

# MODELING AND EXPERIMENTAL STUDY OF NANO-ELECTROMECHANICAL OSCILLATOR USING SINGLE ZINC OXIDE NANOWIRE

R. Zhu<sup>1</sup>, D.Q. Wang<sup>1</sup>, S.Q. Xiang<sup>1</sup>, Z.Y. Zhou<sup>1</sup>, X.Y. Ye<sup>1</sup>

<sup>1</sup> State Key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instruments and Mechanology, Tsinghua University, Beijing, China

## ABSTRACT

This paper reports a novel nanoelectromechanical oscillator using a single zinc oxide (ZnO) nanowire suspended across two micromachined Au electrodes. The oscillator is self-driven into a motion that is self-detected by using a field effect transistor (FET) configuration and a lock-in detection method. A continuum electromechanical model is established to realize a theoretical analysis on the oscillator and the primary experimental measurements are performed to validate the effectiveness of the device. Compared with other nanoelectromechanical oscillators, such as that with carbon nanotubes, the oscillator based on ZnO nanowire is provided with an enhanced electromechanical response and an observable resonance with a frequency on the order of tens of megahertz driven in an air environment. These merits significantly enhance the device's practicability. The device can be potentially applied for actuators and sensors.

## 1. INTRODUCTION

Nanoelectromechanical systems (NEMS) have attracted many attentions in fields of science and technology due to their remarkable properties. One of the most attractive devices is a NEMS resonator that uses a one-dimensional semiconducting nano-structure, such as a carbon nanotube, which can be used as free-frequency mixers to realize a self-driving and self-detecting mechanical motion [1-2]. The advantages of using nano-scale materials as resonators consist that a high-free frequency (on the order of MHz) can be reached, and a small tension or displacement can be measured by using the free-frequency mixer, which is typically used to implement a high-sensitivity, tenability, and high-frequency operation of NEMS oscillators.

A semiconducting zinc oxide (ZnO) nanowire is a one-dimensional material that has been used in many nano-devices, such as transistors [3], resonators [4], and nano-sensors [5]. They are pure, structurally uniform, single crystalline, and most are free from dislocation. Many novel properties of ZnO nanowires have been demonstrated, such as piezoelectricity, optoelectronic effects and thermoelectricity. In this paper we report on a NEMS oscillator based on a single semiconducting ZnO nanowire suspended on two Au electrodes. We successfully drive and detect its resonant motion at a frequency range of 10 to 30 MHz in an air environment. A continuum electromechanical model is established to extract the vibration mode of the resonator, the results of which are in accordance with the experimental measurement results.

## 2. FABRICATION OF OSCILLATOR

Figure 1 shows a diagram and a scanning electron microscope (SEM) image of our resonator. A single ZnO nanowire is doubly clamped and suspended on two metal electrodes. The fabrication process of the electrodes including top two electrodes and lower gate electrodes, shown in Fig. 1(a), starts with the preparation of a phosphorus-doped (P-doped) silicon substrate ( $1.5\sim 4.0\times 10^{16}\text{ cm}^{-3}$ ) that is covered by a 40 nm  $\text{SiO}_2$  layer formed by thermal oxidation. The doped silicon substrate acts as the lower electrode. Afterwards a 300 nm Cr/Au film is sputtered. The Cr/Au layer is masked and etched to form the top electrodes that subsequently serve as supporting platforms for suspending the nanowire. Using a field effect transistor (FET) terminology, we define the top two electrodes as the source and drain and the bottom substrate as the gate. The ZnO nanowires used in our device are synthesized by thermal evaporation of ZnO powders under controlled conditions without the presence of catalyst [6]. The synthesized nanowires, with a length of 1-15  $\mu\text{m}$  and a diameter of 10-500 nm, are freed from being bound up in bundles by ultrasonically dissolving the bundles in ethanol solvent for several minutes. Dispense a drop of the nanowire-containing solvent onto the prepared wafer and apply alternating current (AC) electric field to the top two electrodes for trapping and aligning the nanowire onto the electrodes, which is based on dielectrophoresis assembly technology [7-8]. In this process, the desirable frequency is 5-20 MHz and the peak-to-peak amplitude of the applied AC voltage is 2-20 V [8]. After the assembly of the nanowire onto the electrodes, Focused ion beam (FIB) (A 30 keV  $\text{Ga}^+$  ion beam with a 7 pA current aperture) is employed to deposit Pt on the contact between the nanowire and electrodes in order to clamp the nanowire. The FIB process also helps to eliminate the Schottky barriers at the interfaces between the semiconducting nanowire and the metal electrodes. A near Ohm-contact is formed between ZnO nanowire and Au electrode by this post-treatment.

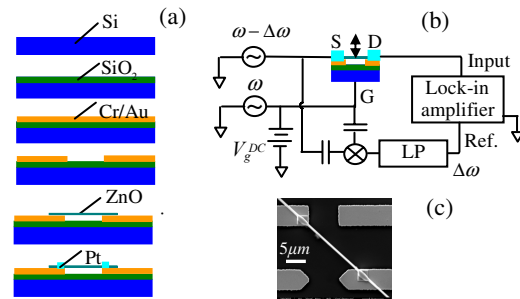


Figure 1: The diagram of the fabrication and measurement set-up of the NEMS oscillator using a single suspending ZnO nanowire.

### 3. ELECTROMECHANICAL MODELING FOR OSCILLATOR

We drive the suspending nanowire into motion using the electrostatic interaction with the gate electrode underneath the nanowire. A combination of a static (DC) voltage  $V_g^{DC}$  and a time-varying AC voltage  $\delta V_g$  with a high driving frequency of  $\omega$  is applied to the gate, induces a driving electrostatic force on the nanowire, which is given by:

$$F = C'V_g^2/2 = C'[(V_g^{DC})^2 + 2V_g^{DC} \cdot \delta V_g + \delta V_g^2]/2 \quad (1)$$

where  $C' = \partial C / \partial z$  is the derivative of the gate capacitance with respect to the distance between the nanowire and the gate. The first term in equation (1) refers to a component of the static force on the nanowire that determines the tension in the nanowire. The later two terms in equation (1) refer to the alternating force components with different frequencies that drive the nanowire into periodic motion. The second term is with a frequency of  $\omega$ , and the third is with a frequency of  $2\omega$ . When either of the frequency  $\omega$  and  $2\omega$  approaches the mechanical fundamental frequency of the nanowire  $\omega_0$ , the resonance takes place. To explain the motion mode of the nanowire resonator, we use a continuum model:

$$\rho A \frac{d^2 z}{dt^2} + \eta \frac{dz}{dt} + EI \frac{d^4 z}{dx^4} + T \frac{d^2 z}{dx^2} = F \quad (2)$$

where  $\rho A$  is nanowire mass density,  $\eta$  is damping constant,  $EI$  is bending rigidity of the nanowire, and  $T$  is the tension in the nanowire. Using a numerical methodology, the normalized motion response to the periodic force at the frequency of  $\omega$  is solved in the frequency domain, which is given by:

$$H(j\omega) = \frac{Z(j\omega)}{F(j\omega)} = \frac{1}{(j\omega)^2 + \frac{\eta}{\rho A}(j\omega) + \left(\frac{EI\beta^4}{\rho A} + \frac{0.5499T\beta^2}{\rho A}\right)} \quad (3)$$

where  $\beta$  is the mode factor, for the fundamental mode,  $\beta = 4.73/l$ ,  $l$  is the suspending length of the nanowire. Extract the amplitude and phase difference of the motion response as:

$$|H(j\omega)| = \frac{1}{\sqrt{\left(\frac{EI\beta^4}{\rho A} + \frac{0.5499T\beta^2}{\rho A} - \omega^2\right)^2 + \left(\frac{\eta}{\rho A}\omega\right)^2}} \quad (4)$$

$$\angle H(j\omega) = -\arccos \frac{\frac{EI\beta^4}{\rho A} + \frac{0.5499T\beta^2}{\rho A} - \omega^2}{\sqrt{\left(\frac{EI\beta^4}{\rho A} + \frac{0.5499T\beta^2}{\rho A} - \omega^2\right)^2 + \left(\frac{\eta}{\rho A}\omega\right)^2}} \quad (5)$$

As explained in equation (1), the driving electrostatic forces on the nanowire contains one static force and two alternating forces at two different frequencies of  $\omega$  and  $2\omega$ . Thus the motion response of the nanowire can be represented by:

$$Z(j\omega) = Z_0 \cdot H(j0) + Z_1 \cdot H(j\omega) + Z_2 \cdot H(j2\omega) \quad (6)$$

where  $Z_0 = \frac{1}{2}C'(V_g^{DC})^2 + \frac{1}{4}C'|\delta V_g|^2$ ,  $Z_1 = C'V_g^{DC}|\delta V_g|$ ,

$Z_2 = \frac{1}{4}C'|\delta V_g|^2$ . The nanowire motion goes into resonance at  $\omega_0/2$  and  $\omega_0$  according to the equation (6), where

$$\omega_0 = \sqrt{\frac{EI\beta^4}{\rho A} + \frac{0.5499T\beta^2}{\rho A}}$$

The vibration motion of the nanowire is self-detected by using the frequency mixer of the semiconducting nanowire and a lock-in detection method. The conductance change is proportional to the induced charge  $\delta Q$  in the nanowire:

$$\delta Q = C_g \cdot \delta V_g + V_g^{DC} \cdot \delta C + \delta C \cdot \delta V_g \quad (7)$$

Thus the conductance change is written as:

$$\delta G = \frac{\partial G}{\partial V_g}(\delta V_g + V_g^{DC} \cdot \delta C / C_g + \delta C \cdot \delta V_g / C_g) \quad (8)$$

where  $\partial G / \partial V_g$  is the transconductance of the semiconducting ZnO nanowire, which in our devices is typically 0.5-50  $\mu S/V$ . The first term in the equation (8) is induced directly by the AC gate voltage that is with zero phase difference. The later two terms are induced by the mechanical motion of the nanowire that produces the gate capacitance change  $\delta C = C' \cdot Z$ , which is proportional to the displacement of the nanowire  $Z(j\omega) = Z_0 \cdot H(j0) + Z_1 \cdot H(j\omega) + Z_2 \cdot H(j2\omega)$ .

The mixer scheme to detect the resonance is illustrated in Fig. 1 (b). An alternating voltage  $\delta V_{sd}(\omega - \Delta\omega)$  is applied to the top source electrode at a frequency offset from the high frequency gate voltage  $\delta V_g(\omega)$  by an intermediate frequency  $\Delta\omega$ . The signal  $\delta V_{sd}(\omega - \Delta\omega)$  mixes the conductance change of the nanowire that has alternating components at  $\omega$  and  $2\omega$ , which results in an output current at the top drain electrode with AC components at  $\Delta\omega$ ,  $\omega + \Delta\omega$ ,  $\omega - \Delta\omega$ ,  $3\omega - \Delta\omega$ . The AC current component at  $\Delta\omega$  is picked up through the lock-in amplifier while the other components are filtered. The lock-in current at  $\Delta\omega$  is induced from the conductance change components at  $\omega$  mixing with the source voltage  $\delta V_{sd}(\omega - \Delta\omega)$ . Three terms in equation (8) contribute to the alternating signals at  $\omega$ , but with different phase differences. The first one is a standard transistor gate effect directly induced by the AC gate voltage  $\delta V_g(\omega)$  with zero phase, the second one is induced by the mechanical motion component  $H(j\omega)$  with a phase of  $\angle H(j\omega)$ , and the third one contributes to an alternating conductance change at  $\omega$  that is the product of the mechanical motion component  $H(j2\omega)$  and the AC gate voltage  $\delta V_g(\omega)$  that is with a phase of  $\angle H(j2\omega)$ . Synthesizing the above three factors, the magnitude of the current extracted by the lock-in amplifier is given by:

$$|I_{lock-in}| = A_0 \sqrt{\left[A_1 + A_2 \cos \angle H(j\omega) + A_3 \cos \angle H(j2\omega)\right]^2 + \left[A_2 \sin \angle H(j\omega) + A_3 \sin \angle H(j2\omega)\right]^2} \quad (9)$$

where  $A_0 = \frac{1}{2} \frac{\partial G}{\partial V_g} |\delta V_{sd}|$ ,  $A_1 = L \cdot |\delta V_g|$ ,

$$A_2 = V_g^{DC} \cdot C' \cdot Z_1 \cdot |H(j\omega)| \cdot \frac{(\int_0^L Y(x) dx)^2}{\rho A \int_0^L Y^2(x) dx} / C_g,$$

$$A_3 = C' \cdot Z_2 \cdot |H(j2\omega)| \cdot |\delta V_g| \cdot \frac{(\int_0^L Y(x) dx)^2}{\rho A \int_0^L Y^2(x) dx} / (2C_g).$$

It is

noted that some smaller factors have been omitted in equation (9).

#### 4. PRIMARY EXPERIMENTS AND ANALYSIS

The experimental measurements on the amplitude frequency of the lock-in current that responds to the motion of the oscillator at different pressure conditions from atm. ( $10^5$ Pa) to 1.3Pa at  $\delta V_{sd} = 0.1V$ ,  $\delta V_g = 0.1V$ ,  $V_g^{DC} = 1V$  are given in Fig. 2. Figure 3 shows the corresponding theoretical predication of the current response of the nanowire with a length  $L = 12\mu m$ , and a diameter  $d = 500nm$  at  $\delta V_{sd} = 0.1V$ ,  $\delta V_g = 0.2V$ ,  $V_g^{DC} = 0.1V$  in the air environment based on equation (9). From both of the experimental measurement and the theoretical prediction, two peaks are observed in the frequency response of the current at  $\omega_0/2$  and  $\omega_0$  respectively, which are both correlated with the mechanical fundamental resonance of the nanowire at the frequency of  $\omega_0$ . The fundamental frequency of the oscillator is measured and estimated to be around 24 MHz. Nevertheless our oscillator now provides a poor quality factor even working in a vacuum environment shown in Fig. 2, which maybe due to an unsatisfied clamping mode on the two ends of the nanowire that needs to be further improved in our future works. The poor clamping effect on the quality factor of the oscillator was also reported by other researchers [2].

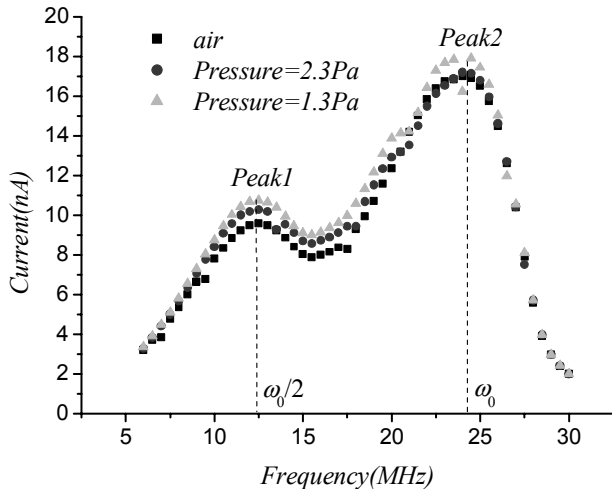


Figure 2: Experimental measurements of current responses of the device at different pressures.

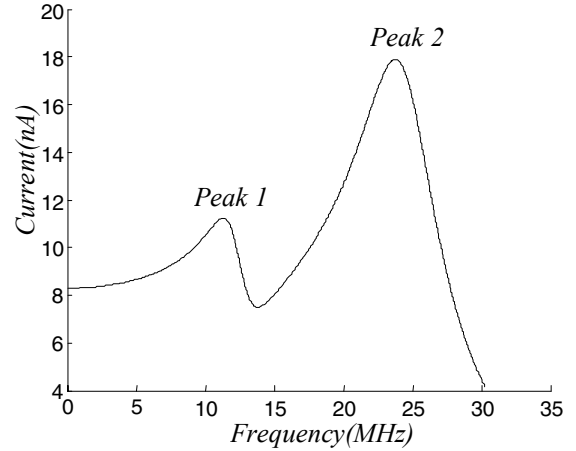


Figure 3: Theoretical predication for the current response of the device.

Equation (9) indicates that the first peak at  $\omega_0/2$  is dependent on  $A_3$  that is in the third power of the AC gate voltage and the second peak at  $\omega_0$  is dependent on  $A_2$  that is in the second power of the DC gate voltage. Equation (9) also indicates that the total current can be lifted up by increasing the magnitude of the AC gate voltage that is related with  $A_1$ . Figure 4 and 5 give the theoretical predictions for the current dependence on the AC and DC gate voltages. The practical measurement results of the current depending on the AC and DC gate voltages are shown in Fig. 6 and Fig. 7. It is obvious that the practical measurements related with the AC gate voltage in Fig. 4 accords well with the theoretical prediction in Fig. 6, but the measurements on the DC gate voltage is dissimilar between Fig. 5 and Fig. 7. We suspect that the DC potential on the nanowire is correlated with several coupling factors that have not yet been concerned in the theoretical prediction, such as work function differences between the nanowire and the metallic electrodes, the band-bending between two polar surfaces of ZnO nanowires, and otherwise. More detailed researches are required to be done to understand the evidence.

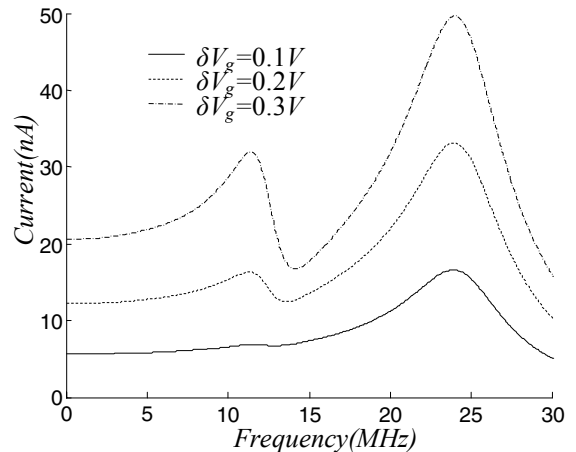


Figure 4: Theoretical prediction for current dependence on AC gate voltage at  $\delta V_{sd} = 0.1V$ ,  $V_g^{DC} = 0.2V$ .

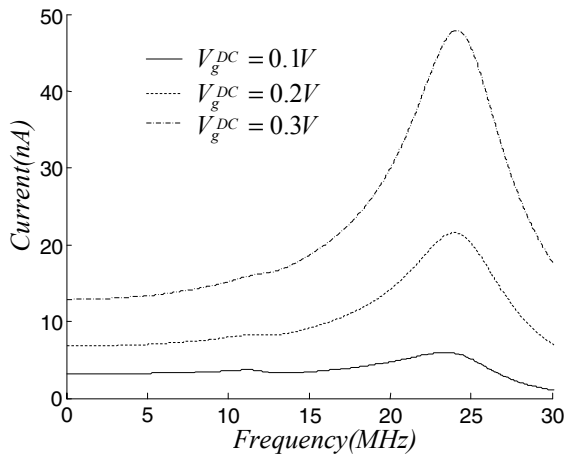


Figure 5: Theoretical prediction for current dependence on DC gate voltage at  $\delta V_{sd} = 0.1V$ ,  $\delta V_g = 0.2V$ .

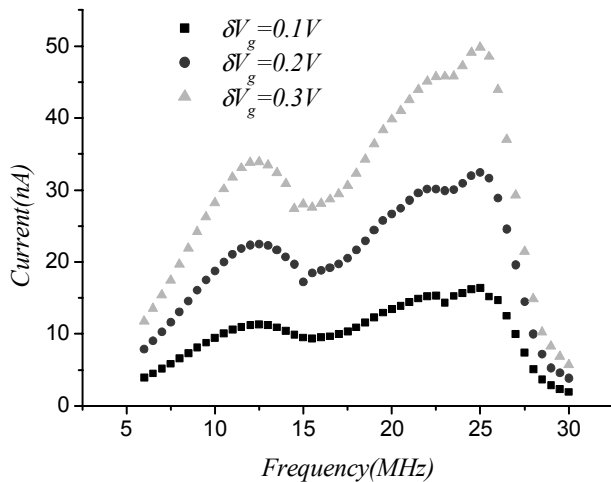


Figure 6: Experimental measurements of the current dependence on AC gate voltage at  $\delta V_g = 0.1V$ ,  $V_g^{DC} = 0V$ .

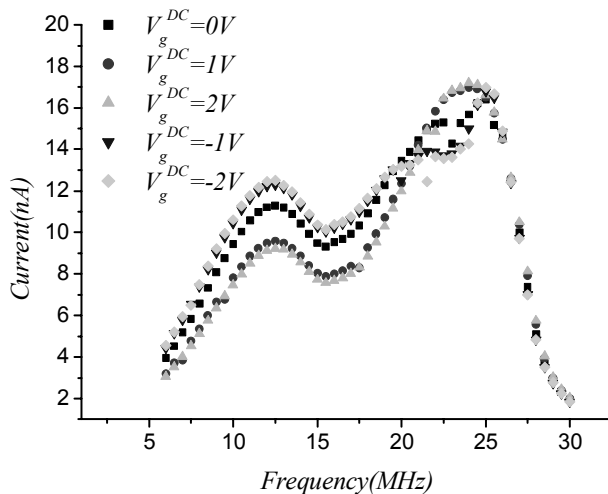


Figure 7: Experimental measurements of the current dependence on DC gate voltage at  $\delta V_{sd} = 0.1V$ ,  $\delta V_g = 0.1V$ .

Compared with other oscillators using such as carbon

nanotubes [1-2], the resonance of our oscillator based on ZnO nanowire can be self-detected in the air environment and its electromechanical response is greatly enhanced, specifically the detected current of the carbon nanotube oscillator was reported on the order of pA, while that of the ZnO nanowire measured in our device is typically on the order of nA. The reason for this enhancement might be due to the perfect single crystalline and freedom of dislocation of the ZnO nanowire.

## 5. CONCLUSIONS

The paper has demonstrated a novel nanoelectromechanical oscillator using a single suspending semiconducting ZnO nanowire. The oscillator is self-driven and self-detected in an air environment by the aid of a FET configuration and lock-in detection methodology. The resonant frequency of the oscillator reaches tens of megahertz. The current response of the oscillator detected by the lock-in amplifier can be adjusted by the AC and DC gate voltages. Compared with other NEMS oscillators, the enhanced electromechanical traits can significantly improve the device's feasibility for practical applications. The oscillator can be potentially used for actuators and sensors.

## ACKNOWLEDGMENT

The authors thank Zhonglin Wang at the Georgia Institute of Technology, U.S.A. for providing samples of ZnO nanowires. This work is financially supported by National Natural Science Foundation of China Project (50575113) and Program for NCET.

## REFERENCES

- [1] V. Sazonova, Y. Yaish, H. Ustunel, D. Roundy, A tunable carbon nanotube electromechanical oscillator, *Nature*, vol. 431, pp. 284-287, 2004.
- [2] B. Witkamp, M. Poot, H. S. J. Zant, Bending-Mode Vibration of a Suspended Nanotube Resonator, *Nano Letter*, vol. 6, pp. 2904-2908, 2006.
- [3] M. S. Arnold, P. Avouris, Z. W. Pan, Z. L. Wang, Field-Effect Transistors Based on Single Semiconducting Oxide Nanobelts, *J. Phys. Chem. B*, vol. 107, pp. 659-663, 2003.
- [4] X. D. Bai, E. G. Wang, P. X. Gao, Z. L. Wang, Dual-mode electromechanical resonance of individual ZnO nanobelts, *Applied Physics Letters*, vol. 82, pp.4806-4808, 2003.
- [5] E. Comini, G. Faglia, G. Sberveglia, Z. W. Pan, Z. L. Wang, Stable and highly sensitive gas sensors based on semiconducting oxide nanobelts, *Applied Physics Letters*, vol. 81, pp. 1869-1871, 2002.
- [6] W. P. Zheng, R. D. Zu, Z. L. Wang, Nanobelts of Semiconducting Oxides, *Science*, vol. 291, pp.1947-1949, 2001.
- [7] X. Q. Chena, T. Saito, H. Yamada, K. Matsushige, Aligning single-wall carbon nanotubes with an alternating-current electric field, *Applied Physics Letters*, vol. 78, pp. 3714-3716, 2001.
- [8] D. Q. Wang, R. Zhu, Z. Y. Zhou, X. Y. Ye, Controlled assembly of zinc oxide nanowires using dielectrophoresis, *Applied Physics Letters*, vol. 90, pp. 103110, 2007.