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A Feedback Controlled Carbon Nanotube Based NEMS Device

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ABSTRACT

A switchable carbon nanotube based nano-electromechanical systems (NEMS) device with close-loop feedback is examined. The device is made of a multi-walled carbon nanotube (MWNT) placed as a cantilever over a micro-fabricated step. A bottom electrode, power supply and a resistor are also parts of the device circuit. The pull-in/pull-out and tunneling characteristics of the device are investigated by means of an electro-mechanical analysis. The model includes the concentration of electrical charge, at the end of the nanocantilever, and the *van der Waals* force. Finite kinematics accounting for large deformations of the cantilever is also included in the modeling. The result shows that the device has two well-defined stable equilibrium positions as a result of the tunneling and the incorporation of a feedback resistor to the circuit. The potential applications of the device include NEMS switches, random-access memory (RAM) elements, logic devices and electron-counters

1. INTRODUCTION

Nanoelectromechanical systems (NEMS) are attracting significant attention because of their properties to enable superior electronic components and sensors. Carbon nanotubes (CNTs) have been considered ideal building blocks for NEMS devices due to their distinguished electrical and mechanical properties. CNT-based NEMS devices reported in literature include nanotweezers,[1-2] nonvolatile random access memory (RAM),[3] nanorelays[4] and rotational actuators.[5]

In this paper, a CNT-based NEMS device with feedback control is investigated. The device, schematically shown in Fig.1, is made of a multi-walled carbon nanotube (MWNT) placed as a cantilever over a micro-fabricated step. A bottom electrode, a resistor and a power supply are parts of the device circuit. When the applied voltage $U < V_{PI}$ (*pull-in* voltage), the electrostatic force is balanced by the elastic force from the deflection of the CNT cantilever. The CNT cantilever remains in the "upper" equilibrium position. The deflection is controlled by the applied voltage. When the applied voltage exceeds a *pull-in* voltage, the system becomes unstable. With any increase in the applied voltage U, the electrostatic force becomes larger than the elastic force and the CNT accelerates towards the bottom electrode. When the tip of the CNT is very close to the electrode (i.e., gap ? ~ 0.7 nm) as shown in Fig.1, substantial tunneling current passes between the tip of the CNT and the bottom electrode. Due to the existence of the resistor R in the circuit, the voltage

applied to the CNT drops, weakening the electric field. Because of the kinetic energy of the CNT, it continues to deflect downward and the tunneling current increases, weakening the electric field further. In this case, the elastic force is larger than the electrostatic force and the CNT decelerates and changes the direction of motion. This decreases the tunneling current and the electrical field recovers. If there is damping in the system, the kinetic energy of the CNT is dissipated and the CNT stays at the position where the electrostatic force is equal to the elastic force and a stable tunneling current is established in the device. This is the "lower" equilibrium position for the CNT cantilever. At this point, if the applied voltage U decreases, the CNT cantilever starts retracting. When U decreases to a certain value, called *pull-out* voltage V_{PO}, the CNT cantilever is released from its lower equilibrium position and returns back to its upper equilibrium position. At the same time, the current in the device diminishes substantially. Basically the *pull-in* and *pull-out* processes follow a hysteretic loop for the applied voltage and the current in the device. The upper and lower equilibrium positions correspond to "ON" and "OFF" states of a switch, respectively. Also the existence of the tunneling current and feedback resistor make the "lower" equilibrium states very robust, which is key to some applications of interest.

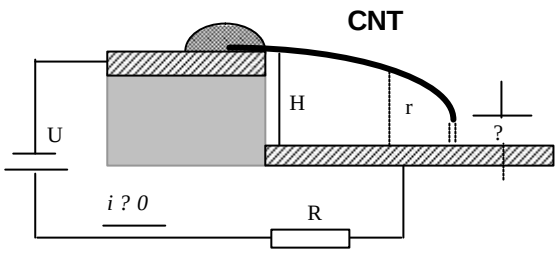

Figure 1. Schematic of CNT based device with tunneling contacts. H is the initial step height, r is the distance between the axis of the cylinder and the substrate, and ? is the gap between the deflected tip and bottom conductive substrate. R is the feedback resistor.

2. MODELING

A quantification of the phenomenon previously described is made here by means of electro-mechanical modeling of the device. The carbon nanotube considered here is a homogeneous, perfect conductor of length L, with outer and inner radii R_{ext} and R_{int}, respectively.

The capacitance per unit length along the nanotube cantilever can be approximated as[6]

$$C = C_d(r)\left\{1 + 0.85\left[(H + R_{ext})^2 R_{ext}\right]^{1/3}\delta(z - L)\right\} = C_d(r)\left(1 + f_c\right) \qquad (1)$$

where the first term in the bracket accounts for the uniform charge along the side surface of the tube and the second term, f_c, accounts for the concentrated charge at the end of the tube. d(z) is the Dirac distribution function and z *is* the axial coordinate of the nanotube. $C_d(r)$ is the distributed capacitance along the side surface per unit length for an infinitely long tube, which is given by[7]

$$C_d(r) = \frac{2\pi\varepsilon_0}{\cosh^{-1}(r/R_{ext})} \tag{2}$$

where r is the distance between the axis of the cylinder and the substrate, and ε_0 is the permittivity of vacuum ($\varepsilon_0 = 8.854 \times 10^{-12}\ C^2N^{-1}m^{-2}$).

Considering the cantilever under small deformation, the electrostatic force per unit length is given by

$$q_{elec} = \frac{1}{2}V^2\left(\frac{dC_d}{dr}\right)\{1+f_c\} \tag{3}$$

The *upper equilibrium* equation for the CNT cantilever, based on a continuum model, is given by,

$$EI\frac{d^4w}{dz^4} = q_{elec} + q_{vdw} \tag{4}$$

where E is the Young's modulus of CNT and *w* is the deflection. I is the moment of inertia of the nanotube cross-section, i.e., $I = \pi(R_{ext}^4 - R_{int}^4)/4$. q_{vdw} is the *van der Waals* force (per unit length) between the nanotube and the substrate and can be evaluated using the method reported by Dequesnes et al.,[8] assuming that the substrate consists of 30 graphite layers.

For cantilever with large deformation, finite kinematics needs to be considered as the governing equation for equilibrium should be rewritten as

$$EI\frac{d^2}{dx^2}\left(\frac{\frac{d^2w}{dx^2}}{\left[1+\left(\frac{dw}{dx}\right)^2\right]^{\frac{3}{2}}}\right) = (q_{elec} + q_{vdw})\sqrt{1+\left(\frac{dw}{dx}\right)^2} \tag{5}$$

where q_{elec} and q_{vdw} are the same as in Eq. (4).

Numerical integration of Eq. (4) or (5) provides the tip deflection, as a function of applied voltage, as well as the *pull-in* voltage.

In regard to the *pull-in* voltage, an analytically derived formula based on energy method has been reported recently, without considering the *van der Waal* force, as [9]

$$V_{PI} \approx k\sqrt{\frac{1+K^{FK}}{1+K^{TIP}}}\frac{H}{L^2}\ln\left(\frac{2H}{R_{ext}}\right)\sqrt{\frac{EI}{\varepsilon_0}}$$

$$k \approx 0.85\,;\ K^{FK} \approx \frac{4H^2}{9L^2},\ K^{TIP} \approx \frac{2.55\left(R_{ext}H^2\right)^{\frac{1}{3}}}{L} \qquad (6)$$

Here superscript FK and TIP refer to finite kinematics and concentrated charge at the tip of nanotube, respectively. This analytical formula for *pull-in* voltage shows good agreement with the results by numerically solving Eq. (4) or (5), thus provides an efficient way to assess the *pull-in* voltage based on geometry of the device.

To examine the *lower equilibrium configuration*, the current flow in the system needs to be included. The resistance of the tunneling contact between the tip of the nanotube and the bottom electrode can be described as $R_T[\Delta] = R_0 \exp(\Delta/\lambda)$.[10] Here R_0 is the contact resistance between the nanotube and the bottom electrode. ? is a material constant defined by ?$^{-1}$ = $1.02\sqrt{\Phi(eV)}\,\mathring{A}^{-1}$, with F being the work function (for MWNT F ~ 5.0 eV).[11] Hence, ?$^{-1}$ ~ 2.28 Å^{-1}, which implies that the contact resistance increases by nearly one order of magnitude for every 1 Å increase of the gap size.

When the gap between the free end of the CNT and the substrate becomes very small (e.g., ? ~ 0.7 nm), a tunneling current is established in the device. Since in our approach the resitance of the CNT itself and the contact resitance between the CNT and electrode are negligible compared with the feedback resistor in the circuit, so the potential along the CNT is considered to be constant and the relation between the voltage drop V across the gap and the gap size ? can be described as:

$$\frac{V}{U}\frac{R}{R_0}\exp(-\Delta/\lambda) = 1 - \frac{V}{U} \qquad (7)$$

The corresponding tunneling current is $i = \frac{V}{R_0}\exp(-\Delta/\lambda)$. From Eq. (7), we can see that the voltage drop across the gap, V, is not only dependent on gap size, but also dependent on the feedback resistance R.

By solving Eqs. (5) and (7) simultaneously, the voltage-gap relation for the "lower" equilibrium position is obtained.

3. RESULT AND DISCUSSION

In regard to the selection of the device geometry, we consider current available techniques for positioning carbon nanotubes, such as nanomanipulation,[12-13] CVD selective growth[14] and DC/AC dielectrophoretic trapping.[15-16] An initial step height H in the range of 100 nm ~ 1.5 μm seems realistic and consistent with demonstrated experimental techniques. For an examination of the device performance, we used the following paramters: multiwall CNT with E = 1.2 TPa, R_{int} = 6 nm and 10 layers (intra-layer distance is assumed 0.335 nm), L = 500 nm and H = 100 nm. Resistances R_0 = 1 KΩ and R = 1GΩ are also employed. By numerically solving Eqs. (5) and (7) using integration method,[17] we identify a *pull-in* voltage V_{PI} = 22.80 volts and a *pull-out* voltage V_{PO}= 2.77 volts. Fig. 2 shows

the plots of the ?–U and *i*-U characteristic signatures. It is clearly seen that there is a hysteresis loop on each of the two characteristic curves shown in Fig. 2, which describes the "lower" and "upper" equlibrium stable positions and the *pull-in* and *pull-out* processes. The hysteresis loop can be controlled by appropriate selection of geomertic and electric parameters. This hysteretic behavior can be exploited to build NEMS switches or random access memory (RAM) elements operating at GHz frequencies.

The simulation result shows that the *van der Waals* (*vdw*) force is important in the design and optimization of the device. As expected, the *vdw* force becomes substantial when the deflected tip almost touches the substrate. If the *vdw* force is large enough to balance the elastic force, "stiction" occurs, which means that the nanotube cantilever will be held at the "lower" stable equilibrium position. For example, for the device considered above, if the length of the nanotube increases to 1 µm, "stiction" will take place. For some applications, this effect could be desirable, while for others such as switches in memory elements, it should be avoided.

In order to assess the effect of thermal vibrations on the device performance, the vibration of the nanotube is approximated by the model reported by Treacy, et al..[18] For the nanotube cantilever with the above-considered parameters, the vibration amplitude is evaluated to be 1.86 Å at room temperature (300K) and 0.2 Å at 4.2 K. It is noted that the tunneling current will vary with temperature. However, the overall characteristics of the device will not change, i.e., the thermal effects can not switch the CNT cantilever from the "lower" equilibrium position to the "upper" equilibrium position or vice versa.

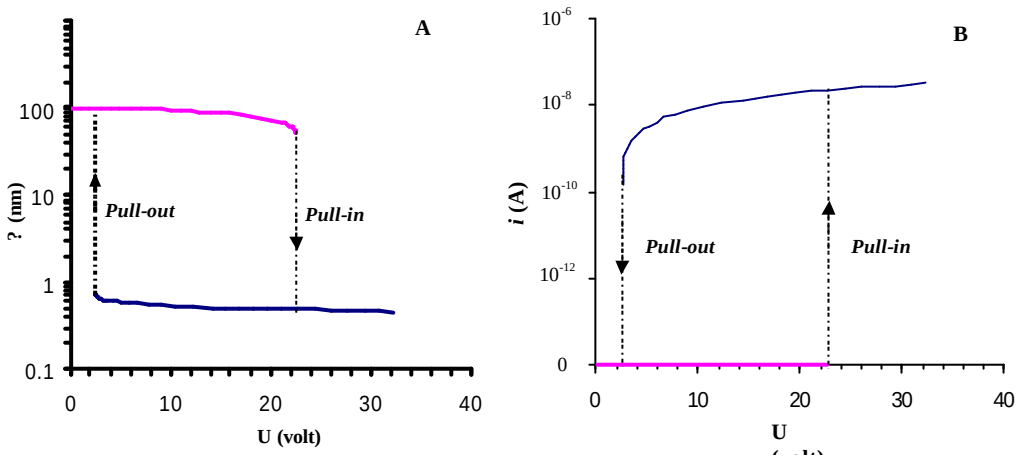

Figure 2. Characteristic of *pull-in* and *pull-out* processes for a device with R_{ext}=9.015 nm, R_{int}=6 nm, L=500 nm, H = 100 nm, R_o=1 KΩ and R = 1 GΩ. (A) shows the relation between the gap ? and the applied voltage U. (B) shows the relation between the current *i* in the circuit and the applied voltage U.

In summary, in this paper, an innovative feedback-controlled switchable CNT-based NEMS device is proposed. Although the discussion is based on CNT cantilevers, other possibilities include doped Si nanowires and other materials, which could be more easily integrated to current microelectronics technology. The electrical-mechanical characteristics of the device were examined, and some key issues in its design were highlighted. Future

work would focus on the micro/nanofabrication of the device and its dynamic analysis. Potential applications for the device include: NEMS switches, non-volatile random access memory (RAM) elements, electron counters, logic devices and gap sensing devices

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