國立交通大學

電子工程學系 電子研究所碩士班

碩士論文

低驅動電壓橫向式 CMOS 微機電開關

Low Actuation Voltage Lateral CMOS MEMS Switch

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中 華 民 國 一 百 零 一 年 七 月

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碩士論文

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摘要

由於電晶體開關在高頻系統效率極低，應用微機電系統於高頻射頻系統是近年來的一個趨勢。國家晶片系統設計中心也目前提供一套微機電製程技術，可以整合微機電系統於半導體電路之中。本文旨在使用這一套新的製成技術，去作一個可以應用於高頻的微機電開關。並且設計一個控制開關的電路，來探討蝕刻基版是否會對電路造成影響。

在本論文中實現的晶片用的是 TSMC 0.18μm CMOS 製成與 MEMS 後製程，晶片相對於傳統 CMOS 製程多出一層 RLS 光罩作為後製程蝕刻使用。目前的 CMOS MEMS 製程技術尚不成熟，蝕刻技術只能掏空基版部分，使上方金屬層與 SiO2 層懸浮。金屬材質只能選擇鋁或金，選擇性相比起傳統 MEMS 製程較少。目標是在 CMOS MEMS 的蝕刻限制下，嘗試去設計一個適合應用在 RF 系統的開關。

Low Actuation Voltage Lateral CMOS MEMS Switch

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ABSTRACT

Because CMOS switch has low efficiencies in high frequency system, the application of MEMS switch in high frequency system is the trend in the recent years. CIC offers a new CMOS MEMS technology now, the MEMS structure can be combined with the electronic circuit by this process. The thesis presents the MEMS switch is the design of the new process and application for the high frequency system. The electronic circuit is combined with the chip, and then discussed the etching of substrate how to affect the electronic circuit.

The circuit is fabricated by TSMC 0.18μm CMOS process with the MEMS post - process. The chip has an extra RLS mask compare to the traditional CMOS process. The CMOS MEMS is imperfect now. The etching can only hollow out the substrate and let the metal and the SiO2 structure to float. And the material of metal has only Aluminum and Gold. The choice of design in CMOS MEMS is less than traditional MEMS process. The aim is trying to design a CMOS MEMS switch that is limited by the etching and application for RF system.

誌 謝

感謝我的指導教授，溫教授與郭教授的指導與栽培。提供了我電路設計與結構設計的一些想法，促成了此篇論文的完成。

感謝子超、俊興等學長的指導，還有一同努力奮鬥過的佑偉、勁夫、敬修、馳光、哲誠、柏亨、崇閔的幫忙。感謝國家高速網路與計算中心提供模擬上的幫助，還有國家系統晶片中心在晶片製作上所提供的協助。

最後我要感謝我的家人，在我學業路上一直鼓勵與扶持我。

張景喆

一百零一年七月

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Chapter 1

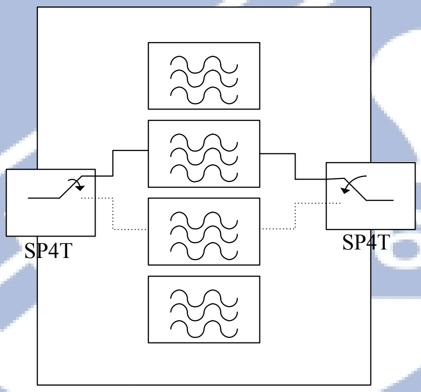
Introduction

Microelectromechanical system (MEMS) is the tiny movable system. The usual applications of MEMS are accelerators and switches. Accelerators can measure the acceleration by measuring displacement of cantilever beams. There has a varactor between cantilever beams and electrodes. The displacement of cantilever beams can change the distance between cantilever beams and electrodes. Capacitance is much larger when acceleration is increasing. MEMS switches are controlled by electrostatic force. If applied voltage is larger than a specified voltage, electrostatic force will let MEMS switches to be closed. The specified voltage is called the pull in voltage.

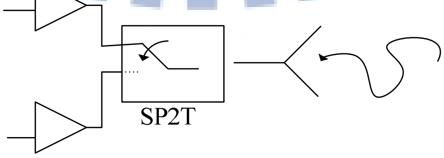
The MEMS switches have higher isolation (2-4fF off state capacitance at 0.1~40GHz), higher linear (30dB better than FET switch), low loss (-0.1dB up to 40GHz), and low power consumption as compared with the MOS switches.[1] In RF system, the MEMS components can be applied in switches network of filter and transmitter/receiver.

1.1 Motivation

Multi tunable power amplifiers are used to increase the power dynamic of multi-system transmitter in the traditional. But multi tunable power amplifiers will sacrifice the power efficiency. Switched power amplifier can be applied to raise the power efficiency. As shown in Fig1.2, the output power can be controlled by the switches. When the systems don’t need the maximum power, the switches can pass through one of the PA for lower power. If the switch has high linear, the efficiency of transmitter can be increased. And the bypass switch should have high tolerance of power. MEMS switches have higher linear and tolerance than MOSFET switch. The application of MEMS switch can improve the power efficiency of the PA. The CIC offers the new MEMS post-process based on TSMC process. The new process has an extra mask for post-process. The new process allows combination circuits of MEMES structure and electronic circuit. The thesis shows that the combination circuit is the application of the RF systems.



(a) Switched filter



(b) Switched rtx

Fig1.1: MEMS application

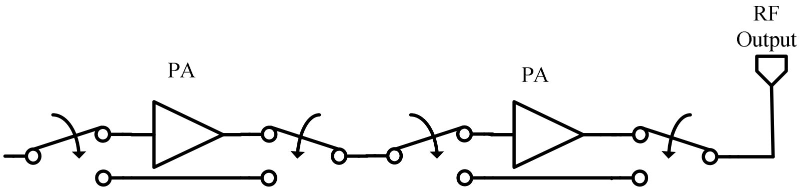


Fig1.2: Switched PA

1.2 Development of MEMS Switch

Typical MEMS switches can be divided into resistance and capacitive switches. The resistance switches were proposed by Rockwell Scientific Company in 1995 as shown in Fig1.3. The resistance switches are controlled by the electrostatic force. If the electric potential between the cantilever beams and the electrodes are enough, the cantilever beams will push down and the signal paths will contact. The switches are usually manufactured of gold for good insertion loss and low contact resistance, and the reliability of switches is usually more than 100 millions. In the recent, the resistance switches are largely applied in phase shifters, varactors, and filters.

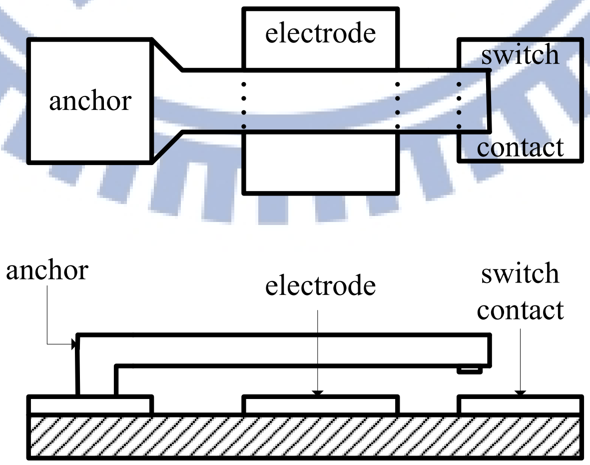


Fig 1.3: Series resistance switch

The capacitive switch was proposed by Raython Company in 1999, and the structure is shown in Fig 1.4. When the switch is closed, the cantilever beam didn't connect to the electrode directly. There has a small capacity between the cantilever beam and the electrode when the switch is closed. The capacitive switch normally applied in high frequency communication system. The low frequency signal will be isolated by the capacitance between the electrode and the cantilever beam.

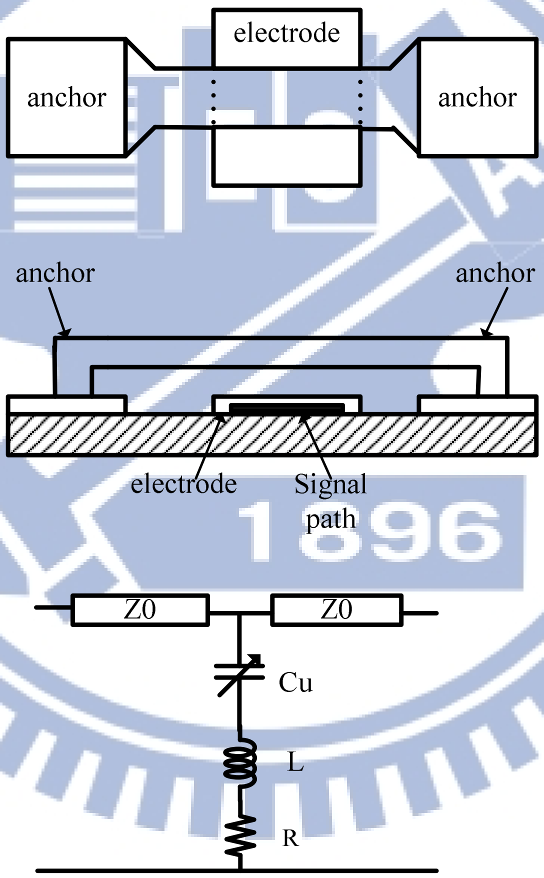


Fig1.4: Shunt capacitive switch

1.3 CMOS MEMS Technology

The visible CMOS MEMS technology is based on TSMC 0.35μm 2P4M CMOS process or 0.18μm 1P6M CMOS process. The Post-CMOS processing is offered by

APM. The Post-CMOS processing has an extra mask (RLS) for defining the etching region. In the etching region, the isotropic dry plasma etching will clean the SiO2 dielectric material. And then the anisotropic dry plasma etching will etch the silicon substrate. The depth of substrate cavities is more than 25μm.

The CIC offers extra RLS layer for MEMS process, the etching is as shown in Fig 1.5. The minimum etching width should be 4μm, and the distance between the active component and the etching zone must be larger than 200μm. The minimum distance between two etching regions is 4μm. The etching from the passivation layer to the oxide is vertical, and the substrate will be anisotropic etching. The structure is unsettled by the substrate etching. So the mid metal can be moved by outside force.

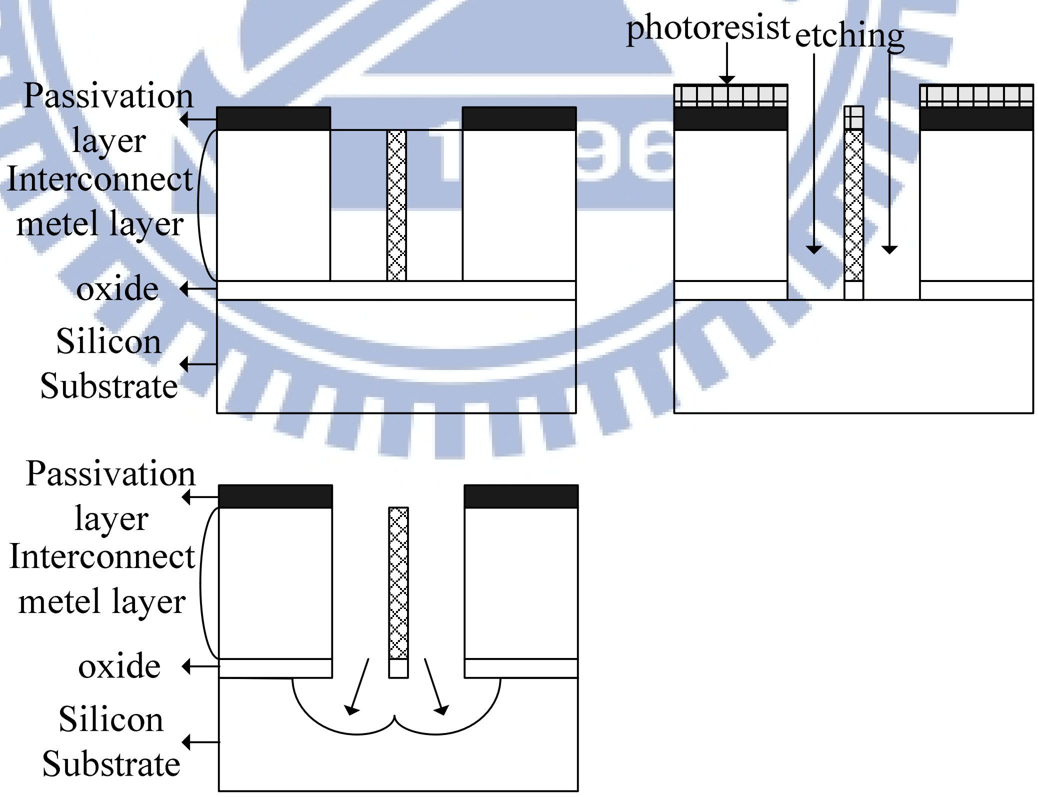


Fig1.5: CIC MEMES process

1.4 Organization

The thesis presents the MEMS switch applied in RF system. Chapter 2 introduces the basic concept in MEMS switch design. Chapter 3 presents the MEMS switch and the design of the circuit. The full structure will be shown in this chapter. Chapter 4 performs the simulation of the MEMS switch and the charge pump. The Chapter 5 shows with the chip photo and the measurement method. The final chapter 6 is conclusions and future work.

Chapter 2

Fundamental of MEMS Switch

MEMS switches have some parameters to help us to design. The main point is included the pull in voltage, the resonant frequency, and the operation time. The pull in voltage is the control voltage of the MEMS switches. When the control voltage reaches the pull in voltage, the cantilever beams will touch down to the electrodes and the switches will be closed. If the control frequency is near the region of the resonant frequency, the MEMS switches have more opportunity to crash. Because switch time of MEMS switch is larger than FET switch, the operation time of MEMS can't be neglected. The detailed description of them will be shown as follows.

2.1 Pull In Voltage of MEMS Switch

The pull in voltage is the most important parameter of MEMS switch. The pull in voltage is the control voltage of the MEMS switches, and the pull in voltage can be designed by the distance of the cantilever beams and electrodes, the material of the MEMS switch, and the area of the electrode. The equation 2.1 shows the formula of the pull in voltage.

$$Vp = \sqrt{\frac{8kg0^3}{27\varepsilon A}} \qquad (2.1)$$

The ε is the dielectric constant of the MEMS switch, the A is the area of the electrode, the g0 is the gap between the electrodes and the cantilever beams, and the k is the spring constant.

The pull in voltage of MEMS switch is larger than the control voltage of MOS switch. Even if the metal area is huge and the gap is small, the pull in voltage is usually larger than 5V. The applied voltage of MEMS switch is a big problem when the MEMS region combining with MOS circuit. Designers usually add an extra circuit of charge pump to solve the problem.

2.2 The Resonant Frequency

The resonant frequency is important to design the operation frequency. The equation 2.2 shows the formula of resonant frequency.

$$\omega 0 = \sqrt{\frac{k}{m}} \qquad (2.2)$$

The k is the spring constant, and the m is the mass of the switch. If the switch has low mass, the resonant frequency will be in the region of 30~100k Hz.

2.3 The Operation Time

The operation time of MEMS switch is larger than FET switch, and the order of it is about micro second. The formula is shown in below.

$$t = 3.67 * \frac{Vp}{Vs\omega 0} \qquad (2.3)$$

The Vp is the pull in voltage, the Vs is the applied voltage, and the ω0 is the resonant frequency.

2.4 The Advantages of MEMS Switch

When the MEMS switch is in close state, the equivalent series capacitance is about 2-4fF and the resistance is 1Ω. That will be result in isolation of -46 to -40dB at 4GHz and -0.1dB loss at 40 GHz. The cutoff frequency of MEMS switch is 30-80THz. The near ideal behavior of MEMS switch is better than FET switch. The details are shown as table 1.1.

	MOS Switch	MEMS Switch
Control Voltage	Less than 0.5V	Usually larger than 5V
Linearity	Low	Better than 30dB
Operation Time	Can be neglected	About microseconds
Power Tolerance	Low	High

Table 1.1 MOS switch compare to MEMS switch

2.5 The Lateral MEMS Switch

The technology of CIC can hollow out substrate of chips instead of dielectric material between metals. So the technology can't build a vertical switch shown in chapter 1. The simple structure is shown in Fig2.1. If the two signal lines connect to ground and the contact has high voltage, the contact will be attracted and move to right. If the voltage is enough, the contact will touch the two signal lines and the signal line will contact. The spring structure can decrease the spring constant of the system. It is important because pull in voltage of lateral MEMS switch is larger than vertical MEMS switch. It is conducive to reducing pull in voltage of MEMS switch.

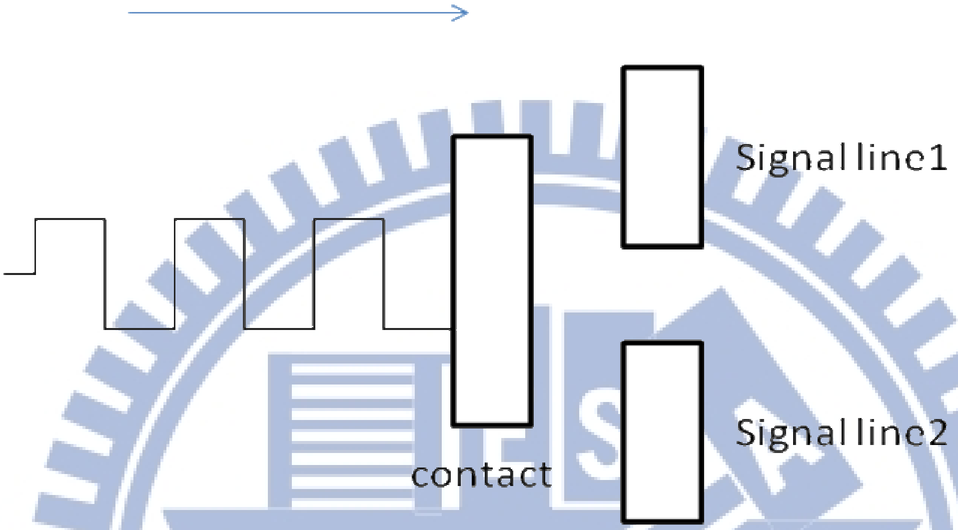


Fig2.1: Simple structure of the lateral switch

2.6 The Purposed MEMS Switch

The applied voltages of normal MEMS switches are larger than 10voltst, so I wish the applied voltage of the MEMS switch will be smaller than 10voltst. The operation of the MEMS switch will be provided by the charge pumps. The switch will be a SPDT type for the application of bypass PA. The overall structure is like Fig2.2. A lateral MEMS switch is controlled by two charge pumps.

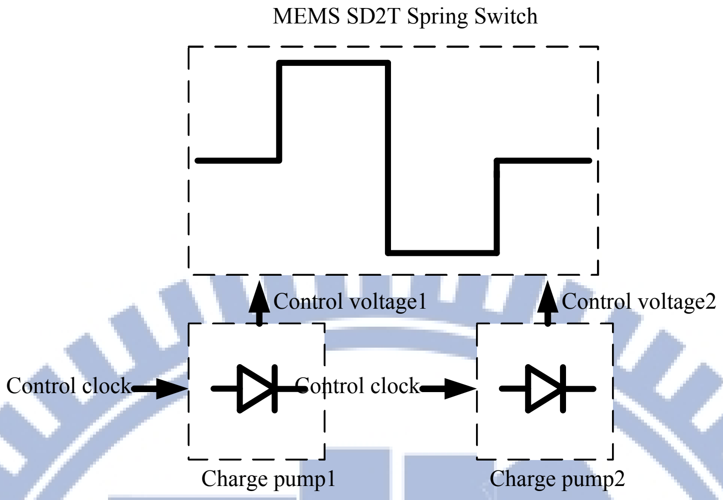


Fig2.2: Simple structure of the MEMS switch

Chapter 3

Design of the MEMS Switch and the Charge Pump

The design of the MEMS switch will be limited by the technology. The CMOS MEMS technology is provided by CIC MEMS technology. In this condition, the minimum distance of the electrode and the cantilever beam is 4μm. The MEMS switch will be lateral type because the etching is vertical. The detail etching technology is illustrated in 1.3.

The MEMS structure is simulated by CoventorWare. The main simulation is included the pull in voltage, the resonant frequency, and the operation time. The charge pumps are simulated by Spectre. And the output voltage and the operation time will be shown in the result.

3.1The Considerations of MEMS Switch

The pull in voltage depends on the dielectric constant, the area of the electrode, the gaps between the cantilever beams and the electrodes, and the spring constant. The dielectric constant and the width of the gap are limited by the technology. If we want to decrease the pull in voltage and the chip size, the spring constant should be depressed. The spring constant can be calculated by formula 3.1.

$$k = \frac{EWT}{4L^2} \qquad (3.1)$$

The E is the vertical spring constant, the W is the vertical length of the cantilever beam, the T is the width of the cantilever beam, and the L is the length of the cantilever beams. The technology limits the vertical length of the beam, and the width of the beam. The spring constant can be depressed by increasing the length of the beam or adding series of spring.

Because the structure of the cantilever beams is not single material, the spring constant is difficult to be calculated. The pull in voltage of single cantilever beam is simulated by CoventorWare first, and then the pull in voltage of the spring can be calculated by formula 2.1. The task can simplify the calculation of the pull in voltage.

3.2 Structure of MEMS Switch

The SDPT type MEMS switch structure is realized by one spring suture with two sets of electrodes. The spring can move to left or right to connect each signal line. The right moved MEMS switch structure is shown as Fig3.1. The black stuffed beam is the electrode, and the void beam with arrow is the spring. The spring connects to ground. If the electrode has a voltage, the electrostatic force will let the spring move as arrow. If the voltage is enough, the spring will connect to the signal line and the signal can pass through. The distance between the spring and the electrode is 4.5μm. The distance between the contact and the signal line is 4μm. The width of the contact and the signal lines are 20μm, and the gap between the contact and the signal is also 20μm. The spring and the electrode use the layers of Metal6 to Metal1 in order to increase the electrode area. Signal line uses the layer of Metal6 of the main structure.

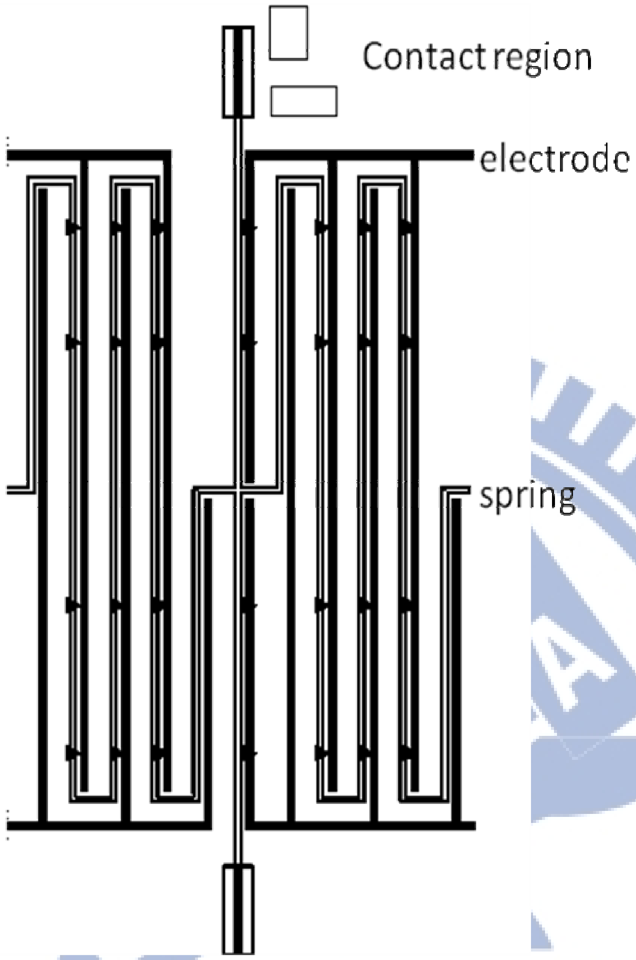


Fig3.1: Structure of half electrode and overall spring (right move)

The left moved MEMS switch structure is shown as Fig3.2. The black stuffed beam is the electrode, and the void beam with arrow is the spring. The spring connects to ground. If the electrode has a voltage, the electrostatic force will let the spring move as arrow. If the voltage is enough, the spring will connect to the signal line and the signal can pass through. The distance between the spring and the electrode is 4.5μm. The distance between the contact and the signal line is 4μm. The spring and the electrode use the layers of Metal6 to Metal1 in order to increase the electrode area. Signal lines use the layer of Metal6 of the main structure.

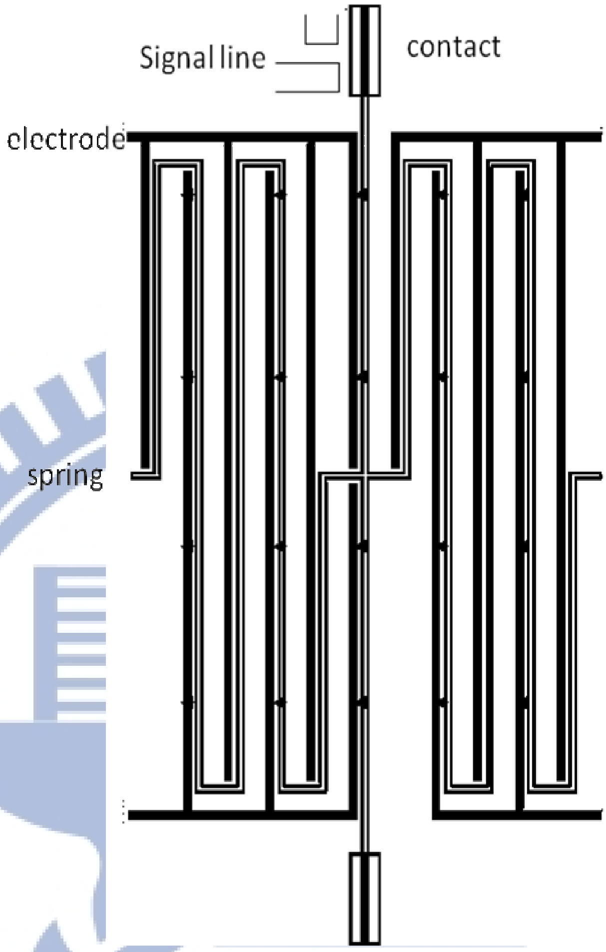


Fig3.2: Structure of half electrode and overall spring (left move)

The electrode contains SiO2 oxide without etching to prevent the short of spring and electrode. The oxide structure is called stoppers. The stoppers are shown as Fig3.3. The SiO2 between the contact and the spring can avoid that the signal lines to connect to ground when the switch is closed and decrease the insertion loss. The vertical length of the cantilever beams is 360μm. The horizontal length of the cantilever beams is 30μm. The width of the cantilever beams is 4μm. The width of the contact and the signal lines are 20μm.

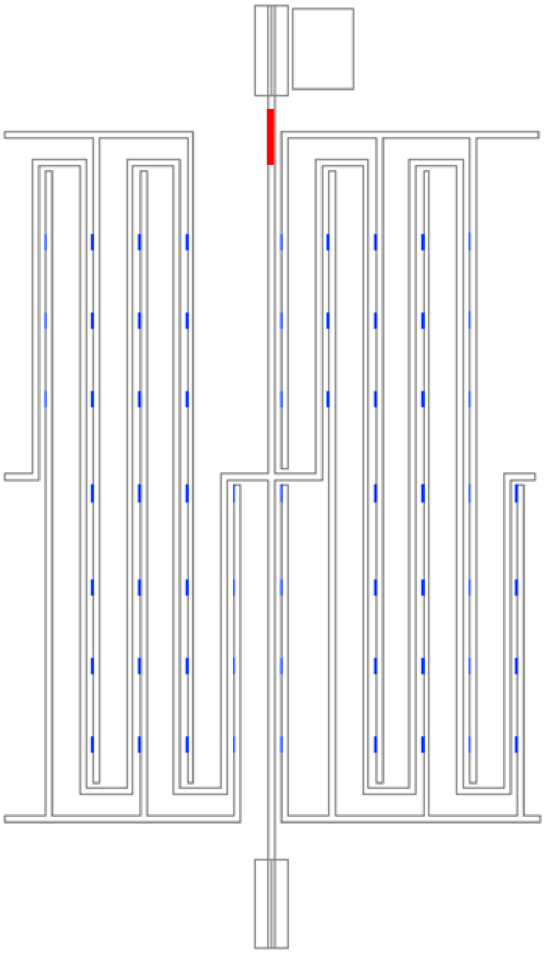


Fig3.3: Stoppers of the MEMS switch

3.3 Structure of the Charge Pump

The charge pump is composed by the charge transfer block in reference [2]. The designer replaces the NMOS of Dickson charge pump with the charge transfer block. The block is shown as Fig3.4. When there has a forward voltage between the input and the output, the Mx and the MDx will open. And the MDx will fix the body and source voltage of Mx. When there has a reverse voltage between the input and the output, the Mx and the MSx will open. And the MSx will fix the body and the source voltage of the Mx. It can solve the body effect of the Mx and increase the output voltage. The output voltage of the charge pump is N* (Vpp-Vt). The N is the stages of the charge pump. The Vpp is the supply voltage. The Vt is the conduct voltage of the MOS.

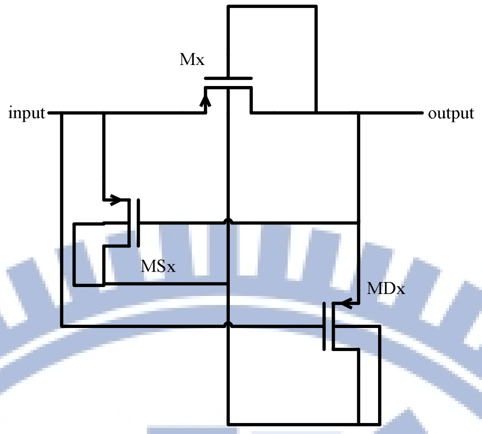


Fig3.4: The charge transfer block

The finally charge pump is shown in Fig 3.5. The circuit replaces NMOS with charge transfer blocks of Dickson charge pump, and the circuit has a discharge path in the output. When the control voltage changed to high voltage, the output can transfer in the ground quickly. The capacitors and the load capacitor are 1pF, and the sizes of transistors are listed in table3. 1.

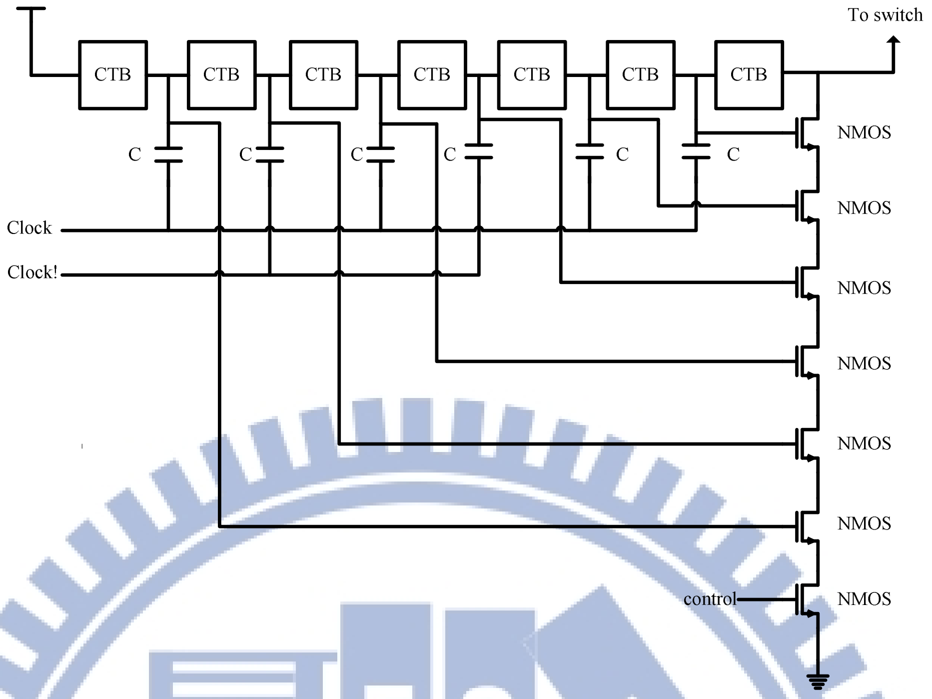


Fig3.5: Structure of the charge pump

Component	W/L	Fingers
Mx	220 μ m/180 μ m	5
MSx	220 μ m/180 μ m	5
MDx	220 μ m/180 μ m	5
NMOS	220 μ m/180 μ m	10

Table 3.1 MOS size of the charge pumps

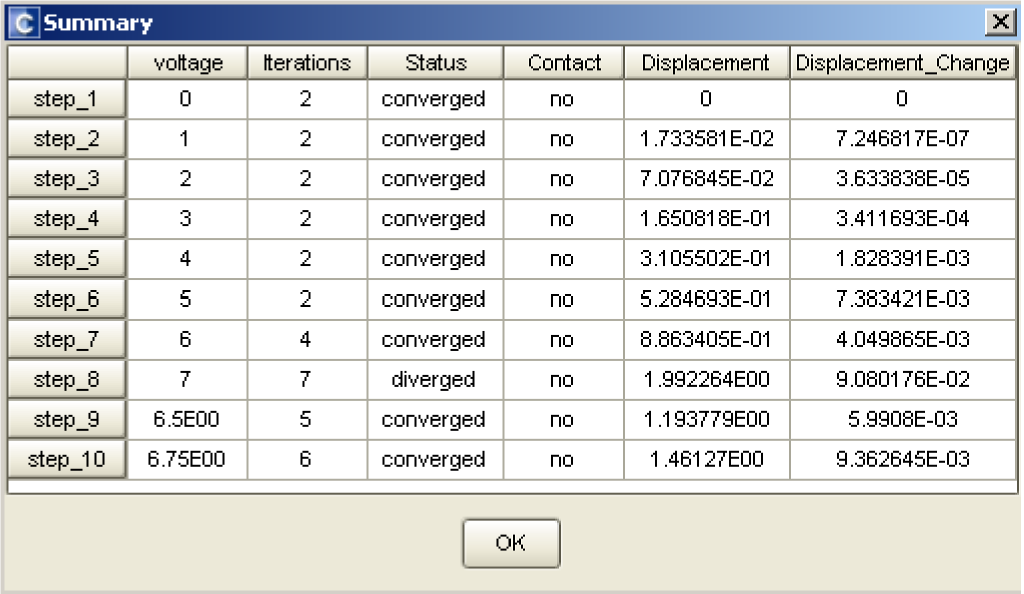
Chapter 4

The Simulation of the MEMES Switch and the Charge Pumps

The MEMS structure can be simulated by CoventorWare. The software can simulate the behavior of the component with gravity, voltage, and acceleration. For the example, CoventorWare can build an electrode and a cantilever beam. Setting a voltage between the electrode and the cantilever beam, and we can observe different displacement of different voltages. After simulating the displacement of different voltages, CoventorWare can build the SNP model of the MEMS system. Then we can simulate the SNP model with the electronic components at ADS system.

4.1 Simulation of the Pull In Voltage

The following will describe the steps of the simulations. At the first stage, the parameters of TSMC process include the thickness of the metals, the thickness of the dielectric materials, the thickness of the oxide, and the dielectric constant of the dielectric materials should be entered into the environment setting. The materials are included from Metal1 to Metal6, the dielectric materials are insulation between the metals, and the oxide. At the second stage, the layout of the MEMS switch can be complete by the layer setting of stage1. The layout of MEMS can be drawn in the steam of Cadence Virtuoso and steam in ConventorWare. But the layout can be simplified by drawing in ConventorWare directly. On the third stage, the contact plane and the applied voltage will be set on the simulation page. Finally, the MEMS switch can be simulated in ConventorWare. The Fig 4.1 (a) is the simulation result of the pull in voltage. The applied voltage is from 0 to 10, and interval of the voltage is 1. If the simulation result is diverged, it will simulate by dichotomy until getting a converged value. Fig 4.1 (b) is the pull in voltage of the MEMS switch with 6.75V.



	voltage	Iterations	Status	Contact	Displacement	Displacement_Change
step_1	0	2	converged	no	0	0
step_2	1	2	converged	no	1.733581E-02	7.246817E-07
step_3	2	2	converged	no	7.076845E-02	3.633838E-05
step_4	3	2	converged	no	1.650818E-01	3.411693E-04
step_5	4	2	converged	no	3.105502E-01	1.828391E-03
step_6	5	2	converged	no	5.284693E-01	7.383421E-03
step_7	6	4	converged	no	8.863405E-01	4.049865E-03
step_8	7	7	diverged	no	1.992264E00	9.080176E-02
step_9	6.5E00	5	converged	no	1.193779E00	5.9908E-03
step_10	6.75E00	6	converged	no	1.46127E00	9.362645E-03

Fig 4.1 (a): Simulation of the pull in voltage

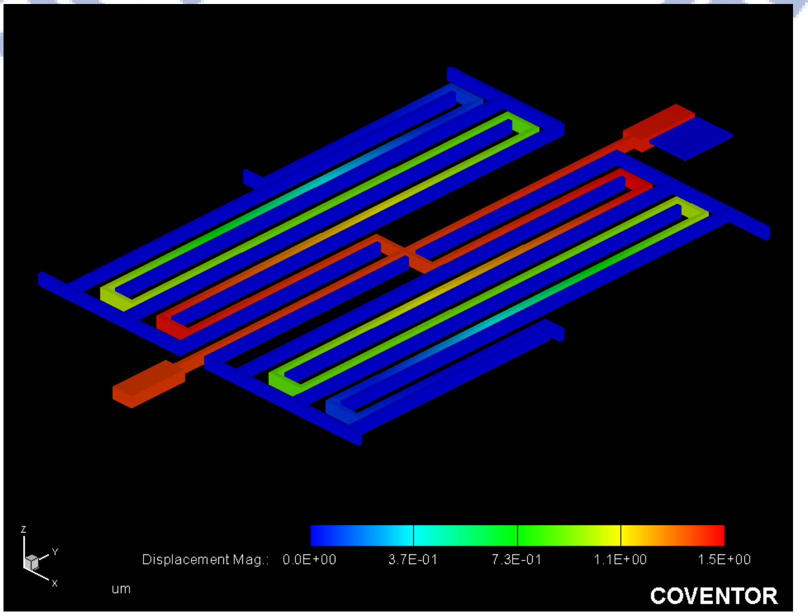


Fig 4.1 (b): Simulation of the pull in voltage

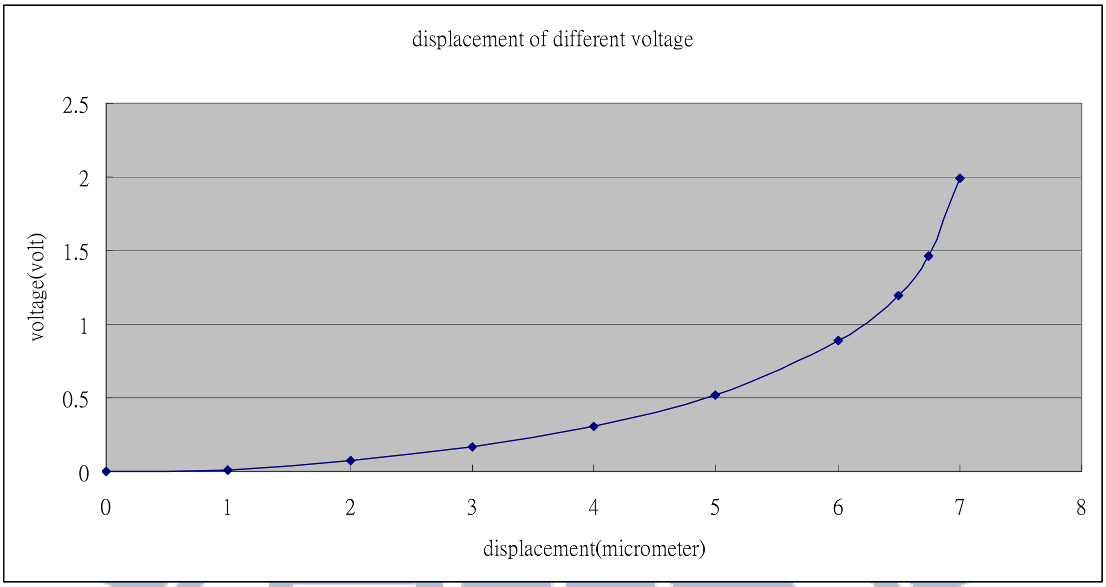
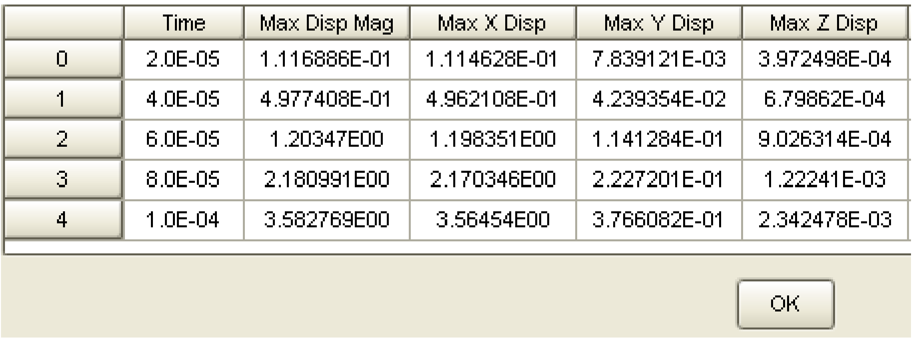


Fig 4.1 (c): Diagram of the simulation

4.2 Simulation of the Operation Time

The observe point of the simulation is the contact of the switch. The contact will touch to the signal lines in close state. The simulation applied the pull in voltage to the MEMS switch and simulates the displacement of the contact. Fig4.2 is the simulation result of the operation time. The displacement unit is micrometer, and the time interval of simulation is 20 microseconds. If the MEMS switch is on, the maximum x displacement should be 4.5 micrometers. The time simulation of Coventorware will be diverged and resulted in the faults when the displacement is more than 4.5 micrometers. The simulation result is not precision, but it can help that we know the approximately time of operation time. The operation time of this MEMS switch is about 100 microseconds.



	Time	Max Disp Mag	Max X Disp	Max Y Disp	Max Z Disp
0	2.0E-05	1.116886E-01	1.114628E-01	7.839121E-03	3.972498E-04
1	4.0E-05	4.977408E-01	4.962108E-01	4.239354E-02	6.79862E-04
2	6.0E-05	1.20347E00	1.198351E00	1.141284E-01	9.026314E-04
3	8.0E-05	2.180991E00	2.170346E00	2.227201E-01	1.22241E-03
4	1.0E-04	3.582769E00	3.56454E00	3.766082E-01	2.342478E-03

Fig4.2: Table of the displacement simulation

Fig4.3 is the diagram of the displacement about time. The major displacement of MEMS switch is in x direction.

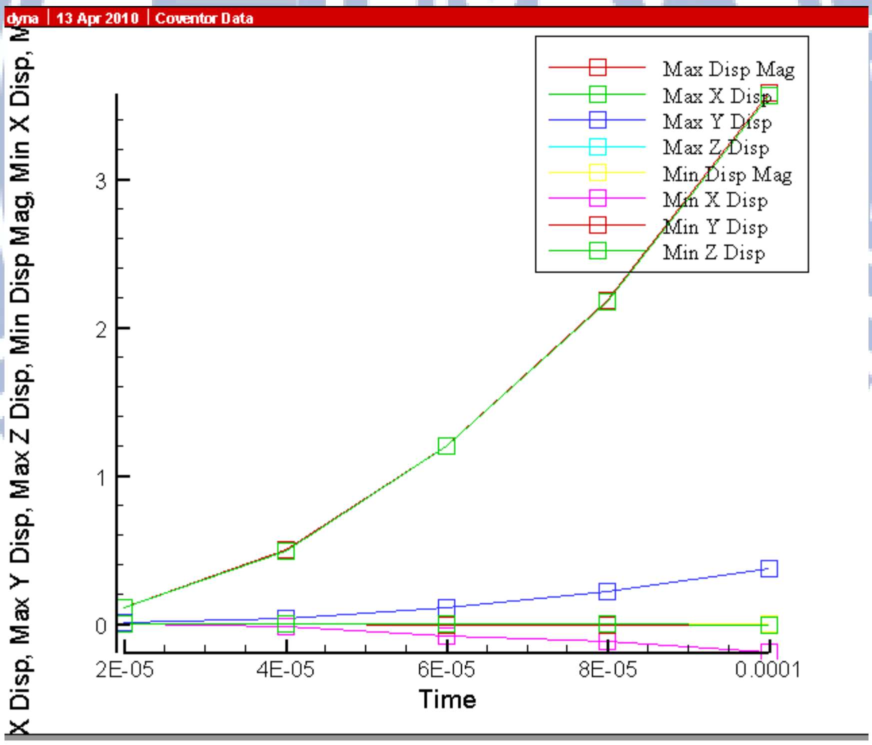
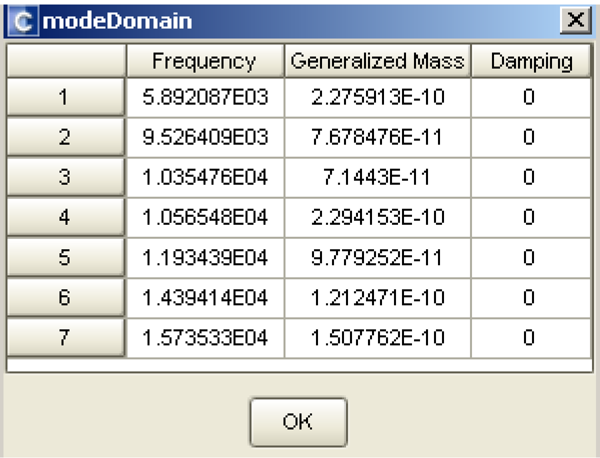


Fig4.3: Displacement of the MEMS switch with time

4.3 Simulation of the Resonant Frequency

The operation frequency will not be near the resonant frequency to avoid collapse.

The operation frequency of the MEMS switch is about 10 kHz. Then setting the frequency of simulation from 1 kHz to 20 kHz, Fig4.4 is the simulation result. The nearest resonant of 10 kHz is 9.5 kHz.



	Frequency	Generalized Mass	Damping
1	5.892087E03	2.275913E-10	0
2	9.526409E03	7.678476E-11	0
3	1.035476E04	7.1443E-11	0
4	1.056548E04	2.294153E-10	0
5	1.193439E04	9.779252E-11	0
6	1.439414E04	1.212471E-10	0
7	1.573533E04	1.507762E-10	0

Fig 4.4: The resonant frequency of MEMS switch

4.4 Simulation of the Isolation

Fig 4.5 is the simulation of the isolation. The input and the output is the pad of the chip. The isolation is -28dB at 10G Hz.

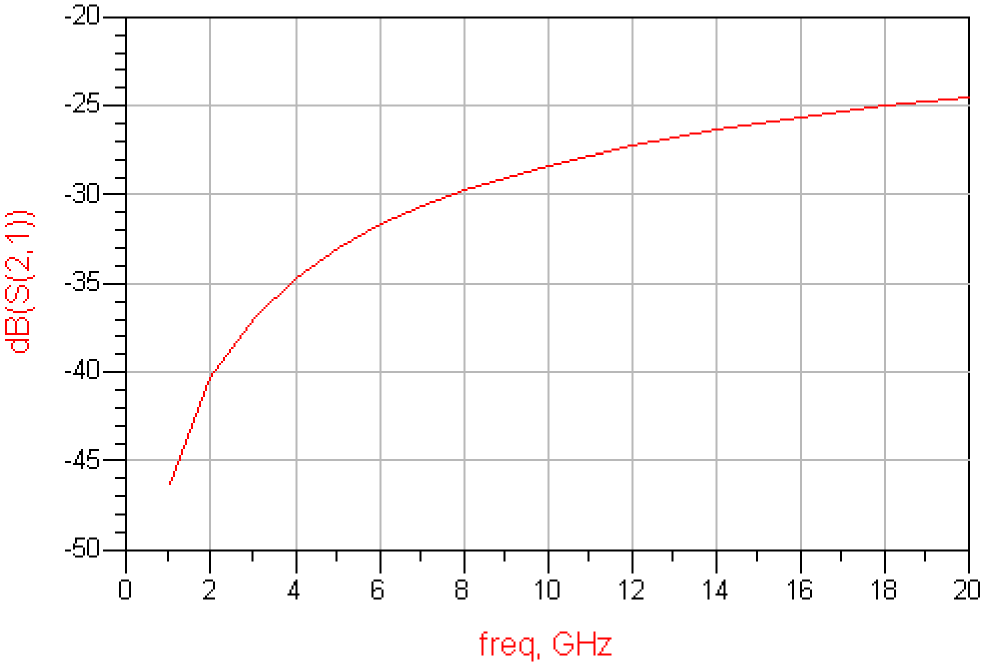


Fig 4.5: The simulation of isolation

4.5 Simulation of the Charge Pumps

The charge pumps afford voltage of the MEMS switch. The applied voltage must be larger than pull in voltage. The pull in voltage of MEMS switch is 6.75 volts. The result shows the voltage at FF TT SS corner is enough. The leakage path is open and the output voltage becoming 0 immediately at 100 microseconds. When the output voltage reached the pull in voltage, the operation time of the charge pump is between 6.4 to 15.4 microseconds.

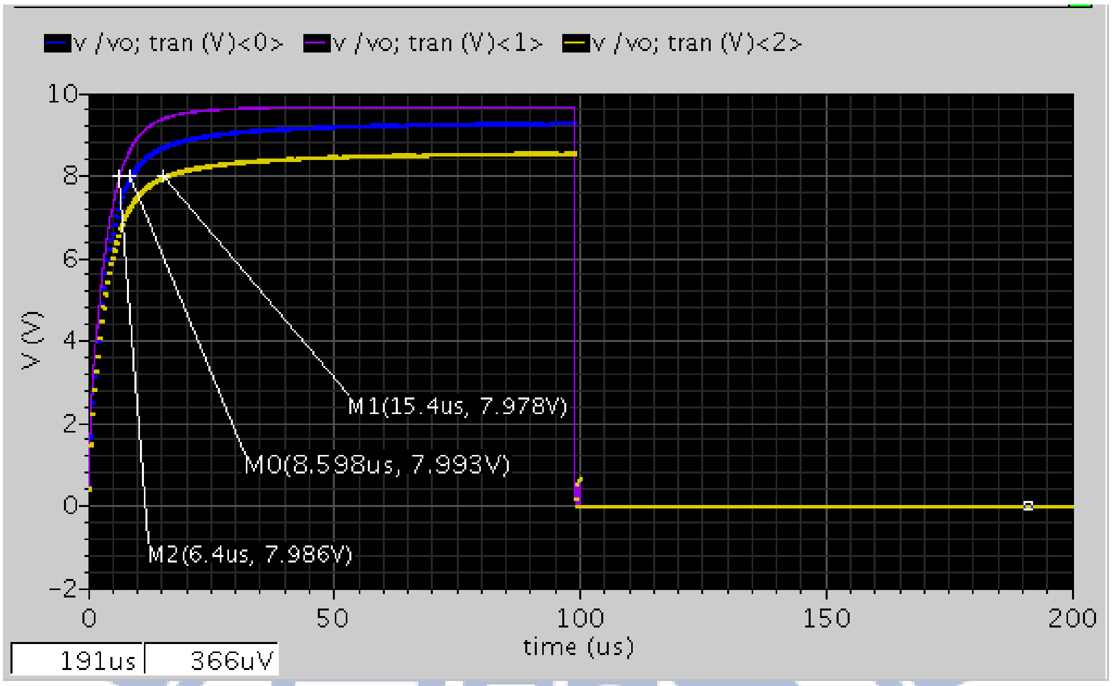


Fig4.6: Output voltage of charge pumps

Corner	**Operation Time**
SS	**6.4 μ s**
TT	**8.6 μ s**
FF	**15.4 μ s**

Table4.1: The operation time of 3corners

4.6 Simulation Results of the Circuit

Table4.2 is the simulation results of the circuit. There have some resonant frequencies near the region of 100k Hz. The switching time is more than 110 μ sec for avoiding unexpected crash.

	This work
Process	0.18 μm
Actuation Voltage	8V (offer by charge pump)
Switching Time	More than 110 μsec
Chip Size	804.34 μm*712.71 μm
Switch type	SPDT
Isolation	About 25dB at 20GHz

Table4.2: Simulation Results

4.7 Control Signal of the Charge Pumps

Control signal of the charge pumps is important for this work. The clock period will be involved in the speed of MEMS switch. But the maximum operation frequency will be defined by the MEMS switch structure. In this case, the maximum frequency will not be larger than 10 kHz because the operation time of MEMS switch is larger than 100 microseconds. If the MEMS switch operation time is t1 and we assume the operation of charge pumps is t2, the overall operation time will be t1+t2. The t1 and the t2 are fixed by design. But we can improve efficiency of the charge pumps by improving control signal. It will be shown in Fig4.6. The SPDT is controlled by voltage. If the path1 will be connected, the electrode1 charge in act1. The voltage of electrode is higher than pull in voltage and path1 is open, and then the electrode2 charge in act2. If the path2 will be connected, the electorde2 discharge in act3. And contact will to attract to electrode2 and path2 connect in act4. The process can be left out of the charge time of charge pumps. And the operation time of the system just depends on the operation time of the MEMS switch.

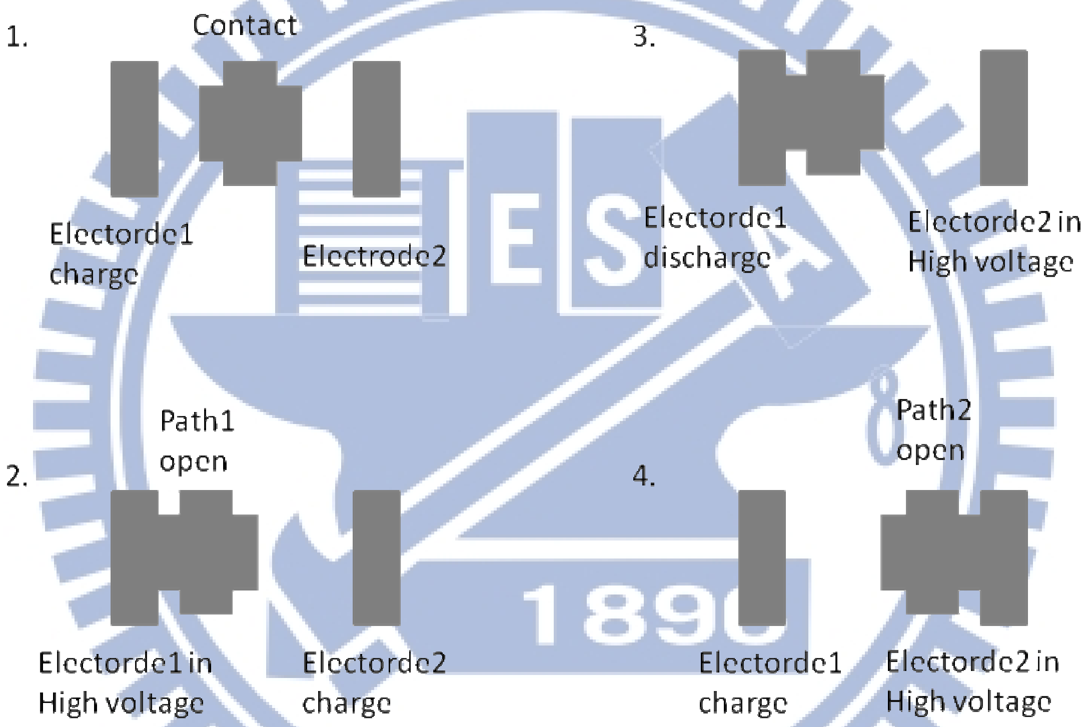


Fig4.7: Control of MEMS switch

Fig4.9 shows the control clock of the charge pumps. The clock1 control the charge of the charge pump1. The clock2 control the charge of the charge pump2. And the leakage signal controls the discharge of the the charge pumps. If the clock voltage is high, the charge pump will be active. When the clock1 has high voltage, the charge pump1 charges and path1 connects. Then the charge pump2 charges high voltage in status2.

Activating the charge pump1 leakage path in status3, and path2 will connect later in status4. When you want to connect path1, the control signal is applied form act1 to act4 again. That will reduce the operation of the overall system.

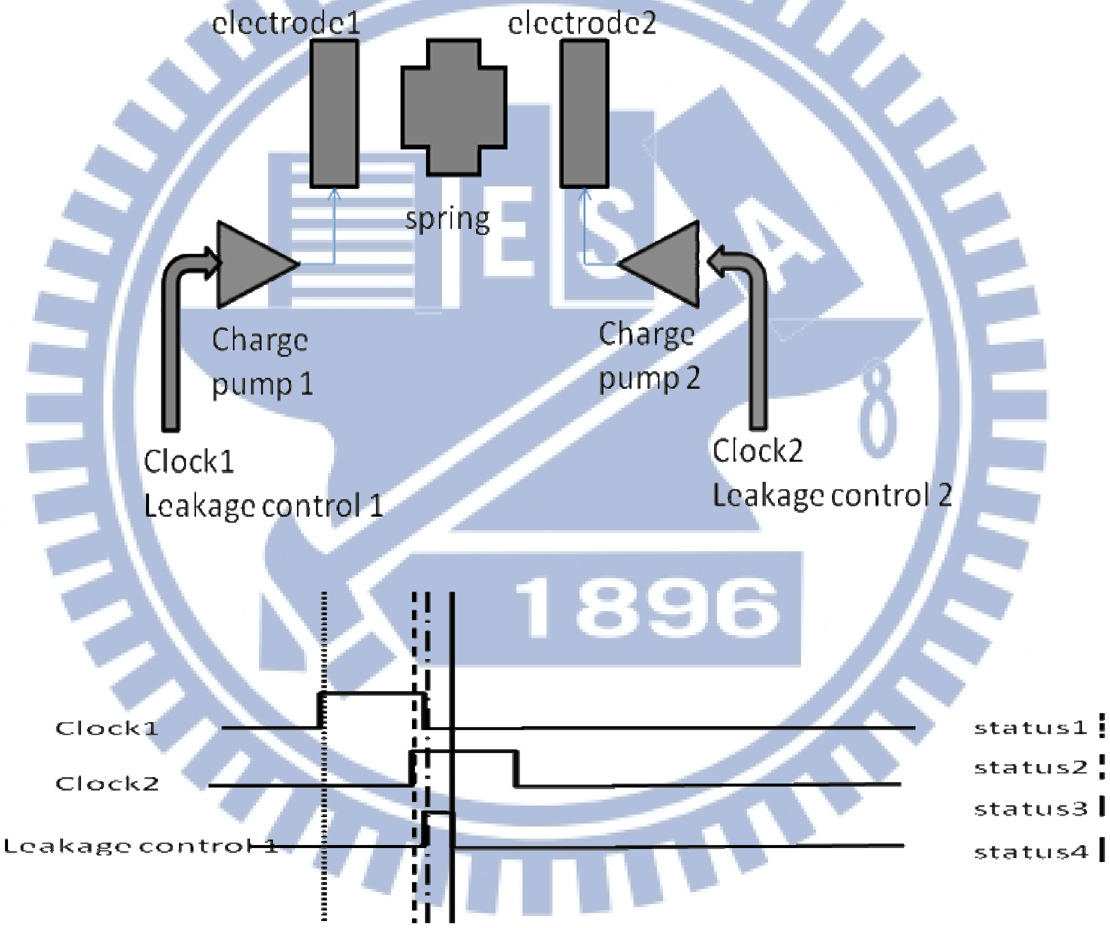


Fig4.8: Control clock of the charge pumps

Chapter 5

CHIP Implementation

In this chapter, the measure method will be described. And the photo of the chip will be offered. This project has failed because some reasons of process. And how to avoid the problem will be mentioned in future work.

5.1 Layout of the MEMS Switch

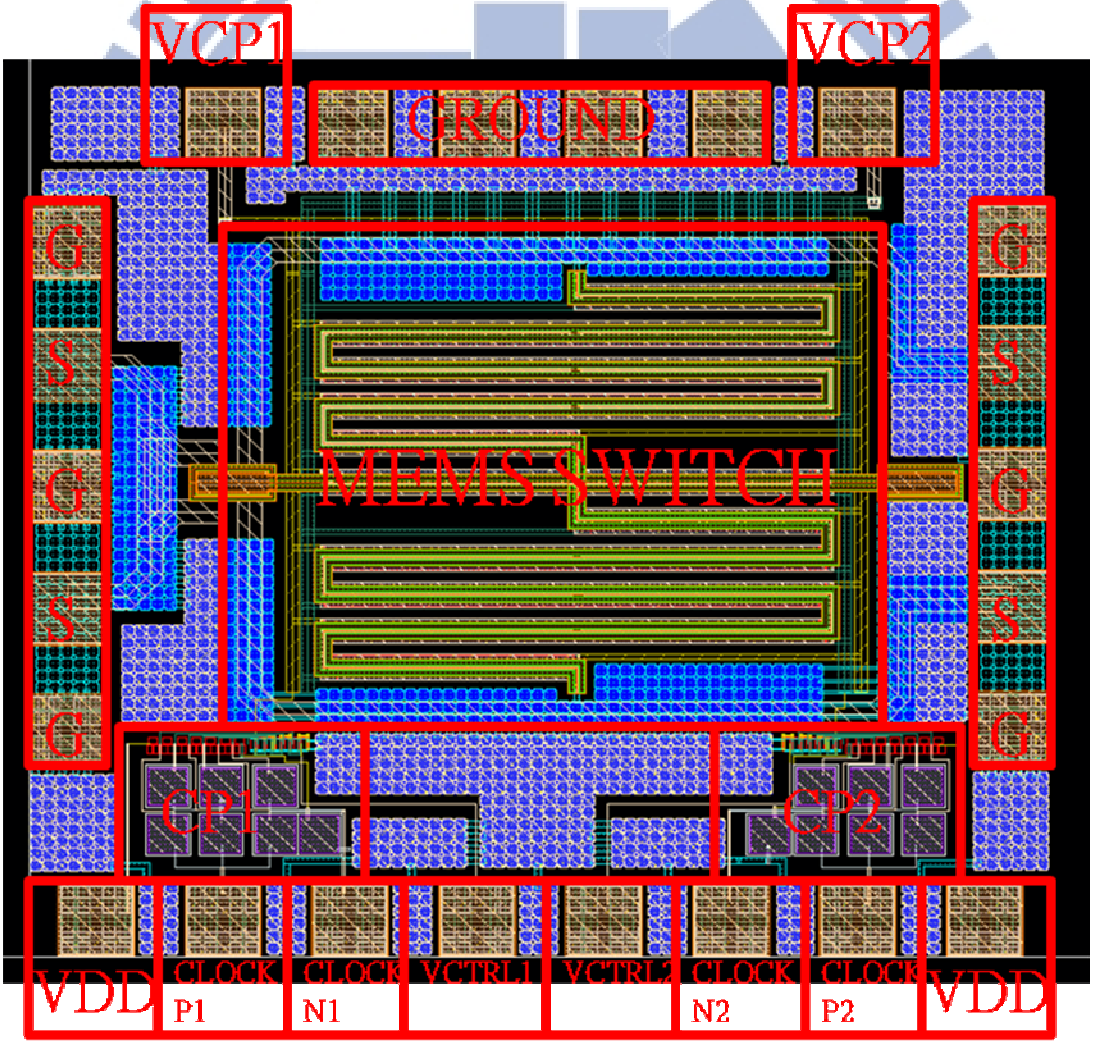


Fig5.1: Layout of overall circuit

The layout of the MEMS switch is shown in Fig5.1. The spring structure in mid is the MEMS switch, and bottom left and bottom right is the charge pumps. The chip size is 804.34 μm*712.71 μm.

The left side S is the signal input, and the right side S is the signal output. The clockp1 is the positive clock of charge pump1. The clockn1 is the negative clock of charge pump1. The clockp2 is the positive clock of charge pump2. And the clockn2 is the negative clock of charge pump2. The vctrl1 and the vctrl2 can control the leakage path of the charge pumps. The vcp1 and the vcp2 is the output of the charge pumps.

5.2 Measurement of the Circuit

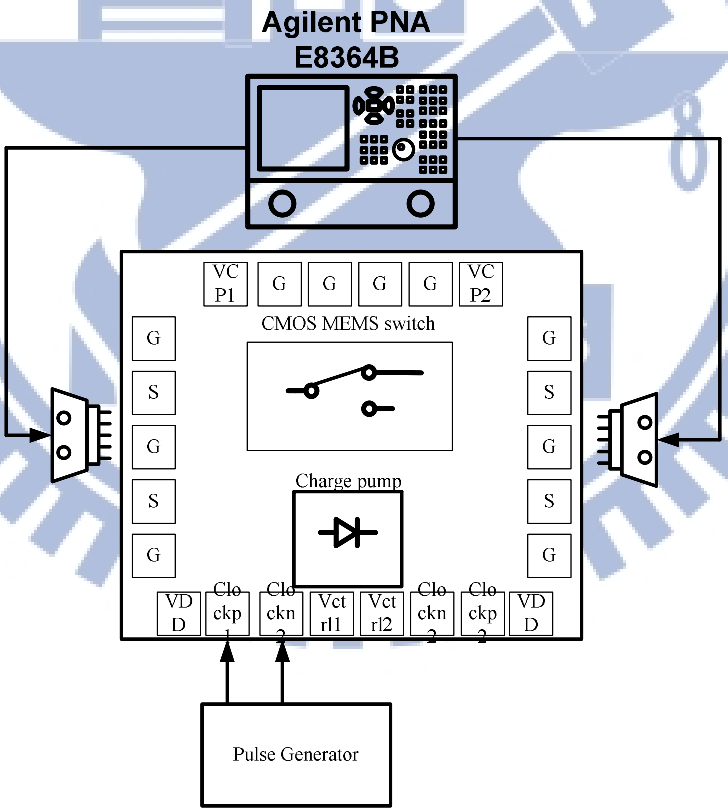


Fig5.2: S parameters measure

The Fig5.2 is shown how to measure the S parameters. The pulse generator applies positive and negative square ware for charge pump1 or charge pump2, and then the PNA network analyzer can measure the S parameters of the MEMS switch.

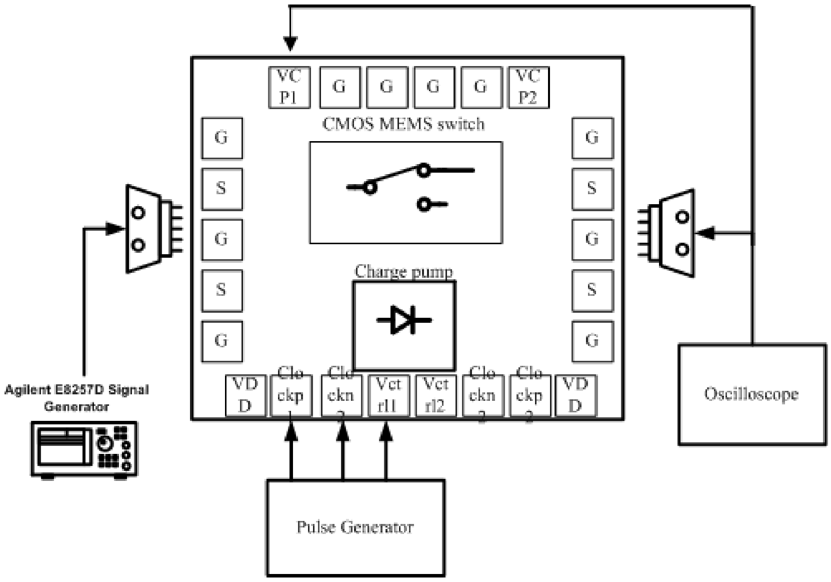


Fig5.3: Measure of switch settling time

The measurement of switch settling time is shown in Fig5.3. The pulse generator applies three control clocks of charge pump, and then the oscilloscope input a low frequency signal to MEMS switch input. The scope can measure the delay between the input and the output.

5.3 Chip Photo

Fig5.4 shows the chip photo. The mid MEMS structure is broken. The possible reasons are: 1. the imperfect etching technology cause the cantilever beams of the switch to break. 2. The mass of the switch is too heavy causes the beams crashed down to the substrate of the chip. The output of the charge pumps connects to the electrodes causes the output voltage of the charge pumps can’t be measured.

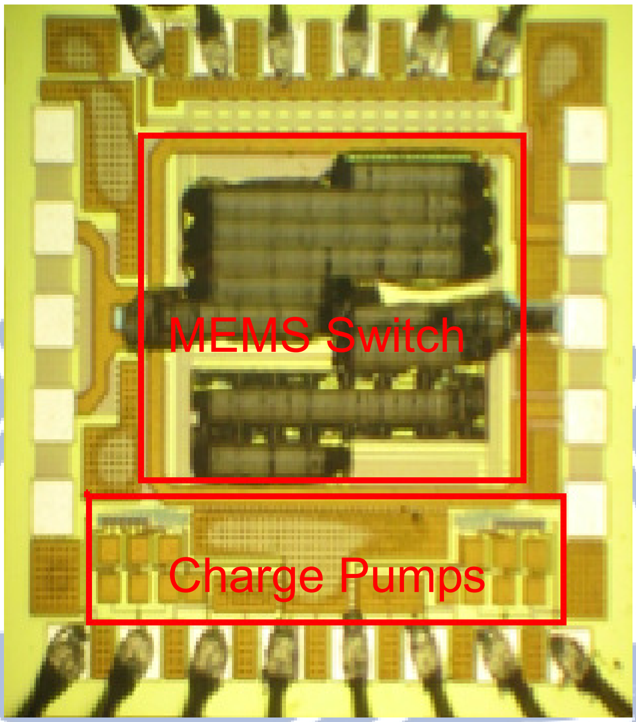


Fig5.4: Chip photo

Chapter6

Conclusions and Future Work

6.1 Conclusions

The etching technology of CMOS MEMS compares to the traditional MEMS technology is not perfect. The SiO2 layer between the metals is difficult to simulate and predict behavior. The constituted of MEMS switch is usually single metal material. But the etching technology of CMOS MEMS will maintain the SiO2 layer and the oxide. And the thickness of the CMOS MEMS component is fixed. The thickness from oxide to Metal6 is more than the width of the cantilever beams. The thickness of cantilever beams will increase the mass and the stiffness of the overall structure. The effect will increase the spring constant of the system, and the displacement of the cantilever beams will be limited. The additional mass will be result in the collapse of the system. The CMOS MEMS technology can be improved by etching the SiO2 under Metal6.

6.2 Future Work

The metal MEMS switch has some unexpected phenomenon after metal etching. One of them is curl. The curl will be causing increasing the pull in voltage of MEMS switch or decrease the capacitor of close stats. And the phenomenon should be considered in the design. The reliability analyzes is important to the MEMS components. The reliability is close to the amounts of charges. We can measure the reliability by the input clock or the pull in voltage directly. The structure of the charge pumps can improve by CST charge pumps. The CST charge pumps can eliminate the actuation of MOS. The reference [3] is the improved CST charge pumps. And the new type charge pumps can be applied to the thesis.

Reference

[1] Gabriel M. Rebeiz, Jeremy B. Muldavin ,"RF MEMS Switches and Switch Circuit" Microwave Magazine, IEEE Vol2 Page:59-71Dec. 2001

[2] D. S. Hong, "Low Operating Voltage and Short Settling Time CMOS Charge Pump for MEMS Applications", IEEE ISCAS, 2003, Vol. 5, pp. 281-284.

[3] J. Wu and K. Chang, "MOS Charge Pumps for Low-Voltage Operation," IEEE J. Solid-State Circuits, vol. 33, no. 4, pp. 592-597, April 1998.