Thermal switch design by using complementary metal–oxide semiconductor MEMS fabrication process

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The present study focuses on implementing a complementary metal–oxide semiconductor (CMOS) microelectromechanical system thermal switch by using the commercially available Taiwan Semiconductor Manufacturing Company (TSMC) 0.35 μm two-poly four-metal CMOS process. There are two novel designs: first, the soft contact structure and post-processing fabrication; second, a new design of thermal actuator. To create the soft contact structure, residual stress effect has been utilised to make different bending curvatures. According to the experiments, the layer metal-1 has the largest residual stress effect that can achieve the largest deflection in the z-axis. Because the residual stress of the layer metal-1 is negative, the structure will bend down after release, hence providing larger contact area, which has been set up to obtain the lowest contact miss ability. In the post-processing fabrication, 0.3 μm thickness gold will be patterned at the contact tips. Since gold, rather than aluminium, has no oxidation issue, it has more reliability in preventing the problem of oxidation than aluminium. In the new thermal actuator design, the authors designed a novel folded-flexure with the electrothermal excitation to turn the switch on or off. In the prototype, the device size is 500 × 400 μm and the gap between two contact pads is 9 μm in off-state. Depending on the simulation results, the switch can work stably at 3 V, and the working temperature and operating bandwidth are individually 20–200°C.

1. Introduction: The complementary metal–oxide semiconductor (CMOS) microelectromechanical system (MEMS) utilises the CMOS stacked layers to form the micro-sensors and the micro-actuators. It has great potential for commercial production. However, stacked CMOS layers are composed of compound materials like metal, via, poly-silicon and oxide layers. There is stress in and between these layers. The extraction for individual layers in CMOS spends large chip area. Also, the simulation time for the microstructure with the complicated multi-layers is much longer by using this method. The efficient method is to extract the effective mechanical properties of some basic metal–oxide combination structures. It not only costs less testing area and simulation time but also includes the stress of interlays. In this Letter, the effective mechanical properties extracted from eight combinations of CMOS metal–oxide stacked structures were used to simulate and predict the static and dynamic behaviour of the MEMS device. The problem of the lateral contact switch has been solved in this study by depositing gold on the aluminium layer.

2. Device design

2.1. Soft contact structure: In a normal switch design, the contact area is so small as to make a poor contact. To solve this problem, we designed a new contact profile that used negative residual stress effect and different configurations of the contact tip. Every metal used in the Taiwan Semiconductor Manufacturing Company (TSMC) 0.35 μm two-poly four-metal (2P4M) CMOS process has its own effective residual stress. Combining different metal layers can also get different residual stress [1].

Only the layer metal-1 has the negative residual stress, as shown in Fig. 1. Thus, the contact profile will bend down after release (Fig. 2). With this profile, it provides larger contact area than the normal design. This Letter also reports the design of different configurations of the tip with different contact profile which can get more contact area than normal design (Figs. 3*a* and *b*).

In the post-processing, 0.3 μm thickness gold will be deposited on the surface of the element. Since gold is non-active, it has more reliability in avoiding the problem of oxidation and in increasing the conductivity at the contact area.

2.2. New design of thermal actuator: In the new thermal actuator design, this Letter proposes a novel folded-flexure with the

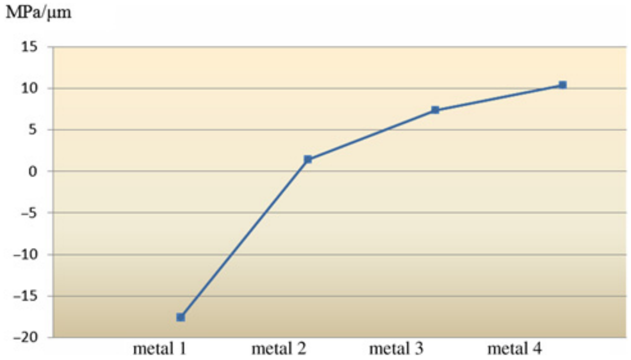

Figure 1 *Effective gradient stress against metal layer*

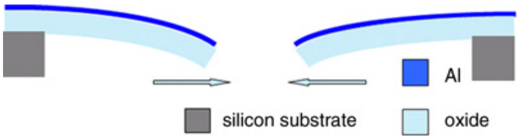

Figure 2 *Cross-section view of proposed contact profile*

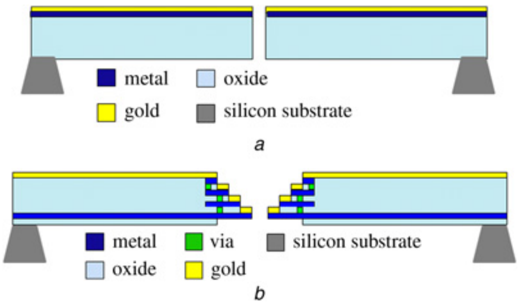

Figure 3 *Different configurations of the tip with different contact profile*
a Cross-section view of normal contact tip
b Cross-section view of proposed contact tip

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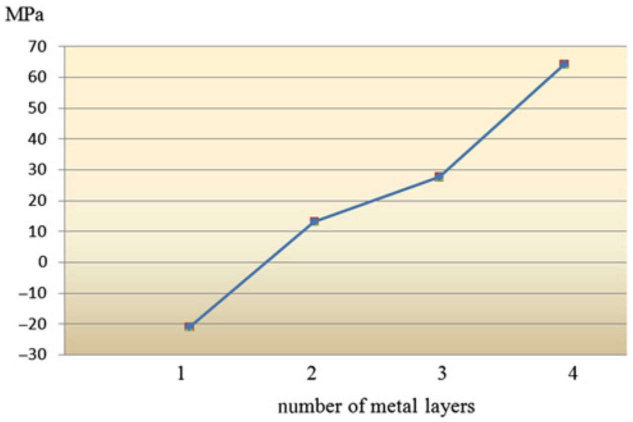

Figure 4 *Effective residual stress against number of metal layers*

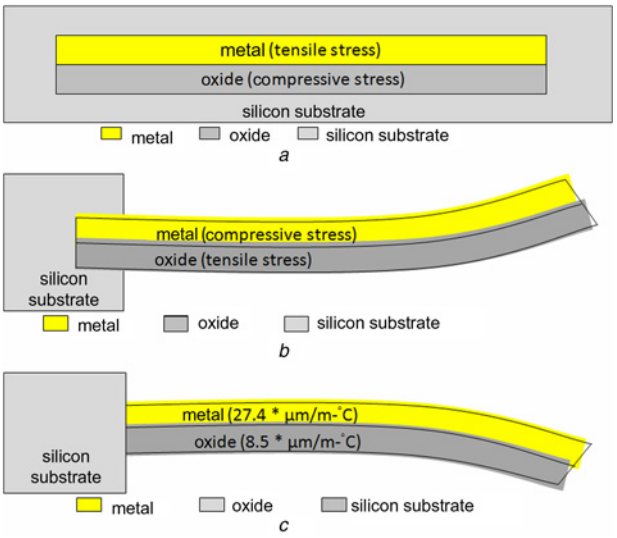

Figure 5 *Structure of the metal–oxide–silicon substrate before and after release*

a Top view of microcantilever beam before release

b Structure after release at 293 K (20°C)

c Owing to different thermal coefficient, the structure will pull back with temperature increase to 473 K (200°C)

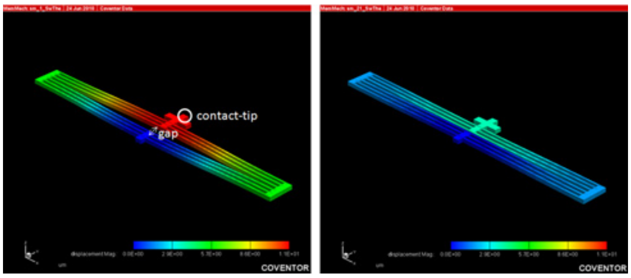

Figure 6 *Simulation of the switch between 293 K (20°C) and 473 K (200°C)*

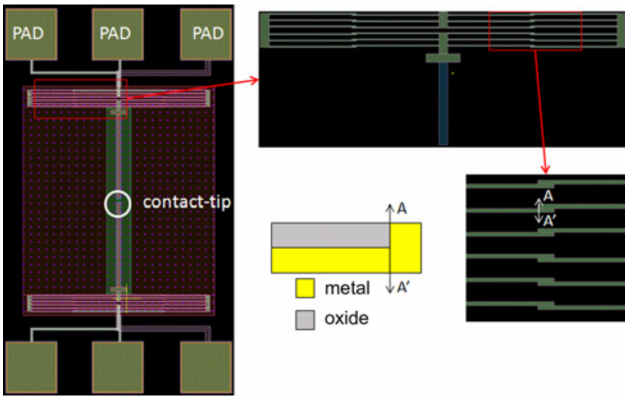

Figure 7 *Layout of the switch*

electro-thermal excitation to turn the switch on or off, as seen in Fig. 6. In the normal design [2, 3], the number of the layers used are metal-1, metal-2 and metal-3. In this proposed design, different numbers of layers are used.

In this design, effective gradient stress and thermal coefficient are obtained using the finite-element-method software in simulation. The stress increases with the number of metal layers, as shown in Fig. 4. It indicates that the oxide layer in the CMOS process has compressive stress and the metal layer has tensile stress before post-processing release, as illustrated in Fig. 5*a*. Owing to the isotropic dry silicon etch and structural release, the oxide layer has tensile stress and the metal layer has compressive stress after release, as shown in Fig. 5*b*.

When the switch is turned on, the current passes with heat. Because the oxide layer (0.4×10^{-6}/K) and metal layer

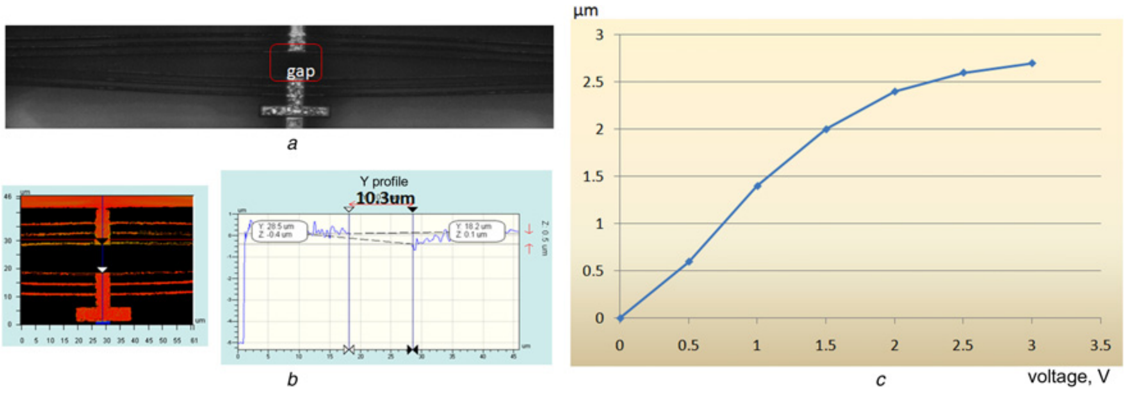

Figure 8 *Diagram of the switch with measurement result and voltage–displacement curve of the contact tip*

a One side of the switch

b Measurement result by optical profiler

c Contact-tip displacement against voltage

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(23×10^{-6}/K) [4] have different thermal coefficients, the folded-flexure of the switch will pull back and the switch will turn off, as shown in Fig. 5*c*. So, we can use this folded-flexure structure to control the switch turn on or turn off.

3. Simulation and experimental result: In this Letter, simulation software, Coventor-Ware, was used to verify our design as we designed. The simulation results are shown in Fig. 6. In the left image of Fig. 6, the initial gap is 11 μm at 293 K (20°C). In the right image of Fig. 6, due to temperature increase, the gap pulling back and the displacement of the contact-tip is 6 μm at 473 K (200°C).

Fig. 7 is the layout of our design. Also, it has been implemented by using TSMC 0.35 μm 2P4M CMOS process and Chip Implementation Center (CIC) micromachining post-process. The width of the device is 500 μm, and the length is 400 μm. In the measurement, we used MEMS motion analysis to measure the device. The measurements include static state and dynamic state.

In the static state, we used six probes to control the voltage given and signal analysis. Fig. 8*a* is a photo by an optical microscope (OM) and Fig. 8*b* is the measurement result by an optical profiler. The gap is 10.3 μm at initial time (0 V and 300 K). Fig. 8*c* is the correlation between displacement of the contact-tip and input voltage. The voltage source between the contact profiles are 0 and 3 V.

4. Conclusion: In this Letter, a new thermal switch is proposed and implemented by using TSMC 0.35 μm 2P4M CMOS process and CIC micromachining post-process has been developed. In the prototype, the device size is 500 × 400 μm and the gap between the two contact pads is 9 μm in off-state. According to the measurement result and the photo by the OM, the switch can work stably at 5 V, and the working temperature and operating bandwidth are individually 20–200°C.

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