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A self-tuning mechanism of zinc oxide nanoelectro-mechanical resonator based on joule heating

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Abstract

This paper has demonstrated a doubly clamped zinc oxide nanowire resonator to illustrate the self-tuning mechanism of resonant frequency based on joule heating. From the theoretical analysis, it is observed that the resonant frequencies are related with thermal expansion coefficient α, Young's modulus E, thermal conductivity k, density ρ, side length a, and length l of the beam, as well as external parameters such as input electrical power P. Clearly one of approaches to achieve tuning of resonant frequencies of the beam is to adjust the externally applied electrical power P. From both numerical calculations, it is found that the resonant frequency varies from 54.45 MHz to 140.91 MHz, with the temperature increased from 294.92 K to 1587.92 K.

Keywords: Self-tuning; Zinc Oxide; Nanoelectromechanical resonator; Joule heating

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1. Introduction

Recently, there has been research interest on the study of nanoscale detection and thermal transport in nanoelectromechanical systems [1] [2]. Several types of nanoresonators such as cantilevers [3] [4], fixed-fixed beams [5], ring shape nanowire resonators [6], carbon nanotubes [7] have been investigated by researchers. However, most of the above works mainly concentrated on deriving the relation of the resonant frequency and effective mass, joule heating effects of the resonators were neglected. The frequency-tuning ability of nanowire resonator is crucial for its application in mechanical signal processing, compensation for variability in manufacturing and thermal drift, etc. Although many tuning

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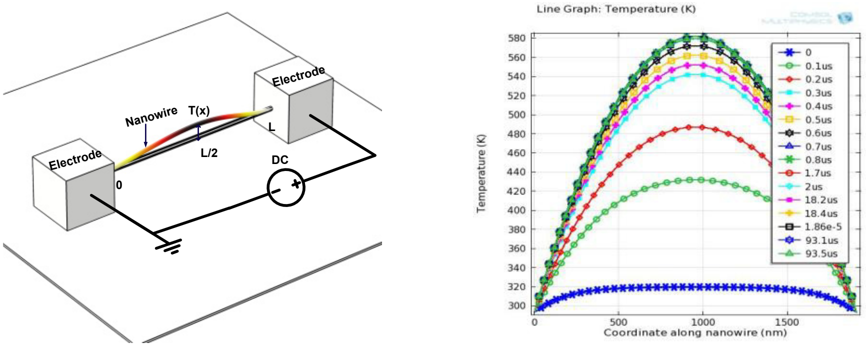
methods have been mentioned previously, self-tuning mechanism based on joule heating has greater potential in reducing system's complexity and improving system operation flexibility.

Here self-tuning of a fixed-fixed ZnO nanowire resonator based on joule heating is proposed. Figure 1(a) is the schematic diagram of doubly clamped nanowire, where two anchors also serve as electrodes. When applying direct current bias across the nanowire, the temperature of the nanowire will be increased under joule heating. The heat in the nanowire causes thermal expansion and thermal stress, which in turn changes resonant frequencies. A combined analytical and FEM model of the system is used to predict the relation of temperature and resonant frequencies, in particular the fundamental resonant frequency.



(a) (b)

Fig. 1: (a)Schematic of doubly clamped nanowire resonator under Joule heating, which could be coupled with thermal stress and mechanical stress; (b) Temperature distribution along nanowire under different response time.

2. Theoretical study

When the biased voltage is applied between the two electrodes, it will induce the resistive heating, and temperature along the nanowire can be expressed as the function of time and position, $T(x,t)$. Then combining with heat equation of joule heating model, the electro-thermal coupling model is given and shown as equation (1),

$$\rho C_p \frac{\partial T}{\partial t} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) = \dot{Q} \qquad (1)$$

Combining with Fourier's law, it is easy to obtain the one-dimensional steady state heat diffusion equation for the nanoresonator. Since the transverse expansion hardly affects the volume and inertial moment, these parameters and $\dot{Q}$ can be treated as constant values when input power is given. Because the thermal conductivity of both the electrodes is good enough to dissipate the heat into environment, the temperature on both of them can be treated as fixed room temperature, i.e. $T(0,t) = T(L,t) = T_{room}$. Combining with these boundary conditions, the temperature distribution along the nanowire is a parabolic shape and with highest temperature at the midpoint. Therefore, internal thermal strain will be induced because of changes in temperature along the longitude of nanowire. Based on the relationship of stress and strain, the thermal stress could be yield as (2)

$$\sigma_t = -E\alpha\Delta T = -E\alpha\left(\frac{P}{2kA}x - \frac{P}{2kV}x^2\right) \qquad (2)$$

Where α is the resistivity temperature coefficient, E is young's modulus. If the transverse deflections of the zinc oxide nanowire are very small, the resonant frequency can be found taken into consideration of the axial load [8], which is caused by thermal stress. The resonant frequency f_0 of fixed fixed beams under no biased voltage and resonant frequency f_t under biased voltage is shown as formulas (3)

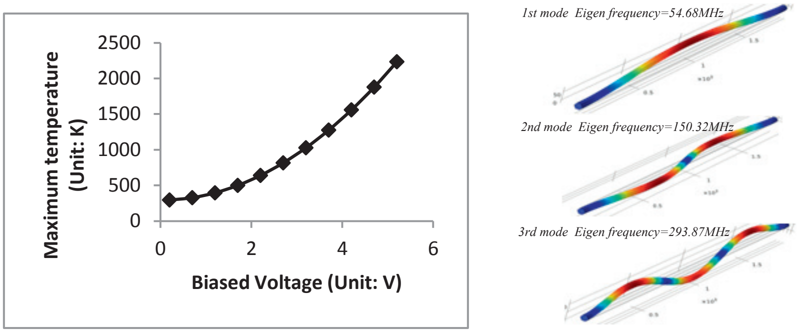
$$f_0 = 1.626\frac{a}{L^2}\sqrt{\frac{E}{\rho}} \quad f_t = f_0\sqrt{1+\frac{6\sigma_a L^2}{5\pi^2 E a^2}} \tag{3}$$

From the above formulas, it can be seen that the resonant frequencies are related with a, L, E, ρ, α, k, and P. σ_a is the average thermal stress of the beam. It is seen from the equation (3) that the self-tuning mechanism can be achieved by adjusting the input electrical power P of the fixed-fixed beam system.

3. Finite element simulation

In order to prove the effectiveness of the self-tuning mechanism, simulation is conducted using the commercial multidisciplinary finite element software COMSOL 4.2. The geometry of the ZnO nanowire cross section is modeled as regular hexagon. The side length is 20 nm, and length of the nanowire is 1.91µm. Material property of Zinc Oxide nanowire is selected in COMSOL material library.

It is first to conduct time dependent analysis of the nano resonator under DC biased voltage. Nanowire is set to be fixed at both two ends. One of the ends is electrically grounded; and the other end is set to 2 V. In addition to this, the temperatures at both two electrodes are set to be 293 K. Through the simulation, the temperature versus the arc length under different response time is shown as figure 1(b). Based on the time dependent simulation, voltage V is selected as the swept parameter to conduct the further simulation. V varies from 0.2 V to 5.2 V, while other boundary conditions are the same as previous simulations. Figure 2(a) is the result that shows the relationship between maximum temperature and biased voltage.



(a) (b)

Fig. 2 (a) Maximum temperature versus different biased voltages (b) Mode shapes of Zinc Oxide nanowire resonator in simulation,where thermal effect is considered, 1st mode Eigen-frequency=54.68MHz; 2nd Eigenfrequency=150.32MHz; 3rd Eigenfrequency=293.87MHz

Furthermore, Eigen frequency analysis is conducted using COMSOL. In the simulation, the thermal stress and strain are considered as boundary conditions. The initial stress and strain are calculated to be 241.2×10^6 Pa and 1.149×10^{-3} when applied voltage is 2 V using equation (2). Then the simulated first three resonant frequencies of the beam are 54.68MHz, 150.32MHz and 293.87MHz respectively. Compared with the results of 54.59MHz, 150.22MHz and 293.8MHz that do not take thermal strain and stress into consideration, it is found that the resonant frequencies of nanowire resonator are increased around 10^5 Hz. Figure 2(b) are the mode shapes of ZnO nanowire resonator, and the corresponding frequencies are 54.68MHz, 150.32MHz and 293.87MHz respectively. Combining with joule heating analysis, the tuned fundamental frequency can be rewritten as the function of average temperature. Using equation (3), the fundamental resonant frequencies of the beam under the applied voltage of 2 V are calculated to be 73.75 MHz, compared with resonant frequency 54.22 MHz that do not take thermal stress into consideration, which presents an obvious shift in resonant frequency. In addition, it is easy to draw the varying trend between resonant frequency and average temperature, which is shown as figure 3. From figure 3 it is easy to observe that resonant frequency of Zinc Oxide nanowire resonator is monotonously increased with temperature.

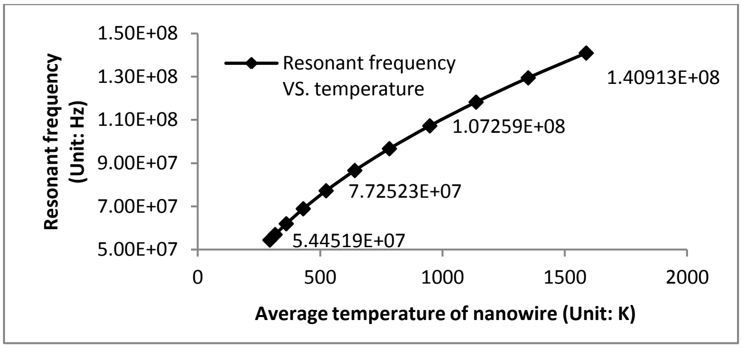


Figure 3 Resonant frequency data of Zinc Oxide nanowire resonator with increasing temperature.

4. Conclusion

Theoretical study of the frequency self-tuning mechanism which includes both joule heating and thermal dynamic models has been introduced for the clamped-clamped ZnO nanoresonator. The principle of the frequency tuning is based on temperature dependence of the thermal stress inside the resonator. The equation for calculating the change of fundamental resonant frequency of a hexagon shaped ZnO nanowire upon different average temperature has been derived, and calculation results for a given ZnO nanowire has been obtained. It is found from the theoretical analysis that resonant frequency of a doubly clamped nanoresonator could be shifted from 54.45 MHz to 140.91 MHz, with the average temperature increased from 294.92 K to 1587.92 K.

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