CARBON NANOTUBES NETWORK CONTACT LUBRICATION FOR HIGHLY RELIABLE MEMS SWITCH

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ABSTRACT

This paper firstly reports a highly reliable MEMS-switch employing a CNTs-network lubricant in the contact-area. By covering the contact-area with the CNTs-network, we achieved more than an order of magnitude extension in the lifetime of the MEMS-switch. We determined that this drastic improvement in the reliability arises from the compressibility of the CNTs-network, generating remarkable contact-area widening with suppressed adhesive interaction at the contact interface. We also observed that the highly flexible CNTs-network does not deteriorate high-speed operation of the device. The proposed switch exhibited a lifetime more than 10 times longer under hot-switching condition than a device without CNTs.

INTRODUCTION

Micro-electro-mechanical system (MEMS) switches have received a great deal of attention as promising candidates for next-generation switching devices [1]. Based on their exceptional switching performances, impressive progress has been attained in many applications [2]. However, it is still a challenge to achieve long-term stable micro-mechanical switches operated under hot-switching conditions [1], including general logic, memory, and power-gating applications, which has posed a major obstacle in the practical use of the MEM-switch [1, 2].

To enhance the poor reliability, researchers have made enormous efforts with various approaches based on structural [3] and material [4, 5] insights, and it is now well understood that one of the key factors is adopting a superior material at the contact interfaces [3, 5]. In this context, gold (Au) is a promising material for highly reliable switches because of its excellent electrical, mechanical, and chemical properties [1-4]. However, its high ductility and weakness against plastic deformation can easily generate physical degradations, which still limits reliable switching operation [1, 3, 4]. Thus, it is necessary to investigate more durable and reliable contact materials.

Recently, carbon nanotubes (CNTs) have attracted a good deal of interest as a key factor in the performance of MEMS-devices [5-7]. We previously reported that vertically aligned CNTs could be applied for a reliability enhanced MEMS switch [5]. Although wear-resistive operation was achieved, the tip end-to-end contact of the vertical CNTs resulted in very high contact resistance (~290 Ohm); thus, an improved CNT contact adopted device is required. In this work, we introduce a decumbent CNTs network as MEMS-switch contact to achieve both high reliability and low contact resistance. Using the compressible CNTs-network in a vertical contact-type MEMS-switch, a greatly increased contact area is achieved, resulting in both low contact-resistance and high long-term reliability.

CONCEPT

Schematics of the proposed device and operational principle are shown in Figure 1. The switch has a 3-terminal vertical contact-type switch configuration. Figure 1(b) shows that the CNTs network is formed on the designated region of the bottom electrode and under the dimple of a suspended beam electrode. Figure 1(c) depicts how the contact is made between the dimple and CNTs network. When a gate-voltage is applied, the dimple approaches the CNTs, making slight contact. At this moment, the contact force of the dimple is not large enough to deform the CNTs fully; thus, the real contact area is tiny. The contact area is greatly increased by applying a higher gate-voltage, generating a much larger contact-force because of the compressible CNTs network. Interestingly, even though the dimple and CNTs make contact throughout an increased area, the contact is in the Van der Waals range, maintaining the low adhesive interface. As a result, the remarkably increased contact area generates very low contact-resistance with high reliability (Figure 1(d)).

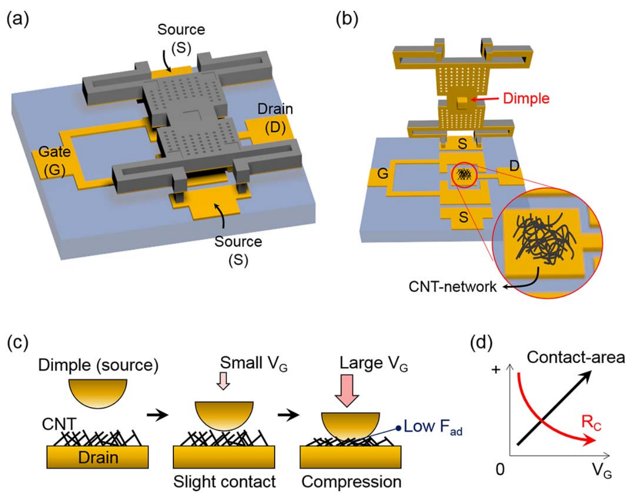

Figure 1: Schematic illustration of (a) the proposed CNT network contacting switch and (b) the structural details. Schematic diagrams of (c) the CNT network contact behavior and (d) the expected results

DEMONSTRATION

To demonstrate the CNTs network contact micro-mechanical device, we developed a novel fabrication method, as shown in Figure 2(a). The fabrication starts with a gold (Au) bottom electrode patterned on silicon dioxide (SiO_2) grown on a silicon (Si) wafer. To restrict the CNTs network to the contact surface, a commercial multi-wall CNT dispersed N,N-dimethylformamide (DMF) liquid (2 mg/ml) was deposited onto the whole wafer and dried. Then, the CNT was patterned by a positive photoresist (PR) mask using oxygen plasma treatment (100 W, 40 s). Then, the device structure was fabricated using a conventional photoresist sacrificial layer and nickel (Ni) electroplating process. It should be noted that the gold was deposited on the photoresist sacrificial layer not only for the electroplating seed, but also as a counter-part contact material. Finally, the device was released by removing the photoresist sacrificial layer with solution-based etching and employing a critical point drying (CPD) process. The successfully fabricated device is confirmed with a scanning electron microscopy (SEM) image (Figure 2(b)). We also visually inspected the formed CNTs network on the bottom electrode. As shown in Figure 2(c), the deposited CNTs were optically observed, and the SEM image confirmed the network formation. Moreover, Raman spectroscopy measurement revealed that there was no contamination during fabrication (Figure 2(e)).

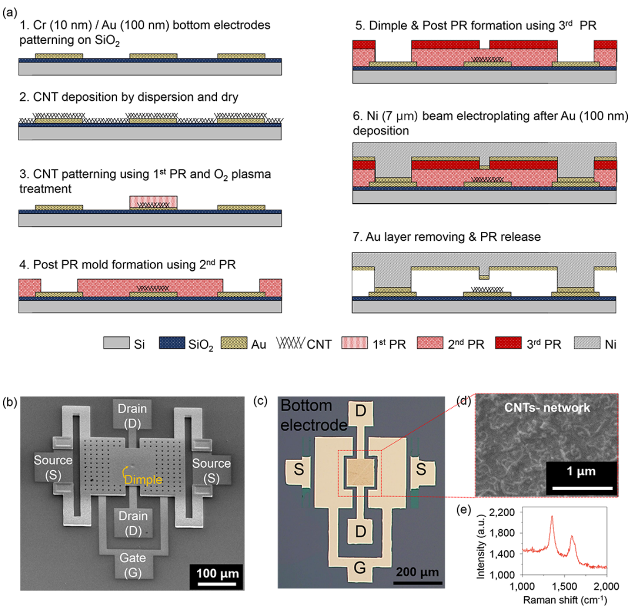

Figure 2: (a) Schematic illustration of whole fabrication process. (b) SEM image of the fabricated switch. High-quality CNT network on drain-electrode is confirmed with (c) optical, (d) SEM images, and (e) Raman-spectroscopy.

RESULTS & DISCUSSIONS

The fabricated CNTs network MEMS-switch was characterized with our highly accurate measurement system at ~20 °C and ~50 % relative-humidity as shown in figure 3(a) [8, 9]. To verify the effects of the CNTs network clearly, we also characterized a device with same dimensions, without the CNTs on the bottom

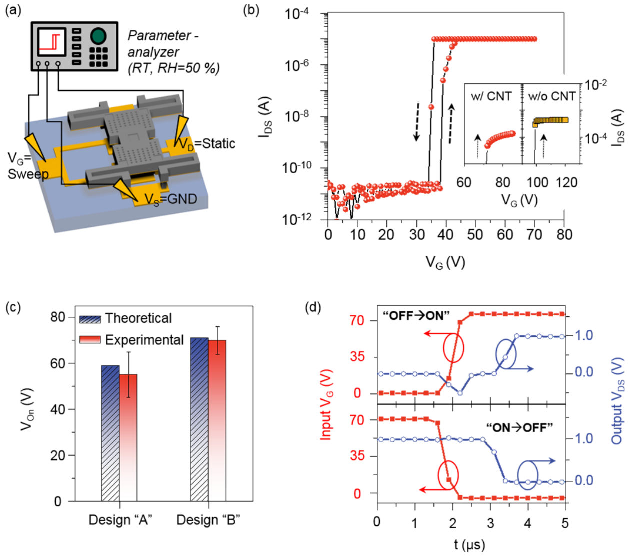

Figure 3: (a) Schematic illustration of our measurement set-up system. (b) I-V characteristics. Inset shows the non-compliance on-state of two-type devices (left: CNT contact, right: non CNT contact). (c) Theoretical and measured on-voltage comparison. (d) Transient responses of the CNT contact device when it was turned (upper) on and (lower) off.

electrode as a control sample (gold-to-gold contact). Figure 3(b) shows the measured I-V curve with a 10 μA drain-source current (I_{DS}). The sudden current-increase with increasing gate-voltage (V_G) ensures the successful fabrication of a 3-D micro-device and the mechanical-operation. Because of the CNTs networks between gold interfaces, a slightly higher on-resistance is measured for the CNTs network device (Figure 2(b) inset), but its level is similar to the gold-gold contact device. The on-voltage (V_{On}) inspection of the devices is one important factor to determine the CNT device stability because the CNT formation on the bottom electrode can influence the device dimension parameters, such as the drain-source gap, generating unexpected device operation. However, the measured on-voltage variations of design- "A" and "B" defined as different structural dimensions, such as mechanical spring constant and gate-electrode area, are highly corresponded with the theoretically calculated results using the lumped model as shown in Figure 3(c), confirming the device stability and scalability. The CNT devices do show some deviations in the on-resistance and on-voltage because of the deposited CNTs network roughness, but it can be improved by optimizing the CNT deposition conditions. Dynamic switching response was also measured, as presented in Figure 3(d), where the turn-on and -off times of the fabricated device were both 1.2 μs.

While the gold-to-gold contact device shows sudden turn-on characteristics with increasing gate-voltage, the CNTs network contact device represents a distinctive intermediate region in the middle of turning on; a drastic current increase occurs at 40 V, but above that, it is continuously increased by additional gate-voltage (Figure 3(b)). To comprehend the intermediate state further, we analyzed the drain-source voltage (V_{DS})-current (I_{DS}) characteristics under various gate-voltage conditions.

Figure 4(a) shows the measured V-I results. As the switch is turned on by V_G=40 V, the drain-source voltage changes linearly with the current variation, indicating an ohmic contact. When the gate-voltage is increased up to 70 V, the drain-source electrical response maintains its linear characteristic, but a drastic decrease of the slope occurs, implying the decrease in on-resistance (R) of few orders of magnitude. Even though the gold also generates a lower on- resistance by the additional gate-voltage, because of its mechanical softness [1], but it is generated at a small level under 10 times. We understand this result with respect to the compressibility of the CNTs network. When the switch is first turned on, the device flow I_{DS} goes through a narrow contact area (A_C) because the CNTs network and dimple make slight physical contact. As the gate-voltage increases, it generates stronger contact-force electrostatically. At this moment, the CNTs network is compressed and more contact points are made with the dimple. Moreover, the CNTs are pressed together, and the effective CNT density increases because of sideways bending of CNTs, which results in more CNT-CNT sidewall contact points. Because the contact points act as parallel resistors, an increase in the number of contact point results in reduced overall resistance as shown in Figure 4(b) [10]. To evaluate the enlarged contact area quantitatively, we extracted the normalized contacting area from the contact-resistance (R_C) using Holm`s contact model, and an area-gain enhancement of 15 times is verified (Figure 4(c)).

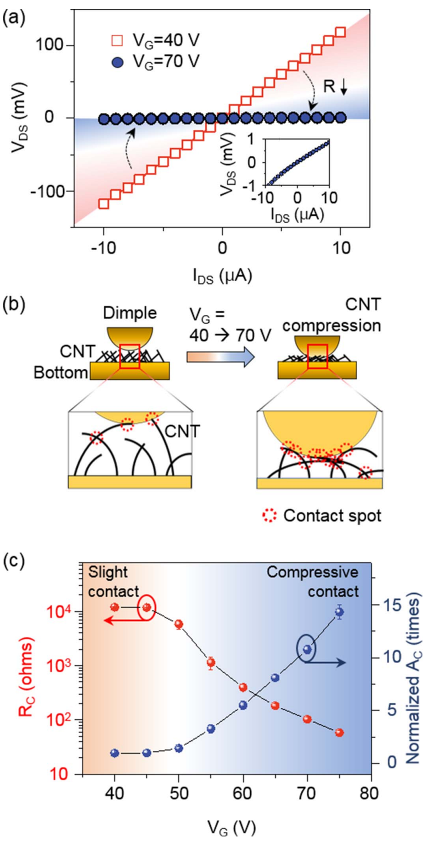

Figure 4: (a) Measured V-I results, when the switch in turned on with V_G=40 (red square) and 70 (blue circle) V. Inset: the magnified V-I result of V_G=70 V (b) Schematic illustrations of the effective contact-area widening by CNT compression. (c) Measured R_C by the V_G changes (red circle) and extracted contact-area (blue circle)

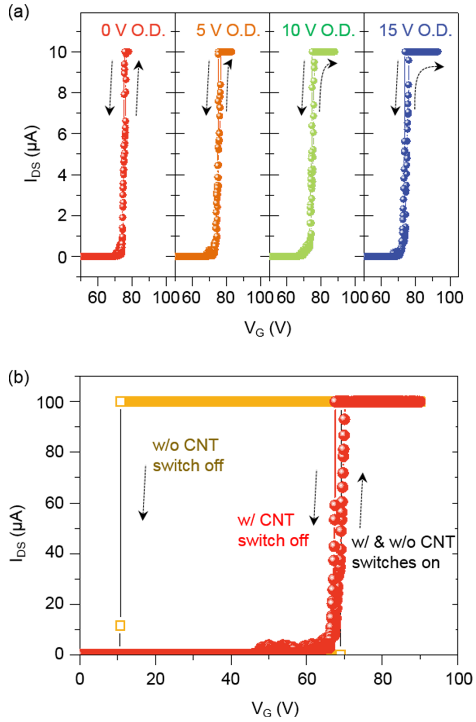

Figure 5: (a) Measured I-V curves of the device. The devices are operated with various additional over-driven V_G up to 15 V after turned-on at V_G=78 V. (b) Cyclic I-V characteristic comparison of devices with (red circle) and without (yellow square) CNT.

Another advantage of the CNTs network contact is that the reduced physical contact can be conducted between the dimple and CNTs network. Micro-/nano-scale wear is easily generated by strong interaction at contact surfaces, and it is one of the major factors in reliability [1]. In contrast to the strong atomic interaction at the contact between metal drain and source electrodes, physically weak Van der Waals interaction is achieved at the contact between the dimple and CNTs network. To confirm the low adhesive properties of the CNTs network, we measured the hysteresis behavior of I-V curves by a cyclic sweep of V_G. I-V curve hysteresis enables the confirmation of the adhesive interaction of the dimple and CNT directly because the device is designed to operate without the pull-in phenomena [11]. Figure 5(a) presents the measured I-V curves at various V_G (0, 5, 10, and 15 V V_G-overdrive (O.D.)). Even though increasing V_G is applied, and the contact area continuously increases, as shown in Figure 4, the proposed CNTs network contact device does not show severe I-V curve hysteresis. Moreover, the CNT device does not generate noticeable I-V curve hysteresis behavior under harsh current conditions (100 μA), whereas extremely large I-V curve hysteresis is measured with the gold-to-gold contact (without CNT) device (figure 5(b)).

Finally, we evaluated the reliability of the CNTs network contact device. To verify the CNTs network effect clearly, we also fabricated a comparison device with identical structures and without CNTs (typical gold-to-gold contact). Figure 6(a) shows the measured life-to-failure of the device under hot-switching conditions (1 μA and 0.01 V) in air. Compared with the gold contact device, the lifecycle was extended 15 times. This result can

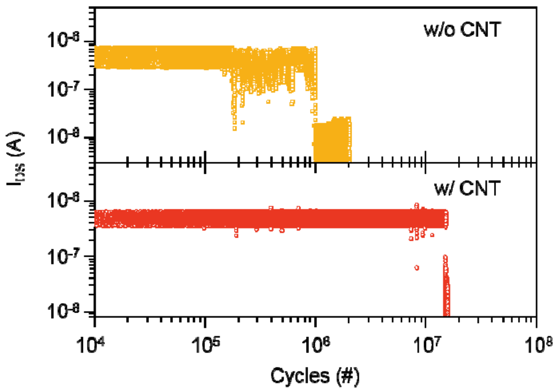

Figure 6: Measured reliability data of devices with (lower panel) and without (upper panel) CNT under 1 μA / 0.01 V hot-switching condition.

be explained by the reduced adhesion at the contact interface between the dimple and CNT. The mechanically durable CNTs network prevents unexpected physical degradation during contact-separation with the dimple. Despite of the reliability enhancement, the CNTs network devices also show the sudden reliability-decrease under higher current and voltage conditions. We interpret this phenomenon as a result of the thermal in-stability of the CNT. As CNTs can thermally decompose at high temperatures, the significant joule heating caused by the high electric stress damages the CNTs [12]. However, this low stability under high electrical stress can be improved with exploiting device-packaging [13] and applying thermally conductive materials [4].

CONCLUSION

We have shown the first beneficial use of CNT-network as a durable contact material in the MEM-switch. Based on the newly developed fabrication method, the micromechanical-switch exploiting the CNT-network at the contacting surface solely. Using the automated CNT contacting micro-device, we reveal that the more than 10 times improved contact-resistance can be achieved than the previous vertical CNT contact device, maintaining the low adhesive properties. Owing to the superior resistance and adhesion properties, the proposed switches, finally, exhibit more than 10 times long lifetime under various hot-switching conditions, compared to a comparison device without CNTs (gold-to-gold contact). We anticipate that the proposed CNT-network will provide many advantages with reliability on various micro-mechanical contact systems such as atomic-force-microscopy, contact-type energy harvester, and mechanical data-storage.

REFERENCES

[1] Y.-H. Song, S.-D. Ko, J.-B. Yoon, "A Highly Reliable Two-Axis MEMS Relay Demonstrating a Novel Contact Refresh Method". *J. Microelectromech. Syst.*, vol. 24, pp. 1495-1502, 2015.

[2] G. M. Rebeiz, *RF MEMS: Theory, Design, and Technology*, Willey, 2003.

[3] Y.-H. Song, M.-W. Kim, M.-H. Seo, J.-Bo. Yoon, "A Complementary Dual-Contact MEMS Switch Using a "Zipping" Technique", *J. Microelectromech. Syst.*, vol. 23, pp. 710-718, 2014.

[4] Y.-H. Yoon, Y.-H. Song, S.-D. Ko, C.-H. Han, G.-S. Yun, M.-H. Seo, J.-Bo. Yoon, "A Highly Reliable MEMS Relay With Two-Step Spring System and Heat Sink Insulator for High-Power Switching Applications", *J. Microelectromech. Syst.*, vol. 25, pp. 217-226, 2016.

[5] 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.

[6] Y. Eun, J.-I. Lee, J. Choi, Y. Song, J. Kim, "Integrated Carbon Nanotube Array as Dry "Adhesive for High-Temperature Silicon Processing", *Adv. Mater.*, vol. 23, pp. 4285-4289, 2011.

[7] 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.

[8] M.-H. Seo, H.-H. Yang, K.-W. Choi, J.-S. Lee, J.-B. Yoon, "A Simple Breathing Rate-Sensing Method Exploiting A Temporarily Condensed Water Layer Formed On An Oxidized Surface", Appl., Phys. Lett., vol. 106, 053701, 2015.

[9] M.-H. Seo, Do.-H. Choi, C.-H. Han, J.-Y. Yoo, J.-B. Yoon, "An Electrostatic Energy Harvester Exploiting Variable-area Water Electrode by Respiration", in *Digest Tech. Papers IEEE MEMS '15 Conference*, Estoril, January 18-22, 2015, pp. 126-129.

[10] O. Yaglioglu, A. J. Hart, R. Martens, A. H. Slocum, "Method of Characterizing Electrical Contact Properties of Carbon Nanotube Coated Surfaces", *Appl. Phys. Lett.*, vol. 77, 095105, 2006.

[11] 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.

[12] T. Kashiwagi, E. Grulke, J. Hilding, R. Harris, W. Awad, J. Douglas, "Thermal Degradation and Flammability Properties of Poly(propylene)/Carbon Nanotube Composites", *Macromol. Rapid Commun.*, vol. 23, pp. 761-765, 2002.

[13] C.-H. Han, M.-Ho. Seo, S.-D. Ko, Y.-H. Yoon, G.-W. Yoon, J.-Bo. Yoon, "Unconventional Use of a Photoresist as a Nitrogen Gas Generator Forming Transparent Dome-Shaped Microcavities", *Adv. Eng. Mater.*, vol. 4, pp. 559-566, 2016.

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