A Bi-stable Electrostatic Silicon Nanofin Relay for Non-volatile Memory Application

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Abstract—We present a nanoelectromechanical (NEM) relay which is capable of demonstrating two stable states without on-hold power due to the influence of van der Waals force. This is realized by leveraging a silicon nanofin (SiNF) as a relay which can switch between two lateral terminals. The smallest dimension of the SiNF is 80 nm width by 2 μm length. The SiNF is able to maintain its geometrical position even after the bias voltage is turned off. Bi-stable hysteresis behavior with pull-in voltage \((V_{PI})\) and reset voltage \((V_{RESET})\) as low as 8.4V and 10.1V is measured. The nano-scale footprint of this device shows great potential for high density non-volatile memory applications.

Index Terms—Nanoelectromechanical systems, relay, switch, van der Waals, non-volatile memory, bi-stable, electrostatic.

I. INTRODUCTION

The ever quest in CMOS scaling has expanded the exploration boundary beyond conventional transistor, listing from quantum devices, ultra thin body silicon on insulator (SOI), finFET and etc. Most devices leverage on the transportation of electrons or the same to determine the on-off criteria [1]–[2]. Until recently, nanoelectromechanical (NEM) relay has drawn great attention due to its exceptional properties. NEM relay is a physically actuated nano-scale mechanical switch that does not rely on transportation or storage of charges. Instead, NEM relay relies on mechanical switching motion and geometrical shape to replicate logic operation in transistor and solid state non-volatile memory (NVM) and its advantages include extremely low off-state leakage current, steep sub-threshold slopes and capability of high temperature operation [3]–[5]. It is already reported that NEMS relay can complement CMOS circuits resulting in faster operation and erasing speed [6]–[7]. Besides that, reports suggest that NEM switches can overcome poor performance usually at the extremes of temperature because of their mechanical switching nature [8]. Here, we propose a non-volatile memory that demonstrates hysteresis behavior under the influence of van der Waals force (VDW).

II. DEVICE CONCEPT AND OPERATION

The operating concept and device structure is illustrated in Fig. 1. A high aspect ratio (1:35) silicon nano-fin (SiNF) is fabricated using entirely CMOS process. The dimension of the SiNF consists of 2, 8 and 12 μm length \((l)\) with 80 nm thick \((h)\) and 3.5 μm height \((d)\). The gap \((g)\) between the SiNF to either terminal is approximately 80 nm. The SiNF is designed to switch between two side lateral terminals by electrostatic force. In contrast to the previous work [9], this reported switch is lateral based, lower pull-in voltage \((V_{PI})\) and its cyclic behavior is clearly demonstrated. Initially, the SiNF is in a neutral state. SiNF is pulled in to the right terminal when a sweeping voltage \((V_{S})\) is applied across SiNF and right terminal at initial sweeping voltage > pull-in voltage \((V_{SI} > V_{PI})\). Subsequently, when this voltage is removed, van der Waals attraction at the interface between SiNF and electrode will maintain the contact without on-hold bias, resulting in hysteresis behavior.

![Fig. 1. Structure and operation of a bi-stable NEM relay.](image)

\(V_{S1} > V_{PI}\)

\(V_{S2} < V_{RESET}\)

\(V_{S2} > V_{RESET}\)

\(V_{S1} > V_{PI}\)

Meanwhile, The SiNF flips and switches towards the opposite lateral terminal when a second sweeping voltage \((V_{S2})\) is applied across the left terminal. In this report, the SiNF structure makes NEM relay switch bi-directionally while...

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exhibiting bi-stability, thus it is able to provide two different states. Both stable states available attributed to van der Waals force enable the NEM relay to serve as storage-layer-free NVM.

III. EXPERIMENT RESULT AND DISCUSSION

NEM relay has been fabricated using CMOS facility and systematically characterized. First, SiNF is defined on SOI wafers with 3.5 µm device layer and 1 µm BOX. Silicon is chosen as the starting material to be implemented due to its compatibility in nanoscale microfabrication processing, the structure consists of single crystal Si and will be stress free upon release, forming a completely straight beam. Dry oxidation 1100°C in O₂ flow is further performed to reduce the SiNF dimension to the desired value of 80nm. The etched surface of the SiNF is also smoothened in this process to enhance the surface forces so that it adheres to the terminal electrode when in contact. The device layer is heavily implanted twice by arsenic with a dosage of 5 × 10¹⁵ ions/cm², and activated in order to make the SiNF as conductive as possible, the impurity concentration at 2.0 µm is approximately 1.0 × 10¹⁵ ions/cm². Dry release of vapor hydrofluoric (VHF) acid is used in the last process to suspend the SiNF while preventing stiction problem. In real application, the SiNF fabrication has to be processed first before CMOS fabrication due to high temperature oxidation. Fig. 2(a) shows the SEM diagram of a 2 µm × 80 nm NEM relay in a neutral state. Fig. 2(b) and Fig. 2(c) show the SEM diagram of an actuated SiNF through sweeping voltage applied across SiNF and either terminal. Note that the charging difference in the SEM showing the connection difference when the SiNF is in contact with either terminal. The 2 µm device’s contact edge to the actuating terminal is minimal at edge. The device inspected in SEM is electrically tested and we found that remains in contact and the direction agree well with where voltage is previously applied.

![SEM photo showing a 2 µm length x 80 nm width SiNF in operation.](image)

In electrical test, a voltage sweep (Vs) is applied across left terminal and right terminal from negative region (0 to -15V) to positive region (0 to 15V) under N₂ purged microchamber (CASCADE RBL6100) at elevated temperature of 50°C to remove any moisture. Hence we assume that capillary force is negligible. The corresponding cyclic behavior of a 2 µm length by 80nm width SiNF is shown in Fig. 3. The pull-in phenomenon is represented by an abrupt increase in sweeping current (Iₛ), usually between two voltage steps. The first pull-in is considered as the SiNF is at neutral position, this pull-in voltage is usually lower due to smaller initial gap. When sweeping voltage is less than pull-in voltage (Vs < Vₚi), continuous flow of sweeping current (Iₛ) shows that the relay maintains its contact with the lateral terminal by surface force, since there is no sign of SiNF pull-out and electrostatic force is lower than spring restoration force. At 0V, sweeping current returns to near fA range as there is no voltage applied by the analyzer. As sweeping voltage reversed from 0 to -15V across left terminal, SiNF flips and pull-in to the left terminal at around 11.5V. The pull-in voltage after the first pull-in is higher but does not scale according to pull-in model, this is due to the non-uniform gap size. To program or erase the device, a pull-in voltage needs to be applied across the SiNF and the terminal. Meanwhile, read operation can be performed by low current measurement where already switched SiNF are subjected to a read potential much less than the pull-in voltage (Vread < Vₚi) in order to sense the current. (Vread < Vₚi).

![Measured Iₛ – Vs curve of 2 µm x 80 nm SiNF, showing bi-stable hysteresis of the device.](image)

The switch continues to operate until the 11th sweep before no pull-in is observed, we found sweeping current returns zero at 2V, resembling a charging curve during the reverse sweep. A repeated 12th sweep shows current follows the charging curve and no pull-in can be detected anymore, depicting that the switch has failed. Observation under SEM shows that the switch is melted, as the SiNF is fused to the right terminal.
The abrupt jump in sweeping current corresponds to on-off current ratio ($I_{on}/I_{off}$) of $10^2$ which is considered far from ideal due to the compliance current setting of 5 nA. Low current compliance prevents excessive current from flowing through SiNF where the excessive current may cause device failure due to fusing and oxidation of Si. Thus, the device suffers from poor yield and reliability. This may improve if the testing is done under vacuum encapsulation which is viable at packaging level and may prove valuable to such devices [10].

Other alternative solution like contact enhance coating like Au, Pt and RuO$_2$ may solve this issue but the fabrication of such small device will be extremely challenging [11, 12]. The on-off current ratio of $10^3$ is demonstrated with 100 µA current compliance as shown in Fig. 4 with the similar device, but the device works for only once. This is shown from when the sweeping current gradually reduce when sweeping voltage is decreasing, resembling current discharging curve, which may be caused by SiNF melted to the respective actuating terminal. To further confirm this, SEM inspection is performed for the same device tested and we confirmed that the SiNF is melted to the terminal under high operating current. The pull-in voltage is 5.95V at 25mV/decade, achieving five order of on-off ratio. From the experimental results, we show that the length is crucial in designing a resettable switch. Fig. 5 shows the correlation between the pull-in voltage ($V_{PI}$) and reset voltage ($V_{RESET}$) versus the length of the SiNF. The measurement is performed statistically for twenty devices and results show that pull-in voltage is inversely proportional to SiNF’s length. The experimental pull-in voltage is found to be higher than the expected value from analytical model [13], possibly due to fabrication tolerance especially in the release process and non-uniform electrostatic force. However, the resetting voltage is agreeable to the finite element analysis performed in ANSYS simulation. The non-volatile hysteresis behavior is only obtainable in 2 µm devices and 8 µm devices. Overwhelming adhesion force causes a drastic increase in resetting voltage as the SiNF length increases in 8 um SiNF, and eventually leads to permanent adhesion in 12 µm SiNF relay. The trade-off between the required pull-out energy and the VDW force has to be taken into design consideration.

Nonetheless, the operating voltages demonstrated are far from ideal, one possible solution is probably applying torsion configuration to further reduce the spring constant of the SiNF and hence to achieve reduction in pull-in voltage while keeping the device nanoscale footprint [14]. Do note that after the initial SiNF pull-in, the resetting voltage will be the operating voltage for write and erase in NVM application.

IV. CONCLUSION

In summary, a lateral high aspect ratio and nanoelectromechanical relay is fabricated and characterized. The switch is capable of providing bi-stable states and therefore it operates as NVM. Meanwhile, the nano-sized gap and width of the SiNF makes the device attractive for scalability with estimated compact density about 390kBits/mm$^2$.

REFERENCES


