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A Nano-Tuneable Pressure Switch System Design Based on Single Wall Carbon Nanotubes

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Abstract: Under hydrostatic pressure, the cross section of a Single Wall Carbon Nanotube (SWNT) reduces uniformly and proportionally to the applied pressure until it reaches to SWNT's first transition pressure. In addition, SWNT kinks, becomes unstable and collapses on a ground plane due to bending loads. This phenomenon is a function of SWNT diameter. Bending loads can be generated by inducing a voltage between SWNT and a conductive ground plane. Therefore, by inducing a certain Pull-in voltage relative to a certain diameter (pressure), SWNT does not collapse until the applied pressure reaches to a certain amount which causes a certain SWNT diameter reduction. In this case, because of SWNT collapse on the ground plane, there will be a connection between them closing an electric circuit. In this study, these characteristics are employed to introduce a tuneable pressure switch. This type of pressure switch, in comparison to previous presented one, uses only one SWNT for switching, is able to sense pressure with higher resolution and has a much simpler system.

Key words: Single wall carbon nanotube, pull-in voltage, electrostatic bending forces, kink, phase transition, transient pressure

INTRODUCTION

Single Wall Carbon Nanotubes (SWNTs) has novel mechanical properties and behaviors which have attracted many considerations and studies recently. Under hydrostatic Pressure, SWNT's cross section is reduced uniformly and proportionally to applied pressure, until it reaches SWNT's first transient pressure. In this case the SWNT physical properties change and its cross section becomes elliptical. This characteristic has been used in previous presented nano pressure sensors by Wu *et al.* (2004), consisting an array of SWNTs with different diameters. When applied pressure reaches to one of the SWNT's transition pressure, its cross section shape changes, turning SWNT into a semi-conductive material. The pressure sensing system has the ability to sense the change of SWNT from a conductive material to a semi conductive substance for switching. Therefore, in this way, pressure sensor needs a number of SWNTs. However, the number of used SWNTs is restricted because Gao *et al.* (1998) showed when SWNT diameter exceeds a limit, its natural shape is collapsed form. Thus, it is impossible to use them in this system. Consequently, the pressure sensor only is able to sense restricted number of pressures (SWNTs' transition pressures) (Fig. 1 and 2).

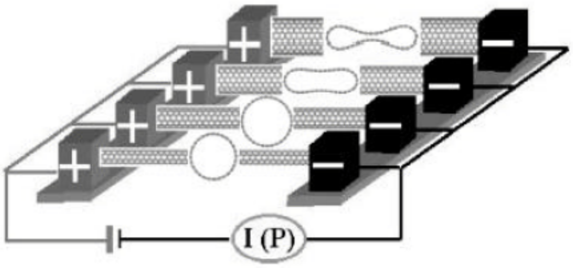

Fig. 1: The schematic of the pressure switch mechanism peoposed by Wu *et al.* (2004)

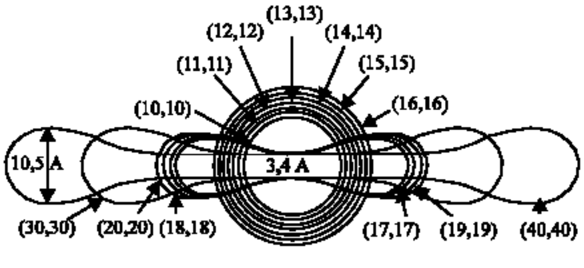

Fig. 2: As SWNT's diameter exceeds a limit its stable shape is collapsed form

To overcome the pressure sensing range restriction of the previous introduced switch, in this study, a

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tuneable pressure switch system has been introduced which can switches with higher resolution using much simpler system. It consists of a fixed ends SWNT and a graphite ground plane which are conductive. When various Pull-in voltages are induced, SWNT collapses on the ground plane only if the relative hydrostatic pressures are applied. The upper bound of pressure sensing range of this switch is the first SWNT's transition pressure. To understand the mechanism of the switch on which the design is based, SWNT transition pressure and pull-in phenomenon are illuminated in the following sections.

TRANSITION PRESSURE

Zang *et al*. (2004), Sun *et al*. (2004) and Sood (2004) showed that SWNTs under applied hydrostatic pressure encounter phase transition. This phase transition is due to difference between energy which is needed to alter Carbon-Carbon bond length and Carbon-Carbon-Carbon angle. At first stage, the SWNT cross section reduces uniformly and proportionally under pressure, which is the result of Carbon-Carbon bond uniform length reduction. At a certain point, the cross section shape collapses from circular to elliptical. In this case, the SWNT deformation is much larger than previous.

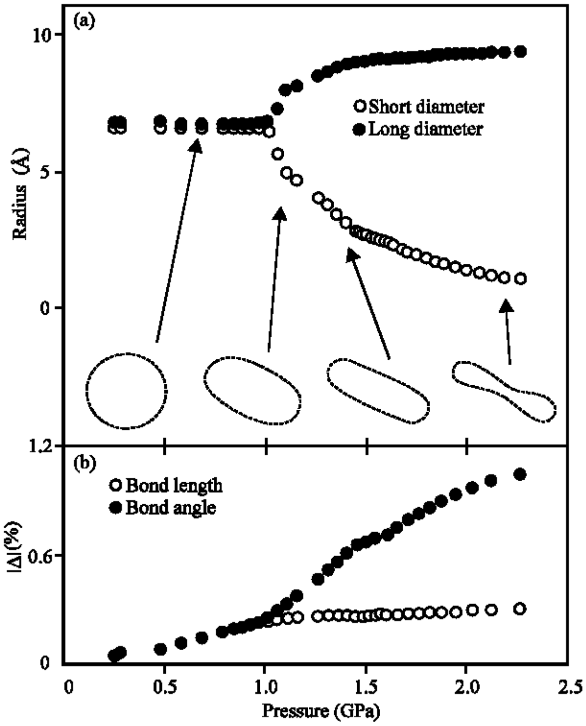

Fig. 3: Cross section, bond length and bond angle deformations of a typical SWCNT under hydrostatic pressure

The reason is;
Carbon-Carbon-Carbon angle variation needs much less energy in comparison to Carbon-Carbon bond length variation. Thus, SWNT undergoes a greater deformation after facing pressures higher than its first transition pressure. As a result, the isotropic SWNT turns into an anisotropic SWNT which is semi-conductive substance. The first SWNT transition pressure is obtained by (Fig. 3):

$$P_{t1} = \frac{3D}{R_0^3} \tag{1}$$

Where R_0 is SWNT initial radius and D is SWNT elastic constant. For SWNTs, D = 0.76 eV which is obtained by Molecular Dynamics. In consequence, the dimension of

P_{t1} is: $\frac{\text{Energy}}{\text{Volume}} = \frac{\text{Force} \times \text{Length}}{\text{Length}^3} = \frac{\text{Force}}{\text{Area}} = \text{Pressure}$

PULL-IN PHENOMENON

Dequensnes *et al*. (2004) has demonstrated when a voltage is induced between a SWNT and a conductive ground plane, due to generated electrostatic bending forces, the SWNT deflects. When the deflection reaches to a certain amount, SWNT becomes unstable and collapses. This phenomenon is called Pull-in and the relative voltage, Pull-in voltage. The applied electrostatic force per length is found by classic capacitance model as:

$$q_{ele} = -\frac{\pi\varepsilon_0 V^2}{R_{NT}\sqrt{\frac{r(r+2R_{NT})}{R_{NT}^2}}\log^2\left[1+\frac{r}{R_{NT}}+\sqrt{\frac{r(r+2R_{NT})}{R_{NT}^2}}\right]} \tag{2}$$

Where ε_0 is vacuum permittivity, V is induced voltage, R_{NT} is SWNT radius and r is SWNT and ground plane distance.

Wang and Varadan (2005) proved that this instability is because of SWNT kink under bending conditions, which has been observed by high resolution transmission electron microscopes too. It is assumed that kink will occur, when the strain energy at the inner wall of the compressive side reaches the critical value. Since stress and strain follow a linear distribution in radial direction, it is reasonable to assume that kink instability happens when compressive strain reaches twice the critical in-plane strain under uniformly distributed compression. The kink slope being a function of d_{NT} can be found by:

$$\theta_{cr} = \frac{L}{4(d_{NT}-h)}.\left(\frac{\pi.d_{NT}}{L}\right)^2 \tag{3}$$

That L is SWNT length, d_{NT}, is its diameter and h is SWNT effective thickness.

DEFINITION OF TUNEABLE PRESSURE SWITCH

By combining the above mentioned concepts about Pull-in phenomenon and transition pressure of SWNTs, the tuneable pressure switch mechanism can be defined. As it can be seen, from Eq. 3, the θ_{cr} is a function of SWNT diameter. While a hydrostatic pressure is applied on SWNT, its diameter reduces uniformly and proportionally to the applied pressure:

$$d_{NT} = d_{NT0}\left(1 - \frac{P.d_{NT0}}{2E.h}\right) \qquad (4)$$

Where d_{NT0} is SWNT's initial diameter (at zero pressure) and E is its effective young Modulus (Fig. 4).

Therefore, for any applied hydrostatic pressure (thus its relative diameter); there is a significant kink angle (Fig. 5).

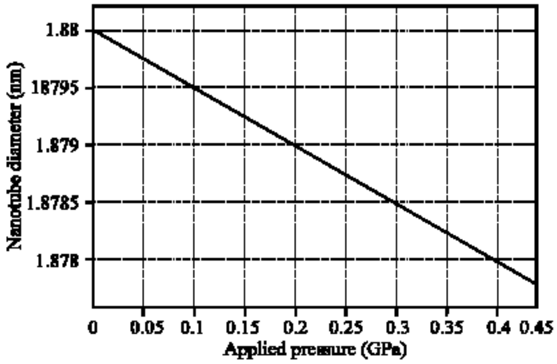

Fig. 4: SWNT diameter variation with respect to applied hydrostatic pressure

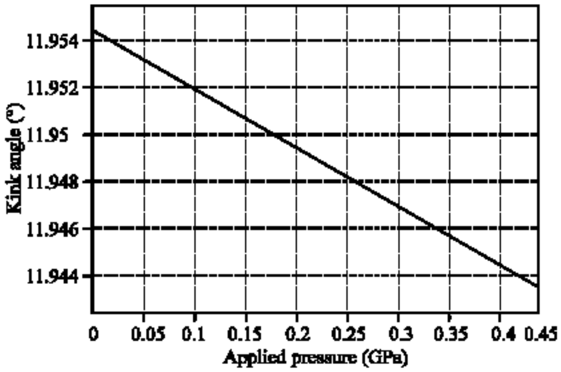

Fig. 5: Kink angle variation with respect to pressure for a typical SWNT

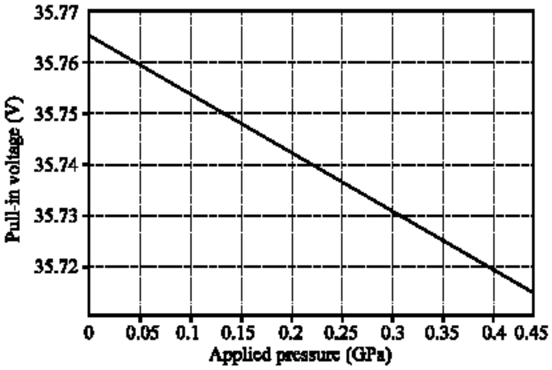

Fig. 6: Pull-in voltage versus applied hydrostatic pressure

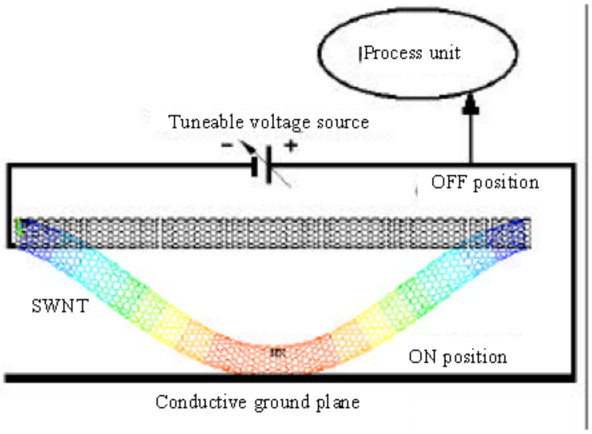

Fig. 7: The schematic of suggested pressure switch mechanism

To calculate the Pull-in voltage, elastic and electrostatic domains should be considered. van der Waals forces are quite small in comparison to electrostatic forces; therefore, they are neglected in this study.

The system obeys the classical beam equation

$$\left(E.I\frac{d^4y}{dx^4} = q\right),$$

which is highly none-linear. Therefore, it has no analytical solution. Without losing the generality, it is possible to use lump model derived by Dequensnes *et al.* (2002) which assumes bending electrostatic force distribution is uniform before Pull-in phenomenon happens. The pull-in voltage for a lump model is calculated by:

$$V_{P-I} = \sqrt{\frac{384E_{effective}I}{L_{NT}^3}(r_{init} - r_{PI})} \times \sqrt{\left(\frac{R_{NT}\sqrt{\frac{r_{PI}(r_{PI}+2R_{NT})}{R_{NT}^2}}\log^2\left(1+\frac{r_{P-I}}{R_{NT}}+\frac{r_{PI}(r_{PI}+2R_{NT})}{R_{NT}^2}\right)}{\pi\varepsilon_0 L_{NT}}\right)} \qquad (5)$$

That r_{init} is the initial distance between SWNT and ground plane and $r_{pl} = 2r_{init}/3$ is the distance which Pull-in happens.

By considering R_{NT} as a function of applied pressure, the relation between Pull-in voltage and applied pressure is obtained (Fig. 6).

In consequence, the mechanism of suggested pressure switch consists of a both end fixed SWNT, a conductive ground plane and a tuneable voltage source to induce voltage between the SWNT and the ground plane (Fig. 7).

CONCLUSIONS

In summary, a tuneable pressure switch has been obtained which uses only one SWNT and its mechanism run as following:

When a Pull-in voltage related to a certain pressure is induced to the system, the SWNT does not kink and does not collapse on the ground plane, until the applied pressure reaches to that certain amount. When due to the application of pressure and voltage, SWNT collapses on the ground plane, because both of them are conductive, an electric circuit is closed and the switch is considered ON. As a result, its sensing and switching mechanism is much simpler in comparison to previous presented pressure sensor because a complicated system which is able to sense the difference between a conductive and semi conductive material is eliminated. The recent system, also, is able to switch at any desired pressure which is obtainable by its resolution within its sensing range (Its pressure sensing range is between zero and used SWNT the first transition pressure). Hence, it is not restricted to few pressures of limited numbers of SWNT's transition pressures. The resolution of voltage inducement, determines the resolution of pressure switching which is $P_t . \Delta V$.

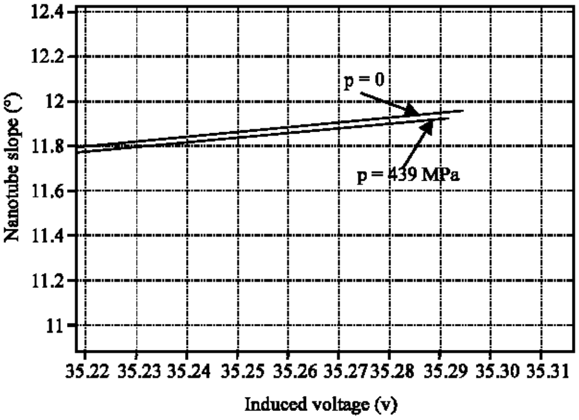

Fig. 8: A typical SWNT slopes comparison for two and cases p = 0 and P = P_t cases

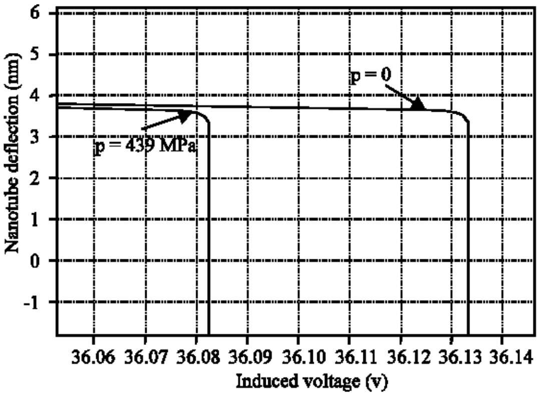

Fig. 9: A typical SWNT deflection comparison for two and cases p = 0 and P = P_t cases

Here for such a typical system, the kink and deflection graphs for two pressure conditions are brought. The SWNT effective physical properties are as followings, which was calculated by authors based on inter-atomic force field constants for Carbon lattice presented by Leamy (2005); L = 27.14 nm, d_{NT0} = 1.88 nm, r_{init} = 6 nm, h = 0.34 nm and $E_{effective}$ = 1.03 nm (Fig. 8 and 9).

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