Microelectromechanical XNOR and XOR logic devices

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Abstract: We have developed a new microelectromechanical logic device using the MEMS (Micro Electro Mechanical Systems) technology. This device consists simply of a single cantilever and two driving electrodes with two contact pads for electrostatic operation. Both exclusive NOR (XNOR) and exclusive OR (XOR) logic devices have been realized using this simple construction.

Keywords: logic circuits, space applications, mechanical switch, electrostatic pull-in

Classification: Micro- or nano-electromechanical systems

References


1 Introduction

As MEMS (Micro Electro Mechanical Systems) devices have a mechanical structure, they can withstand a severe environment of high and low temperatures. This is the reason these MEMS devices, with their excellent resistance to the environment, have been developed. Semiconductor devices or integrated circuits are often used for controlling MEMS. However, normal semiconductor devices are vulnerable to low temperatures as well as to radiation such as cosmic rays.

In particular, in high temperature or radiation environments, latch-ups and errors can occur which cause malfunctions. For example, when CPU (Central Processing Unit)-like integrated circuits are used in space, since the exposure to strong radiation is greater than on the ground, they are much more prone to malfunction and breakdown. Furthermore, the effect of radiation such as cosmic rays can no longer be ignored with the semiconductor devices of recent years which have been designed with increasingly high density and speed for use on earth. These considerations have spurred...
on research into various MEMS logic circuits [1, 2, 3, 4, 5, 6, 7]. However, most of the previous studies concern the simple replacement of the transistor switch, used in the logic circuits constructed from transistors, with a MEMS switch.

In our group, we have been developing random number generators and self-oscillating voltage-control-type oscillators (VCOs) which have, so far, used only a single cantilever [8, 9, 10, 11]. With this technology, in circuits using conventional transistors, or those that have merely had them replaced by MEMS switches, XNOR and XOR devices that normally require multiple devices have been realized with just a single cantilever. Additionally, with the MEMS device analysis technique which uses the circuit simulator we have developed in-house [12, 13], we were able to analyze the operation of such devices.

2 MEMLOG switch principle and simulation

2.1 Basic structure

The structure of MEMS logic (MEMLOG) is shown in Fig. 1. The driving electrodes A and B are placed either side of the cantilever. The cantilever is fixed by the anchor, and contact pads placed at the tip of the cantilever. The cantilever is moved in the direction of the driving electrode due to the electrostatic force of attraction from the voltage applied to the driving electrode, and an output voltage obtained by the cantilever being brought into contact with a contact pad. In this circuit, each respective driving electrode corresponds to the input to the logic circuit, and each contact pad corresponds to the output. Here, $V_L$ is the logic voltage, and $R_p$ the pull-up resistor or pull-down resistor.

2.2 XNOR device principle

Fig. 2 shows the operating principles of the XNOR device. The contact pads are set up so that the cantilever makes contact for whichever driving electrode it is deflected towards. As the contact pads are ‘pulled-up’ by the resistor, the potential in the initial state is equal to the logic output.

![Fig. 1. Basic structure commonly used as XNOR or XOR](image-url)
Fig. 2. Operation model for XNOR

When a driving voltage (input) is applied to driving electrode A, the cantilever is deflected to the side with driving electrode A due to the electrostatic force of attraction and makes contact with the contact pad. Since the cantilever is connected to ground, the contact pad is also connected to ground because of contact with the cantilever. By this means, the output, that is, the contact pad potential, is low (zero potential).

Next, if a voltage is applied to the driving electrode B, the cantilever is deflected to the side with the driving electrode B owing to the electrostatic force of attraction, which makes contact with the contact pad, and the output is Low in the same way as when a voltage is applied to driving electrode A.

When no voltage is applied to either A or B, that is, for Low output, the cantilever does not move and so the output is High (logic voltage). Also, when the driving voltage is High for both of A and B, because the cantilever is drawn to both electrodes, it is balanced and therefore does not move [7, 10, 11]. Thus, the output is High as expected. This is expressed in a truth table, as shown in Table I, and is seen to be XNOR.

With the MEMS device simulation technique which uses the circuit simulator developed in-house [12, 13], we carried out a simulation analysis for this XNOR device. The XNOR model using the simulation is shown in Fig. 3. To simplify the simulation, essentially, the distributed parameter system, which is the cantilever, has been approximated with a lumped parameter system (spring-mass system), as the tip stroke of the cantilever $x$ is designed to be

<table>
<thead>
<tr>
<th>Table I. Truth table of XNOR</th>
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<tbody>
<tr>
<td>Input A</td>
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<tr>
<td>---------</td>
</tr>
<tr>
<td>Low</td>
</tr>
<tr>
<td>Low</td>
</tr>
<tr>
<td>High</td>
</tr>
<tr>
<td>High</td>
</tr>
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</table>
smaller than the initial air-gap length \( g \) between the cantilever and the drive electrode.

The simulation module in Fig. 3 consists of the anchor module and spring module, an equation-of-motion solver, a parallel-plate-type actuator module, and the contact pad module. For the spring module, we used the simple cantilever model with an external force acting normal onto the cantilever tip to extract the spring constant \( k = \frac{E h w^3}{4 l^3} \), where \( E \) is the Young’s modulus, \( h \) the height of the cantilever, \( w \) width, and \( l \) length; the spring constant value is given to the suspension module as an argument. Viscoelastic constant of \( c = 1 \times 10^{-6} \text{N} \cdot \text{s/m} \) is used as an intrinsic mechanical loss without air damping effect; this value corresponds to a quality factor of \( Q = 33.7 \).

The electrostatic force \( F \) acting on the sidewall of the cantilever is modeled as a pair of parallel plates with the initial air-gap length \( g \) and the area \( h \times l \) to find \( F = \frac{\varepsilon_0 h l}{2 (g - x)^2} V^2 \), where \( \varepsilon_0 = 8.85 \times 10^{-12} \text{F/m} \) is the dielectric constant of vacuum, and \( V \) is the differential voltage applied between the cantilever and the drive electrode. Although the force distributes on the sidewall of the cantilever, we presume that it is concentrated at the tip of the cantilever for simplicity.

The equation-of-motion solver module has been designed to read in and compare the electrostatic force of the actuator and the restoring force of the spring to calculate the acceleration of the cantilever by dividing the net force with the cantilever’s lumped mass \( m = \rho w h l \), where \( \rho \) is the material density; the acceleration is then integrated within the module to deliver the velocity \( \dot{x} \) and the displacement \( x \) in a similar manner as analog computing. The detail of simulation protocol has been reported in our previous paper [13].

Based upon this parallel-plate model, operation voltage is predicted by the electrostatic pull-in voltage, which has been known as \( V_{pi} = \sqrt{\frac{8 k g^3}{2l \varepsilon_0 S}} \).
When the initial gap $g$ is sufficiently smaller than the cantilever length $l$, the pull-in voltage of the parallel-plate model agrees with that of the distributed-mass model within a 3.3% margin of error [14]. The mechanical response time is limited by the resonant frequency of the cantilever, $f_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}}$, which is also known to be practically close to that of the distributed-mass model, $f_0 = \frac{1}{2\pi} \sqrt{\frac{35}{33} \frac{Ew^2}{\rho l^4}}$, within a 1.3% error.

In addition to those modules, we have newly used a contact model to represent the electrostatic switch operation at the tip of the cantilever, which is driven either to the right- or left-hand side of the beam axis, as symbolically displayed in Fig. 4. Within this three-port equivalent circuit, the electrical contact is programmed in terms of the short-circuit current as $I_{c1} = \begin{cases} \frac{(V_d - V_b)}{R_c} & \text{if } |x| \geq g \\ 0 & \text{else} \end{cases}$, where $R_c$ is the idealized contact resistance. In our simulation, we used an empirical value of 100 Ω for $R_c$. At this moment, we do not include the tribological physics in the contact model but assume a constant value for $R_c$ that is independent of the exerted contact pressure.

By using the numerical values listed in Table II, we performed the XNOR simulation as shown in Fig. 5. The pull-up resistor $R_p$ in this model is 10 kΩ. As expected, the output voltage becomes Low when only one of either input A or B is High. Some spike noise at High level can be seen in the transient response of the output voltage, due to the finite response time of the cantilever traveling from the neutral position to one of the contact pads, which is determined by the cantilever’s mass $m$ and the electrostatic attractive force.

### 2.3 XOR device principle

An XOR is realized by logically inverting an XNOR. The structure is the same as for an XNOR, but the connection method to the exterior to achieve the logical inversion is different. Fig. 6 shows the operating principles for the XOR device. The contact pad is ‘pulled-down’ to the ground by the pull-down resistor $R_p$. By this means, the initial potential of the contact pad is ground (Low). The cantilever is connected to the logic voltage $V_L$ by the pull-up resistor $R_p$. As for XNOR, the input signal voltage is applied to the driving electrode. If a voltage is applied to driving electrode A, the cantilever is deflected to the side with driving electrode A and makes contact with the contact pad. Since, through contact with the cantilever, the contact pad is the same potential as the cantilever, the output, that is, the contact pad potential, is High. Next, if a voltage is applied to driving electrode B, the
Table II. Parameters used in the simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspension Length</td>
<td>$l$</td>
<td>500 μm</td>
</tr>
<tr>
<td>Suspension Width</td>
<td>$w$</td>
<td>8 μm</td>
</tr>
<tr>
<td>Suspension Height</td>
<td>$h$</td>
<td>8 μm</td>
</tr>
<tr>
<td>Cantilever Mass</td>
<td>$m$</td>
<td>$7 \times 10^{-10}$ kg</td>
</tr>
<tr>
<td>Viscosity Constant</td>
<td>$c$</td>
<td>$1 \times 10^{-6}$ N·s/m</td>
</tr>
<tr>
<td>Spring Constant</td>
<td>$k$</td>
<td>1.62 N/m</td>
</tr>
<tr>
<td>Gap between Cantilever and Driving Electrode</td>
<td>$g$</td>
<td>9 μm</td>
</tr>
<tr>
<td>Gap between Cantilever and Contact</td>
<td>$g_c$</td>
<td>4 μm</td>
</tr>
<tr>
<td>Pull-up Resistance</td>
<td>$R_p$</td>
<td>10 k Ω</td>
</tr>
<tr>
<td>Contact Resistance</td>
<td>$R_c$</td>
<td>100 Ω</td>
</tr>
<tr>
<td>Operation Voltage</td>
<td>$V_L$</td>
<td>10 V</td>
</tr>
</tbody>
</table>

Fig. 5. Simulation results of XNOR

cantilever makes contact with the contact pad, and the output is High as for the case when a voltage is applied to driving electrode A. When the driving voltage for both A and B is 0 V (Low), because the cantilever does not move, the output is Low. When the driving voltage (input voltage) for both driving electrodes A and B is High, since the cantilever is drawn to both electrodes, it is balanced and does not move, so the output is Low. Expressing this in a truth table, it is as shown in Table III, which is seen to be XOR.

We created a model according to Fig. 7 in order to do the simulation for XOR. The structure is the same as for the XNOR mentioned previously, but the peripheral circuitry, such as the connection method for the logic voltage, and similarly, the pull-down resistance, is different. With this connection method, the XNOR is logically inverted and an XOR has been realized.

The XOR simulation results using this model are shown in Fig. 8. With the drive principle as described, for the case of just the input A or B, the output is High, and when both the input A and B are either Low or High, the output is Low. We can verify that the output is Low only when the inputs
Table III. Truth table of XOR

<table>
<thead>
<tr>
<th>Input A</th>
<th>Input B</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>Low</td>
<td>Low</td>
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<td>Low</td>
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<td>High</td>
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</tr>
<tr>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
</tbody>
</table>

Fig. 6. Operation model for XOR

Fig. 7. Simulation model for XOR
have the same logical values. In this way, through the logical inversion of XNOR, we can create an XOR with a single cantilever structure.

3 Experimental results

3.1 Fabrication results

We constructed a device using the preparation process for the metal wiring in CMOS (Complementary Metal-Oxide Semiconductor) integrated circuits (4 layers of gold). The SEM photograph of the constructed device is shown in Fig. 9. The cantilever has a width, length, and thickness of 8, 500, and 12 μm, respectively. The gap with the driving electrode is 9 μm, and the gap with the contact pad is 4 μm. The length of the contact section is 20 μm. Identical values for these dimensions were used in both the XNOR and XOR devices. Also, with the limitations of the process rules, the sizes are of the order given above, but the device size can be made smaller by using finer process rules.

Fabrication error of ±0.2 μm is usually observed in the surface micromachining processes, resulting in the variation of the suspension rigidity as well as the electrostatic attractive force. In a worst-case scenario, this may cause the difference of the initial gaps to be \( g_a = 8.8 \) μm and \( g_b = 9.2 \) μm for the drive electrodes A and B, respectively. Assuming that the cantilever width does not change but the gaps, the fabrication error leads to the deviation of the pull-in voltage between \( V_a = 0.97 V_{pi} \) and \( V_b = 1.03 V_{pi} \) for the smaller and the greater gaps, respectively, where \( V_{pi} \) is the ideal pull-in voltage for \( g_a = g_b = g \). Such small deviation can be negligible for the device of the current design.

Taking a 10% margin for the drive voltage to use \( V_D = 1.1 V_{pi} \), we would safely attract the cantilever to either electrodes A or B. When both electrodes are biased to \( 1.1 V_{pi} \), the cantilever tip theoretically moves towards the narrower electrode A by 0.5 μm; this result suggests that no false signal is
generated when the contact gap length $g_c$ is designed to be greater than that value. Detail study will be reported elsewhere, along with all the derivative devices based on the MEMLOG structures.

### 3.2 XNOR device operation

The results from operating an XNOR device are shown in Fig. 10. The driving voltage is 170 V. The driving frequencies are respectively 20 Hz and 30 Hz for the inputs A and B. As in the truth table, the output is High when both A and B are either High or Low, and when one side is High, the output is Low.

### 3.3 XOR device operation

As shown in Fig. 11, the XOR structure is the same as the XNOR, and only the connecting circuit to the exterior is different. The drive results for the XOR are shown in Fig. 11. The driving voltage is 170 V. The drive frequencies are respectively 20 Hz and 30 Hz for the inputs A and B. We can verify that the output is Low only when the inputs A and B have the same
logical values. In this way, through the logical inversion of XNOR, we can create an XOR with a single cantilever structure.

4 Extended simulation for smaller device

As above with the simulation used in this paper, we have been able to reproduce the results with actual devices. We can see from this that the simulation technique in this paper is also useful for device. Actual device sizes were used for the analysis in order to match the analysis results of this simulation with actual devices, but a similar simulation is possible with smaller structures as well.

The model for simulation of the XNOR device is the same, and Fig. 12 shows the XNOR analysis results for the case when the cantilever size as well as the gap with the driving electrode, are made smaller. The cantilever used in this simulation had a width of 0.5 μm, a length of 30 μm, and a thickness of 1 μm. Also, the gap between the cantilever and the driving electrode was 0.6 μm, and the gap with the contact pad was 0.5 μm.

By reducing the device size in this way, the resonant frequency of the cantilever can be improved to make the operation speed faster. Also, the driving voltage can be lowered by making the gap between the electrodes smaller. Using process rules of the nm order, an electromechanical logic device becomes feasible with high-speed operation, a low driving voltage, and a small footprint.

5 Conclusion

By fashioning the driving electrodes appropriately, with a single cantilever, we have been able to create not only simple logic circuits like NOT circuits but also more complex logic circuits such as XNOR and XOR circuits. Also, by changing the exterior pull-up and pull-down resistors, the driving voltage,
Fig. 12. Simulation result of the XNOR with the nano cantilever.

and how the logic voltage is applied, we have demonstrated the possibility of logic inversion. Using processes with finer rules allows the device size to be reduced. This miniaturization not only enables high-speed operation but also induces a drop in the driving voltage. Because we made this device using the metal wiring process for CMOS integrated circuits, it has a high affinity with such integrated circuits. Furthermore, since multiple logics can be prepared using roughly the same structure, and the process is the same, this device is considered suitable for making devices using the kind of automatic mask pattern generation which is currently being practiced with ASICs (Application Specific Integrated Circuit).

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