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Nanoelectromechanical switches with vertically aligned carbon nanotubes

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Electromechanical switching devices have been fabricated successfully employing vertically grown multiwalled carbon nanotubes (MWCNTs) from the prepatterned catalyst dots on the patterned device electrodes. The devices show various interesting switching characteristics depending on the length and the number of MWCNTs used. The device design not only simplifies the fabrication process, but also improves the integration density greatly. The device has a great potential in realizing technically viable nanoelectromechanical systems, such as switch, memory, fingers, or grippers. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2077858]

The fabrication of nanoelectromechanical systems (NEMS) has recently been a highly active area of research as it holds great promise for a number of scientific and technological applications. Until now, most NEMS have been typically fabricated by high-resolution lithographic and etching techniques.[1–4] However, developing a reproducible and routine nanofabrication method suitable for NEMS by these processes is still far from realization due to much stringent processing conditions. Therefore, there has been significant interest recently in the integration of the nanostructured materials fabricated by growth techniques, such as carbon nanotubes(CNTs),[5–8] semiconductor wires,[9–11] and metal wires[12,13] to develop new types of NEMS. Specifically, employing vertically grown multiwall CNTs (MWCNTs) can be achieved with various nanodevices without severe fabrication conditions due to its control of positioning and population. Here, we report novel electromechanical switch devices employing vertically grown MWCNTs from the prepatterned catalyst dots on the patterned device electrodes. The fabrication technique reported here combines well-established semiconductor fabrication techniques with the controlled growth of CNTs, opening up the possibility of practical applications. The device geometry not only greatly improves the integration density, but also provides a simple fabrication technique applicable for other types of NEMS.

The device consists of three MWCNTs grown from predefined positions on the electrodes as shown in Fig. 1(a). Three Nb electrodes were patterned by electron-beam lithography, sputtering, and lift off, (followed by focused ion-beam etching). Similarly, Ni catalyst dots of 150 nm diameter and 10 nm thickness were also formed on the predefined locations in the electrodes for the vertical growth of MWCNTs. The MWCNTs were then vertically grown at ~600 °C using a C_2H_2 and NH_3 gas mixture from the Ni catalyst dots using the direct current plasma-enhanced chemical vapor deposition system (dc-PECVD). The detailed description of the MWCNT growth by this technique can be found elsewhere.[14,15]

Figure 1(b) shows a schematic drawing of the device structure. Here, the first MWCNT is electrically connected to the earth ground, acting as a negative electrode. Positive electrostatic charges build up in the second and the third MWCNT, when connected to a positive voltage supply with respect to the earth ground. The third MWCNT pushes the second MWCNT toward the first MWCNT, due to electrostatic forces induced when the positive bias of the third MWCNT increases while maintaining a constant positive bias on the second MWCNT. Above a threshold bias, the second MWCNT makes electrical contact to the first MWCNT, establishing "on state." The threshold bias will be determined by the balance of the electrostatic force, the elastostatic force, and the van der Waals force involved in this device operation. If the attractive van der Waals force between the first and second MWCNT is larger than the repulsive elastostatic force between the two, they would remain held even after the driving bias is removed. Otherwise, the second MWCNT should return to its original position when the driving bias is removed.[7,8,16–18] Therefore, it is possible to fabricate two different types of switch devices exhibiting either a nonvolatile or a volatile switch behavior by a the careful control of the forces involved. We attempted to fabricate such switch devices by varying the number and the length of the MWCNT used.

Figure 2(a) shows a scanning electron microscopy (SEM) image of the device. Representative electrical characteristics of current between the first and second MWCNTs versus the voltage driven through the third MWCNT is also shown in Fig. 2(b). Current between the first and second MWCNT increases sharply at 22.5 V and remains saturated above this value. The "off-state" current is found to be very low (less than pA level). This is because the leakage current flows only through the insulating layer (SiO_2), unlike other

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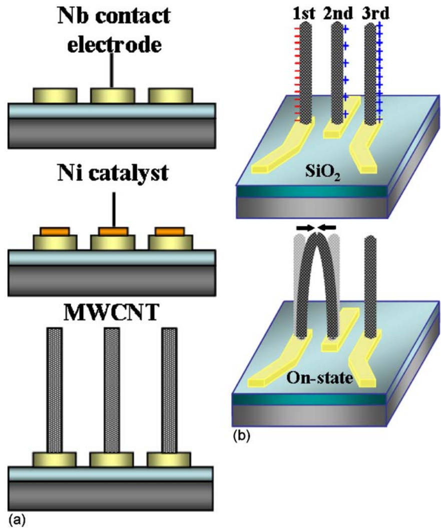

FIG. 1. A schematic illustration of the CNT-based electromechanical switch device (a) Schematic of fabrication process: Three Nb electrodes were patterned by electron-beam lithography, sputtering, and lift off. Similarly, Ni catalyst dots were also formed on the predefined locations for the growth of MWCNTs. The MWCNTs were then vertically grown from the Ni catalyst dots using dc-PECVD. (b) Illustration of CNT-based electromechanical switch action.

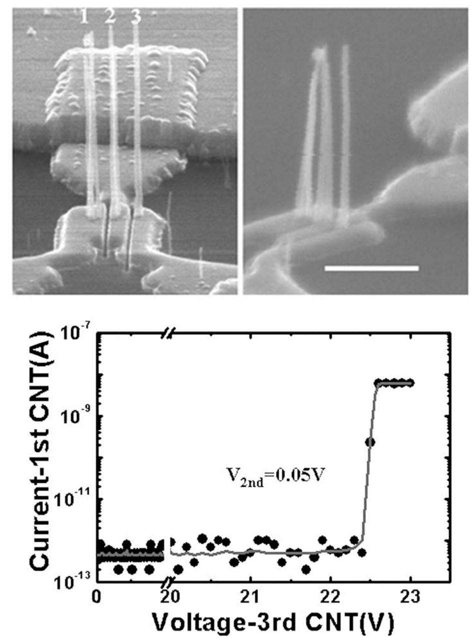

FIG. 2. Electromechanical switch devices consisting of three MWCNTs. (a) SEM image of the device: The length and diameter of the MWCNTs are about 2 μm and 70 nm, respectively. (b) Current-voltage characteristics of switching action in an ambient environment; the electromechanical movement of MWCNTs provides the on and off states. The scale bar corresponds to 1 μm.

nanoscale Si-based memory whose performance is limited by large gate tunnel leakage current due to the gate insulator scaling.[19] The low voltage ($\sim$0.05 V) between the first and second MWCNT offers another important advantage for NEMS device operation, since possible damage caused by a large driving voltage—a problem with some of the CNT-based NEMS devices reported in the literature—can be minimized.[7,16] It should also be noted that the higher turn-on voltage is required in this device compared with other typical Si-based devices.[19] This is mainly due to the large contact area (200 μm$\times$200 μm) in our device, and thus the charge density between MWCNTs is greatly reduced. It is, however, expected that the turn-on voltage may be reduced further by optimizing the device design. As seen in the right image of Fig. 2(a), the second MWCNT does not return to its original position and remains stuck with the first MWCNT, even after the gate voltage bias was removed. It is speculated that the van der Waals force exerted between the two MWCNTs could play some role in this.[7,8,17,18] This is, however, to be confirmed. This interesting electrical characteristic can be exploited for realizing novel nonvolatile memory cells.[8]

The off state can be re-established when the second MWCNT is connected to a floating ground, while the first MWCNT is still connected to the earth ground, as the gate voltage bias to the third MWCNT is swept between 20 and 25 V. It is considered that negative charges will continue to build up through the electrical connection between the first and second MWCNT, even though the floating ground was made to the second MWCNT. As a result of this, the third MWCNT starts to pull the second MWCNT, in which the negative electrostatic charges are accumulated. As the second MWCNT is connected to the floating ground, its possible swing toward the third MWCNT—causing the device to burn out due to high current flow between the second and third MWCNT—can be avoided when the first and the second MWCNTs are separated.

Figure 3(a) shows a SEM image of another MWCNT based electromechanical switch device, a derivative structure from the device described above (see Fig. 2). The device now consists of only two MWCNTs. In this device, the on-state voltage is found to be 24 V. This is slightly higher than that of the three MWCNT-based electromechanical switch device [see Fig. 3(b)]. The second MWCNT in this device structure does not return to the original position either and therefore the electrical contact with the first MWCNT re-

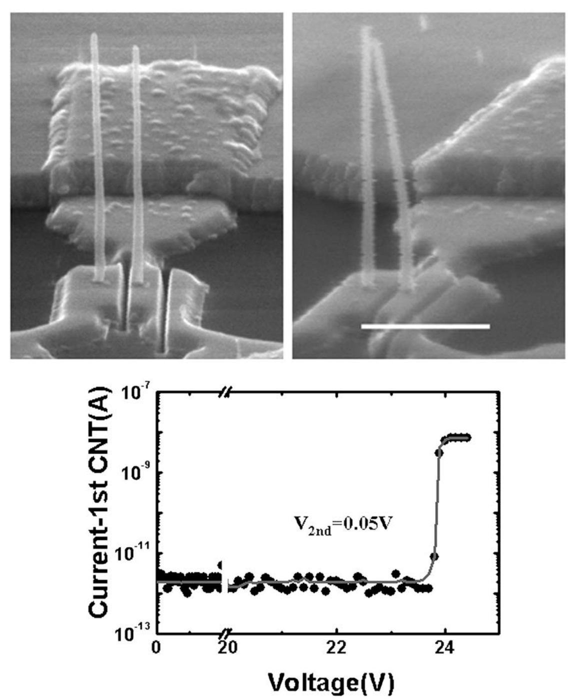

FIG. 3. Electromechanical switch devices consisting of two MWCNTs (length is about 2 μm). (a) Left: SEM image of the electromechanical switch device made of two MWCNTs. Right: The second MWCNT remains stuck with the first MWCNT after the removal of applied bias. (b) Current vs voltage characteristics. The scale bar corresponds to 1 μm.

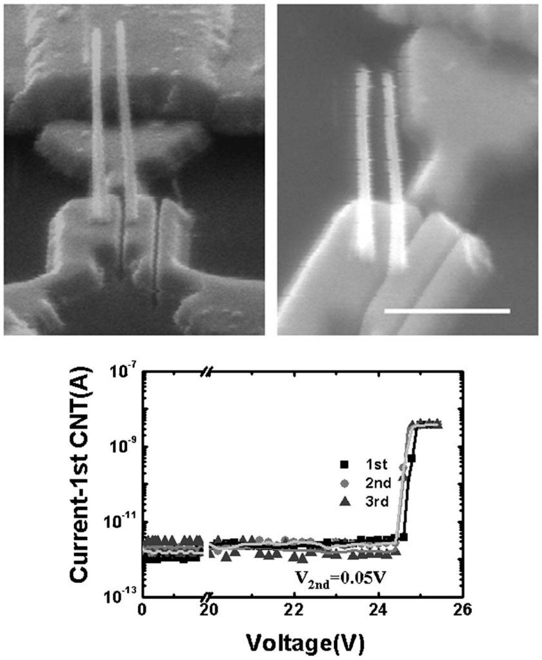

FIG. 4. Electromechanical switch devices consisting of two short MWCNTs. (a) Left: SEM image of the electromechanical switch device consisting of two MWCNTs with much shorter length (~1.4 μm). Right: The MWCNTs are returned to their original position after the removal of applied bias. The scale bar corresponds to 1 μm. (b) Current versus voltage characteristics.

mains on, even after the gate voltage bias is removed. The off state was re-established when the third electrode separated the second MWCNT from the first MWCNT, by pulling them apart while the gate voltage bias was swept between 20 V and 25 V. It is possible that the positive charges induced in the third electrode became large enough to separate the first and the second MWCNTs. Although the second MWCNT was still connected to the earth ground, the device did not suffer from burning out, which was often observed in the case of the device made of three MWCNTs because of removing the third MWCNT. Therefore, this electromechanical switch device—consisting of only two MWCNTs—offers much simpler switch operation and structure than that of the three MWCNT-based electromechanical device that requires the floating ground state of the second MWCNT to establish off state.

It should be noted that a feature of maintaining the electrical connection even after the driving voltage bias is removed could be exploited for various nanodevice applications. However, in some cases, this feature may not be useful. For instance, a switch device for random access memory (RAM) would require a rather complicated driving circuit if it were to be designed based on this characteristic. In order to solve this problem, we fabricated the electromechanical switch device with shorter MWCNTs of ~1.4 μm length (see Fig. 4). The threshold driving voltage of this device is found to be about 24.6 V. Unlike the devices described earlier, in this case, both MWCNTs are found to return to their original positions when the applied bias is removed. This should be obvious as the repulsive elastostatic force should be much higher than the attractive van der Waals force between the shorter MWCNTs. For instance, the elastostatic force F_{elas} can be estimated by $F_{elas}=8E\cdot I\cdot d/L^3$, where E is the Young's modulus, I is the moment of inertia, d is the distance between MWCNTs, and L is the length of MWCNT, respectively, based on a one-dimensional beam model.[17,18] Comparing the elastostatic forces of the devices described in Figs. 3 and 4 with the dimensions of $L=2$ μm, $d=70$ nm and $L=1.4$ μm, $d=70$ nm, respectively, the ratio of elastostatic force, $F_{\text{elas-Fig. 4}}/F_{\text{elas-Fig. 3}}$ is estimated to be about 2.92. This result also supports our observation. The characteristic of switching action of this device is quite similar to those conventional switch devices having a volatile switch characteristic. In addition, as pointed out earlier, for the electromechanical devices described in Figs. 2 and 3, it is necessary to change the bias state of the second MWCNT from the positive bias values to a floating or earth ground state to establish the off state. However, in this case, switching action can be easily established by simply changing the gate voltage. This feature can be exploited for a replacement of silicon transistor-based switches in RAM devices. It should be also noted that the device structure consisting of only two MWCNTs and one gate electrode simplifies the fabrication processing, avoiding complicated lithographic, etching, and implantation processes required in making n-type or p-type silicon transistor based switch devices.[20]

We have succeeded in the fabrication of electromechanical switch devices using vertically grown MWCNTs from patterned catalyst islands, operating reliably in an ambient environment. A combination of top-down (patterning of the electrodes) and bottom-up (growing CNTs from predefined positions) approaches opens up possibilities in realizing different types of technically viable applications. This fabrication technique greatly reduces device dimensions by employing vertical structure and is versatile for the realization of novel NEMS devices.

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