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Carbon Nanotube Based Nano Electro-Mechanical Switches**

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Abstract

The fabrication of carbon nanotube (CNT) based nano electro-mechanical (NEM) switches and their electro-mechanical properties are discussed. Two different types of nano electromechanical switches, cantilever type and doubly clamped type, will be introduced. The proposal of three terminal structures for the CNT based NEM switch could lead to improvements in the stability of the switching performance. Both dc electro-mechanical properties and high frequency measurements are used to study the switching performance. The comparison of the switching performance of both types of nano electromechanical switch is discussed at the end of the paper.

I. Introduction

The development of nano electromechanical systems (NEMS) is rapidly growing due to their possible applications in various fields such as bio molecule detection[1], sensitive mass and displacement sensors[2,3], energy generation[4], and so on. Among the various NEMS, nano electromechanical (NEM) switches are one of the most attractive systems because of their promising applicability to electronic switching processes and NEMS memory devices[5,6]. Carbon nanotubes (CNT)[7] are good candidates for realization of NEMS switches thanks to their extraordinary mechanical strength as well as special electrical properties. It is expected that CNT's high Young's modulus (~1 Tpa) combined with low mass could make high switching speeds (over several GHz range)[8]. Even though several prototypes of CNT based NEM switches and their switching properties have been reported[9-12], more studies are necessary to realize CNT based switch devices having stable operation with long life time. In this paper, we introduce two prototypes of new 3-terminal NEM switches and report their electromechanical properties. The dielectrophoresis technique combined with a simple idea in the application of nano lithography made it possible to fabricate 3-terminal NEMS switch structures without using an etching process. The comparison of the electromechanical performance of the cantilever type and doubly clamped suspended type of CNT based NEMS switch is discussed.

II. Experiments and discussion

Fabrication of CNT based 3-terminal NEMS switches was done using the combination of conventional nanofabrication processes and the dielectrophoresis technique. Figure 1 shows the schematics of the fabrication process of two NEMS switch prototypes. At first, source, drain, and gate electrodes were fabricated on the substrate using electron beam lithography. A poly(methyl methacrylate) (PMMA) pattern with the same height as the source electrodes was then deposited. The area patterned with PMMA is used as a support for the deposited multi wall CNT. Dielectrophoresis was used to align the CNT on top of the source electrode and the patterned PMMA. An ac voltage with 13kHz frequency and 16V peak to peak amplitude was applied to the source electrode after one droplet of CNT-water suspension was deposited on the substrate. The fabrication of the NEMS switch structure was completed by using critical point drying (CPD) after upper electrode fabrication and following lift off with acetone. Details of the fabrication process are explained in a previous report.[13] The CPD process is necessary especially for fabricating cantilever type CNT switches where only one part is clamped and the other is freely suspended. CPD avoids the liquid effect which induces suspended CNT to fall down due to a dragging force caused by the surface tension during drying of the substrate after the lift off process. Even rather long (up to 3.5 μm) and thin (diameter of 10 nm) CNT could be successfully suspended for fabricating the cantilever NEMS using the CPD process[14]. Although we have found that the fabrication of suspended doubly clamped CNT structures is possible without using CPD[13], in the results presented in this paper CPD was used for making both (cantilever and doubly clamped) types of NEM switches. The CNT nanostructures used for the fabrication of all devices reported in this paper were grown by plasma CVD from Ni catalyst and, although mainly hollow, they do not possess the high crystallinity of genuine multiwalled CNT. For this reason they are sometimes referred to as carbon nanofibres (CNF). For simplicity, we will continue to use the abbreviation CNT throughout the paper but it should be borne in mind that the structure is more "bamboo-like" in nature. The diameter range was typically 50-100nm.

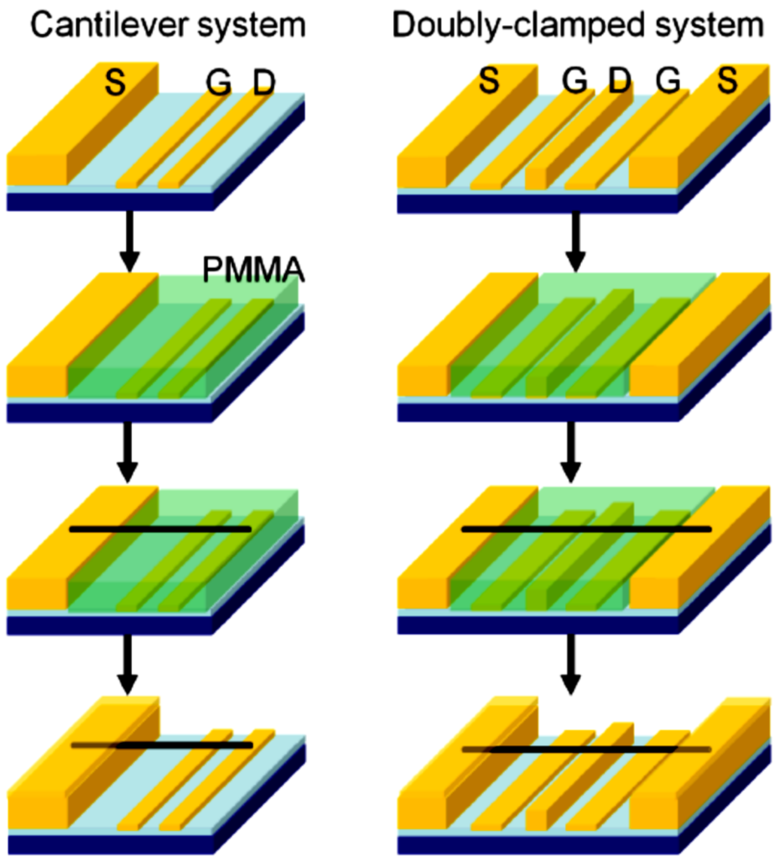

Figure 1. Schematic figure of the fabrication procedure for CNT based NEM switches.

Figure 2 shows scanning electron microscope images of NEM switch structures. The carbon nanotubes in both systems are well suspended above the gate and drain electrodes. In most of the previous reports on suspended structures using CNTs, an etching process has been used in the fabrication process to remove the substrate beneath the deposited CNT. This etching method is widely used because of the simplicity. However, once etching is done on the substrate, it is difficult to continue with further fabrication of nano structures on the etched area. The advantage of our acid free method using patterned PMMA support combined with dielectrophoresis is that it is possible to make various electrode structures underneath the suspended nanostructure.

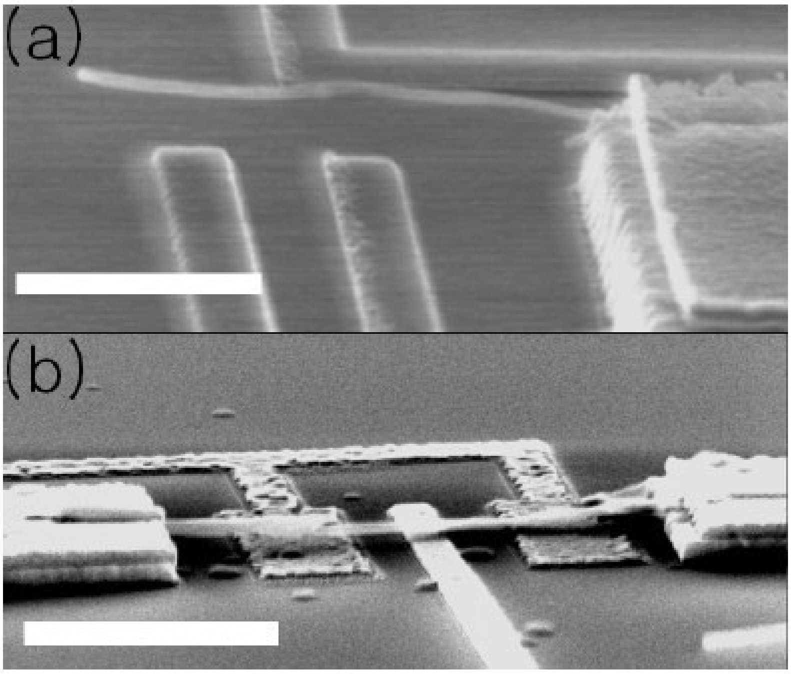

Figure 2. Scanning electron microscope images of two types of CNT based 3-terminal NEM swith. (a) Cantilever structure. The distance between source and drain electrode is 1.5 μm. The height of source electrode is 150nm and that of drain and gate electrode is 20nm. (b) Doubly clamped suspended structure. The distance between two source electrodes is 2 μm, The height of source, gate, and drain electrode is 80nm, 30nm, and 15nm respectively. Scale bar shows 1 μm.

Electromechanical measurements were performed to investigate the switching properties of NEM switches. Figure 3 shows electromechanical measurement results for cantilever systems. Current-gate voltage (I-V_g) characteristics were measured while applying 500mV of source-drain voltage. One can recognize the contact of the suspended CNT with the drain electrode by observing the change of the source-drain current as the gate voltage is increased. 43 cantilever type NEM switch devices were tested and two representative types of the current gate-voltage (I-V_g) curves were found from the measurements. A distinct step-like current increase was found from approximately half of the measured NEM switches as shown in figure 3 (a). The ratio of the current below a gate voltage of 3.4 V to that above it was higher than 40. The measurement result can be explained by considering that the gate voltage induced electrostatic force pulled the suspended CNT down to the drain electrode so that a closed circuit was made between source and drain. It was found that it was typically not possible to switch the structure off again if the initial turn-on behaviour was very sharp as shown in Figure 3(a). The carbon nanotube sticks to the drain electrode and does not come back to the original suspended position when the gate voltage is reduced to 0V. Scanning electron microscope (SEM) observation of the devices after the measurements confirmed this hypothesis.

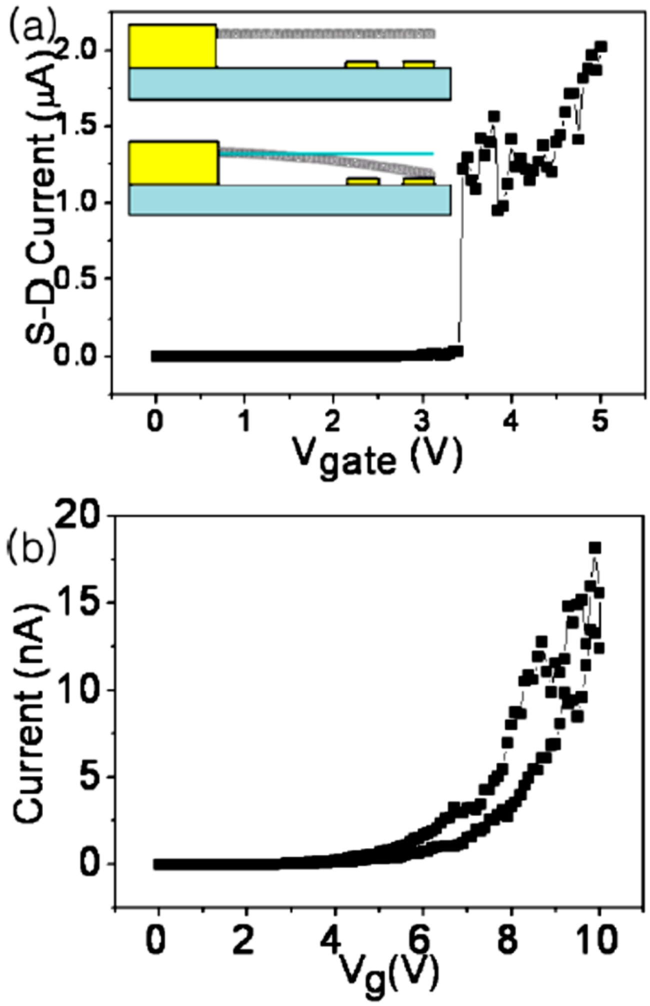

Figure 3. The I-V_g characteristics of cantilever type NEM switch. (a) The step-like current increase was occurred as gate voltage increased. Inset shows the schematics of cantilever type NEM switch before (up) and after (down) actuation. (b) The I-V_g curve shows relatively slow switch on and off behavior. Theoretically expected hysteresis behavior is found from the gate voltage sweep.

The measurement result shown in figure 3 (b) presents the I-V_g characteristics for the other type of switch. The turn on and off behavior of this device are not as sharp as those shown in figure 3 (a), the CNT did not stick to the electrode and reproducible I-V_g curves were shown for several measurement cycles. Theoretically expected hysteresis in the I-V_g curves[5] was found from the measurements during the up and down gate-voltage sweeps. We consider that the nonlinear behavior in the I-V_g curves is caused by tunneling between the wall of the CNT and the electrodes when the CNT approaches close enough to the drain electrode. Since the measurements were done under atmospheric conditions, it is assumed that the presence of some adsorbates on the electrode surface could be a possible reason for the difference in behaviour compared to the example in figure 3(a).

High frequency measurements were used to estimate the switching speed of the cantilever type NEM switch. The maximum switching speed of the NEM switch is known to be determined by the mechanical resonance frequency of the CNT. Several methods for detection of the mechanical resonance of the CNT have been employed, such as mechanical detection using atomic force microscopy (AFM)[15], direct observation using an electron microscope[16], mixing technique using a lock-in amplifier[17,18] and so on. Although a number of studies on the mechanical resonant properties of CNT were reported using those detection methods mentioned above, it has proven to be experimentally challenging to determine the CNT's mechanical resonance using direct transmission (S21) measurements with a network analyzer, the method that is generally used for detecting the resonance of Si based NEM resonator systems[19]. One of the biggest reasons for the difficulty of direct electrical measurements of CNT NEM switches is the high resistance of the nanoscale structures.

We have recently developed a new electrode structure and an amplification circuit for measuring high frequency properties of cantilever type suspended CNT structures[20]. A coplanar wave guide was designed and connected to the source and drain electrode of the device for reducing the output level caused by parasitic capacitances. An operational amplifier circuit was connected to the output port of our device to make the resonant signal measurable[21]. The mechanical resonance of the CNT is electrically sensed when capacitive coupling between the CNT and the drain electrode changes due to the vibration of the CNT at the resonant frequency. A dc bias voltage along with an ac signal is necessary to make the capacitive coupling.

Figure 4 shows the measured transmission parameter (S21) of a two-terminal CNT cantilever structure which was obtained using an Agilent ENA network analyzer E7501B. A distinct resonance signal is found from 8V of bias voltage upwards. A shift of the resonance frequency with increasing bias voltage is found, and this behavior is quantitatively consistent with theoretical expectation, as illustrated for a different resonator in a recent publication [20]. The shift in frequency is due to the change in the electrostatic spring constant [22]

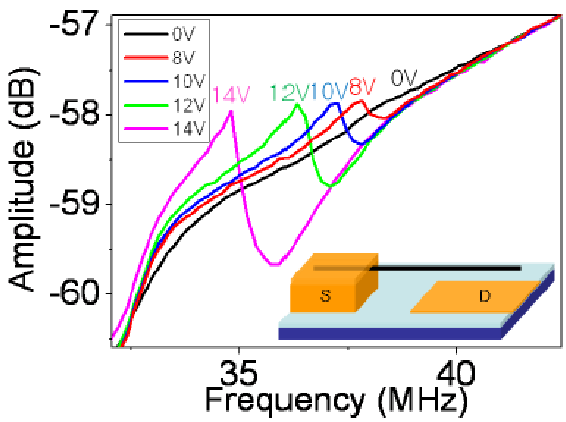

Figure 4. High frequency measurement result of cantilever system. The peak of the transmission parameter S(21) indicates the mechanical resonance of suspended CNT. Inset shows the schematics of device for direct electrical measurement using network analyzer.

The work reported here and by Eriksson et al. [20] is, to our knowledge, the first successful direct transmission measurement of the mechanical resonance of a CNT based NEMS. The large degree of frequency tunability and the fast, 26 ns switching time provides a performance that is superior to that of MEMS devices. Higher resonance frequencies are easily accessible by using shorter CNT (CNF), however, it is difficult to control the length of CNT for fabricating the cantilever structure. Around 3 ns of switching speed was found from a recent study using a 2-terminal doubly clamped NEM switch structure with 130nm suspended length of the CNT[10], which is 10 times shorter than the value used in our cantilever structure.

We expect that the 3-terminal doubly clamped type of NEM switch system as shown in figure 2 (b) to improve the switching properties and to reduce some problems which have been found in the previous NEM switch structures. An advantage of the doubly clamped system is that the suspended length and height of the CNT can be determined in a more controllable manner. The suspended length of the CNT can be determined by controlling the distance between two source electrodes. Our fabrication method makes it possible to fabricate three terminal doubly clamped NEM switches by defining gate and drain electrodes separately below the suspended structure. The drain electrode is placed in the middle of the suspended CNT and is higher than the gate electrode. The suspended CNT will touch the drain electrode first on electrostatic actuation so that the CNT is prevented from burning off by accidentally contacting the gate electrode. Most of the 2-terminal NEM switches are likely to have this kind of burning off problem due to the high voltage difference along the CNT during the switching.

Figure 5 shows the measurement results of a doubly clamped CNT based NEM switch device. The gate voltage dependence of the source-drain current characteristic (figure 5(a)) shows very similar behavior to the typical I-V_g characteristics shown in figure 3(b). The tunneling current is increased as the CNT is brought close to the drain electrode by the electrostatic force. A rapid current increase is found around a gate voltage of 4.5V. Assuming that we set this value for the pull-in voltage, the actual distance between the CNT and the drain electrode can be estimated using continuum beam mechanics[23]. The pull-in voltage is expressed as

$$V_{pull-in} = \sqrt{\frac{8kd^3}{27\epsilon wL}}$$

where d is the distance between the CNT and the electrode, ε is the permittivity, w is the beam width (50nm CNT diameter), and L (2μm) is the length of the beam. The spring constant is $k = 384EI / L^3$ for a doubly clamped system. Young's modulus (E) of our CNT was estimated to be around 500 ~ 700GPa [14,24]. I is the moment of inertia given by $I = \pi D^4 / 64$, where D is the diameter of the CNT.

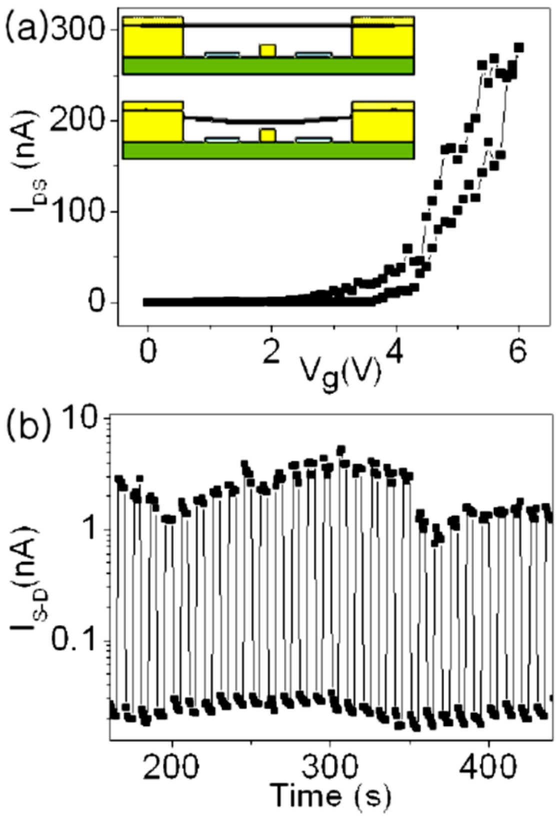

Figure 5. The electromechanical properties of doubly clamped CNT based NEM switch. (a) I-V_g characteristics of doubly clamped system. Inset shows the schematics of doubly clamped CNT based NEM switch before (up) and after (down) actuation. (100mV of Source-drain bias was applied during I-V_g measurements).(b) The source-drain current monitoring as a function of time during repetitive switching on and off operation.

Using this equation, the distance between the CNT and the drain electrode is estimated to be approximately 15-20 nm. Considering that a height difference of 50nm between source and drain electrode was defined by the fabrication, the suspended CNT is likely to have some slack after device fabrication.

Figure 5 (b) shows the results of monitoring the current through the doubly clamped NEM switch as a function of time. 5V of gate voltage was repeatedly turned on and off with 5 seconds of duration time while a 100mV bias was applied to the source electrode. The source-drain current value is acquired every second and it clearly shows discrete on and off steps on changing the gate voltage. The on-off switching was performed over 100 times without stiction problems. Because the CNT is clamped at both ends, this type of NEM switch showed more stable and reproducible switching performance than the cantilever type switches. The current value for the switch-on state, however, is not very reproducible for each step but has strong fluctuations. The current fluctuation may be connected with the fact that the measurements are carried out under ambient conditions. Adsorbates on the electrode surface may lead to differing contact conditions and the domination of tunneling rather than direct physical contact, similar to the situation with the cantilever structures discussed above,. Since this is the first successful electromechanical measurement result on the 3-terminal doubly clamped CNT based NEM switch, more systematic study is necessary to find the optimal condition to make devices operate in a more stable manner. Suspended length (and height) dependence of the I-V characteristics and of the high frequency measurements of the doubly clamped system will be investigated in the near future.

III. Conclusion

In conclusion, carbon nanotube based NEM switches were fabricated and their electromechanical properties were studied. Suspended CNT structures could be fabricated using an acid free method which we have developed. Three-terminal configurations could protect the CNT from high bias voltage application so that it provides more stable switching performance than previously reported two terminal NEM devices. The dc current voltage characteristics and high frequency properties were in agreement with previously studied theoretical models. A recently developed doubly clamped CNT based NEM switch structure showed more stable and reproducible switching performance than the cantilever systems. More systematic experiments are being designed to further investigate the basic properties and possibilities for application.

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