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Capacitively coupled suspended CVD graphene ribbons for electromechanical device applications

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Abstract

Electromechanical devices for pressure, mass, gas, biological sensing made out of graphene promises many futuristic applications in industrial / environmental monitoring, medicine, internet-of-things, etc. In these nanoelectromechanical devices, a suspended nanoribbon of graphene acts as the active mechanical element. An efficient way of actuating and sensing mechanical motion in the suspended graphene nanoribbon is to capacitively couple it with a parallel plate 'gate' electrode. Efficacy of capacitive actuation and sensing method strongly depends on the local capacitance coupling between the graphene ribbon and the gate, which in turn, depends on their dimensions and geometry. Due to the limitations imposed by nano-fabrication techniques and the small-scale nature of the devices, optimizing the gate structure to ensure optimal capacitive coupling is necessary. Using finite element analysis, we investigate capacitive coupling between a local gate and a thin suspended beam structure for different gate geometries. We also experimentally demonstrate capacitive coupling between local gate and suspended ribbon via ambipolar transfer characteristics. Studies presented in this work are expected to find application in graphene nanoelectromechanical sensors.

1. Introduction

Excellent mechanical [1], electrical properties [2] of atomically thin graphene material makes it an ideal candidate for many nanoscale device applications [3, 4]. Graphene based nanoelectromechanical (G-NEM) devices, such as, resonators [4,5], pressure-sensors [6], accelerometer [7], etc. are promising candidates for next-generation sensor technology. A suspended graphene nanoribbon (GNR) acts as the primary electromechanical component in G-NEM devices. Actuation and sensing of the GNR can be achieved via electrical [8], optical [9] routes, etc. For its simplicity, ease of on-chip integration, and fast, reliable response, we chose to investigate and employ a capacitive-coupling based actuation and sensing method in suspended GNR based G-NEM devices. Numerical and experimental results acquired from such G-NEM devices will be presented. A suspended GNR anchored to source and drain electrodes in both ends, and electrostatically coupled with a local gate can be realized through a device configuration shown in the schematic diagrams of Fig. 1(a)-(b). Bottom gate electrode forms a parallel-plate capacitor configuration with the suspended GNR. Local gate capacitance (C_g) depends on the area of overlap (A) and the equilibrium distance (d_0) between the plates, since $C_g \approx (\epsilon_0 A/d_0)$, where ϵ_0 is the permittivity of free space. A fixed DC voltage (V_g^{DC}) and a small AC voltage (V_g^{AC}) are applied at the bottom gate. This generates a periodic electrostatic actuation force ($F_a \propto C_g$) at the frequency of V_g^{AC}. Mechanical motion of the GNR in turn modulates the capacitance, which is then monitored to measure the deflection of the GNR from its equilibrium position. Actuation, and sensing of mechanical motion by capacitive method is reliable, fast, and applicable up to high frequency. However, in nanoscale, employing capacitive method becomes challenging owing to the reduction of C_g due to small size, especially when the parasitic capacitance is large. Optimization of the geometry of the gate to maximize C_g while considering the limitations of nanofabrication tools is therefore necessary.

2. Methods

Finite element Simulation

We employed finite element simulation through Comsol Multiphysics software [10] to simulate the dynamical properties of a capacitively coupled resonator (inset of Fig. 1(c)). Frequency domain analysis was performed with a doubly clamped resonator (clamped along red lines in inset Fig. 1(c)), with a V_g^{DC} = 100 mV, and V_g^{AC} = 30 mV. We investigated the amplitude response, detection signal-strength, gate-voltage tuning of resonance frequency, etc. at different gate geometry.

Experimental details

To measure gate capacitive coupling, we fabricated suspended GNR devices with bottom-gate on Si substrate with 300 nm of SiO_2. A fixed 5 mV DC voltage is applied between source-drain (V_{SD}) while the gate-voltage (V_g) is swept between ±1.6 V to acquire ambipolar transfer-characteristics.

3. Results and discussion

As shown in the inset of Fig. 1 (c), frequency domain response of a doubly clamped GNR (1 μm in length, 200 nm in width, 10 nm in thickness) was simulated for different width

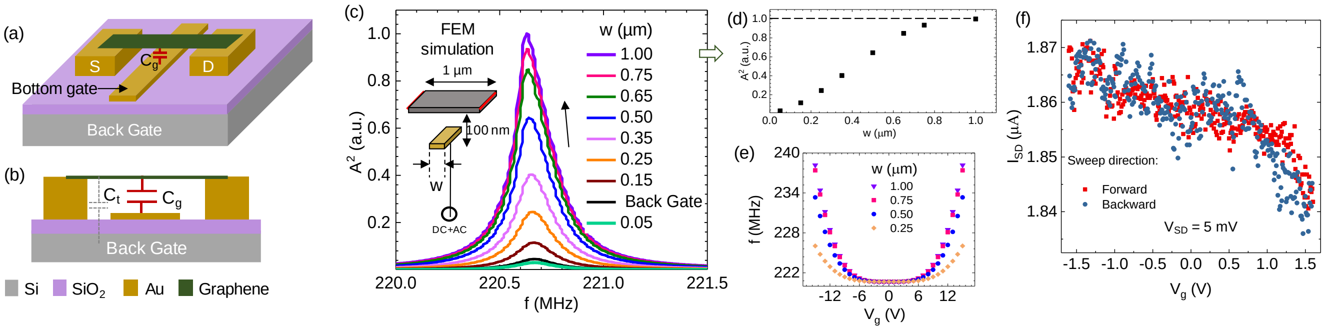

Fig. 1: Schematic illustration of a suspended graphene nano-ribbon with a capacitively coupled local bottom-gate, viewed from (a) side and (top); (c) – (d) Finite-element simulation of electrostatic actuation for different local-gate width (w); (e) experimentally acquired ambipolar characteristic in a suspended graphene ribbon indicating capacitive coupling with local bottom gate.

(w) of the bottom gate (d_0 = 100 nm). Result of the amplitude (A) calculated at the mid-point of the beam around it's resonance frequency is plotted (after normalizing with respect to peak amplitude for w = 1 µm) in the main panel of Fig. 1(c). Black line in Fig. 1(c) labelled as 'Back gate' in Fig. 1(c) indicates when Si substrate is used as a gate instead of a bottom gate (cf. C_t in Fig. 1(b)). Fig. 1(c) shows an increasing trend in A with increasing w, and also indicates advantage of using a local bottom gate over back gate. Relation between w and A is presented in Fig. 1(d). w is essentially limited by the resolution and misalignments of the lithography process during fabrication of the device. Trend shown in Fig. 1(d) indicates the tradeoff between percentage coverage achievable in experiments with the loss of capacitive coupling. Sensing of mechanical vibration is also limited by the local capacitance, since the signal current arising from the modulation of source-drain current (I_{SD}) is directly proportional to C_g [8]. The measurement signal is also inevitably subjected to a background arising from the stray capacitance (C_s). Therefore, local capacitance coupling needs to reach a threshold value below which motion of the GNR will remain buried in the background. Thin GNR resonators also allow tuning of the resonance frequency by V_g^{DC} induced controlled external tension on the ribbon. This 'gate-tuning' of resonance frequency in 2D resonators offers this unique advantage of tuning of the frequency to suit specific requirements vis a vis application [11]. We present the effect of gate geometry on gate-tuning for different gate geometry (w) in Fig. 1(e).

Ambipolar transfer characteristics of graphene provides a second source of signal current due to the modulation of its transfer conductance [8]. This unique property of 2D materials is very useful, particularly for nanoscale electromechanical devices. Ambipolar transfer characteristic is intimately related to the gate capacitance, and therefore, can be used to measure the capacitive coupling between a suspended GNR and the local gate. In Fig. 1(f), we show experimentally acquired ambipolar transfer characteristics in a suspended GNR (1 µm in length, 4 µm in width, $d_0 \approx$ 100 nm). DC gate voltage (in the absence of any AC actuation voltage) was swept from -1.6 V to + 1.6 V ('forward') and then +1.6 V to -1.6 V ('reverse'), while maintaining a fixed source-drain voltage (V_{SD} = 5 mV). Corresponding I_{SD} is shown in Fig. 1(f). Assuming a diffusion limited conduction regime, conductance (G) of the GNR can be modelled by $G = ne\mu$, where e and μ are electronic charge and carrier mobility, and n is the carrier concentration at gate capacitance C_g and gate voltage V_g^{DC}. In order of magnitude calculation, C_g estimated from Fig. 1(e) agrees well with its expected geometrically estimated value (~ 0.1 pF) for a typical carrier mobility of 100 $cm^2V^{-1}s^{-1}$.

Electrical characteristics of GNR is significantly depleted by contaminants left by the fabrication process. We will also present how suitable annealing processes can reasonably remove the contaminants and help recover the electronic properties of suspended GNR.

4. Conclusions

Using numerical analysis, have investigated effects of different gate electrode geometries on the actuation and sensing of suspended GNR based electromechanical devices. We fabricated suspended GNR devices with local bottom gate and estimated capacitive coupling using ambipolar transfer characteristics.

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Appendix

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