Feedback controlled nanocantilever device

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A switchable carbon-nanotube-based nanoelectromechanical systems (NEMS) with close-loop feedback is examined. The device consists of a cantilever carbon nanotube clamped to a top electrode and actuated by a bottom electrode. The actuation circuit includes a source and a feedback resistor. The *pull-in/pull-out* and tunneling characteristics of the system are investigated by means of an electromechanical analysis. The model includes the concentration of electrical charge, at the end of the nanocantilever, and the *van der Waals* force. The analysis shows that the device has two well-defined stable equilibrium positions as a result of tunneling and the incorporation of a feedback resistor to the circuit. Potential applications of the device include NEMS switches, random-access memory elements, logic devices, electron counters, and gap sensing devices. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1767606]

Nanoelectromechanical systems (NEMS) are attracting significant attention because of their properties to enable superior electronic components and sensors. By exploiting nanoscale effects, NEMS present interesting and unique characteristics. For instance, NEMS-based devices can have an extremely high fundamental frequency[1–4] and preserve very high mechanical responsivity.[5] Several NEMS devices have been reported, such as mass sensors,[6] RF resonators,[6] field-effect transistors,[7] and electrometers.[8] Carbon nanotubes (CNTs) have long been considered ideal building blocks for NEMS devices due to their superior electrical and mechanical properties. CNT-based NEMS devices reported in literature include nanotweezers,[9,10] nonvolatile random access memory elements,[11] nanorelays,[12] and rotational actuators.[13]

In this letter, a CNT-based NEMS device with feedback control is investigated. The device, schematically shown in Fig. 1, is made of a multiwalled carbon nanotube (MWNT) placed as a cantilever over a microfabricated 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 $\Delta \approx 0.7$ 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 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.

A quantification of the phenomenon previously described is made here by means of electromechanical 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 can be approximated as[14]

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

where the first term in the bracket accounts for the uniform charge along the side surface of the tube and the second term

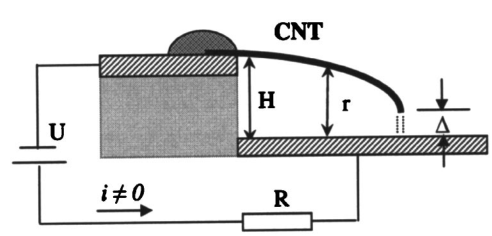

FIG. 1. Schematic of CNT based device with tunneling contacts. H is the initial step height and Δ is the gap between the deflected tip and bottom conductive substrate. R is the feedback resistor.

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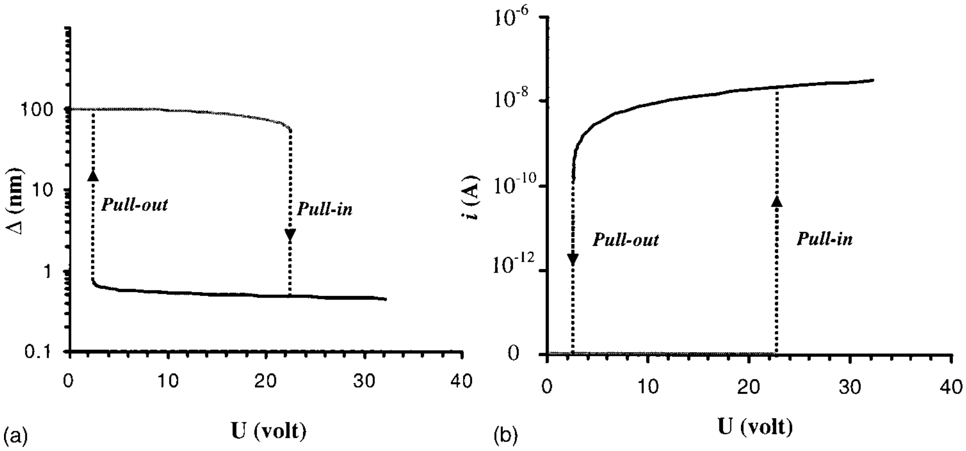

FIG. 2. Characteristic of *pull-in* and *pull-out* processes for a device with $R_{\mathrm{ext}}=9.015$ nm, $R_{\mathrm{int}}=6$ nm, $L=500$ nm, $H=100$ nm, $R_0=1$ KΩ, and $R=1$ GΩ. (a) shows the relation between the gap Δ and the applied voltage U. (b) shows the relation between the current i in the circuit and the applied voltage U.

accounts for the concentrated charge at the end of the tube. $\delta(z)$ 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[15]

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

where r is the distance between the axis of the cylinder and the substrate, and ε_0 is the permittivity of vacuum ($\varepsilon_0=8.854\times10^{-12}$ C^2 N^{-1} m^{-2}).

Thus, the electrostatic force per unit length is given by[16]

$$q_{\mathrm{elec}}=\frac{1}{2}V^2\left(\frac{dC_d}{dr}\right)\{1+0.85[(H+R_{\mathrm{ext}})^2R_{\mathrm{ext}}]^{1/3}\delta(z-L)\}. \tag{3}$$

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

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

where E is the CNT Young's modulus and w is the deflection. I is the moment of inertia of the nanotube crossection, i.e., $I=\pi(R_{\mathrm{ext}}^4-R_{\mathrm{int}}^4)/4$. 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 originally by Reuckes *et al.*[11] and later employed by Dequesnes *et al.*,[17] assuming that the substrate consists of 30 graphite layers.

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

To examine the *lower equilibrium configuration*, the current flow in the system needs to be included. The resistance of the tunneling contact between of the nanotube and the bottom electrode can be described as $R_T[\Delta]=R_0\exp(\Delta/\lambda)$.[3] Here R_0 is the contact resistance between the nanotube and the bottom electrode and can be evaluted from experimental results.[18] λ is a material constant defined by $\lambda^{-1}=1.02\sqrt{\Phi(\mathrm{eV})}$Å^{-1}, with Φ being the work function (for MWNT $\Phi\approx5.0$ eV).[19] Hence, $\lambda^{-1}\approx2.28$ 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 carbon nanotube and the substrate becomes very small (e.g., $\Delta\approx0.7$ nm), a tunneling current is established in the device. In regard to the electron transport inside the MWNT, both ballistic[20] and diffusive[21–24] results have been reported and the difference is infered to be related to the preparation of the sample and measurement techniques.[21] In the analysis of our device, we regard the resistance of the nanotube R_{cnt} as part of the feedback resistance R in the circuit. In our approach, $R_{\mathrm{cnt}}\ll R$, thus, the change in the electrostatic force along the nanotube due to the voltage drop on the nanotube itself is neglected. In the model, we assume the potential along the nanotube is constant, and that the voltage drop takes place at the tunneling gap and feedback resistor R only.[25] The relation between the voltage drop V across the gap and the gap size Δ can be described as

$$\frac{V}{U}\frac{R}{R_0}\exp(-\Delta/\lambda)=1-\frac{V}{U}. \tag{5}$$

The corresponding tunneling current is $i=(V/R_0)\exp(-\Delta/\lambda)$. From Eq. (5), 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. (4) and (5) simultaneously, the voltage-gap relation for the lower equilibrium position is obtained.

In regard to the selection of the device geometry, we consider current available techniques for positioning carbon nanotubes, such as nanomanipulation,[26,27] Chemical vapor disposition selective growth[28] and dc/ac dielectrophoretic trapping.[29,30] 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 $E=1.2$ T Pa, $R_{\mathrm{int}}=6$ nm and ten layers (intralayer distance is assumed 0.335 nm), $L=500$ nm and $H=100$ nm. Resistances $R_0=1$ K Ω and $R=1$ G Ω are also employed. By numerically solving Eqs. (4) and (5) using integration method,[31] we identify a *pull-in* voltage $V_{\mathrm{PI}}=22.48$ V and a *pull-out* voltage $V_{\mathrm{PO}}=2.57$ V. Figure 2 shows the plots of the $\Delta-U$ 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 elements operating at gigahertz 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.

The function of the resistor R in the device is to adjust the voltage applied to the carbon nanotube, V, as a function of its configuration. When there is tunneling, $V \leqslant U$. From Eq. (5), it is clear that R has to satisfy the following relation in order to result in a device with a hysteretic characteristic, namely:

$$R \geqslant \frac{V_{\mathrm{PI}} - V}{V} R_0 \exp(\Delta/\lambda), \quad (6)$$

where V and Δ are obtained by solving Eq. (4).

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.*[32] According to this model, the CNT tip vibration amplitude is $A = \sqrt{0.4243[L^3 kT/E(R_{\mathrm{ext}}^4 - R_{\mathrm{int}}^4)]}$, where k is the Boltzmann's constant $(1.38 \times 10^{-23}\ \mathrm{J/K})$ and T is the temperature in degrees Kelvin. For the nanocantilever with the earlier-considered parameters, this equation gives a vibration amplitude of 1.86 Å at room temperature (300 K) 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.

In summary, in this letter, a 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, nonvolatile random access memory elements, electron counters, logic devices, and gap sensing devices.

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[1]Y. T. Yang, K. L. Ekinci, X. M. H. Huang, L. M. Schiavone, M. L. Roukes, C. A. Zorman, and M. Mehregany, Appl. Phys. Lett. **78**, 162 (2001).
[2]A. N. Cleland and M. L. Roukes, Appl. Phys. Lett. **69**, 2653 (1996).
[3]A. Erbe, R. H. Blick, A. Tilke, A. Kriele, and P. Kotthaus, Appl. Phys. Lett. **73**, 3751 (1998).
[4]X. M. H Huang, C. A. Zorman, M. Mehregany, and M. L. Roukes, Nature (London) **421**, 496 (2003).
[5]M. L. Roukes, "Nanoelectromechanical system," Technical Digest of the 2000 Solid-State Sensor and Actuator Workshop, 2000.
[6]G. Abadal, Z. J. Davis, B. Helbo, X. Borrise, R. Ruiz, A. Boisen, F. Campabadal, J. Esteve, E. Figueras, F. Perez-Murano, and N. Barniol, Nanotechnology **12**, 100 (2001).
[7]R. Martel, T. Schmidt, H. R. Shea, T. Hertel, and Ph. Avouris, Appl. Phys. Lett. **73**, 2447 (1998).
[8]A. N. Cleland and M. L. Roukes, Nature (London) **392**, 160 (1998).
[9]S. Akita, Y. Nakayama, S. Mizooka, Y. Takano, T. Okawa, Y. Miyatake, S. Yamanaka, M. Tsuji, and T. Nosaka, Appl. Phys. Lett. **79**, 1691 (2001).
[10]P. Kim and C. M. Lieber, Science **126**, 2148 (1999).
[11]T. Rueckes, K. Kim, E. Joslevich, G. Y. Tseng, C. Cheung, and C. M. Lieber, Science **289**, 94 (2000).
[12]J. Kinaret, T. Nord, and S. Viefers, Appl. Phys. Lett. **82**, 1287 (2002).
[13]A. M. Fennimore, T. D. Yuzvlnsky, W. Q. Han, M. S. Fuhrer, J. Cummings, and A. Zettl, Nature (London) **424**, 408 (2003).
[14]C. Ke and H. D. Espinosa (unpublished).
[15]W. Hayt and J. Buck, *Engineering Electromagnetics*, 6th ed. (McGraw-Hill, New York, 2001).
[16]Here we consider the deflection of the carbon nanotube cantilever to be small and linear. Thus, the electrostatic force can be approximated by its vertical components. A more accurate modeling, including finite kinematics to account for large deformations and the horizontal component of the electrostatic force, will be reported in a future publication.
[17]M. Dequesnes, S. V. Rotkin, and N. R. Aluru, Nanotechnology **13**, 120 (2002).
[18]R. Tarkiainen, M. Ahlskog, J. Penttila, L. Roschier, P. Hakonen, M. Paalanen, and E. Sonin, Phys. Rev. B **64**, 195412 (2001).
[19]J. Sun, Z. X. Zhang, S. M. Hou, G. M. Zhang, Z. N. Gu, X. Y. Zhao, W. M. Liu, and Z. Q. Zue, Appl. Phys. A: Mater. Sci. Process. **75**, 479 (2002).
[20]S. Frank, P. Poncharal, P. Wang, and W. A. Heer, Science **280**, 1744 (1998).
[21]A Bachtold, M. S. Fuhrer, S. Plyasunov, M. Forero, E. H. Anderson, A. Zettl, and P. L McEuen, Phys. Rev. Lett. **84**, 6082 (2000).
[22]A. Bachtold, C. Strunk, J. P. Salvetat, J. M. Bonard, L. Forro, T. Nussbaumer, and C. Schönenberger, Nature (London) **397**, 673 (1999).
[23]C. Schönenberger, A. Bachtold, C. Strunk, J. P. Salvetat, and L. Forro, Appl. Phys. A: Mater. Sci. Process. **69**, 283 (1999)
[24]P. L. McEuen, M. Bockrath, D. H. Cobden, Y. G. Yoon, and S. G. Louie, Phys. Rev. Lett. **83**, 5098 (1999).
[25]The resistance of nanotube itself $(\sim \mathrm{M}\Omega)$ and the contact resistance between the nanotube and the upper electrode $(\sim \mathrm{K}\Omega)$ are several orders of magnitude smaller compared to the feedback resistor $R(\sim \mathrm{G}\ \Omega)$. Thus, for large gaps (i.e., $\Delta > 0.7$ nm), the votlage drop will occur mostly on the gap. For small gaps, (i.e., $\Delta < 0.5$ nm) most of the voltage drop will take place on the feedback resistor.
[26]P. A. Williams, S. J. Papadakis, and M. R. Falvo, Appl. Phys. Lett. **80**, 2574 (2002).
[27]M. F. Yu, O. Lourie, M. J. Dyer, K. Moloni, T. F. Kelly, and R. S. Ruoff, Science **287**, 637 (2000).
[28]Y. G. Zhang, A. Chang, J. Cao, Q. Wang, W. Kim, Y. M. Li, N. Morris, E. Yenilmez, J. Kong, and H. J. Dai, Appl. Phys. Lett. **79**, 3155 (2001).
[29]K. Yamamoto, S. Akita, and Y. Nakayama, J. Phys. D **31**, L34 (1998).
[30]A. Bezryadin and C. Dekker, Appl. Phys. Lett. **71**, 1273 (1997).
[31]D. G. Fertis, *Nonlinear Mechanics*, 2nd ed. (CRC Press, Cleveland, 1999).
[32]M. M. J. Treacy, T. W. Ebbesen, and J. M. Gilbson, Nature (London) **381**, 678 (1996).