Novel interdigital actuators and sensors based on highly overlapped branched carbon nanotubes

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ABSTRACT

We report a novel interdigital sensor and actuator device based on branched treelike carbon nanotubes (CNT) on silicon-based membranes with an ultra high capacitance value. The presence of treelike CNTs leads to a high overlap between interdigital fingers as well as high electron emission thanks to many nanometric branches attached to their central stem. The fabricated B-CNT-based device resulted in a high capacitance value in comparison to typical devices, leading to a stronger electromechanical coupling behavior. The electro-mechanical behavior of the device has been investigated both with electron emission and capacitive characteristic of the sensor, which confirm superior performance of the investigated devices over silicon-based devices.

Keywords: Carbon nanotubes, branched carbon nanostructures, micro electromechanical actuator, sensor.

I. INTRODUCTION

Exceptional electrical and mechanical properties of carbon nanotubes have attracted the attention of many researchers in different fields. Their unique characteristics such as small size, high stiffness, flexibility and strength [1], high electrical and thermal conductivity as well as their exceptional electromechanical characteristics [2] propound great applications in nano-technology, as well as offering an absolute structure to study nano-cosmos. The incorporation of nano-structures in micro and nano-electromechanical systems has made great enhancement in the performance of such devices [3]. As examples of carbon nanotube-based devices are nano tweezers and grippers [4], nano switches and nano relays [5] and CNT-based bearing for nano-rotational devices [6]. The high aspect ratio of CNTs has exemplified them as excellent electron emitters suitable for field emission displays [7] and nano lithography [8].

We have recently reported the realization of novel branched carbon nanotubes on silicon substrates by means of a plasma enhanced chemical vapor deposition [9]. In this paper, we report for the first time, the application of branched nano structures in silicon-based electrostatic actuator-sensor systems to realize a considerable improvement in the devices.

II. FABRICATION PROCESS

The growth of CNTs is achieved using plasma enhanced CVD method on patterned structures. Nickel is used as the seed layer for the CNT growth and can be patterned using precision photolithography with features around 0.8µm. Once the initial growth is achieved, the formation of branched treelike structures is feasible by applying a sequential treatment and growth steps on the previously grown CNTs. Since a "tip-growth" mode is dominant, the Ni seed is present at the very top side of the vertical CNTs. After the initial growth, individual CNTs are coated with an amorphous carbon layer to encapsulate Ni on top of them. The sample is then exposed to hydrogen plasma to leach the nickel from the tip side. The treated sample is then subjected to a subsequent growth of nanotubes in the same reactor. The second growth is achieved from the tiny nickel seeds just at the very tip of the already grown CNTs. Figure 1 shows in detail, the evolution of branched CNTs on silicon substrates.

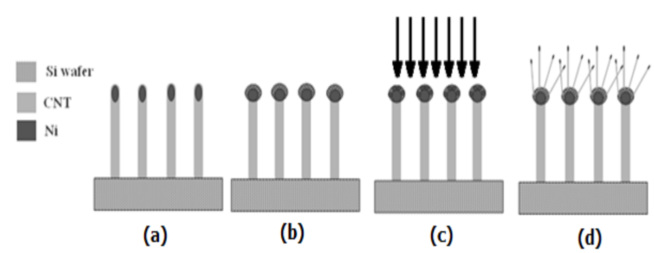

Fig. 1: The fabrication process of branched nanostructures. (a) The growth of vertical CNTs and (b) their encapsulating by a TiO_2 layer during an intermediate treatment step. (c) The hydrogenation step to expose the encapsulated Ni at the very top of the CNT, and (d) the subsequent growth to realize branched carbon nano structures.

To realize a sensor/actuator system a Si-based membrane is needed. Figure 2 depicts schematically the formation of the interdigital (I/D) structures on such a membrane and the subsequent growth and actuation of B-CNTs. A Si membrane (2-4μm thick) is obtained by standard backside micromachining in KOH solution, followed by deposition of Si_3N_4 on the backside. After doping the Si membrane, a 9-nm thick layer of Ni is deposited on the front side of the membrane and it is patterned to form proper interdigital structures on the membrane. A deep reactive ion-etching step is needed to remove Si from unwanted areas and to reach the bottom Si_3N_4 layer. Backside silicon-nitride layer behaves as the ultimate membrane for the sensing/actuation device. The growth of branched treelike CNTs is then achieved only on the parts, which have nickel remaining from previous steps (parts 4 to 6 of figure 2).

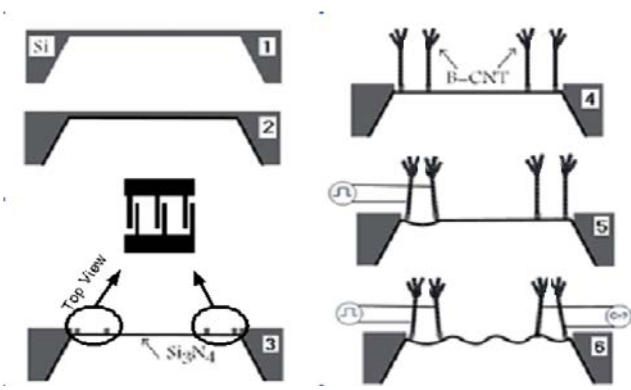

Fig. 2: Formation of sensor/actuator system by B-CNTs, (1) Si membrane, (2) back-side Si_3N_4 coating, (3) interdigital structures on top, (4) growth of B-CNT on digital structures, (5) actuation is possible by applying external ac voltage, (6) sensing the plane wave by measuring the capacitance of the opposite fingers.

III. RESULT AND DISCUSSION

The value of the capacitance has been measured at different stages of the fabrication. For a simple interdigital structure without CNTs, we observe a value of 0.2pF while this value rises to 20 pF for the branched CNTs, thanks to a heavy overlap between parallel lines. By applying a pulsed signal to one interdigital part, the electrical oscillation leads to a mechanical resonance which can be propagated through the membrane and reach the other I/D side. Figures 3 collects several SEM images pertaining to vertical CNTs grown on closely patterned parallel lines of catalyst layer (left image) that have been converted to B-CNTs in next parts of the figure. There is a heavy overlap between parallel lines of B-CNTs, displayed apparently when the lines are placed with a little spacing as SEM images of figure 3. Figure 4 shows the device structure prior and after the B-CNTs have been grown. From inset, one can deduce there is a heavy overlap between neighboring lines.

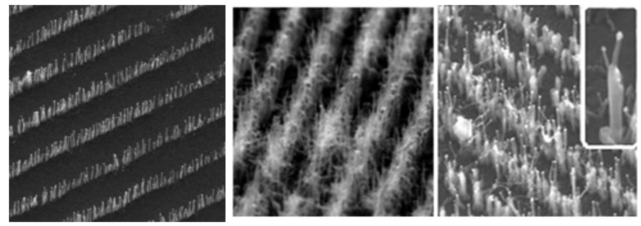

Fig. 3: A collection of SEM images corresponding to various stages of B-CNT formation on linear and dotted arrays. The left-most image shows the growth of normal vertical CNTs on parallel lines whereas other images correspond to the formation of branched treelike structures with one or two subsequent growth steps.

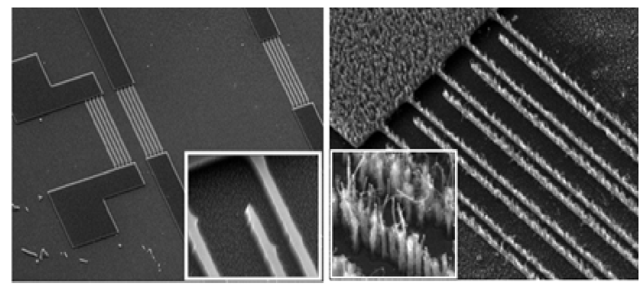

Fig. 4: The left image shows the sensor/actuator system on silicon membrane prior to the growth of CNTs. Inset magnifies individual fingers. The image at right shows the interdigital structure after the B-CNTs have been grown. Inset B-CNTs.

The sensing/actuating characteristic of the system has been investigated by applying a pulse generator to the actuator and the value of capacitance has been affected and measured at the opposite I/D side. For this purpose a 1MΩ resistor has been placed in series with the I/D capacitor and its voltage has been measured.

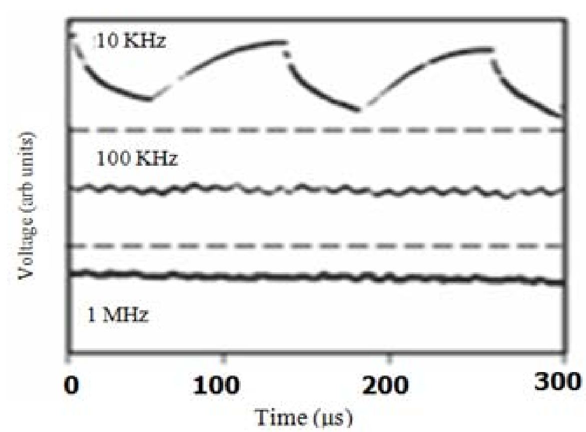

Fig. 5: Signal at the sensor side at various frequencies of actuation. Top curve shows the response to an actuation frequency of 10 KHz with actuation amplitude of 1V. Raising the frequency to 1MHz lowers the signal dramatically.

Figure 5 shows the results of the sensing operation in response to the actuation from the first I/D actuator. The actuation caused by the source signal leads to a mechanical vibration of the membrane and in turn a change in capacitance value of the other I/D capacitance in the opposite side of the membrane. The alternative capacitance value causes the fluctuation of the measured voltage drop over the resistance, which has been recorded in figure 5, for three different actuation frequencies.

As seen by raising the stimulation frequency to values of 100 KHz, the sensed signal vanishes. The optimum frequency is found to be around 10 KHz. Similar experiment has been carried out at a frequency of 10 KHz but with varying the amplitude of the actuator signal (see figure 6). Apart from sensor/actuator capability, such structure can be used as a source for efficient electron emission in a controlled manner.

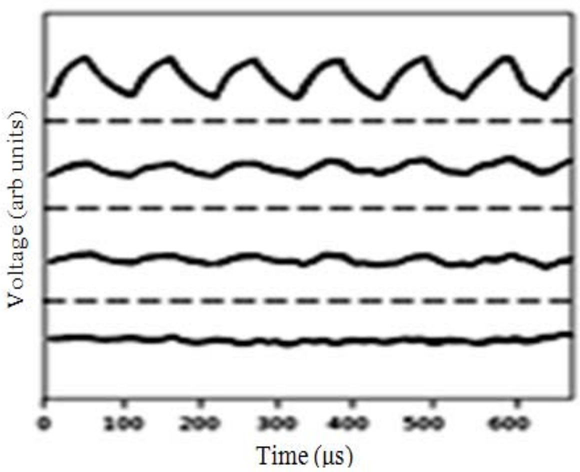

Fig. 6: Signal at the sensor side at various intensities of the actuator part. As observed a nearly linear response is observed between the applied voltage and the measured signal. The frequency of actuation is set at 10 KHz.

The field emission behavior of branched CNTs has been thoroughly examined and part of the results are presented in Figure 7, showing the superior performance of branched CNTs as opposed to vertical regular CNTs. In an attempt to observe the controllable field emission by means of the electromechanical actuation, the setup of Figure 8(a) is proposed where the anode electrode has a small surface and it is placed, with a narrow air gap, against the B-CNT holding substrate. By applying proper signal to one of the I/D parts, a mechanical wave propagates through the membrane which in turn vibrates the emitter part. The current measured at the anode electrode is significantly altered by the vibration of emitter, which itself has been imposed by the actuator I/D (part b). We believe such structure can be used for the fabrication of high sensitivity electro-mechanical pressure and acceleration sensors not achievable using standard silicon technology.

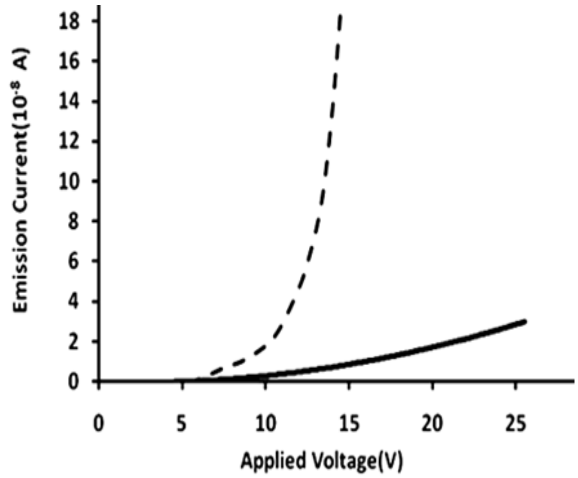

Fig. 7: The field emission behavior of B-CNTs measured in vacuum (dashed line) as opposed to normal CNTs (solid line) further confirming the superiority of the branched structure.

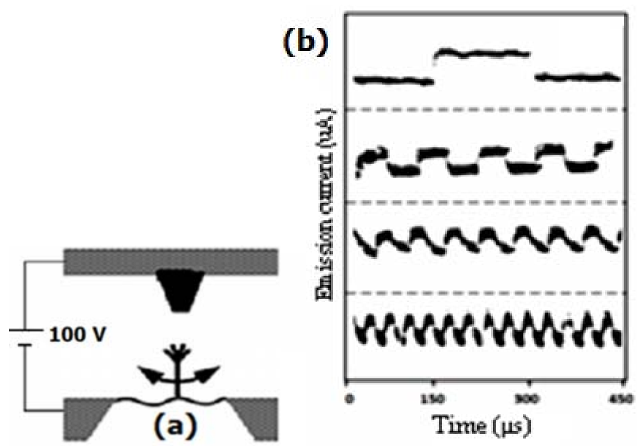

Fig. 8: (a) The schematic of the emission measurement. Top substrate is connected to negative and B-CNT-holding substrate is connected to the positive voltage.
(b) Signal (emission current) at the anode side due to actuation at different frequencies.

Figure 9 illustrates the response of investigated emission current of the structure to a pressure difference of about 1 atmosphere applied to the backside of the upholding membrane, at time intervals of about 10 seconds. The considerable increment in emission current in response to the mechanical stimulation confirms the potential to be applied as high sensitive pressure and acceleration sensors. Further investigation on the application of such devices in low frequency seismologic sensors is being pursued.

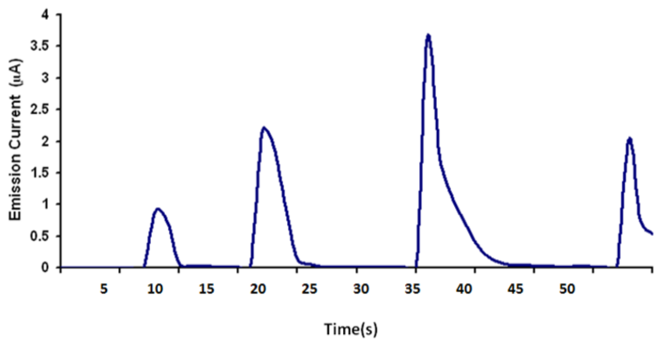

Fig. 9: The response of the emission current to the applied pneumatic pressure with step-like values with time intervals of 10 S.

IV. CONCLUSION

The fabricated structures show the efficacy of branched carbon nanotubes to realize high sensitivity sensors and actuators on silicon-based membranes. The heavy overlapping of neighboring lines, which is not possible using standard silicon technology, leads to a high value of capacitance and subsequently the actuation has become possible. Such structures are suitable devices for high sensitivity vibration sensors.

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REFERENCES

[1] M. M. Treacy, T.W. Ebbesen, J.M. Gibson, “Exceptionally high Young's modulus observed for individual carbon nanotubes” Nature, vol. 381, June 1996, pp. 678–680.

[2] T.Tombler, C. Zhou, L. Alexeyev, J. Kong, H. Dai, W. Liu, C. Jayanthi, M. Tang, S.Y.Wu,” Reversible electromechanical characteristics of carbon nanotubes under local-probe manipulation”, Nature, vol. 405, June 2000, pp. 769–772.

[3] M. H. Huang, C. A. Zorman, M. Mehregany, and M. L. Roukes, “Nanoelectromechanical systems: Nanodevice motion at microwave frequencies” , Nature (London), vol. 421, Jan. 2003, pp. 496-498.

[4] P. Kim, C.M. Lieber, “Nanotube Nanotweezers” Science, vol. 286, Dec.1999, pp. 2148–2150.

[5] J. E. Jang, S. N. Cha, Y. Choi, and Gehan A. J. Amaratunga, D. J. Kang, D. G. Hasko, J. E. Jung and J. M. Kim, “Nanoelectromechanical switches with vertically aligned carbon nanotubes”, Applied Physics Letters, vol. 87, Oct. 2005, pp. 1631141-3.

[6] A.M.Fennimore, T.D. Yuzvinsky, W.Q. Han, M.S. Fuhrer, J.Cumings and A.Zettl, “Rotational actuators based on carbon nanotubes.”, Nature, vol. 424, July 2003, pp. 408–410.

[7] W. B. Choi, D. S. Chung, J. H. Kang, H. Y. Kim, Y. W. Jin, I. T. Han, Y. H. Lee, J. E. Jung, N. S. Lee, G. S. Park and J. M. Kimd “Fully sealed, high-brightness carbon-nanotube field-emission display”, Appl. Phys. Lett, vol. 75, Nov.1999, pp. 3129-3131.

[8] Y. Abdi, S. Mohajerzadeh, H. Hoseinzadegan, and J. Koohsorkhi, “Carbon nanostructures on silicon substrates suitable for nanolithography”, Appl. Phys. Lett., vol. 88, 2006, pp.1-3.

[9] Y. Abdi, A. Ebrahimi, S. Mohajerzadeh and M. Fathipour, “High sensitivity interdigited capacitive sensors using branched treelike carbon nanotubes on silicon membranes”, Appl. Phys. Lett., vol. 94, Apr. 2009, pp. 1735071-3.

[10] A. Sammak, S. Azimi, N. Izadi, B. Khadem Hosseinieh, and S. Mohajerzadeh, “Deep vertical etching of silicon wafers using a hydrogenation assisted reactive ion etching.”, J. Microelectromech. Syst. Vol.16, Aug.2007, pp. 912-918.