Piezoresistive transduction of graphene-based nanoelectromechanical systems

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The nanomechanical resonators exhibits exceptional sensitivity in the frequency domain due low mass and high quality factors [1-6]. Thus it has been used as an ultrasensitive force [2-3] and mass [3] sensors, showcasing measurements ranging from single spin detection [1] to mass spectroscopy [6]. Mass spectroscopy with NEMS is particularly appealing because the vibrational frequency of NEMS is a sensitive function of its total mass; thus minute changes in mass due to added or removed adsorbate will change the resonance frequency of a nanomechanical resonator. To maximize mass as well as force sensitivity, resonators with low mass and high quality factors are required. Hence extreme stiffness, low mass, a high young's modulus and good conductivity makes one atom thick graphene a most suitable candidate for NEMS. Previously extensive studies have been carried out on graphene NEMS by employing both optical [8], and electrostatic actuation techniques [4]. In this work [5], we utilize the intrinsic piezoresistivity of graphene [9] as a self-sensing component. We have thus employed a four-sided clamped H shaped graphene beam [5], which allows us to measure across the regions of maximum stress near the supports of the mechanical beam to maximize the piezoresistivity. Figure 1 shows a schematic of our measurements. Figure 2 shows a scanning electron micrograph of a fabricated H shaped graphene resonator clamped at the base by four gold electrodes and silicon dioxide. We measure the resistivity across any two adjacent pairs of legs, and this resistance varies as a result of the piezoresistivity. As this resonator vibrates, most of the mechanical stress at maximum deflection of the first mechanical mode (shown by the Finite Element Simulation in Figure 3) is concentrated near the legs for effective piezoresistive transduction. Figure 3 shows that the leg area has the highest stress. Figure 4 shows amplitude of fundamental resonance frequency (f_0) of this device at 1.0374MHz.

We have demonstrated that the intrinsic piezoresistivity of graphene is an effective technique to transduce the motion of monolayer graphene nanomechanical resonators. We find that such graphene resonators show very high Q-factors as high as 1000-2000 in ambient temperatures and pressures of ~ 4×10^{-6} torr. The mass resolution estimated of such a resonator is around 10 zeptogram. Moreover, we demonstrate this on commercially available chemical-vapor-deposition-grown graphene to allow for scale-up, and at room temperatures, thus demonstrating its potential for applications requiring exquisite force [2] and mass resolution [3] such as mass spectroscopy [6] and magnetic resonance force microscopy [1]. Our electrical read-out is effective, yet simple; a compact vacuum chamber is sufficient to carry out these measurements in ambient temperatures, and thus could be commercialized on hermetically sealed packages in future.

References:

[1] D. Rugar, R. Budakian, H. J. Mamin, B. W. Chui, Single spin detection by magnetic resonance force microscopy. *Nature* **430** (2004) 329-332.

[2] T. Kenny, Nanometer-scale force sensing with MEMS devices. *IEEE Sens. J.* **1** (2001) 148.

[3] K. L. Ekinci, M. L. Roukes, Nanoelectromechanical systems. *Rev. Sci. Instrum.* **76** (2005) 061101.

[4] C. Chen, J. Hone, Graphene nanoelectromechanical systems. *Proc. IEEE* **101** (2013) 1766–1779.

[5] M. Kumar, H. Bhaskaran, Ultrasensitive room temperature piezoresistive transduction in graphene-based nanoelectro-mechanical systems. *Nano Lett.*, **15** (4) (2015) pp 2562–2567.

[6] A. K. Naik, M. S. Hanay, W. K. Hiebert, X. L. Feng and M. L. Roukes, Towards single-molecule nanomechanical mass spectrometry. *Nat. Nanotechnol.* 4 (2009) 445–450.

[7] A. K. Geim, & K. S. Novoselov, The rise of graphene, *Nat. Mater.* 6, (2007)183-191.

[8] J. S. Bunch, A. M. Zande, S. S. Verbridge, I. W. Frank, D. M. Tanenbaum, J. M. Parpia, H. G. Craighead, P. L. McEuen. Electromechanical Resonators from Graphene Sheets. *Science* 315 (2007) 490-493.

[9] A. D. Smith et al., Electromechanical Piezeoresistive Sensing in Suspended Graphene Membranes., *Nano Lett.* **13** (2013) 3237−3242.

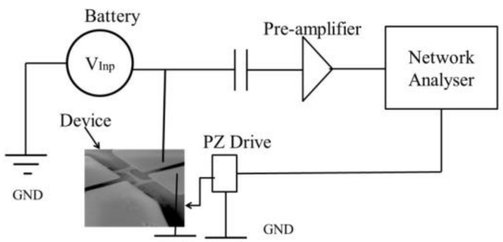

Figure 1. Schematic of piezoresistive measurements.

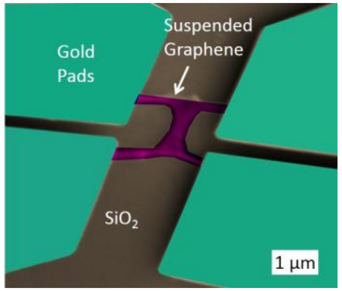

Figure 2. Scanning micrograph image of suspended graphene device

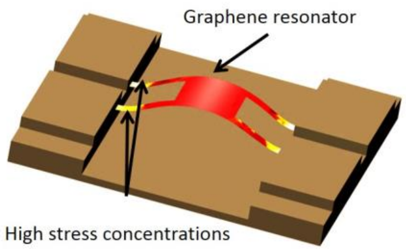

Figure 3. Modal analysis of graphene resonator

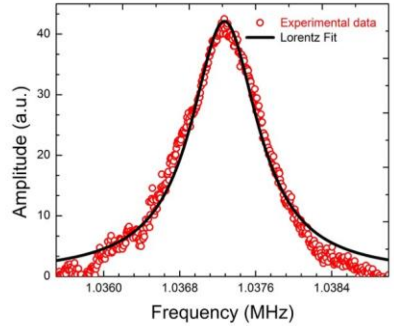

Figure 4. Frequency response of the resonance Frequency.