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Modeling and control of threshold voltage based on pull-in characteristic for micro self-locked switch

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ABSTRACT

Micro self-locked switches (MSS), where execution voltage corresponds to the output signal, are efficient and convenient platforms for sensor applications. The proper functioning of these sensing devices requires driving accurate displacement under execution voltage. In this work, we show how to control the actuating properties of MSSS. This switch comprises microstructures of various shapes with dimensions from 3.5 to 180 μm, which are optimized to encode a desired manufacture deviation by means of mathematical model of threshold voltage. Compared with pull-in voltage, threshold voltage is more easy to control the pull-in instability point by theoretical analysis. With the help of advanced manufacture technology, switch is processed in accordance with the proposed control method. Then, experimental results show that it is better, which have been validated by corresponding experiments. In addition, they can be known from experiments that the manufacturing technology is advanced and feasible, and its high resilience and stably self-locked function can achieve instantaneous sensing.

1. Introduction

In recent years, the electrostatic one of MEMS switches is the most commonly used, because of the advantages, such as the compatibility with the integrated circuits fabrication process, the high linearity and the low power consumption [1,2]. Several efforts have been done for developing MEMS capacitive switches and switched capacitors with low actuation voltage [3]. For reducing the actuation voltage, membranes with low spring constant were used [4]. Thin-film (~0.8 μm) and cutout structure have been presented to decrease the actuation voltage to 32 V [5]. A cantilever based MEMS switched capacitor with a beam thickness of 4–4.5 μm is optimized using two independent electrodes, which results in an actuation voltage of 50–65 V [6]. There was serious concern that the actuation voltage of MEMS devices cannot be obviously decreased, and even be increased. Once the displacement that is slightly greater than the pull-in point is driven by the applied voltage that is at present called the execution voltage, instability of pull-in occurs in a short amount of time. As actuation voltage is applied between the electrodes, there are no more static equilibrium positions [7]. Then, the moving electrode will actually snap to the fixed electrode and they will stick together, which achieves the self-locked function and presents nice works to quantitatively explain the pull-in phenomenon [8–11]. Switch can be stably locked in the bottom contact electrode because electrostatic force is far more than elastic force in pull-in stage, which results in the signal output. The instability of pull-in severely restricts the range of stable operation of MEMS/NEMS devices. Spengen et al. [12] presented a comprehensive analytical model that can explain the failure by expanding the earlier model of Wibbeler et al. [13] to large deflections and pull-in and pull-out phenomena. Since the pull-in voltage corresponding to the pull-in point in the static analysis is very critical, an important goal of MEMS modeling is the prediction of reliable pull-in voltages and displacements [14,15]. Consequently, the understanding and control of this instability presents a challenge of great technological importance [16]. Based on control method of pull-in voltage on the MEMS inertial switch integrating actuator and sensor [17], the adaptive control of parameters has been taken into account and the pull-in voltage in the static analysis is close to actuation voltage. What is best for the self-locked stability depends on the formulation of process errors in the static analysis or dynamic analysis. As electromechanical microsystems are operated quasi-statically, pull-in is the most dominant effect caused by non-linear interaction in the dynamic analysis [18]. As a typical electrostatic pull-in instability experiment at the instantaneous collapse, the pull-in instability point can be determined by applying a voltage between the cantilever and the substrate and slowly increasing the voltage until the system shifts from a stable to an unstable equilibrium [19].

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In this paper, we are interested in achieving the stability of MSS by understanding the pull-in instability point in the dynamic analysis and governing the gap between dielectric layer and drive electrode. We therefore design, fabricate and test it, and compare its experimental behavior with an analytical model. An advanced manufacture technology was used for acquiring the exact value of actuation voltage and achieving stably the self-locked function under the low actuation voltage. Based on the established mathematical model for threshold voltage corresponding to the pull-in point in the dynamic analysis, structure parameters are optimized to put forward the corresponding control method of processing errors, especially for the gap. Due to the responsiveness of a movable polysilicon electrode [20] and the mechanical properties of Si_3N_4 [21], polysilicon and silicon nitride are regarded as the moving part. Size-dependent effect can be investigated by experimental results to verify the feasibility and advancement of manufacturing technology and control method. Finally, resilience time as one of reliability indexes of sensor can be revealed under different materials of movable electrode.

2. Model of threshold voltage

In Fig. 1, the total structure of switch is established based on the cantilever beams, which are well applied to the electrostatically MEMS sensing devices. Symmetrical structure can be adopted so that the upper contact electrode below movable electrode and dielectric layer can steadily contact with bottom contact electrode by electrostatic force. Electrostatic force is brought out through the electrostatic field formed by movable electrode and drive electrode.

2.1. Difference of pull-in voltage and threshold voltage

In order to find the cause of instability for actuation voltage, the corresponding analysis can be made.

Based on control method of pull-in voltage on the MEMS inertial switch integrating actuator and sensor [17], the K value of this switch is

$$K = \frac{1}{\frac{b^3}{2Ex_3h_3^3} + \frac{4a^3+6ba^2+3b^2a}{E(x_1-x_2)h_4^3}} \tag{1}$$

where K is stiffness coefficient, E is elastic modulus, h_i (h_1, h_2, h_3 and h_4) is thickness of corresponding part in Fig. 2, and other parameters can be displayed Fig. 2.

The resultant force of electrostatic force and elastic force is

$$\begin{cases} F_{ele} - F_K = F_1 \\ F_{ele} = \frac{\varepsilon AV^2}{2(g_0-y)^2} \\ F_K = Ky \end{cases} \tag{2}$$

where F_{elec} is electrostatic force of this switch, F_K is elastic force of this switch, F_1 is the resultant force of electrostatic force and elastic force, ε is dielectric coefficient of capacitor, A is the area that the drive electrode is faced with the movable electrode, V is the applied voltage, y is displacement of drive electrode, and g_0 is the gap between dielectric layer and drive electrode.

Combined with Eq. (2), the relationship between the electrostatic force and the elastic force can be obtained by the use of MATLAB and be described as Fig. 3.

According to Shengjin's formula [22], if $V = V_P$ where V_P is pull-in voltage in static analysis, the applied voltage and the corresponding displacement in Fig. 3 can be acquired as follows:

$$\begin{cases} V = V_P = \sqrt{\frac{8Kg_0^3}{27\varepsilon A}} \\ y_1 = y_2 = -\frac{\delta_B}{2\delta_A} = \frac{1}{3}g_0 \\ y_3 = -\frac{\delta_b}{\delta_a} + \frac{\delta_B}{\delta_A} = \frac{4}{3}g_0 > g_0 \ (\text{ignore}) \end{cases} \tag{3}$$

If $V < V_P$ ($V = 0.4V_P$, $V = 0.9V_P$), the applied voltage V_I and the corresponding displacement y_5 are

$$\begin{cases} V = V_I = \sqrt{\frac{2Ky_5(g_0-y_5)^2}{\varepsilon A}} \\ K = \frac{E}{\frac{b^3}{2x_3h_3^3} + \frac{4a^3+6ba^2+3b^2a}{(x_1-x_2)h_4^3}} \\ y_5 = \frac{2g_0}{3}\left(1 + \cos\frac{\theta+\pi}{3}\right) \\ \theta = \arccos T \\ T = \frac{2\delta_A\cdot\delta_b - 3\delta_a\cdot\delta_b}{2\sqrt{\delta_A^3}} = 1 - \frac{108\varepsilon AV^2}{16Kg_0^3} \end{cases} \tag{4}$$

While the switch closes or restores under Eq. (4), the state depends on the work done. As long as the work done is large enough, the switch passes through the pull-in point of y_5 and closes quickly.

Fig. 3 shows different implementations of MSS. y_4 and y_5 are the equilibrium points where electrostatic force is equal to elastic force in the dynamic analysis. As the applied voltage V gradually increases to the pull-in voltage in static analysis, the driving displacement is equal to $g_0/3$ and switch quickly closes in short order. For the dynamic analysis, it in Fig. 3 experiences acceleration stage ($0 < y < y_4$) and deceleration stage ($y_4 < y < y_5$), and then pull-in stage ($y_5 < y < g_0$) under the applied voltage V_I. Whatever stage it is in depends on the work done by the resultant force.

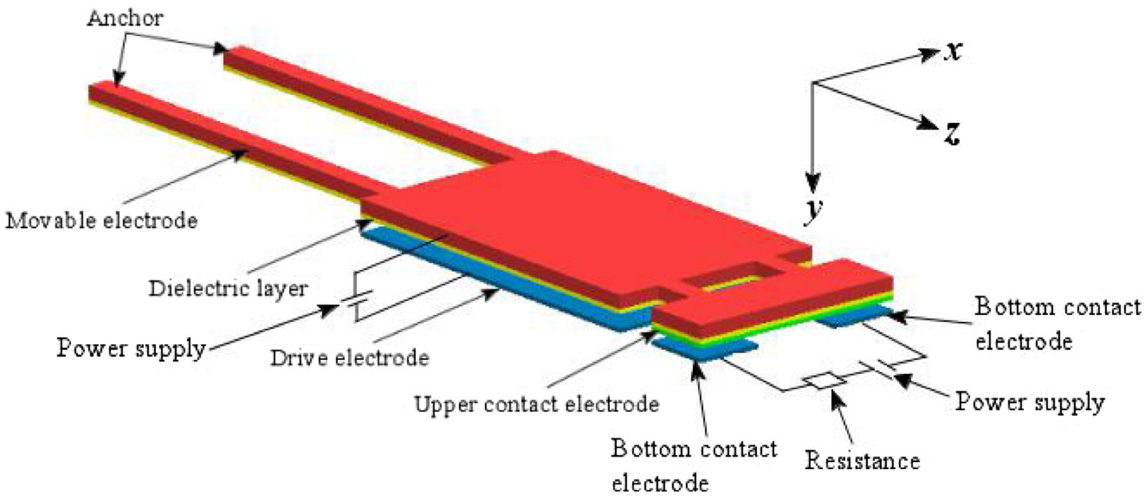

Fig. 1. Switch model.