MICROELECTROMECHANICAL SWITCH WITH CARBON NANOTUBE ARRAYS FOR HIGH-TEMPERATURE OPERATION

Eunhwan Jo[1], Yunsung Kang[1], Sangjun Sim[1], Jungwook Choi[2], and Jongbaeg Kim[1]*
[1]School of Mechanical Engineering, Yonsei University, Seoul, Republic of Korea
[2]School of Mechanical Engineering, Yeungnam University, Gyeongbuk, Republic of Korea

ABSTRACT

This paper reports a micro-electro-mechanical (MEM) switch based on carbon nanotube (CNT) array-to-CNT array contact operating at high temperatures. The outstanding interfacial thermal stability of the CNT arrays allowed the successful operation of the switch at 300 °C, under which condition the solid-state transistors or metal-based MEM switches would not be functioning. Our device operated as an n-type MEM switch by forming an air gap based on the intended stiction induced by the wet processes and the recovery after the synthesis of CNTs. Additionally, we investigated the possible degradation in switching behavior and the change in contact resistance at various temperatures. The switch exhibits stable and repetitive operations over 1,000 cycles at 300 °C under hot-switching conditions in nitrogen at atmospheric pressure without a significant change in the switching characteristics.

KEYWORDS

Mechanical switch, high-temperature operation, carbon nanotube, logic circuit

INTRODUCTION

The necessity of integrated circuits working at high temperatures has been consistently proposed for harsh-environment applications such as aerospace or automotive electronics, where the operating temperature is higher than 150 °C. However, due to the intrinsic carriers of semiconductors, which increase exponentially with increasing temperature, transistors are not functioning at such a high temperature [1]. Although nano-electro-mechanical (NEM)/MEM switches have been well known to work at high temperature, the softening of contact materials induces micro-/nano-scale welding even below their melting temperature [2]. Thus, only three conductive materials with exceptionally high-melting temperature, SiC, Si, and Mo, have been adopted as contact materials of NEM/MEM switches for the operation at above 300 °C, but their current delivering capability is limited to 0.5 µA or less due to the local softening caused by Joule heating at the contact interfaces [3-5].

Recently, CNTs have been focused as reliable contact materials of microdevices due to the remarkable mechanical properties such as high mechanical modulus and strength, deformability, and thermal conductivity [6-10]. We previously reported highly reliable microswitches with self-assembled CNT array, but they had a large footprint area per each device (>1 mm^2), and only p-type switches could be demonstrated due to the limit in CNT growth control [6]. Therefore, it is still challenging to build various bipolar logic gates capable of functioning at high temperatures. Here, we demonstrate a MEM switch with CNT arrays working at high temperatures. CNT arrays having the superior interfacial thermal stability enabled successful operations of the switch at a high temperature of 300 °C. We formed an air gap between the contact electrodes of the switch by introducing the intended stiction and the recovery after the CNT growth, and thus the switch could operate as an n-type MEM switch. The switch exhibits repeatable operations over 1,000 cycles at 300 °C under hot-switching conditions. Additionally, we examined the possible degradation in switching behavior and the change in the contact resistance at various temperatures from room temperature to 300 °C.

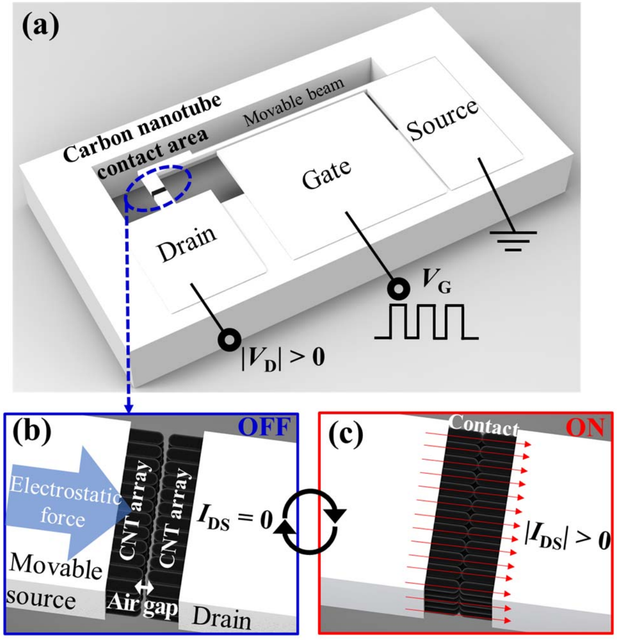

Figure 1: Schematic illustration of (a) the proposed switch with carbon nanotube (CNT) arrays and (b, c) schematics of contact region at off- and on-state, respectively. When a gate voltage (V_G) was applied, the source beam was bent down by electrostatic force between the gate and source electrode. Then, the contact between CNT arrays was established and provide conductive paths at on-state.

CONCEPT

Figure 1(a) depicts a schematic diagram of the proposed three-terminal switch consisting of a movable source, fixed gate, and drain electrodes on the substrate. The CNT arrays are directly integrated into the contact region. There is no conductive path between the drain and source electrodes because the two electrodes are electrically separated with an air gap at off-state, as shown in Figure 1(b). When a gate voltage (V_G) was applied, the movable beam was bent down by electrostatic force generated between the gate and source electrodes. Then, the CNT array-to-CNT array contact is formed and provides conductive paths as shown in Figure 1(c). The

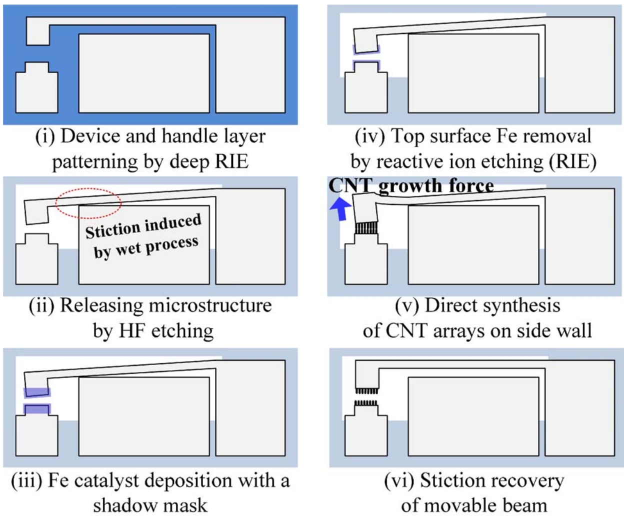

Figure 2: Fabrication process of the MEM switch including direct growth of CNT arrays (top view). Device and handle layers on a 4-inch silicon-on-insulator (SOI) were patterned by using deep reactive ion etching (RIE) to define the switch structures. The switch was released by hydrogen fluoride (HF) etching of a 2-µm-thick buried oxide layer for 4 minutes. (iii) Iron (Fe) catalyst of 3 nm thickness for the synthesis of CNTs was deposited selectively by using sputtering with a shadow mask that was fabricated together in the same wafer. (iv, v) After removal of the Fe catalysis on the top surface, CNTs were directly synthesized only on sidewall of the contact region. (vi) The stuck beam was detached by a probe tip forcefully.

typical conductive solid-based switches have limited contact sites owing to the lack of deformability [11], compared with their large apparent contact area. However, the contact sites of our switch are larger than that of the typical switches, because many CNT tips participate in the contact owing to its deformability [12]. Besides the outstanding thermal stability of CNTs which can theoretically withstand up to 4,000 K without sublimation or melting [13], the increased contact sites of the switch with CNTs enable successful operations at high temperatures and high-current density.

FABRICATION

Figure 2 shows the microfabrication process including the integration of CNT arrays onto the switch. To define the switch structures, a 20-µm-thick silicon (Si) device layer on a 4-inch silicon-on-insulator (SOI) wafer was patterned by deep reactive ion etching (RIE) with a positive photoresist mask. After patterning a handle layer by deep RIE, the switch structures were released through hydrogen fluoride (HF) etching of the buried oxide layer. During drying after a deionized water rinse, the flexible movable beam was stuck on the gate electrode. Subsequently, 3-nm-thick iron (Fe) catalyst for CNT synthesis was selectively deposited by sputtering with a shadow mask that was co-fabricated in the same wafer. The Fe catalyst on the top surface of wafer was removed by using RIE to suppress the growth of CNTs in an undesired direction. Then the CNTs were directly synthesized only on the sidewall surfaces of the two separated electrodes. After

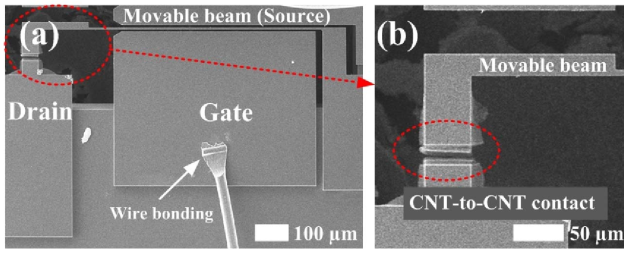

Figure 3: (a) SEM images of (a) the fabricated switch and (b) CNT array-to-CNT array contact region with an air gap.

the growth of CNTs was terminated in the middle of the gap, the stuck beam was detached by a probe tip forcefully.

RESULTS & DISCUSSION

Scanning electron microscopy (SEM) images in Figure 3(a,b) show the fabricated switch and CNT array-to-CNT array contact region with an air gap. We observed that the CNTs were successfully synthesized only on the sidewall of the contact region through the sputtering and directional etching known as a spacer patterning. We measured the hysteretic switching characteristics of the switch with CNT arrays. Figure 4 shows the measured drain-source current (I_{DS}) versus V_G dual sweep curves at the bias V_{DS} of 0.5 V and various temperatures from 300 to 423 K. The V_{ON} and V_{OFF} remained constant at the different temperatures. The small hysteresis between the forward and reverse sweep of the V_G implied low adhesion force between the CNT arrays [7, 14].

We also investigated the switching characteristic at a high temperature, at which the solid-state transistors and metal-based MEM switches could not be functioning [1, 2]. Figure 5(a) shows the high-temperature operation of the switch at 573 K. The I_{DS}–V_G sweep curve was measured in nitrogen (N_2) environment and the bias V_{DS} of 0.5 V. There is no significant change of the switching voltages from 300 to 573 K. The I_{DS} at on-state increased from 19 to 70 µA.

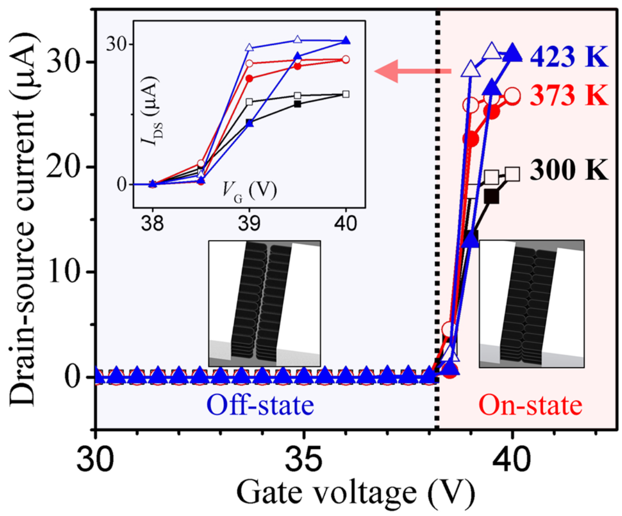

Figure 4: Measured drain-source current (I_{DS})–gate voltage (V_G) sweep curves of the switch with various temperature ranges from 300 to 423 K. In dual sweeps of the V_G from 0 to 40 V, the I_{DS} was recorded with bias V_{DS} of 0.5 V.

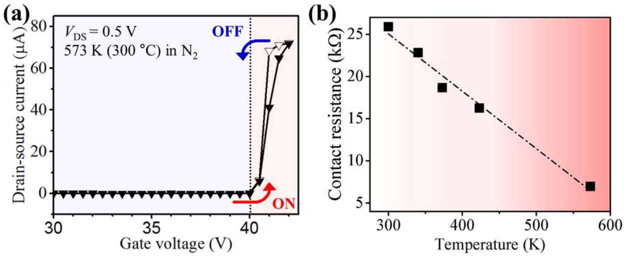

Figure 5: (a) Measured I_{DS}–V_G sweep curve at 500 K (300 °C) in the atmospheric N_2 environment. (b) The linear decrease of contact resistance with increasing temperature. The linearly decreased electrical resistance of the switch originated from the negative temperature coefficient of the resistance of multi-wall CNT and CNT-to-Si junction.

as the ambient temperature increased. Figure 5(b) exhibits the corresponding change of the electrical resistance between drain and source electrodes with respect to the increment of the ambient temperature. The linearly decreased electrical resistance originated from the negative temperature coefficient of the resistance of the multi-wall CNT and CNT-to-Si junction [6, 15].

We investigated the possible degradation of the switch with CNTs at 573 K. The measured I_{DS} was recorded simultaneously by using a source-meter with the bias V_{DS} of 0.1 V while 1 Hz and 50% duty ratio square-wave V_G of 42 V was applied by a function generator and a voltage amplifier as shown in Figure 6 (a). The ambient temperature in N_2 was controlled by a furnace. The increased contact sites generated by the CNT arrays

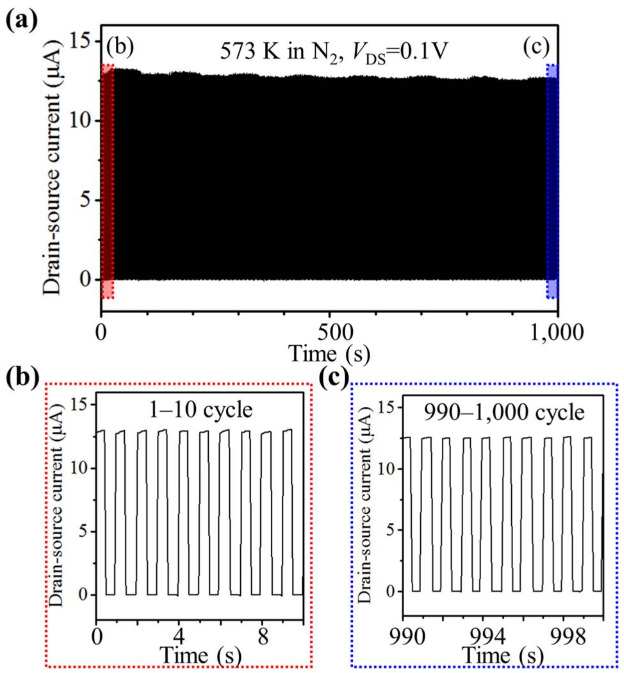

Figure 6: (a) Consecutive switching cycles at 573 K (300 °C) over 1,000 cycles under hot-switching condition (0.1 V and 12.5 μA) in atmospheric N_2 environment. (b, c) Measured I_{DS} from 1 to 10 cycles and 990 to 1,000 cycles, respectively.

prevented excessive local heating at the contact interface, and thereby the switch operated over 1,000 cycles at 575 K without a significant indication of degradation or failure as shown in Figure 6(b, c).

CONCLUSION

We demonstrated a laterally operated MEM switch capable of working at high temperatures. By adopting CNT arrays having outstanding thermal stability, the switch successfully operated up to 300 °C in an atmospheric N_2 environment. Our device operated as an n-type switch with an air gap which has been difficult to make due to the limit in control of CNT growth. We also examined the possible degradation in switching behaviors and the change in electrical resistance of the switch at various temperatures. Besides its outstanding thermal stability, the increased contact sites generated by the deformable CNT arrays suppressed local heating at the contact interfaces and thus the switch operated over 1,000 cycles at 300 °C under hot-switching conditions without failure. It is expected that the switch with CNT arrays can be used for logic applications in harsh environment where normal transistors and metal-based MEM switches could not be functioning.

ACKNOWLEDGEMENT

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REFERENCES

[1] P. G. Neudeck, R. S. Okojie, L.-Y. Chen, "High-Temperature Electronics—A Role for Wide Bandgap Semiconductors?" *Pro. IEEE,* vol. 90, pp. 1065-1076, 2002.

[2] R. Holm, *Electric Contacts—Theory and Applications*, 4th ed., Springer, 1967

[3] T.-H. Lee, S. Bhunia, M. Mehregany, "Electromechanical Computing at 500°C with Silicon Carbide", *Science*, vol. 329, pp. 1316-1318, 2010.

[4] B. W. Soon, E. J. Ng, V. A. Hong, Y. Yang, C. H. Ahn, Y. Qian, T. W. Kenny, C. Lee, "Fabrication and Characterization of a Vacuum Encapsulated Curved Beam Switch for Harsh Environment Application" *J. Microelectromech. Syst.*, vol. 23, pp. 1121-1130, 2014.

[5] Y. Qian, B. W. Soon, P. Singh, H. Campanella, C. Lee, "All metal nanoelectromechanical switch working at 300 °C for rugged electronics applications" *Nanoscale*, vol. 6, pp. 5606-5611, 2014.

[6] J. Choi, J.-I. Lee, Y. Eun, M.-O. Kim, J. Kim, "Aligned Carbon Nanotube Arrays for Degradation-Resistant, Intimate Contact in Micromechanical Devices", *Adv. Mater.*, vol. 23, pp. 2231-2236, 2011.

[7] E. Jo, M.-H. Seo, S. Pyo, S.-D. Ko, D.-S. Kwon, J. Choi, J.-B. Yoon, J. Kim, "Integration of a Carbon Nanotube Network on a Microelectromechanical Switch for Ultralong Contact Lifetime", *ACS Appl. Mater. Interfaces*, vol. 11, pp. 18617-18625, 2019.

[8] J.-I. Lee, Y. Song, H. Jung, J. Choi, Y. Eun, J. Kim, "Deformable Carbon Nanotube-Contact Pads for Inertial Microswitch to Extend Contact Time" *IEEE Trans. Ind. Electron.*, vol. 59, pp. 4914-4920, 2012.

[9] J. Choi, Y. Eun, J. Kim, “Investigation of Interfacial Adhesion between the Top Ends of Carbon Nanotubes”, *ACS Appl. Mater. Interfaces*, vol. 6, pp. 6598-6605, 2014.
[10] J.-I. Lee, Y. Eun, J. Choi, D.-S. Kwon, J. Kim, " Using Confined Self-Adjusting Carbon Nanotube Arrays as High-Sensitivity Displacement Sensing Element" *ACS Appl. Mater. Interfaces*, vol. 6, pp. 10181-10187, 2014.
[11] B. F. Toler, R. A. Coutu, J. W. McBride, “A review of micro-contact physics for microelectromechanical systems (MEMS) metal contact switches” *J. Micromech. Microeng.*, vol. 23, 103001, 2013.
[12] A. Cao, P. L. Dickrell, W. G. Sawyer, M. N. Ghasemi-Nejhad, P. M. Ajayan, “Supuer-Compressible Formlike Carbon Nanotube Films” *Science*, vol. 310, pp. 1307-1310, 2005.
[13] Y. Miyamoto, S. Berber, M. Yoon, A. Rubio, D. Tomanek, “Onset of nanotube decay under extreme thermal and electronic excitations’ *Physica B,* vol. 323, pp. 78-85, 2002.
[14] S.-D. Ko, J. Lee, H.-H. Yang, M.-W. Kim, Y.-H. Song, J.-B. Yoon, “An Insulating Liquid Environment for Reducing Adhesion in A Microelectromechanical System”, *Appl. Phys. Lett.*, vol. 99, 113516, 2011.
[15] J. Choi, J. Kim “Batch-Processed Carbon Nanotube wall as pressure and flow sensor” *Nanotechnology*, vol. 21, 105502, 2010.

CONTACT

*J. Kim, tel: +82-2-2123-2812; kimjb@yonsei.ac.kr