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Pull-in Voltage Calculations of TiN-based NEMS Torsion Switch

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***Abstract*—A TiN-based nano-electro-mechanical systems (NEMS) torsion switch for non-volatile memory application has been developed. Compared to conventional cantilever switches, the NEMS torsion switch prevented the coupling effect of electrostatic torque and mechanical torque. Through numerical simulation, we compute the pull-in voltage of the NEMS switch. Meanwhile, the influence of the design parameters, such as the length and width of the torsion bar and the length of the cantilever etc, on the pull-in voltage is discussed. These results could provide guidance and convenience for the further design of NEMS switch device.**

***Index Terms*—NEMS switch, pull-in voltage, torsion bar, titanium nitride, design parameters**

I. Introduction

Steady scaling of complementary metal–oxide –semiconductor (CMOS) devices has been a significant stimulation for a huge advancement in the semiconductor industry over the past four decades. However, as the CMOS design rule is scaled into the nanometer regime, many difficult challenges were encountered, for example, short channel effects, junction leakage and gate oxide leakage. To introduce the new materials and device structures into the Si platform is a promising solution to realize nanoelectronics as the next-generation microelectronics. Because carbon nanotubes (CNTs) display exceptional mechanical and electronic properties, the use of CNTs in NEMS switch brings significant advantages to the fabrication of a device. Recently, extensive research for CNTs is being carried out on NEMS applications. Jang *et al* designed a NEMS switch using the vertically grown multiwalled CNTs and the pull-in voltage is found to be about 24.6 V [1]. When the distance between gate and drain of this CNT-based switch was decreased to 30 nm, the pull-in voltage reduced to 4.5 V distinctively [2]. However, it is a challenge to control the arrangement of CNTs and the lack of techniques for controlled mass production of CNT-based nanodevices using conventional COMS technology.

By using standard CMOS process technology, Soon et al. designed a Si-based NEMS nanofin switches with the dimension of 12 μm×3.5 μm×80 nm in length, width and thickness, and the gap between the electrode and nanofin of 80 nm [3]. The pull-in voltage is about 5.95 V. Jang et al. reported a TiN-based NEMS cantilever switch [4]. When the width, length, thickness and air-gap of this switch are 200 nm, 300 nm, 30 nm and 20 nm, respectively, the pull-in voltage is stabilized at 13 V with the variation within 1 V. through these devices were fabricated by CMOS process, the pull-in voltage still can't satisfy the requirements of memory application. According to the standard of the national technology roadmap for semiconductors, the operated voltage of NEMS memory is smaller than 1.5 V [5]. In this work, we design a new-type TiN-based NEMS torsion switch to minimize the pull-in voltage. The electrostatic torque and mechanical torque can be controlled by the cantilever and torsion bar in this device, respectively. The structural parameters, such as cantilever length (L), torsion bar length (l), torsion bar width (w), the device thickness (t) and the gap (g) between the free end of cantilever and bottom electrode, are taken as variable factors and the impact of the different factors on pull-in voltage is investigated.

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II. MODELING AND SIMULATION

Figure 1 exhibits a schematic illustration of the NEMS torsion switch device with rectangular plates. The NEMS switch is fabricated on the Si wafer with a thin silicon dioxide layer. The TiN device layer with a certain thickness was deposited on buried oxide layer by pulsed laser deposition. Then, the NEMS torsion switch comprising a suspended titanium nitride cantilever supported by a torsion bar is formed by the dry-etching. The Cr (5 nm)/Au (150nm) layers were deposited as the electrodes. Lastly, The NEMS torsion switch is released using hydrofluoric-acid (HF) vapor etching technique to remove the silicon dioxide layer.

As a voltage is applied, an electrostatic field will be formed

on the cantilever as the movable plates and bottom electrode of NEMS torsion switch. The cantilever will be pushed down to bottom electrode by twisting the torsion spring. By increasing the applied voltage above a certain voltage, the electrostatic torque increases and eventually overcomes the mechanical torque, resulting in instability or a

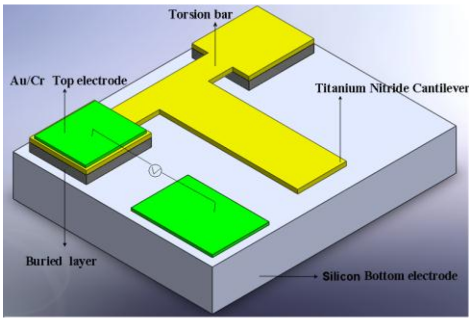

Fig. 1. A schematic illustration of th NEMS torsion switch device

collapse condition, where a contact between the two plates is formed. The cantilever will switch back to the initial state after the voltage is removed.

An important parameter of NEMS switch which are actuated by electrostatic forces is the pull-in voltage. The mechanical torque of torsion switch is given using the equation as fellows [6]:

$$K_{\alpha}\alpha = \frac{Gwt^3}{8l}\left[\frac{16}{3} - 3.36\frac{t}{w}\left(1-\frac{t^4}{12w^4}\right)\right]\alpha \quad (1)$$

where K_α is the spring torque coefficient, α is the rotation angle, $G=E/2(1+v)$ is the shear modulus, E is the Young's modulus, v is the Poisson ratio. The electrostatic torque $M(\alpha)$ of the NEMS switch can be calculated by using MAXWELL software. Then the pull-in voltage can be given and it is the solution of the following equation will yield the angle of the switch under the applied voltage:

$$K_{\alpha}\alpha = M(\alpha) \quad (2)$$

For the pull-in voltage, there are the two solutions of equation (2) coincide. For voltages above the pull-in voltage, the electrostatic torque is greater than the mechanical torque for any angle, thus, there are no solutions for equation (2). In this simulation, the young's modulus and Poisson's ratio of Si and TiN are 130 GPa, 390 GPa, 0.3 and 0.3, respectively.

III. RESULTS AND DISCUSSION

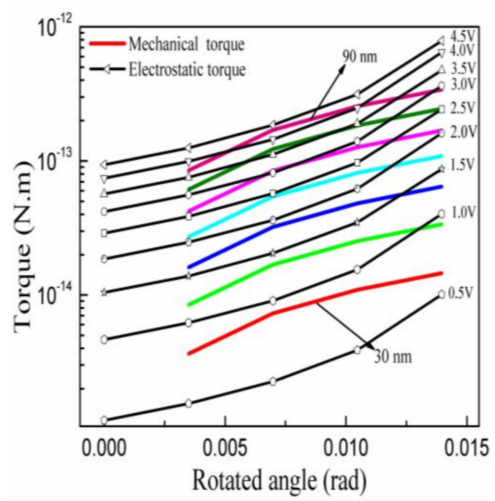

Fig. 2. The mechanical torque (solid lines) and the electrostatic torque (symbol lines) applied on the torsion switch (w=300nm, l=800nm, L=4µm, W=500nm, g=60nm).

Figure 2 shows the electrostatic torque and mechanical torque of the NEMS switch. The pull-in voltage of the NEMS switch (shown in Fig. 2) as a function of the thickness of cantilever is shown in Fig. 3. Nonlinear relationship is observed for the variation of pull-in voltage regarding to thickness. When the t increased from 30 nm to 90 nm, the pull-in voltage increased about 3.5 V. Figure 4 shows the relationship between the pull-in voltage and the gap. It is clear that while the gap enhances from 40nm to 100 nm, there is a nearly linear relationship and the gradient is increasing. The pull-in voltage increase ~ 2 V when the gap is changed from 40 nm to 100 nm.

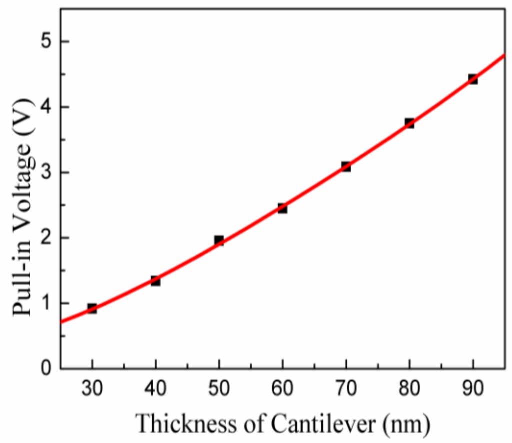

Fig. 3. Pull-in voltage shift versus the device thickness of cantilever as shown in Fig. 2

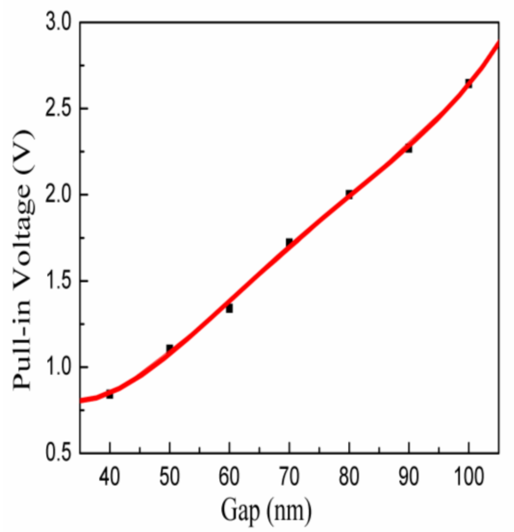

Fig.4. Pull-in voltage shift versus the gap between the cantilever and the bottom electrode. (w=300 nm, l=800 nm, L=4 µm, W=500 nm, t=40 nm)

The variations of the pull-in voltage with the size of torsion spring such as length and width are, respectively, shown in Fig.5 and 6, when the other size are given. It is obtained from the equation (1) that the mechanical torque of torsion bar decreases with the length increasing. Conversely, the mechanical torque increases when the width increased. In addition, there is a negligible impact of the variation of torsion spring for electrostatic torque. As a result, the pull-in voltage increases as the mechanical torque increases. As shown in Fig.5, the pull-in voltage decreases with the increment of the torsion spring length and trend becomes considerably obvious when the length is less than about 500 nm. When the l increased from 100 nm to 500 nm, the pull-in voltage increased about 3.1 V. It can be seen that from Fig. 6 the pull-in voltage increases with the increment of the torsion spring width and a nearly linear relationship is observed when the width is greater than 500nm. The pull-in voltage increase ~ 2 V when the gap is changed from 100 nm to 1 µm.

The pull-in viltage is plotted as the function of the cantilever length as shown in Fig. 7. The pull-in voltage decreases with the increment of the cantilever length. Compared to the influence of other structural parameters, the maximum change range of pull-in voltage induced by the cantilever length is observed. When the L increased from 1 μm to 5 μm, the pull-in voltage increased about 8.5 V.

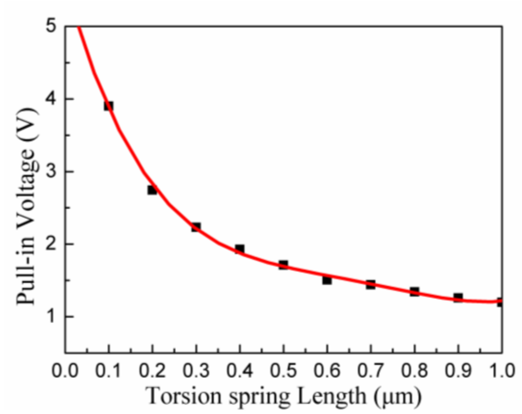

Fig.5. Pull-in voltage shift vs the torsion bar length. (w=300 nm, L=4 μm, W=500 nm, g=60 nm, t=40 nm)

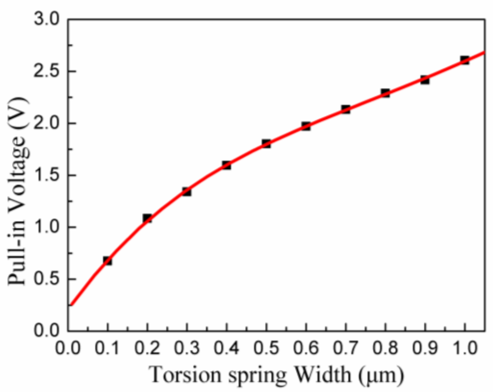

Fig.6. Pull-in voltage shift vs the torsion bar width. (l=800 nm, L=4 μm, W=500nm, g=60 nm, t=40 nm)

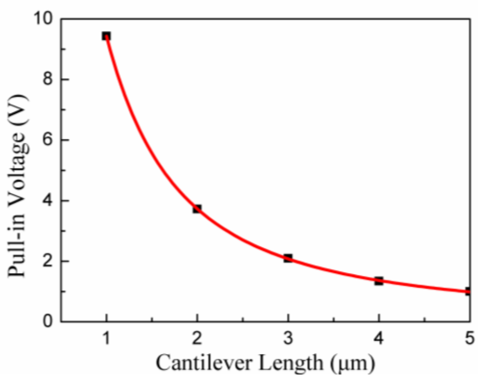

Fig.7. Pull-in voltage shift vs the cantilever length. (w=300 nm, l=800 nm, W=500 nm, g=60 nm, t=40 nm)

From the investigation of pull-in voltage of NEMS torsion switch, it can be found that all the design parameters have an importantly influence on the change of the pull-in voltage. In order to minimize the pull-in voltage to 1.5 V, the change range of w, l, g and t is designed in nanoscale. However, the cantilever length should be designed in micro dimension. At the same time, these design parameters are not influence the pull-in voltage independently, which are closely interrelated. Fig. 9 shows the pull-in voltage versus cantilever length with different cantilever thickness in the range from 30nm to 90nm. When the cantilever length is larger than 5μm, the cantilever thickness has no distinct influence the pull-in voltage. It indicated that the cantilever thickness plays a insignificant role for decreasing the Pull-in Voltage of the device. At this

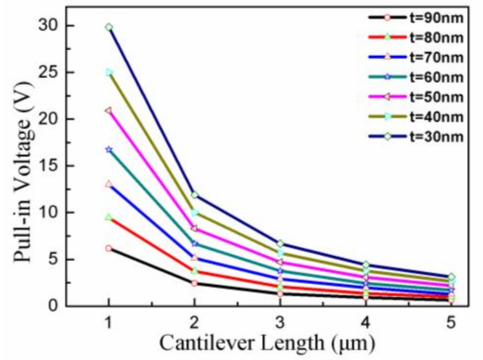

Fig.8. The Pull-in Voltage versus the cantilever length with the different cantilever thickness of t. (l=800 nm, w=300 nm, W=500 nm, g=60 nm)

time, it should make the other way to change the Pull-in Voltage, for example, changing the dimensions of the torsion bar and gap. On the contrary, the thickness plays a crucial factor for the Pull-in Voltage in this range, while the cantilever length is smaller than 5 μm.

IV. CONCLUSIONS

We designed the novel TiN-based NEMS torsion switch, which consist of torsion bar and cantilever. The pull-in voltage of NEMS switch is calculated. At the same time, the influence of design parameters of switch on the pull-in voltage is analyzed. It will contribute to design an optimal NEMS switch with a driven voltage as low as 1.5 V to satisfy the requirement of nonvolatile memory devices.

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