Design and Fabrication of Electromechanical Tweezers based on CNT Ropes

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ABSTRACT

This paper deals with the design, modeling, fabrication and electrical characterization of electromechanical tweezers fabricated with carbon nanotubes (CNT) ropes. We used vertically grown multi-walled carbon nanotubes (MWCNTs) deposited by CVD technique. In this work we show a novel approach to develop CNTs tweezers consisting of two arms of vertically aligned CNT ropes that will operate electromechanically. The device was fabricated by optical lithography combined with lift-off process. The same fabrication technique has been used to obtain pre-patterned catalyst dots on patterned electrodes which results on CNT ropes on predefined locations. These ropes have 3 µm in diameter and 35 µm in length. The pull-in voltage measured on a first prototype was about 20 V for a tweezers gap of 5 µm. We calculated the moment of inertia of CNT rope and its average Young's modulus in order to calculate the pull-in voltage of CNT rope tweezers.

Keywords: NEMS, CNT Rope, electromechanical tweezers, pull-in voltage.

1 INTRODUCTION

The development of nanoelectromechanical systems have recently been a highly active area of research as it holds great promise for a number of scientific and technological applications. However, there has been much interest in the integration of nanostructured materials fabricated by growth techniques, such as carbon nanotubes (CNTs) to develop new types of NEMS. Carbon nanotubes exhibit remarkable mechanical strength and electrical conductivity that make them ideal candidates to develop various devices. Specifically, we can employ vertically grown MWCNTs for in-situ fabrication of devices in order to avoid difficulties in depositing and fixing CNTs on metal substrate on specific positions. Some prospective applications of NEMS include random access memory, resonators, nanotweezers[1-2] for miniaturized robotics and other applications. Nanotweezers and NEM switches are fundamental building blocks for the design of NEMS applications. The pull-in phenomenon, an inherent instability of MEM and NEM switches, is one of annoying problems in design.

Here we fabricated CNT rope tweezers with vertically aligned MWCNT. Our CNTs ropes have an aspect ratio of about 11. The entire rope behaves as a beam of the same dimension, which makes our device the first CNT rope tweezers fabricated up to date. The design of such tweezers requires the knowledge of the bending modulus of CNT rope. We studied the mechanical behavior of CNT rope and calculated for this aim its Young's modulus using homogenization models and its moment of inertia using Huygens theorem. Then, we used previous existing analytical models for the calculation of the pull-in voltage and adapted them to our ropes.

2 TWEEZERS FABRICATION

We used optical lithographic technique instead of e-beam technique usually used for individual growth of CNT. We combined this technique with lift-off process in order to fabricate the device. Our device consists on two patterned electrodes; on the end of each electrode we deposited patterned catalyst of 3x3 µm² area (see Figure 1a) which can give rise to CNT rope.

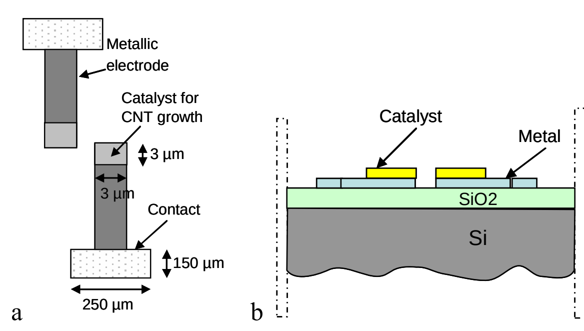

Figure 1: a) Top view of tweezers device, b) The flowchart process step for tweezers device

We used a silicon substrate with a top layer of 2µm of silica. We operated a first lithography level to pattern a photoresist monolayer and we deposited TiN metal by sputtering. Then, a lift-off process has been made to eliminate photoresist and keep patterned TiN electrodes. The same steps as for the first level have been repeated to deposit the catalyst (see Figure 1b). The catalyst is deposited by ion beam sputtering. It consists of a bi-layer stack: a 5 nm thick amorphous silicon film covered by a 1nm thick iron film. CVD technique has been used for the growth of CNTs. The CVD growth process consists of different consecutive steps performed in the same reactor, previously described [3]. An oxidizing RF-plasma treatment is achieved under an air atmosphere at room temperature at 0.2mbar. Then, the sample is heated at 580°C under the same atmosphere for 20 minutes. Finally, the growth is performed at 0.4mbar for 1 hour from a gaseous mixture made of acetylene, hydrogen and helium. The synthesized multi-walled CNTs have diameter of 5nm and are assembled in cylindrical ropes. First prototype is presented in Figure 2, the ropes are separated by a gap of 3 µm at their base. Performing growth technique on device is still in progress.

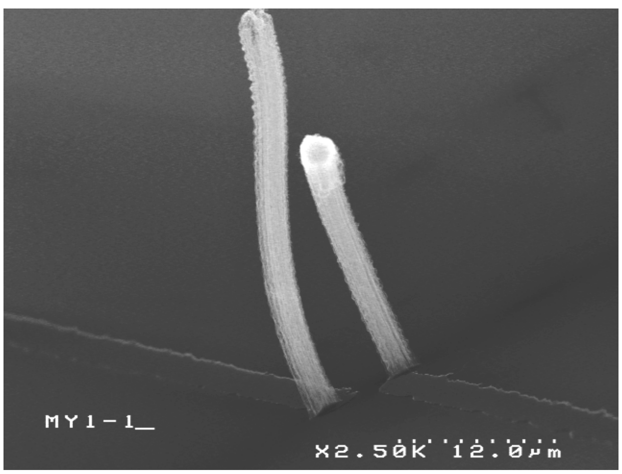

Figure 2: SEM image of tweezers made by vertically aligned CNT ropes at the end of patterned electrodes

3 ELECTROMECHANICAL TWEEZERS MODELING

In this section we study the electromechanical behavior of CNT rope and calculate the pull-in voltage of CNT rope tweezers.

3.1 Principle of operation

The potential difference between the CNT rope tweezers arms produces an attractive electrostatic force that can overcome the elastic restoring force of the CNT rope and induces the deflection of the ropes. For an applied voltage, an equilibrium position of the two arms is defined by the balance of the electrostatic, elastic and van der Waals forces. Pull in occurs when the applied voltage rises above a voltage threshold corresponding to the unbalance state of the system. Then, the rope could find no equilibrium position except going to the contact. When the applied voltage is removed two situations would be possible. The nanotube would remain stuck to the ground plane if the attractive van der Waals force between the nanotube and the ground plane is larger than the elastic force of the nanotube. Otherwise, the nanotube should return to its initial position. For pull-in analysis, we neglected van der Waals forces due to the gap range of tweezers. But for pull-out analysis these forces must be considered.

For a first hypothesis, we considered that the mechanical behavior of the CNT rope can be approximated by continuum mechanics models. The strong electromechanical coupling is governed by the equation of Euler-Bernoulli presented below:

$$E_R I_R \frac{d^4 w}{dx^4} = q_{elec} \tag{1}$$

In eq.(1), w represents the rope deflection, x the position along the rope length, E_r the average Young's modulus of the CNT rope, I_r the moment of inertia of the CNT rope and q_{elec} the electrostatic force per unit length. The electrostatic force per unit length exerted on an infinitely long cylindrical tube suspended over a ground plane is given by the eq.(2),

$$q_{elec} = \frac{\pi \varepsilon_0 V^2}{\sqrt{r(r+2R)}a\,cosh^2\left(1+\frac{r}{R}\right)} \tag{2}$$

where V is the applied voltage, r is the gap between the tube and the ground plane, R is the radius of the tube or the rope.

3.2 Mechanical behavior of CNT rope

We assume that ropes are cylindrical with an estimated diameter of 3µm and a length of 35 µm and are composed by CNTs of a typical diameter of 5 nm. The CNT rope density, n, obtained by SEM observation of CNT on a full sheet is approximated by 5.10^{14} CNTs/m². The CNTs ropes cannot be simply taken as an assembly of free tubes; rather, the ensemble of tubes must be considered as one anisotropic beam [4]. We have used homogenisation models to determine the Young's modulus of the rope E_R.

$$E_R = n.A_t.E_{CNT} \tag{3}$$

where n is the rope density and A_t the cross-section area of a nanotube and E_{CNT} the Young's modulus of individual CNT.

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SEM observations showed that synthesized MWCNT by our CVD technique present defects in their structures which should induce a decrease in CNT Young's modulus [5], thus we estimated its value to $E_{CNT} = 0.6$ TPa.
Using eq.(3), we calculated the Young's modulus of the rope $E_r = 5.8$GPa. It is clear that the stiffness of the ropes can be tuned by varying n.

To calculate the moment of inertia of the rope section we considered the moment of inertia of all the sections of CNTs inside the rope. When the rope is submitted to a bending moment, all the sections of CNTs are supposed to move around the neutral axis Δ' of the cross-section of the rope (see Figure 3). We supposed that CNTs are uniformly distributed in the ropes with an intertube distance $dz=dy$.

The moment of inertia for a circular CNT section of axis Δ_i with regard to the axis Δ', is calculated thanks to the Huygens theorem and is given by

$I_{\Delta'}(i) = I_{\Delta} + A_t.d_i^{\,2}$ where $I_{\Delta} = \dfrac{\pi R^4}{4}$ is the moment of inertia of CNT section with regard to its own axis, d_i is the distance separating the two axis Δ_i *and* Δ'.

Thus, the entire moment of inertia of the rope section can be expressed by:

$$I_{R\Delta'} = p_0.I_{\Delta} + 2\sum_{i=1}^{k} p(i).I_{\Delta'}(i) \qquad (4)$$

where p_0 is the number of CNTs along the axis Δ'. $p(i)$ is the number of CNTs along the axis Δi, this number is constant for a rectangular section but it varies with i in the case of circular section, k is the number of CNTs along the axis y in the half section of the rope.

We considered a rectangular section with an area of $l.L$. Then $p_0 = p(i) = l.\sqrt{n}$ and $k = \dfrac{L}{2}.\sqrt{n}$.

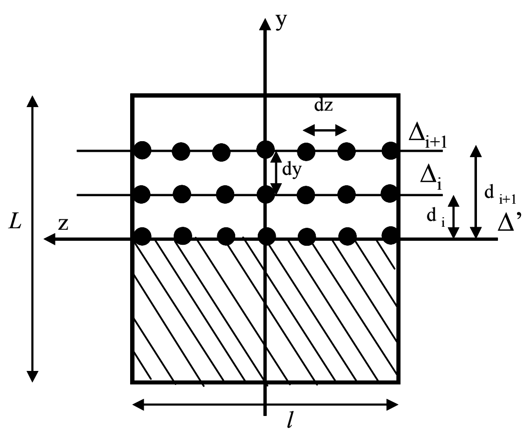

Figure 3: Rectangular cross-section of a rope composed by sections of CNTs, Δ' is the neutral axis of the rope section

For the equation (4) we calculated in the case of rectangular section an analytical form expressed by the equation (5),

$$I_R = A_t\left(\frac{l.\sqrt{n}.R^2}{4} + \frac{l.L.n.R^2}{4} + \frac{l.L^3 n}{12} + \frac{l.L^2\sqrt{n}}{4} + \frac{l.L}{6}\right) \qquad (5)$$

In the case of $R < \dfrac{L}{10}$ the equation (5) can be reduced to a simple analytical formula presented by:

$$I_R = A_t.A_R\left(\frac{L^2 n}{12} + \frac{L\sqrt{n}}{4} + \frac{1}{6}\right) \qquad (6)$$

The moment of inertia of a square section in comparison with the one for a circular section with a diameter equal to the dimension of the square section is shown in Figure 4. The difference between the two moments rises with n. Thus, we cannot approximate the circular section of a rope by a square one, so we should use eq. (4) to compute the moment of inertia.

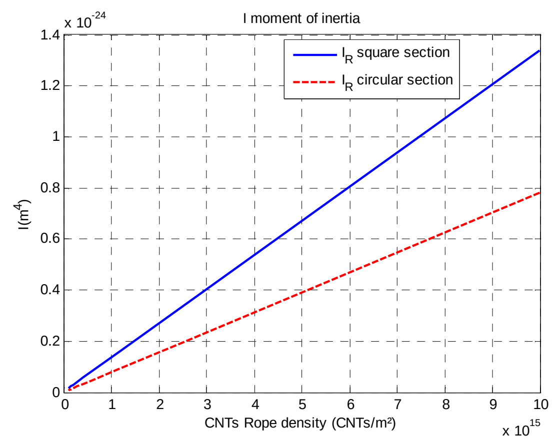

Figure 4: Curve of the moment of inertia versus rope density, n, for concentric circular and square section

3.3 Calculation of Pull-in voltage

Recently, Ke and al.[6-7] proposed analytical formulas to compute the pull-in voltage, corresponding to the approximated solutions of the nonlinear eq.1. These formulas have been obtained equating to zero the first two derivatives, related to equilibrium and instability, of the free energy of the system. Another formula has been given by Dequesnes et al. [8], where the deflected beam over a ground plane have been represented by a parallel plate configuration and approximated by a one dimensional model. We used these models and the previous calculation of E_R and I_R to compute the pull-in voltage for CNTs rope tweezers of 5 µm gap in the case of different CNT Young's modulus (see Figure 5). The dimensions of the rope are 35 µm in length and 3 µm in diameter.

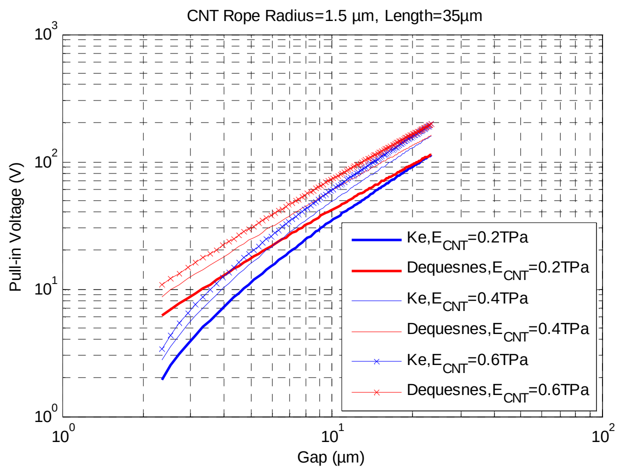

Figure 5: Pull-in voltage of CNT rope tweezers versus the gap for different E_{CNT}

4 RESULTS AND DISCUSSIONS

We conducted the electrical test on first prototypes and measured a pull-in voltage of 20 V for the tweezers cited in subsection 3.3. In comparison with the analytical calculation (see Figure 5) we can give a first estimation for the Young's modulus of CNT E_{CNT}. We notice that the model of Ke and al. consider that $R/H \ll 1$. R is the radius of the beam and H is the gap between the beam and the ground plane. In our case this approximation is not valid, thus the model of Dequesnes is more accurate. Then, if we looked to the point on Figure 5 corresponding to a gap of 5µm and a pull-in voltage of 20 V, we can find that is located between the two curves plotted by Dequesnes formula for E_{CNT} of 0.2 and 0.4 TPa. Then the estimated Young's modulus is in the range of [0.2-0.4] TPa.

5 CONCLUSION

This value of Young's modulus is not definitive; we are actually performing our devices to get a better alignment of vertical ropes in order to obtain tweezers with a well defined gap and dimensions. More electrical tests is in progress which we hope could achieve better estimation of the Young's modulus of MWCNTs and the well understanding of the electromechanical behavior of CNT rope tweezers.

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