-solid” contact. The RF MEMS switch based on liquid metal is characterized by small contact resistance, no moving parts, high reliability and long life. Using electrowetting-on-dielectric (EWOD) way to control the movement of liquid metal in the RF MEMS switch, to achieve the “on” and “off” of the switch. In this paper, the electrical characteristics and RF characteristics of RF MEMS switches are simulated by fluid mechanics software FLUENT and electromagnetic simulation software HFSS. The effects of driving voltage, switching time, dielectric layer, hydrophobic layer material and thickness, switching channel height on the RF characteristics are studied. The results show that to increase the external voltage to the threshold voltage of 58V, the liquid metal began to move, and the switching time from “off” state to “on” state is 16ms. In the 0~20GHz frequency range, the switch insertion loss is less than 0.28dB, isolation is better than 23.32dB.

1. Introduction
Previously, semiconductor devices like PIN diodes and FETs have been extensively used as switching devices in many Radio Frequency (RF) systems due to fast working speed, low voltages and have high power handling. However, they suffer from high insertion loss, low isolation and inferior linearity [1]. Since 1990’s, Radio Frequency Micro-Electro-Mechanical Systems (RF MEMS) technology have been introduced in novel switches. The RF MEMS switches have the good operating characteristics with low insertion loss, high isolation and low cost of fabrication [2-5], and there is a very good application prospect in the test system, satellite communications, radar systems as well as the military field [6-7]. Conventional RF MEMS switches rely on metal-to-dielectric or metal-to-metal contacts. The contact reliability of solid-solid contacts becomes more important for MEMS switches as surface plays an increased role at microscale [8]. The contact degradation due to arcing, welding and material transfer, and the limited contact area due to the roughness of these surfaces, easily lead to contact bounce and limit the operational life of these devices [9]. These problems in solid-solid contact can be solved by using liquid-metal contact. The liquid metal is liquid at room temperature, characterized by good electrical conductivity, thermal conductivity and liquidity, and has been used as the contact
material of switch in MEMS. The liquid metal in RF MEMS switch conforms almost perfectly over the CPW transmission line, which results in high on-state capacitances. By controlling the movement of liquid metal based on Electrowetting-on-dielectric (EWOD) effect, the RF MEMS switch is in the “on” state or “off” state. EWOD is well established as a fluid manipulation technique in such areas as lab-on-a-chip, visible light optics, and displays, RF electronics and electromagnetics [10-14]. Thus, the basic principle of liquid metal RF MEMS switches is to control the movement of liquid metal by controlling the applied voltage to change the wettability of liquid metal and solid surface.

In the paper, the characteristics of liquid metal RF MEMS switch are studied mainly from two aspects of the electrical and RF characteristics. The numerical simulations of RF MEMS switch are carried out by fluid mechanics software FLUENT and electromagnetic simulation software HFSS, the flow characteristics of mercury in RF MEMS switch, the driving voltage of switch and the influence of various structural parameters on RF performance are studied.

2. Structure and Modelling

2.1. Working Principle of EWOD-Based Liquid Metal RF MEMS Switch

2.1.1. Driving Principle of Droplet

The micro droplet control method based on EWOD has been studied in recent years. The basic idea is to control the droplet movement by the change of surface tension [15]. The EWOD system is usually composed of electrodes, hydrophobic layer, dielectric layer, micro droplet, as shown in Figure 1. When the droplet is located on both electrodes covered with the dielectric layer and the hydrophobic layer, the left electrode is unactuated and the contact angle of the left droplet remains unchanged. When the external voltage is applied to the right electrode, the contact angle of the right side will be reduced and the wettability of the micro droplet will be increased to spread to the right. Since the radius of curvature of the surface of the left and right sides of the micro droplet does not coincide, the droplet will move to the right when the internal pressure difference of the droplet caused by the change in the radius of curvature is greater than the received resistance.

![Figure 1. Principle of droplet control based on EWOD](image)

When the micro droplet is located on the rectangular driving electrode, according to the Young-Lippmann equation, the driving force F can be defined as [16-17]:

$$F = \frac{\varepsilon_0 \varepsilon_r}{2 \times d} \times V^2 \times L_{eff}$$

Where $\varepsilon_0$ is the vacuum dielectric constant, $\varepsilon_r$ is the relative dielectric constant, $V$ is the driving voltage, $d$ is the thickness of the dielectric layer, and $L_{eff}$ is the length of the droplet in the direction perpendicular to the driving force when the droplet is in contact with the driving electrode.

2.1.2. Structure and Principle of Liquid Metal RF MEMS Switch

The liquid metal RF MEMS switch utilizes the EWOD effect to drive the liquid metal droplet movement and control the status of the RF signal. RF MEMS switch is composed of the silicon substrate, glass cover, liquid metal droplet, CPW transmission line, driving electrode, the upper
electrode, block, hydrophobic layer and dielectric layer. The overall structure is illustrated in Figure 2. In RF MEMS switch, the liquid metal is always in contact with the upper electrode to ensure that the liquid metal has a suitable bias voltage. The external voltage is applied to the upper electrode and the driving electrode, and becomes the main power source for driving the liquid metal droplet.

When the voltage is not applied and the liquid metal is on the CPW transmission line, the large capacitance to the ground is formed and the RF signal from the signal line conducts to the ground. Thus, the switch is in the “off” state. When the driving force is greater than the resistance, the liquid metal starts to move to the right. It moves to leave the CPW transmission line, the liquid metal is not in direct contact with the signal line, and the RF signal transmit to the on state with smaller loss. Two blocks are used to limit the movement of liquid metal in the switch.

2.2. Modelling of RF MEMS Switch

In this paper, the research of characteristics of liquid metal RF MEMS switch is carried out mainly from two aspects of the electrical characteristics and RF characteristics. The numerical simulation model is established by using the numerical simulation software Fluent, and the driving voltage and switching time are simulated to study the flow characteristics of liquid metal droplet in RF MEMS switch. The “on” state and “off” state models of the switch are established by the electromagnetic simulation software HFSS. The impact of the dielectric layer, the thickness of the hydrophobic layer and the height of the switching channel on RF performance such as the return loss, insertion loss and isolation are studied.

2.2.1. Numerical model of RF MEMS switch by FLUENT

Liquid metal is influenced by multi-physical field coupling such as the electrostatic attraction, surface tension and viscous force in the whole movement process. After the upper electrode is earthed and the driving electrode is actuated, the droplet began to move right because of electrostatic attraction. If the upper electrode and driving electrode are applied the same voltage, the droplet and the CPW transmission line are subjected to electrostatic attraction, and the droplet and the driving electrode are driven by repulsing force, causing the droplet to move to the left. In this paper, the flow characteristics of liquid metal droplet in the switch are simulated by FLUENT. In the simulation, the volume of fluid (VOF) method and the continuum surface force (CSF) model are used. The user defined functions (UDF) are also used to realize the setting of boundary conditions such as driving force and contact angle. The numerical simulations are focused on the minimum driving voltage and switching time of RF MEMS switch.

The RF MEMS switch numerical model is shown in Figure 3. In order to facilitate the observation of the movement position of the liquid metal droplet in the RF MEMS switch, the
numerical model established only contains the fluid region and the solid region below the switch. The CPW line and the driving electrode can be clearly seen from the numerical model. The size of the entire switch model is 1360μm×1220μm×600μm, and the size of the CPW line is 50μm/80μm/50μm. The discretization of the numerical model is realized by using the hexahedral mesh. According to equation (1), the UDF of driving force is written and loaded in the momentum source terms of FLUENT software. After applying the external voltage, the contact angle of the droplet on the dielectric layer changes, so it is necessary to set different contact angle hysteresis at different motion positions, and write the UDF of contact angle hysteresis. The FLUENT software calculates the value of the driving force and the contact angle at each iteration and returns it to the FLUENT solver.

Figure 3. Numerical simulation model of RF MEMS switch

The contact angle of the liquid metal on the surface of the hydrophobic layer changes due to the applied external voltage. The external voltage $V$ and the contact angle $\theta$ satisfy the Young-Lippmann equation [18]:

$$\cos \theta = \cos \theta_0 + \frac{\varepsilon_0 \varepsilon_r}{2 d \sigma_n} \times V^2$$

(2)

Where $\theta$ is the contact angle when the applied voltage is $V$, $\theta_0$ is the static contact angle when there is no applied voltage, and $\sigma_n$ is the surface tension between the droplet and the gas. It can be seen from the Young-Lippmann equation that the contact angle $\theta$ after applying the voltage decreases as the applied voltage $V$ increases. However, as the voltage increases, the contact angle finally tends to a fixed value. This phenomenon is called the contact angle saturation. According to the literature [19], when the voltage increased to 90V, the contact angle of the liquid metal droplet on the silicon dioxide surface is 80° when the phenomenon of contact angle saturation occurs. In the RF MEMS switch, the liquid metal droplet is always in contact with the CPW line and the driving electrode at the same time, and the contact angle (right side) of the contact portion with the driving electrode decreases due to the applied external voltage. In numerical simulations, FLUENT software invokes the UDF function at each iteration to read the x-direction size of each grid of liquid metal droplet. If the droplet moves above the driving electrode, set the contact angle according to equation (2).

2.2.2. Numerical model of RF MEMS switch by HFSS

The influence of the switch parameter including the material and thickness of the dielectric layer, the thickness of the hydrophobic layer and the height of the switching channel on RF performance are analyzed by HFSS software. RF MEMS switch adopted silicon as the substrate material and the relative dielectric constant is 11.9. The material of dielectric layer is silicon dioxide and the relative dielectric constant is 3.8. The material of the CPW transmission line and driving electrode is gold and the conductivity is $4.1 \times 10^7$ S/m. The geometry parameters of RF MEMS switch are shown in Table 1. The switch simulation models are established in the HFSS software, as shown in Figure 4.
Table 1. The geometry parameters of the switch

| Symbol | Size  | Material       |
|--------|-------|----------------|
| width of substrate | length | 1020μm | Silicon |
| height of substrate | ground | 200μm | Silicon |
| interval of signal line and ground line | g | 50μm | Gold |
| width of signal line | signal | 80μm | Gold |
| thickness of the thermal oxidation silicon dioxide layer | t | 200nm | Silicon dioxide |
| thickness of CPW line | t1 | 1100nm | Gold |
| thickness of dielectric layer | t2 | 300nm | Silicon dioxide |
| thickness of dielectric layer | t3 | 10nm | Teflon |

3. Results and Discussion

3.1. Simulation Results of Electrical Characteristics by FLUENT

Set the external voltage as 80V, the flow characteristics of liquid metal in the switch are shown in Figure 5. When the time is 0ms, the droplet is located on the entire CPW line, and the switch is in the “off” state. After 4.7ms, the droplet is driven by the external voltage to completely leave the signal line, and the switch is in the “on” state. If the initial position of the switch is in the “on” state, the droplet moves toward the CPW line direction with the action of external voltage. After 2.8ms, the entire droplet relocated on the CPW line, and the switch is in the “off” state.
Table 2 shows the contact angle under different driving voltages and the switching time required for the switch from “off” to “on”. The simulation results show that when the driving voltage is less than 58V, the driving force is too small and the droplet does not move. The switch is still in the off-state. The larger the driving voltage, the faster the droplet moves, and the less time is required. When the driving voltage increased to 90V, the contact angle saturation of the liquid metal droplet on the surface of the silicon dioxide appears, and the contact angle is 80°.

Table 2. The contact angle and the switching time from “off” to “on” under different driving voltage

| Driving voltage (V) | Contact angle of right side (°) | Switch time (ms) |
|---------------------|-------------------------------|------------------|
| 58                  | 107.8                         | 16.5             |
| 60                  | 106.1                         | 16.1             |
| 70                  | 97.3                          | 12.6             |
| 80                  | 87.3                          | 4.7              |

3.2. Simulation Results of RF Characteristics by HFSS
The S parameters of the switch in the “on” and “off” state are shown in Figure 6 and Figure 7 respectively. The simulation results show that the insertion loss $S_{21}$ is $-0.037$~$-0.282$dB and the return loss $S_{11}$ is $-47.33$~$-19.30$dB in the frequency range of 0~20GHz when the switch is in the “on” state. The isolation is better than 23.32dB when the switch is in the “off” state.

Figure 6. S parameter of the switch in the “on” state

Figure 7. S parameter of the switch in the “off” state
3.2.1. Effect of the Thickness of Dielectric Layer on RF Performance of the Switch

When the thickness of the dielectric layer is 300nm, 400nm and 500nm respectively, the variations of the insertion loss and isolation with the thickness of the dielectric layer are shown in Figure 8.

![Figure 8. Variations of $S_{21}$ parameter with thickness of dielectric layer](image)

(a) Insert loss $S_{21}$

(b) Isolation $S_{21}$

It can be seen from Figure 8 that the isolation of the switch is -23.32dB when the frequency is 20GHz and the thickness of dielectric layer is 300nm, and the isolation of the switch is -20.40 dB when the thickness is 500nm. The isolation of RF MEMS switch is related to the capacitance of “off” state. The thinner the dielectric layer, the better the isolation and the greater capacitance of the switch in the “off” state. Therefore, reducing the thickness of the RF MEMS switch dielectric layer can effectively improve the isolation of the switch. However, reducing the thickness of the dielectric layer may lead to the acceleration of the breakdown in the dielectric layer. There is a minimum thickness of the dielectric layer. The breakdown field strength of the silicon dioxide is about 2MV/cm. Considering the contact angle saturation phenomenon of liquid metal droplet occurs with the external voltage of 90V, so the working voltage should be lower than 90V and the dielectric layer thickness should be greater than 180nm to ensure that the dielectric layer will not be punctured by the field. The results also show that the thickness of the dielectric layer has not much impact on the insertion loss. The insertion loss of the switch is mainly the loss of the transmission line. Since the size of the CPW does not change, the thickness of the dielectric layer of the switch has little effect on the insertion loss of the switch.

3.2.2. Effect of the hydrophobic layer thickness on RF performance of the switch

In the RF MEMS switch, hydrophobic layer formed on the dielectric layer is used to increase the initial contact angle between the liquid and solid surfaces [20], which facilitates the movement of liquid metal droplet in the switch. When the thickness of the hydrophobic layer is 7.5nm, 10nm and 12.5nm respectively, the resulting insertion loss and isolation are shown in Figure 9.

![Figure 9. Variations of $S_{21}$ parameter with thickness of hydrophobic layer](image)

It can be seen from Figure 9 that the insertion loss is -0.27dB, -0.28dB and -0.25dB at the frequency of 20 GHz and the thickness of the hydrophobic layer are 7.5 nm, 10 nm and 12.5 nm, respectively, and the isolation is -23.21dB, 23.31dB and -22.95dB. The hydrophobic layer is used to adjust the contact angle between the droplet and the solid surface, and the hydrophobic layer has little effect on the insertion loss and the isolation.
3.2.3. Effect of dielectric layer material on RF performance

In order to study the effect of different dielectric layer materials on the RF characteristics, SiO$_2$ and Si$_3$N$_4$ are used as the dielectric layer materials, and their dielectric constants are 3.8 and 7.0 respectively. The insertion loss and isolation achieved from the numerical simulation analysis of HFSS software are shown in Figure 10.

It can be seen from Figure 10 that the isolation of the switch with a dielectric layer made of Si$_3$N$_4$ has been significantly improved in the frequency range of 0–20GHz, while the isolation of the switch made of SiO$_2$ material is -23.10dB at 20GHz. The use of high dielectric constant material effectively improved the capacitance of the switch in the “off” state. The higher the capacitance in the “off” state, the greater the isolation of the switch. The dielectric layer material has little effect on the insertion loss, since the change of dielectric layer material has no impact on the loss of the CPW transmission line, so that the insertion loss of the switch is substantially unchanged. From the RF performance of the switch, the use of high dielectric constant material can more effectively improve the RF performance of the RF MEMS switch.

3.2.4. Effect of channel height on RF performance

Mercury droplet is in contact with the upper and lower electrodes, and the volume of droplet is related to the microchannel height. The microchannel height increases and the volume of mercury droplet increases accordingly. Considering the microchannel height of 400μm, 425μm and 450μm respectively, the insertion loss and isolation of the switch are shown in Figure 11.
As can be seen from the figure, the microchannel height has little effect on the insertion loss and isolation. At the frequency of 20 GHz, the insertion loss corresponding to the microchannel height of 400μm, 425μm and 450μm is -0.22dB, -0.26dB and -0.26dB, respectively, and the isolation is -23.11dB, -22.86dB and -23.21dB.

4. Conclusions
Liquid metal gradually being applied in the MEMS devices with its excellent physical properties. Liquid metal RF MEMS switch control the movement of liquid metal to achieve the “on” and “off” of the switch through the EWOD method. In addition to liquid metal, the switch has no moving parts. The switch has the advantages of reliable contact, low contact resistance and so on. In this paper, the electrical characteristics and RF characteristics of liquid metal RF MEMS switches are studied by numerical simulation. When the external voltage is too small, the electrowetting force is less than the contact angle hysteresis force, and the liquid metal does not move. When the external voltage is increased to the threshold voltage of 58V, the liquid metal starts to move, the switching time of the switch from the “off” state to the “on” state is 16ms. The greater the external voltage, the faster the switching speed. In the frequency range of 0~20GHz, the insertion loss of the switch in the “on” state is -0.037~0.282dB, and the return loss is -47.33~19.30dB. The isolation in the “off” state is better than 23.32dB. Parametric simulation studies show that the dielectric layer thickness and material have a great influence on the RF performance.

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