Pull-in과 release 전압차 감소용 돌기구조를 갖는 비틀림형 초소형 기계적 스위칭 소자

論 文
50C - 9 - 8

Torsional Micromechanical Switching Element Including Bumps for Reducing the Voltage Difference Between Pull-in and Release

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Abstract – In this paper, a micromachined micromechanical switch is presented. The presented switch is operated in the vertical direction to the substrate by an electrostatic force between two parallel plates. The moving plate is pulled down to connect the bumps of the bias node(V_{DD} or GND) to the bumps of the output node when a voltage difference exists between the moving plate and the input plate. The switch was designed to operate at a low switching voltage(≒5V) by including a large-area, narrow-gap, parallel plate capacitor. A theoretical analysis of the designed switch was performed in order to determine its geometry fitting the desired pull-in voltage and release voltage. The designed switch was fabricated by surface micromachining combined with Ni electroplating. From the experimental results of the fabricated switch, its pull-in voltage came out to be less than 5V and the measured maximum allowable current was 150mA. The measured average ON-state resistance was about 8Ω, and the OFF-state resistance was too high to be measured with digital multimeter.

Key Words : a micromachined micromechanical switch, bumps, pull-in voltage, release voltage, Ni electroplating

1. Introduction

As the industrialization rapidly progresses, the main resource of the world, electrical energy, is increasingly demanding. The control circuits that can handle high temperature and large current are required as the energy is supplied by using high voltage and large current, elevating the operating temperature of electrical devices, to reduce the loss of the electrical energy. Also, to fulfill this requirement, many researches to develop power semiconductor devices and heat sink technologies are in progress.

However, for power semiconductor devices, there exist fundamental limitations of operating temperature, that is, E-H pairs are generated due to the heat within the devices and the elevation of temperature surrounding the devices. This is the reason that a temperature of 125 ℃ is used to test one of the power semiconductor devices, IGBT (Insulated Gate Bi-polar Transistor). And, heat sinks or coolers are utilized as heat sink technologies but, in this case, the size of the devices become quite large. So, to overcome this demerit, developing a new type of switching devices that can operate with large current independent of the surrounding temperature is inevitable.

One way to implement the new type of switching devices is to use a MEMS technology. This method is based on a mechanical switch that is insensitive to the surrounding temperature so no leakage current exists compared to semiconductor switching devices and the breakdown voltage is very high. Therefore, it is possible to develop a switching device that can operate with large current and high temperature.

Some of the actuation methods using the MEMS technology for switching devices are thermal, electromagnetic, and electrostatic actuation. There are some disadvantages for each method. The thermal actuation shows low speed and dissipates high power. The electromagnetic actuation gives high power consumption, high complexities of assembly processes, and difficulties in the integration with control circuit[1-4].

In, previous work, three problems arose with the surface micromachined poly-Si switching device driven in the parallel direction to the substrate using electrostatic force[5]. The operating voltage and the turn-on resistance were high. And the whole area of the device was large.

When the electrostatic actuation is used, the area of electrodes must be increased, or the distance between electrodes must be decreased in order to increase the actuation force. But, in the case of the horizontal motion type, the distance can't be indefinitely decreased by the limitation of the photolithography. And also, in order to increase the electrode area, the thickness of the structure

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接受日字 : 2001年 6月 7日
最終完了 : 2001年 7月 26日

should be increased but it is not easy in surface micromachining using thin films.

In order to resolve these problems, this paper proposes a vertical motion type of electrostatic actuation that can easily increase the electrostatic force and thus reduce the operating voltage. And, since the resistivity has direct influence on the turn-on resistance and it has limitation in reducing the poly-Si resistivity through doping method, the metal structural is used in this proposal.

Recently, two types of vertical switching device using electrostatic force were published[3-4]. However, one required high driving voltage and consumed large area and the other should be fabricated with E-beam lithography. Considering these drawbacks, the proposed device was designed to have a low actuation voltage and small area and the surface micromachining using Ni electroplating was selected for easy fabrication.

2. Proposal and Design

2.1. Operating Principle

The proposed switching device is designed to be operated by voltage difference in the parallel plate capacitor as shown in Fig. 1. The moving plate transfers V_{DD} or GND signal through the bumps to output node when the electrostatic force is generated(ON state). If the moving plate has the same voltage with the underlying input electrode, the electrostatic force vanishes and thus the moving plate goes back to OFF state due to the elastic force of the twisted beams supporting the moving plate.

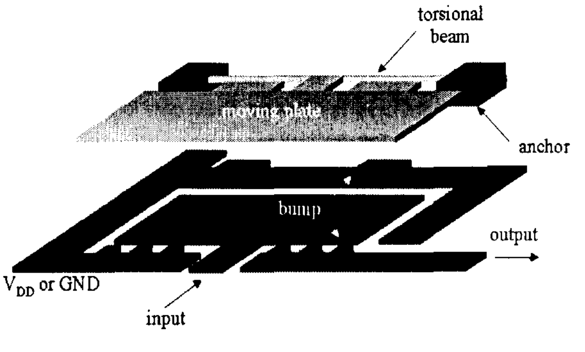


Fig. 1. Schematic of the proposed switch

The six bumps in front side are used to contact the moving plate to the output node and the back side bumps works as the mechanical stop. If the electrostatic force pulls down the moving plate, this structure has not only torsion motion but also bending motion. Therefore, the back side bumps are needed as the mechanical stop to prevent the electrical short between input node and the moving plate.

2.2. Simulation and Design

In typical MEMS switching devices actuated by electrostatic force, the pull-in voltage is defined as the voltage at which the moving structure is pulled to make contact to the output node by the electrostatic force. This occurs when the electrostatic force is larger than the elastic restoring force generated in the twisted supporting beam and the displacement of the moving structure is limited by the gap between the moving structure and the output electrode [6, 7]. After the moving structure makes contact with the output electrode ($V_{apply}>V_{pull\text{-}in}$), the electrostatic force is decreased and eventually becomes identical to the elastic restoring force as the driving voltage is decreased. At this point, the moving plate moves away from the output electrode and the switch goes to OFF-state. This voltage is defined as the release voltage.

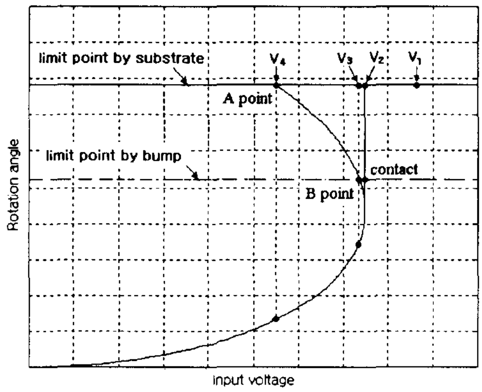


Fig. 2. A typical plot of rotational angle vs. input voltage applied between torsional plate and bottom electrode

In the proposed switching device, the vertical displacement of the moving plate is limited by the bumps. By placing the bumps on the output nodes, the release voltage of the switch becomes different from that of the structure without bumps as shown Fig. 2. When the moving plate is pulled by an electrostatic force to contact on the bumps, the switch becomes ON-state and the applied voltage at this point is defined as the pull-in voltage, V_2 in Fig. 2. In order to find the release voltage, a behavior of the micromechanical switch from V_1 to V_4 in Fig. 2 is considered. V_1 is higher than the pull-in voltage and thus the displacement of the moving plate is limited by the bumps on the output node. V_2 is pull-in voltage and, though the applied voltage is decreased from V_1 to V_2, the electrostatic force is still stronger than the restoring force of the twisted supporting beams. Thus the moving plate is still placed on bumps. If the applied voltage is further decreased to V_3, the electrostatic force becomes the same as the restoring force, and hence the moving plate can be released. Consequently, the voltage V_3 is the release voltage of the switching device with the bumps. Without the bumps, the electrostatic force and the restoring force becomes same when the applied voltage is decreased to V_4, which becomes the release voltage. In conclusion, the bumps can change the release voltage from point A to point B in Fig. 2 [8-9].

Performance expectation for the designed switching device was done based on the relationship between electrostatic force applied on the moving plate from the bottom electrode and the elastic force generated by the twisted supporting beams [10]. Simulation results about actuation voltage versus rotation angle is shown in Fig. 3 where the material of the moving structure was assumed as Ni(Young's modulus 200GPa and Possion ratio 0.30). The calculated pull-in and release voltages were 5.46V and 5.04V, respectively.

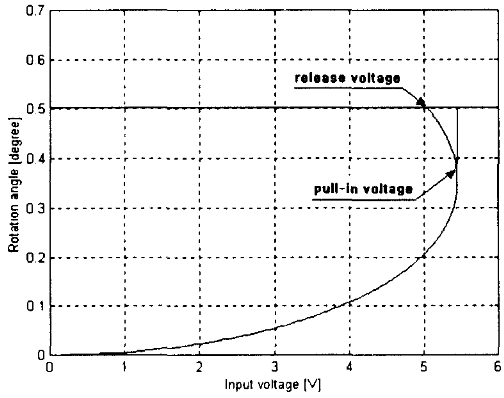


Fig. 3. Simulated results of rotation angle vs. actuation voltage in the proposed switching device

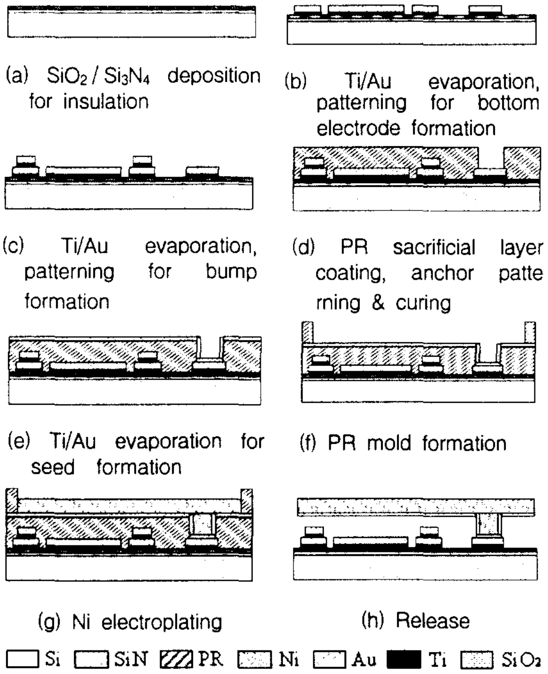
The selected dimensions used in the simulation are following: Torsion beam length of both sides was 45μm, capacitive plate had the size of 150μm×106μm, thickness of the structure including torsion beam, capacitive plate, and anchor was 2μm and heights of the sacrificial PR layer and bump were 1.8μm and 0.6μm, respectively.

3. FABRICATION AND OPERATING EXPERIMENT

3.1. Fabrication Process

Fabrication process of the proposed switch is shown in Fig 3. In this work, surface micromachining using Ni electroplating has been selected for the structure formation.

Firstly, thermal oxide and silicon nitride were deposited on the surface of 4" (100) Si wafer for insulation. And Ti/Au bottom electrode was formed with the thickness of 700/4300Å. Considering the adhesion of metal film, Au was deposited sufficiently high and annealed on hot-plate at 200℃ during 30 minutes after patterning. After the formation of the bottom electrode, Ti/Au layer was deposited and patterned once again for the formation of bumps. Its thickness was 700/5300Å. Polyimide was used as sacrificial layer and after its patterning, Cr/Au(500/2000 Å) seed layer was sputtered. Electroplating was done after the formation of photoresist mold. After electroplating, mold and seed layer were removed in wet etch and polyimide sacrificial layer was eliminated by O_2 plasma dry etching. SEM images of the fabricated structure are shown in Fig. 5.



(a) SiO_2 / Si_3N_4 deposition for insulation

(b) Ti/Au evaporation, patterning for bottom electrode formation

(c) Ti/Au evaporation, patterning for bump formation

(d) PR sacrificial layer coating, anchor patterning & curing

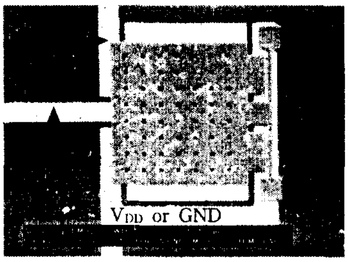
(e) Ti/Au evaporation for seed formation

(f) PR mold formation

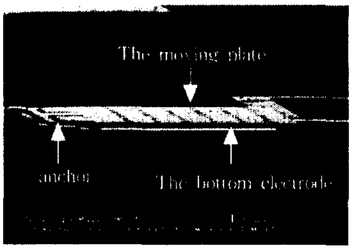
(g) Ni electroplating

(h) Release

Fig. 4. Cross sectional view of the fabrication process



(a) Top view



(b) Side view

Fig. 5. SEM images of the fabricated structure

3.2. Experiment and analysis

For the characterization of the fabricated switching device, bottom electrode, output node and input node were connected to GND, oscilloscope, and function generator, respectively. After doing that, triangular wave was applied to input node. In the experiments using several switching devices, actuation voltages were measured in the range of 3.8~4.5V and were captured by oscilloscope as shown in Fig. 6. The measured voltages were lower than the simulated results because supporting beams were electroplated less than the designed valve.

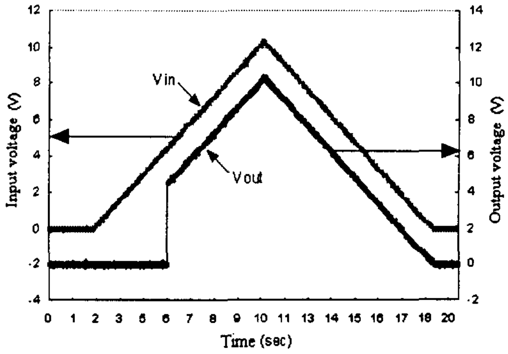


Fig. 6. V_{in} versus V_{out} in the fabricated switching device

The fabricated switching device has showed switching operation but stiction problem appeared after operating once as shown in Fig. 6, where the moving plate was not released from bumps although the driving voltage was decreased. The possible cause of stiction is that the elastic restoring force is decreased due to the thinning in supporting beams and, as a result, the elastic force can not overcome sticking force between the moving plate and bump. Also it is possible that there is a welding problem at the contact due to the current flow. In order to prevent stiction problem, the elastic restoring force can be increased through some modifications in supporting beam and moving plate and the contact materials can be changed considering the welding phenomenon.

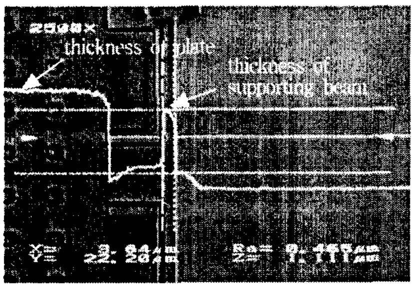


Fig. 7. Laser-profiler measurement in the electroplated structure

The height of the electroplated structure was measured by using laser-profiler as shown in Fig. 7. The measured thickness of the supporting beam was thinner than the designed value and thus the elastic restoring force was decreased in the thin supporting beam. The pull-in voltage was expected to be also decreased from 5.46V to 2.23V in Fig. 8.

In the experiment results, the pull-in voltages were in the range of 3.8~4.5V and it is lower than the simulated result about 0.9~1.7V. In the fabrication, the surface profile of sacrificial layer was not perfectly flat and is reflected in bottom form so the gap between the capacitive plate and bottom electrode is not decreased as much as the height of bump. Also, after releasing the structure, there were different stresses at each layers, respectively, so actuation voltages are not same all switching device.

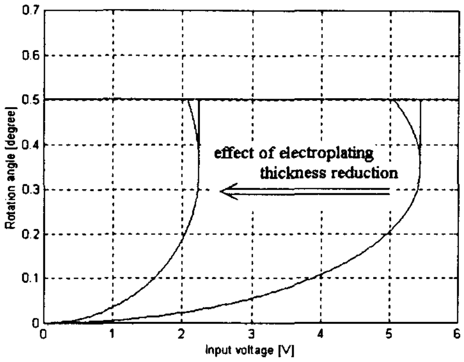


Fig. 8. Pull-in voltage reduction due to the height thinning in electroplating step

ON resistance was about 8Ω at several samples and OFF resistance was too high to be measured with digital multimeter that has 100MΩ measurement range. The maximum allowable current was 150mA and, over this current level, supporting beam was molten and cut off, as shown in Fig. 9. When switch is ON state, V_{DD} node is connected to output node through bumps and two current paths are built up. One path is bumps on V_{DD} electrode - plate - bumps on output node, and the other is V_{DD} electrode - anchor - supporting beam - plate - bumps on output node, which is the current-limiting path.

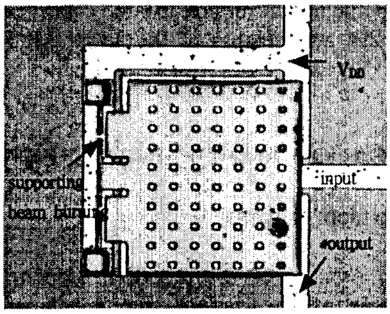


Fig. 9. Supporting beam failure due to the large current

4. CONCLUSIONS

In this paper, a micromechanical switching element was proposed and fabricated by surface micromachining technology using Ni electroplating. Since the fabricated switch had lower thickness than the designed value, the measured actuation voltage of 3.8~4.5V is lower than the simulated result about 0.9~1.7V, and stiction problem was placed during switching operation. ON-resistance was about 8Ω at several samples and OFF-resistance was so large that it's impossible to be measured with digital multimeter that has 100MΩ measurement range. And the maximum allowable current was measured as 150mA. Although more improvements are needed in the aspects of fabrication and material selection, the micromechanical switching element presented in this paper has proven the possibility of MEMS application in switching element for harsh environment where the conventional electronic devices can't be applicable.

Acknowledgement

This research was carried out by supporting of Ministry of Commerce, Industry and Energy and Ministry of Science & Technology.

We would like to thank members of Prof. Kim Yongkwon's lab. in Seoul National Univ. for their help in electroplating process.

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