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Potential application of graphene nanomechanical resonator as pressure sensor

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ABSTRACT

A pressure sensor consisting of graphene nanomechanical resonator and Si/SiO_2 pressure membrane is demonstrated. The resonance frequency of resonator as function of external pressure smaller than 100 kPa is simulated to be linear using the finite element method. The obtained pressure sensitivity for a single-layer graphene resonator can reach 26,838 Hz/kPa, bigger than that of conventional resonant pressure sensors by two orders of magnitude. Moreover, the sensitivity can be further improved by increasing the ratio of side length to thickness of pressure membrane, and reducing the thickness and built-in strain of the resonator.

1. Introduction

Graphene, discovered in 2004 [1], is an interesting material for nanoelectromechanical systems (NEMS) due to its exceptional mechanical and physical properties. Many promising applications, including high frequency transistors [2], pressure sensor [3–6], transparent conductive films [7], ultra-fast photodetectors [8], etc., have been reported in the literatures. More recently, much interest has evolved in the excellent characteristics of graphene resonator because of its extraordinarily small thickness, high Young's modulus, low mass density, and large surface area. Many experimental [9–12] and theoretical [13–15] studies have shown that graphene resonators hold promise as ultrasensitive detectors of force, mass, and charge.

Jiang et al. [15] investigated the enhancement of the mass sensitivity and resonance frequency of graphene nanomechanical resonators that is achieved by driving them into the nonlinear oscillation regime. Atalaya et al. [16] derived and analyzed a nonlinear finite elasticity theory for graphene resonators and found that the tension is almost constant for small external driving force. For small tension in the graphene, the resonance frequency varies linearly. However, very few works focused on the linear resonance properties of graphene resonator, and the pressure sensor based on graphene nanomechanical resonators has not yet been reported.

In this work, the potential of graphene as resonant pressure sensor is explored, and pressure sensitivity is investigated using finite element simulation with membrane bending theory. While considering the influences of size of graphene and pressure membrane as well as built-in tension, frequency shift with respect to the pressure are calculated. In addition, the sensitivity of the resonant graphene pressure sensor is compared with that of the conventional pressure sensor.

2. Schematic and modeling of the pressure sensor

The schematic of the pressure sensor chip, consisting of graphene resonator and Si/SiO_2 pressure membrane, is shown in Fig. 1(a). In our case, the square membrane with an etched pressure cavity is the direct pressure sensing component, and is deformed under the measured pressure. To strengthen the adhesion between graphene and substrate, a 300 nm thick thermally grown SiO_2 is coated on the Si membrane as an insulating layer. A doubly clamped graphene beam is suspended on predefined trenches etched into the SiO_2 surface. The vacuum package of upper surface of membrane provides protection for the resonator from external environment, and improving the reliability of the sensor. The gold electrodes are deposited on the sides of graphene to make electrical contact and the resonator is actuated by using electrical modulation. The readout of graphene nanomechanical resonators including optical detection by interferometry [9] and all-electrical high-frequency mixing approach [10] were demonstrated respectively.

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The generated axial stress (x direction) due to the deformation of membrane is uniformly distributed on the beam, as shown in Fig. 1(b), and accordingly resonance frequency of the beam is changed. Consequently, the measured pressure can be obtained through the change of resonance frequency. The thickness of SiO_2 is much less than that of Si, and thus the pressure membrane can be approximately considered as a consistent Si membrane. For a clamped pressure membrane [17], the axial stress as a function of applied pressure can be expressed as

$$\sigma_x = \frac{6(1+\nu_{Si})}{\pi^2}\left(\frac{a}{2t}\right)^2 P \tag{1}$$

where $\nu_{Si}=0.22$ is the Poisson's ratio of Si, $a=2000\ \mu m$ and $t=500\ \mu m$ are the side length and thickness of membrane respectively, and P is the measured pressure. The fundamental resonance frequency for a doubly clamped beam under axial stress σ_x [18] is given by

$$f(\sigma_x) = f(0)\sqrt{1+\frac{\sigma_x}{\sigma_c}} \tag{2}$$

$$f(0) = 1.028\sqrt{\frac{E}{\rho}}\frac{h}{l^2} \tag{3}$$

$$\sigma_c = \frac{\pi^2 E}{3}\left(\frac{h}{l}\right)^2 \tag{4}$$

where σ_c is the Euler critical buckling load, $f(0)$ is the resonance frequency when $\sigma_x=0$, and the material parameters graphene beam are as follows: $E=1$ TPa is the Young's modulus, $\rho=2200\ kg/m^3$ is the mass density, $h=0.34$ nm is the thickness and $l=0.5\ \mu m$ is the length. The axial stress can be considered as a tension $T=\sigma_x h$ applying to the beam as shown in Fig. 1(a). When $\sigma_x/\sigma_c \le 0.2$ in a small range of pressure, Eq. (2) can be approximated as

$$f(\sigma_x) = f(0)\left(1+\frac{\sigma_x}{2\sigma_c}\right) \tag{5}$$

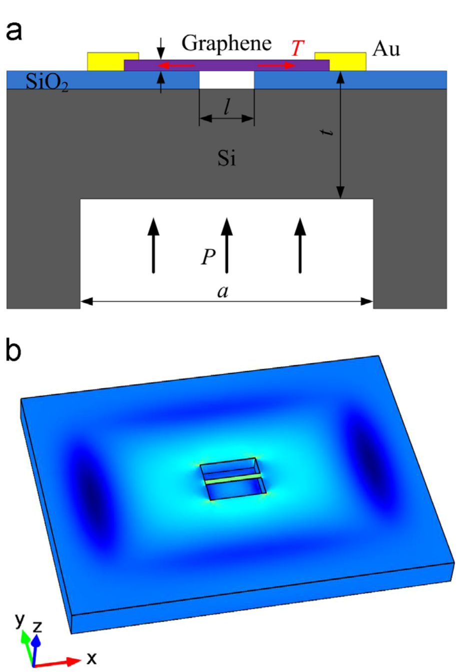

Fig. 1. (Color online) (a) The schematic of the pressure sensor chip under the measured pressure. (b) X component of stress tensor calculated using the finite element simulation; the resonant beam shows tensile stress under pressure.

It should be noted that the sensing principle of proposed graphene pressure sensor is different from that of existing graphene pressure sensor. Here the high resonance frequency property of graphene resonator is utilized, while other pressure sensors [4–6] are based on the piezoresistive effect in graphene. In fact, the graphene in our work is acted as a resonator not a sensing pressure membrane [4,6] or a piezoresistor [5].

3. Results

In order to explore the performance of proposed pressure sensor, the finite element simulation is carried out to determine the pressure response, and compared with theoretical expressions. The graphene beam is regarded as a tensioned membrane and details of simulation model are given out in our previous work [19]. As depicted in Fig. 2, the resonance frequency is found to increase with the increase of the pressure, and gradually following a nonlinear curve. However, the linear relationship occurs for the pressure smaller than 100 kPa. A likely explanation for this is that the resonance frequency increases linearly when $\sigma_x/\sigma_c \le 0.2$ due to a smaller pressure, as shown in Eqs. (1) and (5). The pressure sensitivity (i.e. slope of the straight line) is estimated to be 26,838 Hz/kPa, which is larger than that of resonator pressure sensors based on other materials [20–22], especially higher than conventional resonant pressure sensors by two orders of magnitude [20].

The sensitivity of resonant pressure sensor mainly depends on the variation of resonance frequency of resonator, as shown in Fig. 2. To study the effects of sizes of graphene beam on the sensitivity of pressure sensor, we present Fig. 3. From Fig. 3(a), the resonance frequency slightly increases with the decrease of aspect ratio when beam length is constant. In addition, the resonance frequency is closer to theoretical value when aspect ratio is 10 and aspect ratio has essentially no effect on the sensitivity. As the length of graphene resonant beam decreases, the resonance frequencies of 20.764, 29.898, 46.714, and 83.041 MHz for the four resonators under no tension are calculated, respectively. Nevertheless, the variation of resonance frequency is less than 3 MHz when applied pressure increase from 0 to 100 kPa. The reduction of resonance frequency due to increasing length is considerably larger than the influence of applied pressure. To better observe the effect of length, frequency shift is defined as $\Delta f = f(\sigma_x) - f(0)$ and the slope of frequency shift versus pressure

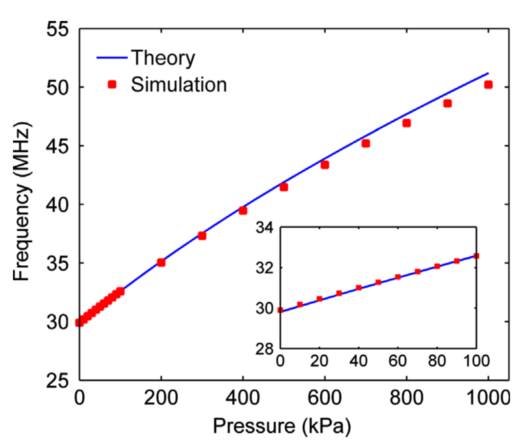

Fig. 2. (Color online) Resonance frequency versus applied pressure from 0 to 1000 kPa using finite element simulation and theoretical expressions. The inset shows the linear relationship when pressure ranges from 0 to 100 kPa. Good agreement is obtained using the two methods.