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Intermixing of motional currents in suspended CNT-FET based resonators

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Abstract—Here, we report the intermixing of piezoresistive and conduction modulation current in a carbon nanotube field effect transistor (CNT-FET) based resonator. We show that due to static displacement of the nanotube, as a result of electrostatic actuation, the motional current at the resonance frequency consist of both current components. For instance at a DC gate bias of 1.3 V, 3/4 of the motional current is conduction modulation current while the rest arises from piezoresistive effects. The intermixing effect due to asymmetry influences the fundamental harmonic response as well as the physical nature of the electrical signal being sensed; both of which are important for understanding frequency harmonics in nanoresonators and developing efficient readout schemes for nanoscale sensors.

I. INTRODUCTION

Various nanomaterials such as silicon nanowires (SiNWs), graphene, carbon nanotubes (CNTs) have been used as building blocks for resonant sensing applications. The ability of these materials in exhibiting multiple electrical characteristics (piezoresistivity or conductivity modulation) results in a mechanical resonance response with multiple harmonics. This also allows for multiple transduction readout schemes such as capacitive or piezoresistive readout among others. For implementation of a selective and efficient readout scheme, in particular for nanoscale sensors, where high bandwidth and SNR can be challenging, it is crucial to know the nature of the electrical signal being sensed. For nanoresonators, most transduction schemes for mechanical resonance characterization are reported to selectively sense either the piezoresistive current or the capacitance or conductance modulation current. Here we investigate the fundamental harmonics and the selectivity of the transduction schemes for the desired component and report a qualitative and quantitative analysis of mechanical motional currents in a nanoresonator based on a single walled carbon nanotube (SWCNT).

II. SIMULATION AND VERIFICATION

The two used transduction schemes for carbon nanotube FET based nanoresonators as shown in Fig. 1 are piezoresistive transduction based on strain modulation and conduction modulation transduction based on field effect induced charge modulation [1]. The transduction scheme uses an RF down mixing and lock-in detection [2] with CNT as a mixer as shown in Fig. 2. This scheme requires a low bandwidth readout and minimizes the effect of parasitic capacitances.

A. Piezoresistive motional current

Piezoresistivity in nanotube arises from the strain induced resistive changes. The beam elongation as a result of out-of-plane resonance induces periodic strain $\epsilon(t)$ given by [2]

$$\epsilon(t) = z(t)^2 \frac{1}{2L} \int_0^L \left(\frac{\partial \varphi(x)}{\partial x} \right)^2 dx \quad (1)$$

where z is the nanotube displacement, L is the length of tube and $\varphi(x)$ is the beam mode shape. The time varying resistive change $\Delta R(t)$ due to strain modulation is then given by

$$\frac{\Delta R(t)}{R_0} = G_F \epsilon(t) \quad (2)$$

where G_F is defined as the CNT's Gauge factor [3]. The resulting piezoresistive current can then be computed by [2]

$$i_p = V / [R_0 + \Delta R(t)] \quad (3)$$

$$i_p = \frac{V_{sd}}{R_0} \left(1 - z(t)^2 G_F \frac{1}{2L} \int_0^L \left(\frac{\partial \varphi(x)}{\partial x} \right)^2 dx \right) \quad (4)$$

The piezoresistive current (II term) represents a quadratic transduction scheme w.r.t CNT's displacement z .

B. Conductance modulated motional current

Conductance modulation due to capacitive changes have been extensively used to characterize CNT nanoresonators. The charge fluctuations due to resulting nanotube motion can be read out as a mechanical current given by [4]

$$i_g = V_{sd} \frac{dG}{dV_g} \left(V_g^{ac} + z(t) \frac{V_g^{DC}}{C_g} \frac{dC_g}{dz} \right) \quad (5)$$

where C_g is the CNT-gate capacitance and G is the CNT conductance. In contrast to piezoresistive current, the conductance modulation current (II term) exhibits a linear transduction w.r.t CNT's displacement z . ($z \ll g_0$; CNT-gate distance)

C. Intermixing of motional currents

For a nanotube resonating at frequency ω with displacement amplitude $z_0 e^{i\omega t}$, the motional currents (considering the II terms only from Eq. 4-5) can be re-written as

$$i_g = z_0 e^{i\omega t} V_{sd} \frac{dG}{dV_g} \frac{V_g^{DC}}{C_g} \frac{dC_g}{dz} = z_0 e^{i\omega t} K_G \quad (6)$$

$$i_p = z_0^2 e^{i2\omega t} \frac{V_{sd}}{R_0} G_F \frac{1}{2L} \int_0^L \left(\frac{\partial \varphi(x)}{\partial x} \right)^2 dx = z_0^2 e^{i2\omega t} K_P \quad (7)$$

where K_G and K_P are introduced as bias dependent proportionality parameters. From Eq. 6-7, the frequency component of motional currents, i_g and i_p , occur at ω and 2ω

respectively and hence can be separated by two source techniques (Fig. 2). This model assumes a symmetrical displacement beam profile. However, in presence of a static bending of a beam, symmetry breaking can occur [5] and can affect the resonance behavior. In such a scenario, the nanotube displacement can be expressed as $z_o e^{i\omega t} = z_s + z_d e^{i\omega t}$ where z_s and z_d represents the static and time-varying dynamic displacement respectively. The modified expression for motional currents would then be given by

$$i_g = z_s K_G + z_d e^{i\omega t} K_G \quad (8)$$

$$i_p = z_s^2 K_P + 2z_s z_d e^{i\omega t} K_P + z_d^2 e^{i2\omega t} K_P \quad (9)$$

In contrast to the symmetrical beam model, both currents are inseparable with motional current at ω consisting of terms proportional to conduction modulation and piezoresistivity, thereby hindering the selectivity of the widely employed ω transduction scheme. To study the impact of static displacement on intermixing of motional currents, we adapt the model to comprehensive CNT parameters experimentally obtained by Ning *et al.* [6]; mentioned in Table I. We simulate the static and dynamic displacements and the resulting motional currents by considering electrostatic actuation on a harmonic beam resonator [4] through Simulink/MATLAB.

Fig. 3 plots the conduction modulation current (Eq. 8) for various DC gate bias exhibiting spring hardening effect and increase in resonance current (Inset-Fig. 3) at resonance frequency ω . The higher order derivatives such as $d^2 C_g / dz^2$ lead to a negligible current at 2ω . In contrast, the piezoresistive current in Fig. 4 has components at both ω and 2ω as expected from Eq. 9. While the 2ω component of total motional current (Eq. 8+Eq. 9) is purely piezoresistive, ω component results from mixing of both currents as shown in Fig. 5. For the considered set of CNT model parameters, the intermixing effect increases the peak resonance signal as well as hinders the selectivity of the ω measurement technique.

III. EXPERIMENTS AND RESULTS

For experimental investigation of the intermixing effect, we use a small bandgap semiconducting (SGS) nanotube resonator device (Fig. 6) as they exhibit both gate dependent conductance modulation and high Gauge factor in contrast to purely semiconducting or metallic nanotubes [3]. We characterize the mechanical behavior of the nanotube by both ω and 2ω transduction at an RF down mixing frequency $\Delta\omega=10$ kHz exhibiting a resonance frequency at 72.6 MHz (Fig. 6f) at room temperature (300K) and low vacuum ($<10^{-3}$ mbar). The measured high resonance frequency in comparison to theoretical eigenmode suggest a slack-free CNT resonator. The Lorentzian fit to measured frequency spectral responses was used to extract the peak resonance current.

Fig. 7 shows purely piezoresistive current at various DC gate bias detected through 2ω scheme. To quantify the currents, the dependency $z_d^2 \propto (V_g^{DC})^2$ was used for power fitting. Peak resonance currents obtained from ω scheme as shown in Fig. 8 were also fitted, with an additional dependency $z_s \propto (V_g^{DC})^2$, to separate the motional currents. To account for the intermixing

effect, square and fourth power fit was used (the peak current was normalized to background current, 1 term of Eq. 5, to account for bias dependent conductance). The proportionality parameter K_P obtained with power fits from ω and 2ω measurements were extracted to be 0.268 and 0.263 respectively supporting the validity of fits and intermixing between motional currents. In addition, the term dG/dV_g extracted from K_G , 4.33×10^{-7} S/V and CNT-FET I_D - V_G transfer characteristic, 3.58×10^{-7} S/V shows a good agreement from the fit based on intermixing effect.

IV. DISCUSSION AND CONCLUSION

With the extracted parameters, we quantify the intermixing effect at resonance frequency ω for the measured nanotube device. As shown in Fig. 9, for low DC gate bias of 0.5 V, piezoresistive current constitutes only an estimated 4% of the total motional current. This increases to 26% while the remaining 74% arises from conduction modulation current at a bias of 1.4 V due to asymmetrical beam profile as a result of DC electrostatic force. Amplitude and Q-factor fluctuations, observed in nanoresonators, could lead to inaccuracies in the estimated current components. Piezoresistivity due to asymmetrical beam profile has also been observed in a 90 nm thick silicon nanowire resonator [2], however at a high gate bias of 15 V, suggesting the significance of intermixing in sub-nanometer resonators at low bias; especially in non-linear resonators operating at higher gate bias resulting in several harmonics. Differences in resonator characteristics like Gauge factor, chirality or conductance such as the one considered in Table I can also lead to an intermixing with 50-50% contribution, thereby effecting the physical nature of the electrical signal and the selectivity of ω transduction scheme, both of which are important for understanding the harmonic components of resonators and in the design of highly efficient and sensitive readout schemes for nanoscale sensors.

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Fig. 1. Schematic of a resonator based on suspended carbon nanotube between source (S) and drain (D) electrode of a field effect transistor with bottom gate (G) architecture.

Fig. 2. (a) Experimental setup using RF mixing and lock-in technique for readout of motional current components at resonance frequency ω ; (b) Modified setup to readout the current component at 2ω .

CNT parameter	Value	Unit
Radius (r)	1.1	nm
Length (L)	1.59	μm
Density (ρ)	1400	kg/m^3
Mass (m)	2.54×10^{-21}	kg
Cross-sectional area (A_c)	2.29×10^{-18}	m^2
Young's modulus (E)	154	GPa
Device resistance (R_0)	1.01	Mohm
CNT-gate distance (g_0)	300	nm
Zero-strain bandgap (E_0)	113.2649	meV
$dE/d\epsilon$	49.8	meV/%
dG/dV_g	1.43×10^{-7}	S/V
Spring constant	1.53×10^{-4}	N/m
Damping factor (b)	9.7×10^{-15}	kg/s
Source bias (V_{sd}^{AC}, V_{sd}^{DC})	10	mV
Gate AC bias (V_g^{AC})	10	mV

Table. I. CNT parameters experimentally extracted by Ning *et.al.*[6] through resonance frequency measurement, DC measurements, Raman spectroscopy, scanning electron microscopy (SEM), and transmission electron microscopy (TEM).

Fig. 3. Conduction modulation current; Eq. 8 simulated for various DC gate bias for CNT resonator at ω . The higher second order terms (d^2C/dz^2) results in a negligible 2ω component. Inset – Peak resonance current vs DC gate bias.

Fig. 4. Piezoresistive current; Eq. 9 simulated for various DC gate bias for CNT resonator at ω and 2ω due to $2Z_s Z_d$ and Z_d^2 respectively. Inset – Peak resonance current vs DC gate bias.

Fig. 5. Total motional current (Eq. 8+Eq. 9) at 3 V DC gate bias for CNT resonator at ω and 2ω . While 2ω is purely piezoresistive, the current at ω consist of 47% conduction modulation current and 53 % piezoresistive current (extracted from peak currents - Inset)

Fig. 6. (a) Device architecture of the CNT-FET based resonator with suspended channel length of 2 μ m and CNT-gate distance of 275 nm. (b) Raman spectroscopy of the fabricated device with a nanotube obtained after dry-transfer process; (c) Raman spectrum measured for the suspended nanotube; (d) DC CNT-FET transfer characteristics exhibiting a small bandgap semiconducting (SGS) behavior; (e) Pulsed gate DC measurement for extracting hysteresis free performance; (f) Resonance frequency characterization through two source ω and 2ω detection technique. Both scheme detects the resonance frequency at 72.6 MHz with different motional current amplitudes.

Fig. 7. Resonance peak current vs DC gate bias for 2ω measurement corresponding to piezoresistive current. Inset – Measured frequency response with Lorentzian fit to extract parameters.

Fig. 8. Resonance peak current (normalized to background current-dG/dV dependency) vs DC gate bias for ω measurement corresponding to conduction modulation and piezoresistive current. Inset – Measured frequency response with Lorentzian fit.

Fig. 9. Strength of intermixing of piezoresistive current and conduction modulation current as a function of DC gate bias. The increase in the nanotube's static displacement is estimated to increase the intermixing component $2z_s z_d K_P$ to one-fourth of the total motional current.