A Bistable Silicon Nanofin

An ideal device for nonvolatile memory applications.

WE PRESENT A SILICON NANOFIN (Si-NF) that can be actuated bidirectionally by electrostatic force between two contact surfaces. The switch is able to maintain its contact leveraging on van der Waals force, which holds the Si-NF to either terminal without an on-hold bias, thus exhibiting bistable hysteresis behavior. The measured pull-in voltage (V_{PI}) and reset voltage (V_{RESET}) are 10 and −12 V, respectively, confirming that the switch can be reset by the opposite electrode. Since the switch toggles between two stable states, it can be an ideal device for nonvolatile memory (NVM) applications.

Developments in information processing technology have revolutionized the way we live and will continue to affect every aspect of our lives in the future. The invention of ICs has played a vital role in determining how products are designed and integrated into our life. One of the limitations is the current fabrication technology, as CMOS is nearing its end. As the gate length scales down, at 32-nm nodes, short channel effects are not greatly reduced, resulting in

BO WOON SOON, NAVAB SINGH, JULIUS MINGLIN TSAI, AND CHENGKUO LEE

Digital Object Identifier 10.1109/MNANO.2013.2260461
Date of Publication: 6 June 2013

1932-4510/13/$31.00©2013IEEE

subthreshold leakage and lowering of threshold voltage (Vth) and drain voltage (Vdd) [1]. At elevated temperatures, the situation deteriorates further, suggesting that CMOS transistors are not ideal candidates to be employed in applications in harsh environments, such as down-hole operation and automotive and aerospace applications.

In contrast, MEMS technology has been successfully commercialized through tremendous growth. Of these devices, electrostatic-based nanoelectromechanical system (NEMS) switches have recently generated considerable interest as an alternative to the CMOS transistor in both computing and memory applications due to their low power consumption, zero leakage, high subthreshold slope, and ability to withstand harsh environments. They have been proposed by many as an answer to the limitations of scaling CMOS transistors [2], [3].

NEMS switches, with their zero leakage and high subthreshold slopes, are an attractive alternative for scaling as well as low-power computing, showing much lower power consumption than CMOS transistors [3], [4]. NEMS switches have also been suggested for nonvolatile memory (NVM) applications, in which they can offer write/erase speeds several orders of magnitude faster than NAND Flash [5]. Furthermore, NEMS switches have the advantage of being able to withstand harsh environments [6]–[8], and such properties may prove invaluable for computing or memory, especially in the area of rugged electronics. This article reports electrostatic NEMS switches that demonstrate hysteresis behavior under the influence of van der Waals force. This is achieved through high-aspect-ratio (1:35) Si-NF fabricated using CMOS processes. The operating concept of this device is illustrated in Figure 1.

Si-NFs are characterized as the source electrode that can be electrostatically switched between two fixed terminals situated on both sides. The switch leveraged on van der Waals attraction between contact surfaces to hold the on-state without on-hold bias, resulting in bistable hysteresis behavior, demonstrating nonvolatile capability. The lowest pull-in voltage (V_{PI}) reported is 10 V and the reset voltage (V_{RESET}) is −12 V by opposite terminal.

The nonvolatile capability and scalability of vertical Si beam have been previously reported [9]. Here, we report a lower operating voltage and analyze the Si-NF's critical length so as to overcome the cantilever spring restoration force by adhesion energy to maintain a contact state. In contrast, this energy cannot be too high to ensure that low V_{RESET} is sufficient to reset the switch.

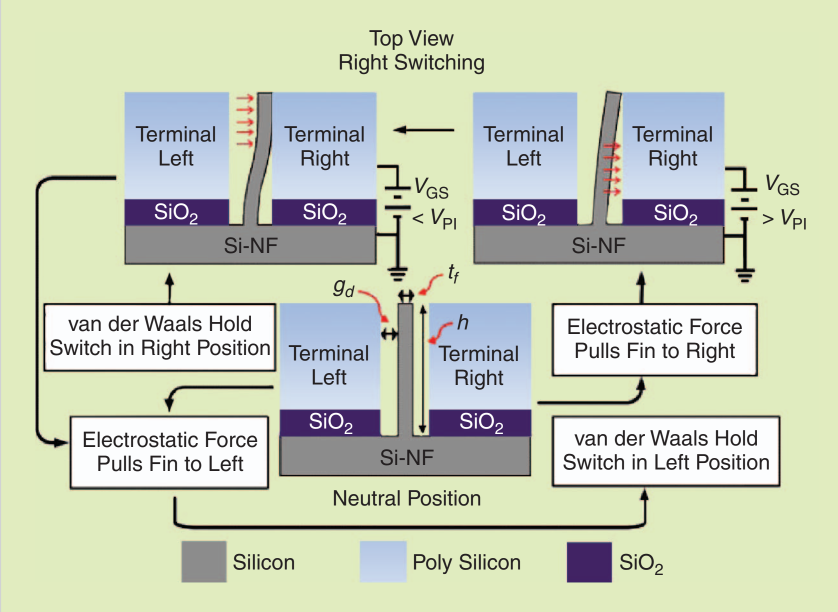

FIGURE 1 Schematics of the switching behavior of the Si fin. V_{GS} is applied to attract and pull in the Si-NF to the right terminal. van der Waals force will hold the fin in contact position even after the electrostatic force is removed.

DESIGN AND SIMULATION

Finite-element analysis (FEM) is coded in ANSYS to compute the corresponding electrostatics and van der Waals forces, as shown in Figure 2.

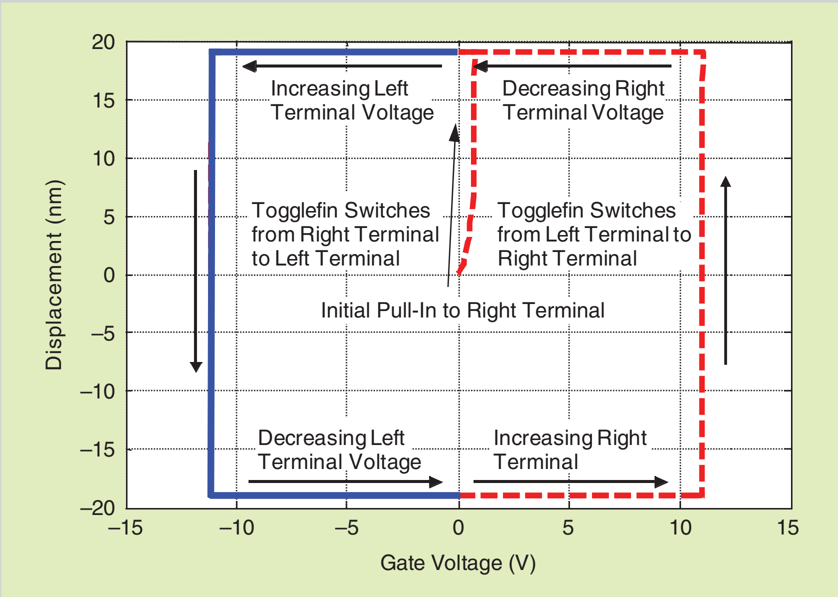

FIGURE 2 FEM simulation (ANSYS) showing bistable state. The length required for Si-NF is 2 μm to continue exhibiting hysteresis behavior.

TABLE 1 Si-NF parameters.

PARAMETER	VALUE
Beam length, h	2, 8, 12 μm
Beam thickness, t_f	80, 90, 100, 110 nm
Gap size, g_d	~80 nm

The structural element PLANE183 and contact elements TARGE169 and CONTA171 are used to simulate the dimension parameters to design a bistable state switch based on van der Waals force. A parallel-plate capacitive model is leveraged to simulate the electrostatic force between the Si-NF and the terminals in accordance to their respective gaps.

Referring to Figure 1 and the simulation results in Figure 2, first, V_{GS} is applied across the Si-NF and right terminal, from 0 V → Vsweep → 0 V. The initial pull-in is detected when the distance between the beam and the terminal is close to zero, with the condition $V_{GS} > V_{PI}$. In this case, the beam is actuated from the neutral position to the right terminal. Next, when V_{GS} is gradually returned to zero, the beam is held in contact by the van der Waals force, with the condition $V_{GS} < V_{PI}$; note that the adhesion force has to be stronger than the spring's restoring force to achieve this phenomenon. The van der Waals energy with Hamaker's constant is given in [10]. After that, V_{GS} is applied across the Si-NF and the left terminal. Another pull-in happens when the Si-NF is retracted from the right terminal to the left terminal. This pull-in voltage is higher because now the gap between the Si-NF and the left terminal is greater.

A notable assumption is that the simulated V_{PI} is consistent, which is considered ideal compared with real measurement. Subsequently, the required critical length can be determined for the switch to be actively actuated and exhibit bistability. This method may serve as a guideline for the device's design, which leverages on van der Waals force. Table 1 shows the parameter considered, including the overdesign value to investigate failure mode for Si-NF in a later experiment. The parameters determined are based on Si-NF's length, h, thickness, t_f, and gap's dimension, g_d.

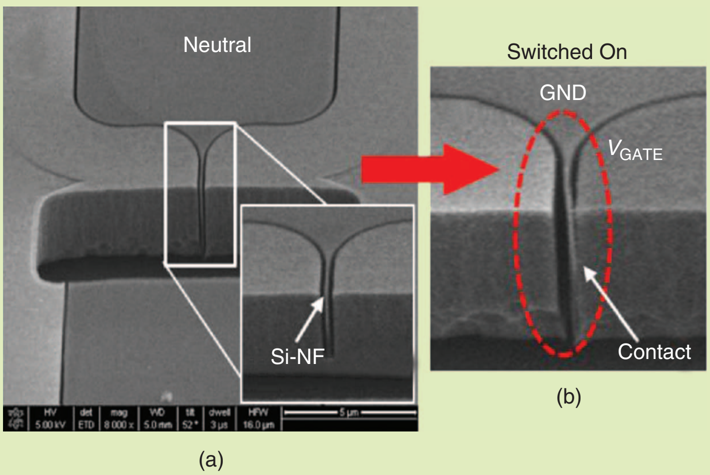

FIGURE 3 SEM showing the operation of a 2-μm Si-NF device. (a) In a neutral state, the Si-NF remains at the center. (Inset) Zoomed-in view of the Si-NF. (b) The Si-NF is switched on by applying potential difference across it. The contact remains even after the potential is removed.

FABRICATION PROCESS

Fabrication flow consists entirely of CMOS-compatible processes, starting from an Si-on-insulator wafer with a 3-μm device layer and 1-μm buried oxide. First, a deep UV 248-nm scanner is used to pattern the Si-NF with minimum critical dimension of 170 nm, and a high aspect ratio (1:17) of deep reactive ion etching of Si device layer with minimal scalloping sidewall is processed to create the Si-NF. Next, dry oxidation at 1,100 °C is performed to further reduce the fin thickness to the final dimension ranging from 80 to 110 nm, rendering the aspect ratio to 1:35. This process also reduces the surface roughness significantly, resulting in a smooth sidewall required for van der Waals attraction.

Meanwhile, the grown silicon oxide (SiO_2) also becomes the sacrificial layer of the switch. An ellipsometer is used to measure the thickness of the sacrificial SiO_2, and this thickness can be controlled by time-based diluted hydrofluoric acid etching, resulting in a final thickness of approximately 80 nm. After that, a 5-μm-thick poly-Si is deposited as the terminal electrode and overfills the entire wafer. Chemical mechanical planarization is done to flatten the entire wafer topography while exposing the Si-NF. Finally, the device is released in hydrofluoric acid vapor to release the Si-NFs. A typical device has an 80-nm air gap between the Si-NF and the terminal electrodes.

Figure 3(a) shows a scanning electron micrograph (SEM) of a 2-μm × 80-nm NEMS relay in a neutral state. Figure 3(b) shows an actuated Si-NF in contact with the right terminal. It is interesting to observe that some of the switches can be actuated under the SEM charging and make contact with either terminal [11]. When the actuated switch is removed from the SEM and measured, we note that the switch remains in contact without on-hold bias, and the direction agrees well with the SEM inspection. The electrostatic force is negligible when the relay is turned off and, thus, the major remaining force that holds the contact is the van der Waals attraction.

TESTING AND DISCUSSION

Although the electrostatic force arising from electron beam scanning in a scanning electron microscope may cause the relay to switch, the actual characterization results are reliable because multiple device tests are conducted. This is done by testing the fabricated device in a Cascade microchamber (RBL-6100), and the measurement is performed using an HP4156 semiconductor analyzer. The Si-NF is grounded, and a sweeping gate voltage (V_{GATE}) is applied across the Si-NF to the right terminal from 0 to 15 V. As the total electrostatic attraction force is proportional to V_{GS}, the electrostatic pull-in of the Si-NF to the right terminal happens when V_{GATE} is increased beyond the pull-in voltage.

Similarly, when a reversed V_{GATE} is applied across the source and left terminal, the fin flips and switches toward the opposite lateral terminal. Electrostatic force is negligible when the relay is turned off and, thus, the major remaining force that holds the contact is the van der Waals attraction.

Figure 4 shows the measured hysteresis loop of the device where the ground measurement point is omitted for the purpose of illustration. The device displayed clear bistable characteristics when voltage was swept from one terminal to the other. We show that the Si-NF's length is crucial in designing a resettable switch.

A device with a 12-μm × 8-nm Si-NF (Figure 5) is initially switched by applying a voltage sweep to the left terminal, and the measurement is confirmed with an SEM inspection. However, the switch could not be reset, and inspection shows that the Si-NF has a large contact area with the left terminal [Figure 5(a)] and is not able to reset due to strong adhesion. The cross-sectional contact area [Figure 5(b)] and the adhesion energy are proportional to the Si-NF length, leading to failure modes such as permanent adhesion. This indicates the importance of tradeoff between the restoration and the van der Waals force. The measurement is performed statistically for 20 devices, and the results show that V_{PI} is inversely proportional to Si-NF's length.

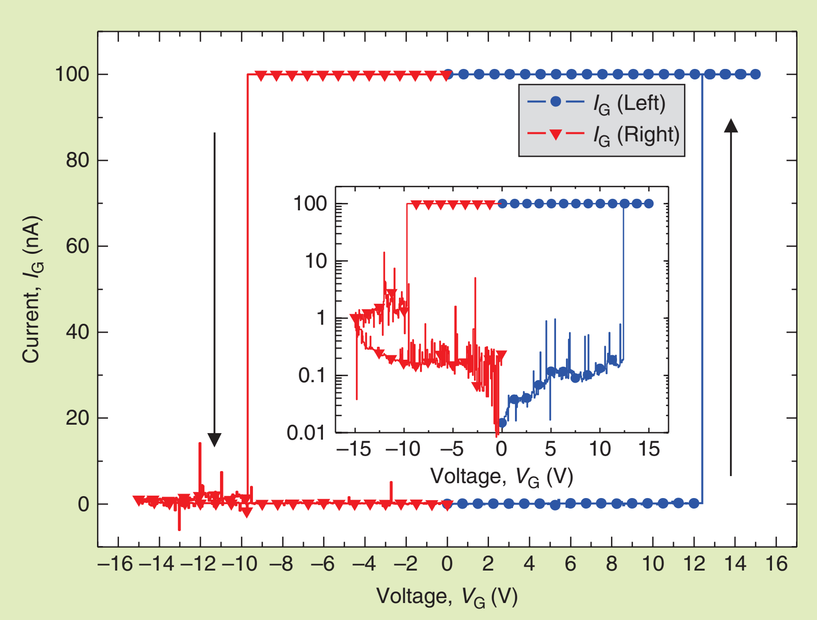

FIGURE 4 Measured hysteresis curve of a 2-μm-long fin showing NVM application. (Inset) A log-scale curve of one hysteresis loop. A 0-V point is omitted for illustration purposes.

Figure 6 shows the correlation of V_{PI}, V_{RESET} versus different lengths of the Si-NF. The statistical results show that V_{PI} reduces with the increase in the Si-NF's length. This is due to the lower spring constant as the length increases, which results in a less stiff Si-NF. However, nonvolatile hysteresis behavior

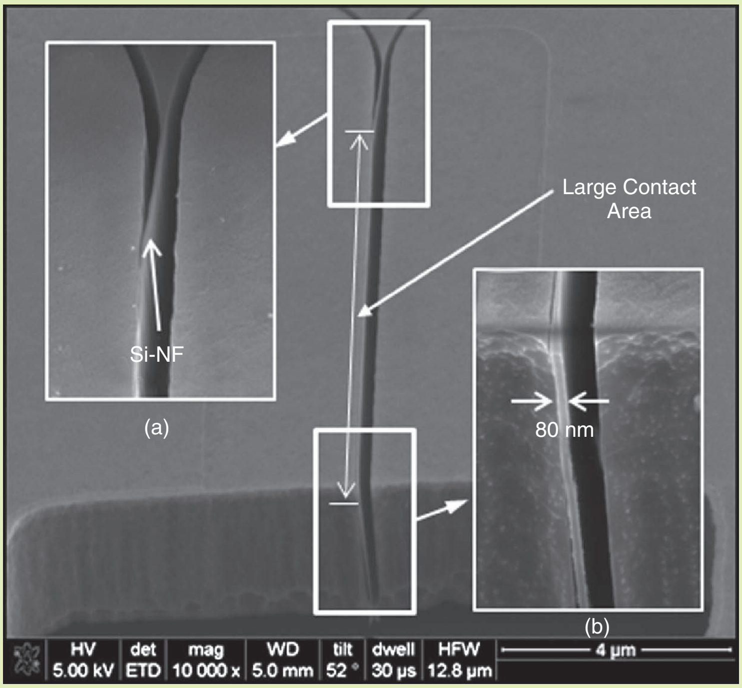

FIGURE 5 SEM of a 12-μm switched device. (a) The Si fin bends and permanently sticks due to strong adhesion. (b) A cross-sectional view of a Si fin adhered to the terminal. The contact area increases due to the longer fin.

and Research (A*STAR) for funding this research (SERC Grant 1021010022).

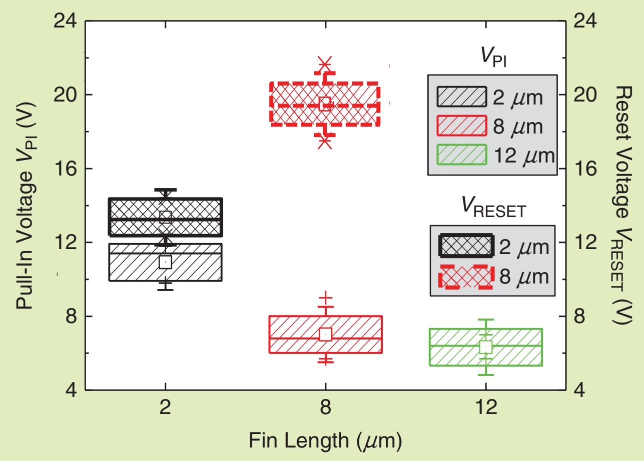

FIGURE 6 V_{PI} and V_{RESET} versus 2-, 8-, and 12-μm Si beam length. V_{PI} reduces with the length of the beam. A 12-μm device cannot be reset due to permanent adhesion.

is only present in 2-μm devices and 8-μm devices. In a 2-μm Si-NF, V_{RESET} is very close to the V_{PI}, as the Si-NF is barely in contact with the side electrode, suggesting that less adhesion force is needed to be overcome by the opposing electrostatic force. Therefore, it is an optimal condition for a switching-based NVM. As the length increases, for instance, in an 8-μm Si-NF, V_{RESET} increases drastically. This is due to the larger adhesion area and higher electrostatic force required to reset the switch.

For a 12-μm-long Si-NF, the switch cannot be reset due to overwhelming adhesion where the entire Si-NF is almost in contact with the side terminal. Thus, operating voltages and the length of the devices must be taken into account when designing the switch. To lower the operating voltage, another approach that can be considered is to reduce the Si-NF thickness, which will lower the spring constant of the beam. Nevertheless, the fabrication processes of the device scaling remains a challenge in current state-of-the-art CMOS facilities.

The switching speed can be assumed from the natural frequency of a cantilever beam, which is given by the harmonic oscillator formula [12] as shown in

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{3EI}{mL^3}}, \qquad (1)$$

where E is the Young's modulus of Si, I is the moment area of inertia, m is the mass of Si, and L is the length of the Si-NF. The switching time of an 80-nm × 2-μm Si-NF is approximately 73 ns.

CONCLUSION

In summary, we have demonstrated an NVM based on an NEMS switch, leveraging on van der Waals force. The tradeoff between adhesion energy, V_{PI}, and V_{RESET} can be optimized by varying the length of the device. The critical length of the device to exhibit hysteresis behavior can be determined by evaluating the contact area and the surface property of an NEMS switch. This is the first time a two-way bistable hysteresis curve based on van der Waals force has been clearly measured as an application in NVM memory.

The material used is single-crystal Si, which has significantly higher resistance than metal. Nevertheless, this material is stress free, and its process technology is established. The current fabrication process produces very low yield, and the current devices have low reliability due to fusing or microwelding because of Joule heating during switching. Hence, improvement must be implemented to enhance the switching capability of the device.

ACKNOWLEDGMENT

The authors would like to thank the Science and Engineering Research Council, Agency of Science, Technology, and Research (A*STAR) for funding this research (SERC Grant 1021010022).

ABOUT THE AUTHORS

Bo Woon Soon (soonbw@ime.a-star.edu.sg) is with the Department of Electrical and Computer Engineering, National University of Singapore, and the Institute of Microelectronics (IME), Agency for Science, Technology, and Research (A*STAR), Singapore.

Navab Singh (navab@ime.a-star.edu.sg) is with the Institute of Microelectronics (IME), Agency for Science, Technology, and Research (A*STAR), Singapore.

Julius Minglin Tsai (jtsai@invensense.com) is with InvenSense, Inc., Sunnyvale, California.

Chengkuo Lee (elelc@nus.edu.sg) is with the Department of Electrical and Computer Engineering, National University of Singapore.

REFERENCES

[1] Y. Taur, "CMOS design near the limit of scaling," *IBM J. Res. Dev.*, vol. 46, nos. 2–3, pp. 213–222, 2002.

[2] F. Chen, H. Kam, D. Markovic, T. K. Liu, V. Stojanovic, and E. Alon, "Integrated circuit design with NEM relays," in *Proc. ICCAD*, 2008, pp. 750–757.

[3] S. Bhunia, M. Tabib-Azar, and D. Saab, "Ultralow-power reconfigurable computing with complementary nano-electromechanical carbon nanotube switches," in *Proc. ASP-DAC 2007*, pp. 86–91.

[4] K. Akarvardar and H.-S. P. Wong, "Ultralow voltage crossbar nonvolatile memory based on energy-reversible NEM switches," *IEEE Electron Device Lett.*, vol. 30, no. 6, pp. 626–628, 2009.

[5] A. B. Kaul, E. W. Wong, L. Epp, and B. D. Hunt, "Electromechanical carbon nanotube switches for high-frequency applications," *Nano Lett.*, vol. 6, no. 5, pp. 942–947, 2006.

[6] J. O. Lee, et al., "3-terminal nanoelectromechanical switching device in insulating liquid media for low voltage operation and reliability improvement," in *IEDM Tech. Dig.*, 2009, pp. 227–230.

[7] W. W. Jang, et al., "Fabrication and characterization of a nanoelectromechanical switch with 15-nm-thick suspension air gap," *App. Phys. Lett.*, vol. 92, no. 10, pp. 103110–103110-3, 2008.

[8] T. Lee, S. Bhunia, and M. Mehregany, "Electromechanical computing at 500°C with silicon carbide," *Science*, vol. 329, no. 1316, pp. 1316–1318, 2010.

[9] V. X. H. Leong, E. J. Ng, J. B. W. Soon, N. Singh, N. Shen, T. Myint, V. Pott, and J. M. Tsai, "Vertical silicon nano-pillar for non-volatile memory," in *Proc. Transducers 2011*, pp. 649–652.

[10] N. Tasy, T. Sonnenberg, H. Jansen, R. Legtenberg, and M. Elwenspoek, "Stiction in surface micromachining," *J. Micromech. Microeng.*, vol. 6, pp. 385–397, 1996.

[11] X. L. Feng, M. H. Matheny, C. A. Zorman, M. Mehregany, and M. L. Roukes, "Low voltage nanoelectromechanical switches based on silicon carbide nanowires," *Nano Lett.*, vol. 10, pp. 2891–2896, 2011.

[12] O. Y. Loh and H. D. Espinosa, "Nanoelectromechanical contact switches," *Nat. Nanotechnol.*, vol. 7, pp. 283–295, 2012.