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Doubly-suspended carbon nanotube resonator for ultrasensitive mass measurement

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1. Introduction

Carbon nanotube (CNT) resonators are one of the potential candidates for ultrasensitive mass and force measurements. Doubly-suspended CNT resonators have been investigated intensively in ultrahigh vacuum under electron microscopy [1], while cantilevered CNT resonators were measured in vacuum and air using an optical technique under light microscopy [2]. Since CNT resonators need to be immersed in viscous fluids in order to measure mass of biological molecules with sub-atogram sensitivity, we investigated the oscillation of doubly-suspended CNT resonators in ambient pressure.

2. Experiments

We first fabricated CNT-FET devices by located catalytically grown CNTs on a highly doped Si substrate coated with a 500 nm thick SiO_2 layer, followed by conventional photolithography and e-beam deposition techniques to make source and drain electrodes. Subsequently, the CNT cannel was suspended by e-beam lithography and etching of the underlying SiO_2 layer using buffered HF. The representative scanning electron and atomic force micrographs of doubly-suspended CNT resonator used in our study are shown in Fig. 1. The etched gap between clamping points to which the CNT channel was suspended was ranged from 500 nm to 4 μm. The narrower the gap is, the higher the resonant frequency of the CNT resonator tends to be.

The oscillation of doubly-suspended CNT-FETs was performed by measuring the drain current of the CNT-FET while applying the AC voltages to the source (V_{SD}) at the frequency of f+Δf, and the gate electrode (V_g^{AC}) at the frequency of f to drive the suspended CNT. The current from the CNT channel was detected by a lock-in amplifier through the drain electrode at the frequency of Δf with the typical time constant of 300 ms.

3. Results and Discussion

The electric characteristics of doubly-suspended CNT-FETs were somewhat degraded compared to those of normal CNT-FETs due to the capacitance of insulators and the possible damage of the CNT channel during the etching process by buffered HF. Figure 2 shows a 3D plot of the normalized drain current as a function of gate voltage and frequency in vacuum. The resonant frequency and quality factor of the CNT were 1.32 MHz and 33, respectively. The resonant frequency of the CNT increased with

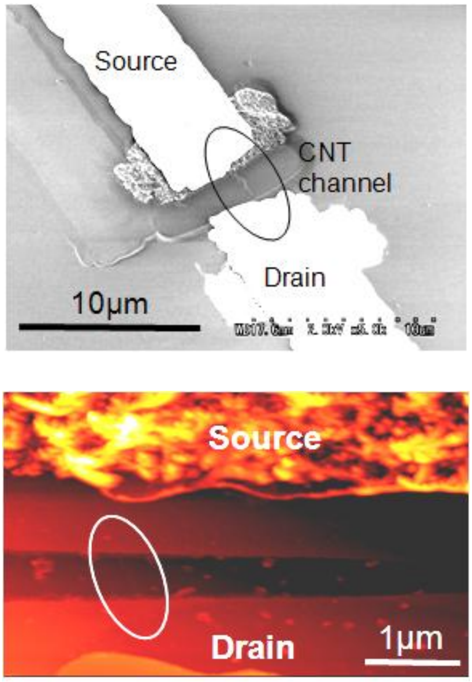

Fig. 1 Typical scanning electron and atomic force micrographs of a doubly-suspended CNT-FET. The suspended CNTs are located in the circles.

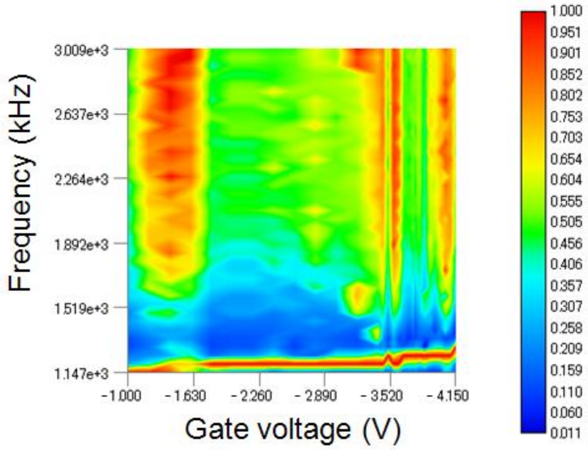

Fig. 2 Drain current through the CNT channel as a function of gate voltage and frequency in vacuum. V_{SD}=V_g^{AC}=500 mV_{pp}. The resonant frequency of the suspended CNT (around 1.3MHz) increased with increasing the absolute value of the DC gate voltage (V_g^{DC}).

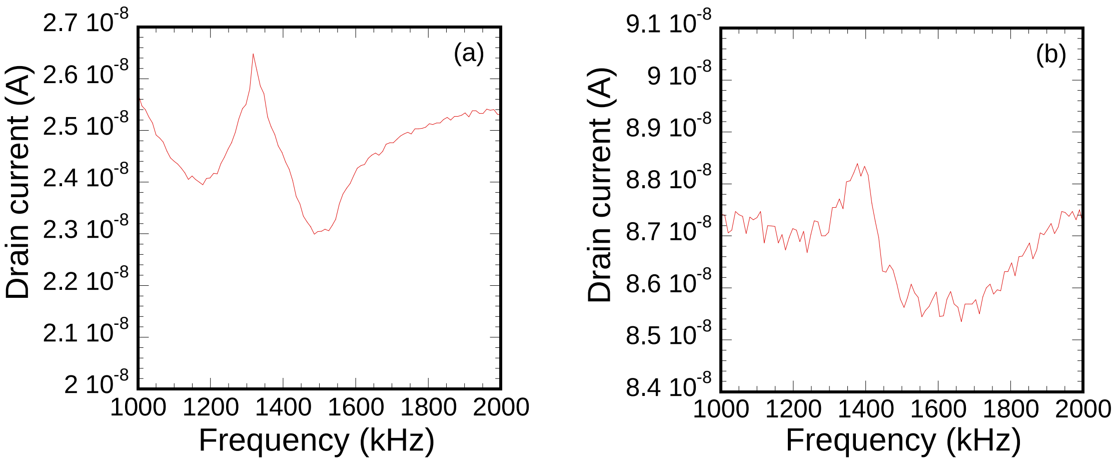

Fig. 3 Frequency response curves of a suspended CNT in vacuum (a) and in air (b). The resonant frequency and quality factor in vacuum were 1.32 MHz and 33, respectively, while in air 1.38 MHz and 21.8. The increase in the resonant frequency in air was possibly because the effective length of the CNT channel became shorter due to meniscus by water molecules in air.

increasing the absolute value of the DC voltage applied to the gate, indicating that the effective spring constant of the suspended CNT was increased due to the increase in electrostatic attraction between the CNT channel and the Si backgate.

We then investigated the resonance of the suspended CNT in air to study the influence of the viscous resistance of the viscous fluid. Figure 3 shows frequency responses of a suspended CNT in vacuum and in air. The resonant frequency of the CNT in air somewhat increased compared to that in vacuum, possibly because the effective length of the CNT channel became shorter due to a meniscus by water molecules in air. However, the quality factor and oscillation amplitude slightly decreased in air due to the viscous resistance in air.

To better understand the resonance of suspended CNTs, we used the Knudsen number (Kn), defined by $Kn = l_{mfp}/w$, where l_{mfp} is the mean free path of the molecule and w the width of suspended CNTs. Kn is the indicator of an influence from viscous fluids. The flow acts as the three regimes based on the Knudsen number: $Kn < 0.01$, the flow is in the continuum regime, at $Kn > 10$, the flow is in the free molecular regime, and it is in the cross over regime at $0.01 < Kn < 10$. As the width of the CNT in this study was 1.5 nm, the Knudsen number Kn = 45 in air, indicating that the oscillation of suspended CNTs can be modeled as in the free molecular regime. Therefore, the slight reduction in the quality factor and oscillation amplitude of the suspended CNT in air is probably attributed by the collision of the air molecules and/or adsorption of water molecules in air.

4. Conclusion

We investigated the oscillation of the doubly-suspended CNT resonator in air as well as in vacuum by measuring the drain current through the CNT channel. The resonant frequency increased with increasing the absolute value of the gate voltage, indicating the increase in the effective spring constant of the CNT. In air, the quality factor and oscillation amplitude of the suspended CNT slightly decreased, possibly due to the collision of the air molecules and/or adsorption of water molecules in air. In contrast, the resonant frequency was merely influenced by the air, suggesting that the suspended CNT is advantageous for ultrasensitive mass measurement of biological molecules in viscous fluids.

References

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