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Frequency self-tuning of carbon nanotube resonator with application in mass sensors

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ABSTRACT

This paper presents a new model for a doubly clamped carbon nanotube (CNT) resonator to investigate the tunability of its resonant frequency under joule heating with the application in adjusting the mass detection sensitivity while it is used as the mass sensor. Taking into account the temperature dependence of resistance, temperature distribution of the CNTs with various sizes under the joule heating has been analyzed using the thermal transfer theory. Temperature profiles and induced thermal stresses of both short and long CNTs have been obtained. The axial thermal stress is then treated as the loading factor in the mechanical Euler-beam equation to calculate the resonant frequency shift. The surface effect has been considered because of the nanoscale of the CNTs. Based on the law of energy conservation and the Euler–Lagrangian equations, the dynamic model of the CNT resonator has been built. Through a systematic multiphysical simulation approach, relations between the applied electrical current and the resonant frequency, the applied electrical current and the mass detection sensitivity of the CNT resonator have been obtained. It is found that the tuning ranges from 2.575 GHz to 7.241 GHz and from 2.759 THz to 3.544 THz for the fundamental resonant frequency of both a long (5.325 μm) and a short (5.67 nm) CNT resonators are obtained respectively. With respect to the mass detection sensitivity, it is found that the mass detection sensitivity of one particular CNT resonator can be improved from 1.783 MHz/zeptogram (zg) to 5.013 MHz/zg and from 1.795 GHz/yoctogram (yg) to 2.305 GHz/yg when varying the electrical current from 0.015 μA to 0.75 μA for the added 5 zg and 5 yg mass, respectively.

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1. Introduction

CNT known for its small size, unique electrical, thermal and mechanical properties has attracted vast research interests in recent decades. In particular, CNT resonators have been widely applied to mass detection, frequency measurement and vibration detection because of their broad operating frequency ranges. As the CNTs usually have a large aspect ratio and their dimensions lie in the nanoscale, their resonant frequencies are sensitive to detect the atomic mass. Li and Chou [1] developed CNT nanobalances with the mass sensitivity at zeptogram and found a logarithmical linear relationship between the resonant frequency and the attached mass. Chiu et al. [2] achieved a mass detector that can sense atomic level mass based on the shift of the resonant frequency of the doubly clamped CNT resonator, and Li et al. [3] succeeded in sensing optical mass based on a similar method. A CNT mass sensor from one of recent publications was reported to have the resolution of 1.7 yg [4]. CNTs were also used as electrochemical sensors due to their high chemical stability and large specific surface area [5]. In addition to this, frequency tuning of the CNT resonator is crucial to realize controllable sensitivity. There have been several tuning mechanisms including gate voltage method [6], axial pre-stress method [7], spring constant and damping constant tuning [8], electrochemical tuning [9], piezoelectric strain tuning [10] and electron transport and mechanical coupling method [11]. Recently, joule heating effect of the CNT has been given increasing attention [12–17]. Huang et al. [18] have proposed a physical mechanism to interpret vacuum breakdown process of single nanotube during field emission. Pop [19] conducted experiments to investigate the electrical breakdown in air of single-wall carbon nanotubes (SWCNTs) and concluded that the heat sinking from nanotube mainly dissipated at SWCNT–substrate and at SWCNT–electrode interfaces, and Baloch et al. [12] discovered that at least 84% of the electrical power supplied to the nanotube is dissipated directly into the substrate by remote joule heating. Lassagne et al. [20] achieved the mechanical vibration detecting resolution improved to 1.4 zg by cooling down the nanotube to 5 K in a cryostat. Remtema and Lin [21] has described the concept of the active frequency tuning using localized thermal stressing effects in a microscale device. Small tuning range (~10%) has been reported using joule heating mechanism on an Al–SiC nanoresonator [22]. Frequency self-tuning of

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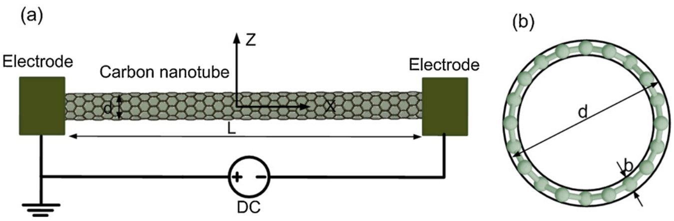

Fig. 1. Schematic of carbon nanotube resonator based on joule heating mechanism.

CNT resonators based on the joule heating is deemed interesting as it can provide an easy and cost effective way of varying the resonant frequency, which in turn could improve the mass sensitivity. The hypothesis of whether the joule heating can improve the mass sensitivity of CNT resonators is theoretically validated in this paper using the multiphysical modeling approach, which has not been reported previously.

In Section 2 of this paper, we concentrate on the heat transfer analysis of CNT resonator considering the temperature dependent heat loss rate γ, and the temperature coefficient of resistance α. Induced thermal stress of the CNT resonator is discussed in Section 3. Dynamic model considering the surface effect and improvement of the mass detection sensitivity by joule heating are discussed in Section 4. Finally the concluding remarks are made in Section 5.

2. Electro-thermal model

In this work, the SWCNT resonator is modeled as doubly clamped one dimensional beam connected with two Pd electrodes shown as Fig. 1(a). Fig. 1(b) is the transverse shape of the CNT, which can be modeled as annulus, and the whole geometry is equivalent to a cylinder obtained by rolling a graphene sheet about a vector with components (M, N). The diameter of the cylinder is d, the wall thickness is b and the length is L. In the model, the nanotube resonator is heated above the silicon nitride substrate under a DC current between two electrodes. The temperature along the carbon nanotube will rise, and thermal expansion is then induced, causing thermal stress increased inside the resonator as its both ends are mechanically constrained by Pd electrodes. The mechanical stress consequently induces the change of the resonant frequency. In this section, analysis of temperature distributions for CNT resonators is presented.

2.1. Heat transfer analysis

When the electrical current is applied to the carbon nanotube resonator, it causes resistive heating, and temperature along the CNT can be represented as a function of time and position, $T(x, t)$. Combining with the heat conduction equation, the electro-thermal model is given as

$$\rho C_p \frac{\partial T}{\partial t} - \frac{\partial}{\partial x}\left(kA\frac{\partial T}{\partial x}\right) + \gamma(T - T_0) - P' = 0 \quad (1)$$

where $p' = I^2R/L$ is the local joule heating rate per unit length, I is the electrical current, and R is the resistance. The term $\gamma(T - T_0)$ indicates the heat loss to the substrate per unit length, and γ being heat loss rate [12,23]. T_0 is the room temperature, ρ is density of carbon nanotube, C_p is the heat capacity, k denotes thermal conductivity, and A refers to the transverse area. In order to have a quantitative study, the parameters in Eq. (1) are designated as $\rho = 1350\ \mathrm{kg/m^3}$, $C_p = 10\ \mathrm{nJ/K}$, $k = 100\ \mathrm{W/(K\,m)}$, $\gamma = 0.17\ \mathrm{W/(K\,m)}$, $b = 0.066$ nm [24], $d = 0.548$ nm, $L = 5.325\ \mu$m, $T_0 = 300$ K, $R = 1370\ \mathrm{M\Omega}$, $I = 0.75\ \mu$A. Calculated using Eq. (1), the temperature response along the CNT can be obtained as Fig. 2. It can be observed from Fig. 2 that after around 0.28 ms, the temperature profile becomes stable. In this paper the focus is on the temperature distribution along the CNT under steady status. In steady state, Eq. (1) is rewritten as an ordinary differential [12,23],

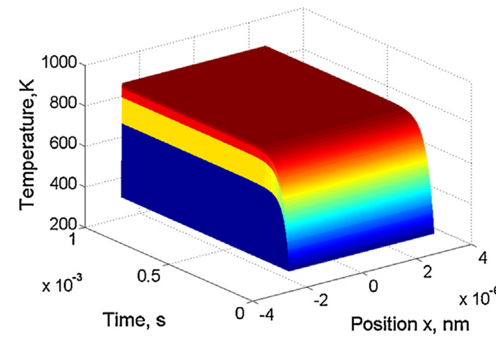

Fig. 2. Time response of the temperature profile of the CNT clamped–clamped beam by joule heating.

$$kA\frac{d^2T}{dx^2} - \gamma(T - T_0) + P' = 0 \quad (2)$$

In order to obtain the analytical solution of Eq. (2), it is assumed that k and γ are constants, and $P' = I^2R/L$ where resistance R is assumed to be linearly dependent on the temperature of the CNT [17,18],

$$R(T) = R_0[1 - \alpha(T - T_0)] \quad (3)$$

where R_0 is the nanotube resistance at room temperature, and α is the temperature coefficient of resistance. Combining Eqs. (2) and (3), the governing equation for the temperature profile of the CNT can be rewritten as,

$$kA\frac{d^2T}{dx^2} - \left(\frac{\alpha I^2R_0 + \gamma L}{L}\right)T = -\frac{\gamma L T_0 + I^2R_0(1 + \alpha T_0)}{L} \quad (4)$$

Assuming that the origin of the coordinate is set at the midpoint of resonator, the solution to Eq. (4) can be derived by integrating Eq. (4) from $-L/2$ to $L/2$,

$$T(x) = C_1 e^{x\sqrt{(\gamma L + \alpha I^2R_0)/kAL}} + C_2 e^{-x\sqrt{(\gamma L + \alpha I^2R_0)/kAL}} + T_0 + \frac{I^2R_0}{\gamma L + \alpha I^2R_0} \quad (5)$$

The unknown coefficients C_1 and C_2 can be determined using boundary conditions of the CNT resonator. As the thermal conductivity of Pd electrodes at both ends of the resonator are good enough to dissipate the heat into substrate, and the peak temperature occurs at the midpoint of the resonator according to Refs. [18,19], the boundary condition here is set by $T(-L/2) = T(L/2) = T_0$ and $T'(0) = 0$. Therefore, Eq. (5) can be re-written as,

$$T(x) = T_0 + \frac{I^2R_0}{\gamma L + \alpha I^2R_0}\left(1 - \frac{\cosh(x/L_H)}{\cosh(L/2L_H)}\right) \quad (6)$$

It can be seen that Eq. (6) describing temperature profile along the nanotube has the similar form as in Ref. [23], except for one additional factor, which is the temperature coefficient of resistance α in the term $L_H = \sqrt{kAL/(\gamma L + \alpha I^2R_0)}$. L_H is characterized as thermal healing length along the CNT. Since α together with d, L, I, γ may have impact on L_H, the relationships among them should be carefully investigated, which is described in the following section.

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