Maneuvering Pull-in Voltage of an Electrostatic Micro-switch by Introducing a Pre-charged Electrode

Hyun-Ho Yang, Jeong Oen Lee, and Jun-Bo Yoon

Dept. of EECS, Korea Advanced Institute of Science and Technology (KAIST)
373-1 Guseong-dong, Yuseong-gu, Daejeon 305-701, Republic of Korea

Abstract

A new method to greatly reduce and control the pull-in voltage of an electrostatic micro-switch was developed, simply by introducing a pre-charged floating electrode. For showing feasibility, the conventional electrostatic micro-switch is used with substrate biasing. Using this method, the original pull-in voltage of 48V was reduced to 3V and symmetrical hysteric curve around 0V was obtained like an ideal non-volatile memory.

Introduction

Micro-actuators has been one of the key components in microelectromechanical systems (MEMS). There are various actuating sources : thermal, piezoelectric, electrostatic, and electromagnetic forces. The electrostatic force has been one of the simplest source that is used to actuate micro-actuators, such as the comb drive actuator (1), gap-closing actuator, and micro motor (2). Specially in electrostatic micro-actuators, a micro-switch has been one of the most successful devices owing to its simple actuation mechanism and structure, high isolation when the switch is off, low signal loss when the switch is on, and low power consumption in the switch operation. In this reason, it has been popularly researched and used in RF applications (3).

However, the most critical huddle for the electrostatic micro-switch to be widely used in various MEMS applications is its relatively high pull-in voltage (V_{pi}, typically several tens of Volts), which is the minimum voltage to turn the switch on (i.e., pulling down the top plate to get into contact with the bottom plate as shown in Fig. 1(a)). Also, the V_{pi} is determined only by the switch's structural dimensions (4) so that there is no way to control further the V_{pi} once the switch is fabricated. For those reasons, several approaches are proposed for reducing high pull-in voltage, such as decreasing the spring constant of micro-switches, increasing the overlap actuating area (comb drive), and including an extra circuit for amplifying potential difference (5). However, when using the above methods, the micro-switches encounter other problems ; mechanical vulnerability, contamination with noise, and consumption of large area.

In this paper, we proposed and demonstrated an innovative way of decreasing and controlling the pull-in voltage simply by introducing a pre-charged floating electrode.

Working Principle and Fabrication

Fig. 1(b) shows our new idea. We introduced an additional plate in between the top and bottom plates. We pre-charged the additional plate with V_1 and let the pre-charged plate electrically disconnected. Now and hereafter, when V_2 is applied between the bottom and top plates as usual, the voltage difference between the pre-charged and top plates becomes approximately $V_1 + V_2$. When $V_1 + V_2$ exceeds the V_{pi} defined between the top and pre-charged plates, the switch becomes turned on. In other words, we can induce pull-in of the switch with less voltage ($V_2 = V_{pi} - V_1$) as long as the charge remains unchanged in the pre-charged plate (so, the charge can be injected only once).

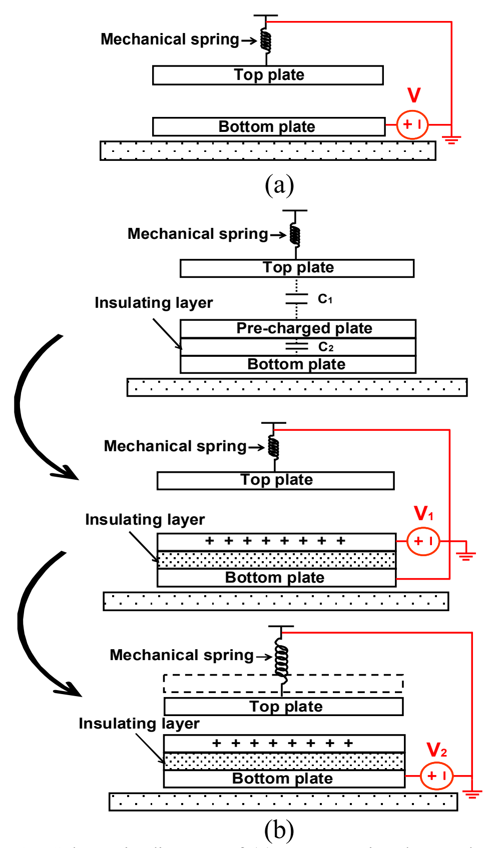


Figure 1. Schematic diagram of (a) a conventional two-plate electrostatic actuator and (b) the new electrostatic actuator with a center pre-charged plate.

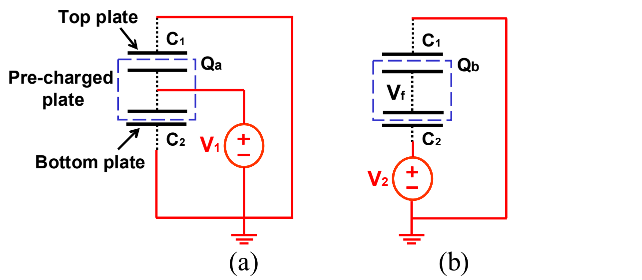


Figure 2. Simplified model of the new system in Fig. 1(b). (a) V_1 is applied to the pre-charged plate. (b) V_2 is applied to the bottom plate after V_1 is disconnected. Note that $Q_a = Q_b$. If $C_2 >> C_1$, V_f becomes $V_1 + V_2$.

This new system can be simply modeled by a series connection of the two capacitors, C_1 and C_2 as shown in Fig. 2. When we apply V_1 to the pre-charged plate, the charge Q_a in the pre-charged plate becomes $Q_a = (C_1 + C_2)V_1$. When V_2 is applied to the bottom plate after V_1 is disconnected, the new charge Q_b in the pre-charged plate becomes $Q_b = (C_1 + C_2)V_f - C_2V_2$. Since $Q_a = Q_b$, the voltage between the pre-charged and top plates becomes $V_f = V_1 + C_2 \cdot V_2 / (C_1 + C_2)$. If $C_2 >> C_1$, V_f becomes $V_1 + V_2$.

Fig. 3 shows the Maxwell 2D simulation result. After the center plate is pre-charged to 40V, 10V is only needed to get 50V potential difference between the top and center plates.

Fig. 4 shows an experimental setup verifying the proposed concept, which utilizes just the conventional electrostatic micro-switch, not the one having the additional plate for pre-charging, so that anyone can easily verify it. This is simply possible when using the original gate electrode as the pre-charged plate and using the substrate as the bottom plate as shown in Fig. 4. The gate electrode was pre-charged through the gate pad using a probe tip then disconnected by lifting up the probe tip.

Fig. 5 illustrates the simplified fabrication process of the conventional metallic micro-switch used for this work. Double sacrificial layers of Cu and Cr were deposited by thermal evaporation for defining precisely the thickness of the gap between the Ni suspended beam and the bottom plate as well as the gap between the dimple and the bottom plate. An electroplated nickel for the suspended cantilever beam and the gold-to-gold contact for reliable switching operations were chosen. After the formation of Ni beam, Cu and Cr double layers were selectively etched by the etchants leaving all other materials unaffected. The fabricated Ni beam is finally released by using critical point dryer (CPD) for preventing stiction.

Fig. 6 presents SEM photographs of the fabricated micro-switch. The length of the micro-switch was 42µm and the thickness of the Ni beam was 1.7 µm. The gaps between the Ni beam and the bottom plate and between the dimple and the bottom plate were defined as 350nm and 150nm, respectively.

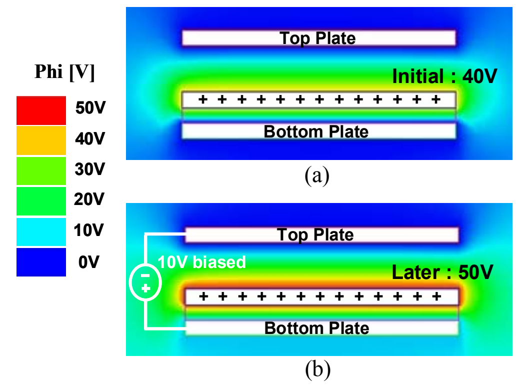


Figure 3. Maxwell 2D simulation result. (a) The center plate was initially charged to have 40V. (b) When 10V is applied to the bottom plate, the potential difference between the center and top plates becomes 50V.

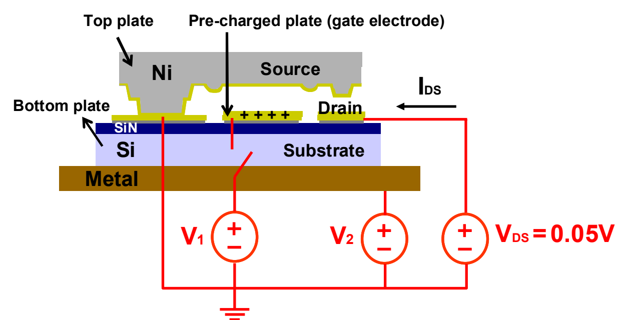


Figure 4. Experimental setup verifying the proposed concept. Note that the gate electrode was used as the pre-charged plate and the substrate was used as the bottom plate. The gate electrode was pre-charged through the gate pad using a probe tip then disconnected by lifting up the probe tip.

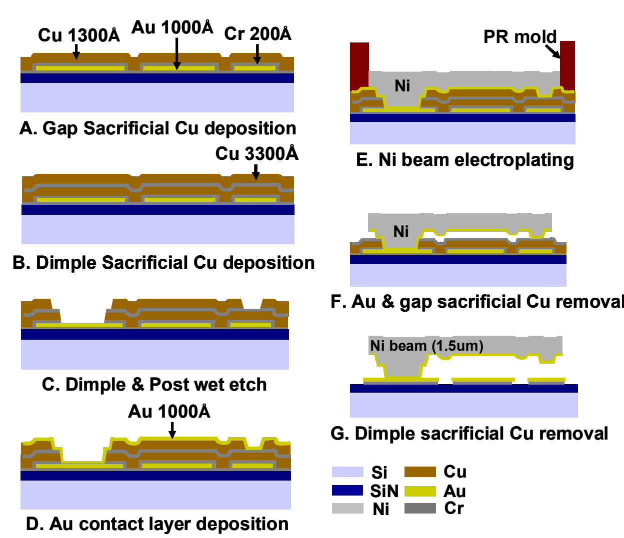


Figure 5. Simplified fabrication process of the conventional metallic micro-switch used for this work.

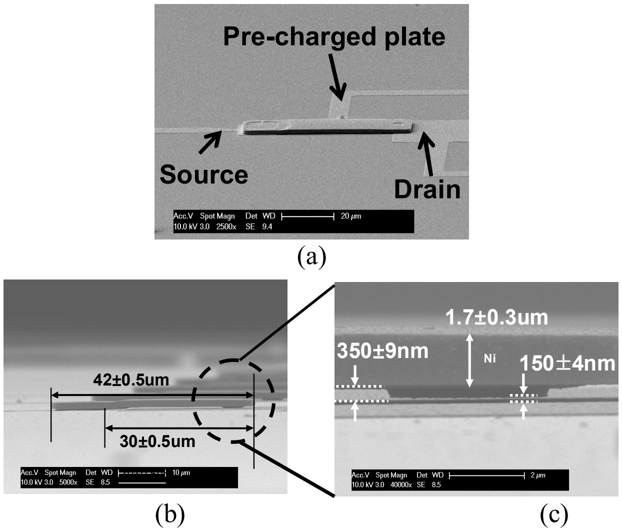


Figure 6. SEM photographs of the fabricated micro-switch (a) perspective-view (b) side-view (c) magnified view showing the gaps between the Ni beam and the bottom plate and between the dimple and the bottom plate.

Result and Discussion

Fig. 7 shows the measured pull-in characteristic of the fabricated micro-switch when biasing between the gate and source electrodes. At this time, we operated the micro-switch as usual, not using the gate electrode as the pre-charged electrode. The V_{pi} was around 48V and typical hysteresis (pull-out voltage of around 27V) was observed. During several operations, the swing of hysteric curve was under 1V.

From now on, the original gate electrode used as the pre-charged electrode. Fig 8 shows reduction of the V_{pi} by pre-charging the gate electrode with V_1 and by biasing between the substrate and source electrode. Substantial decrement of V_{pi} was observed even when the gate electrode was not pre-charged since the extra fringing field was generated from large area of the substrate. As increasing the value of V_1, the hysteric curve goes to shift leftward, and eventually, V_{pi} of 3V (a remarkable reduction from 48V) was obtained as shown in Fig. 8(b). It means that V_{pi} of micro-switch can be freely controlled by the pre-charging voltage of V_1 even after manufacture. Also obtained curve was symmetrical hysteric curve around 0V, which is ideal for the switch to be used as a non-volatile memory (the switch itself can maintains its previous state even when the power is off).

When the gate electrode was charged once and left in air, discharging was observed due to humid in air, resulting in drift of the hysteric curve with time as shown in Fig. 9. Therefore, measurement in vacuum (under 3mTorr) was also performed. Fig. 10 was obtained from the vacuum measurement with another device which has the same dimensions as used in Fig. 8. Fig. 11 shows the measurement result with time when the device was pre-charged and left in vacuum. No significant drift of the hysteric curve was observed. Therefore, the vacuum or hermetic package is thought to be essential in maintaining charges in the pre-charged electrode so that one can use the micro-switch without re-charging in a certain amount of time. It means the vacuum packaging is essential to pre-charging micro-switch for disturbing the leakage of charge. And then, in vacuum, the micro-switch can operate in several volts permanently after pre-charging at first time.

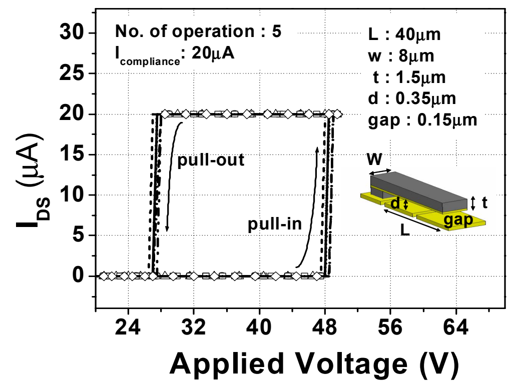


Figure 7. Measured pull-in characteristic of the fabricated micro-switch when biasing between the gate and source electrodes.

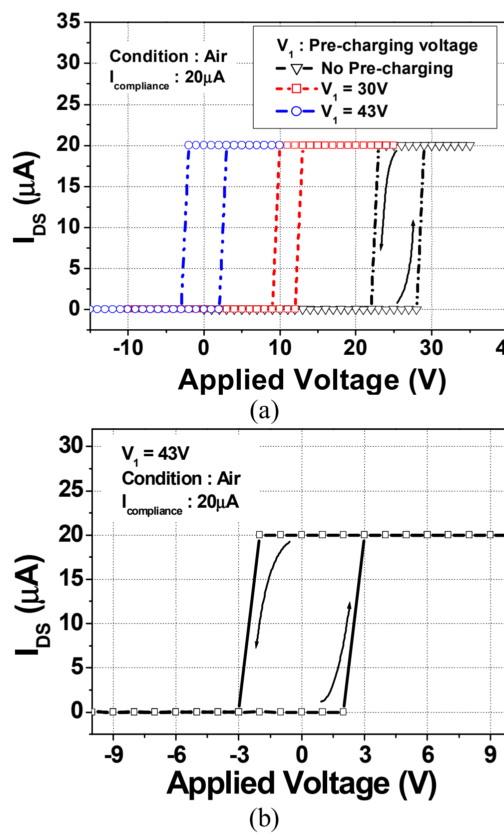


Figure 8. Measured pull-in characteristic of the fabricated micro-switch having the pre-charged gate electrode when biasing between the substrate and source electrode. (a) Pre-charged bias V_1 maneuvers V_{pi} (b) When V_1= 43V, symmetrical hysteresis curve around 0V and V_{pi} of 3V were obtained.

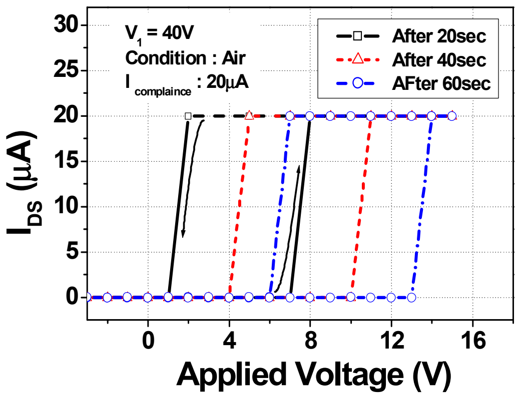
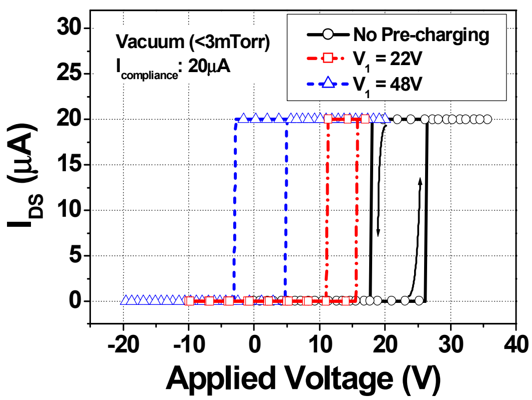
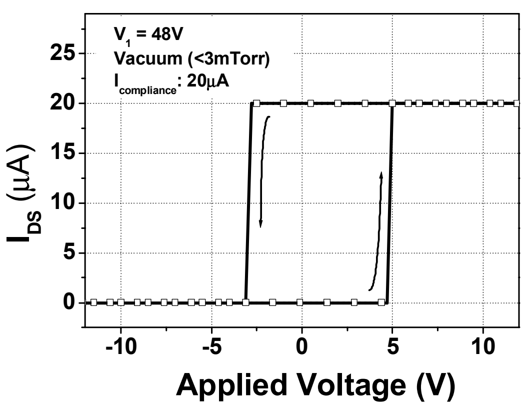


Figure 9. Drift of the hysteresis curve as time goes by after the gate electrode was pre-charged once with 40V and left in air.



(a)



(b)

Figure 10. Vacuum measurement results of another device which has the same dimensions as used in Fig. 8. (a) Pre-charged bias V_1 maneuvers V_{pi} (b) When V_1= 48V, symmetrical hysteresis curve around 0V and V_{pi} of 5V were obtained.

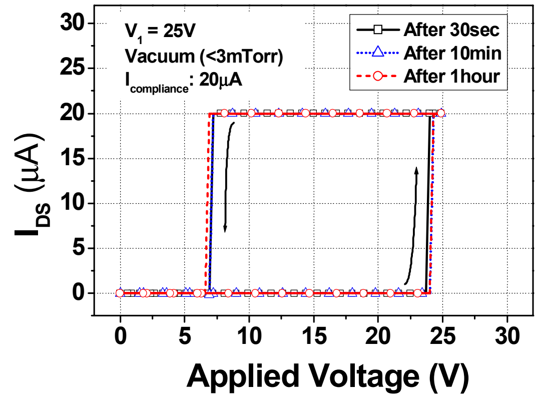


Figure 11. Hysteresis curve obtained as time goes by after the gate electrode was pre-charged once with 25V and left in vacuum.

Conclusion

We proposed and successfully demonstrated an innovative way to maneuver the pull-in voltage of an electrostatic micro-switch, simply by introducing a pre-charged electrode in a properly packaged environment maintaining the pre-charges. Originally, the V_{pi} was relatively high and fixed once the switch was fabricated. The method developed here is expected to greatly enlarge the application areas of the electrostatic micro-switch.

Acknowledgment

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