第 17 卷　第 6 期
2009 年 6 月

光学 精密工程
Optics and Precision Engineering

Vol. 17　No. 6
Jun. 2009

文章编号　1004-924X(2009)06-1279-07

基于氧化锌纳米线的硅谐振式加速度计

陈国炜[1,2]，朱　荣[2]

（1. 中北大学 电子测试技术国家重点实验室，山西 太原 030051；
2. 清华大学 精密仪器及机械学系 精密测试技术及仪器国家重点实验室，北京 100084）

摘要：设计制作了一种基于氧化锌纳米线的谐振式硅加速度计，该加速度计的敏感单元为由氧化锌纳米线横跨金属微电极组成的谐振器。采用介电电泳的方法组装了氧化锌纳米线，并利用 FIB 沉积 Pt 将氧化锌纳米线固定在微结构上以确保结构的可靠性。在加速度的作用下，质量块引起的惯性力通过支撑梁对纳米线施加应力，因此，在谐振条件下，纳米线谐振频率的变化反映了加速度的大小。谐振式加速度计的准数字输出能解决多数 MEMS 器件输出微弱信号检测难的问题。实验结果表明，加速度计的灵敏度随着纳米线的厚度的减小而急剧增加，选择 500 nm 厚度的纳米线作为理论分析，加速度计的灵敏度可达 2.5 kHz/g 以上。

关　键　词：氧化锌纳米线；微机电系统；加速度计；谐振器；介电电泳

中图分类号：TH824.4　　**文献标识码：**A

Silicon micromachined resonant accelerometer based on ZnO nanowire

CHEN Guo-wei[1,2], ZHU Rong[2]

(1. *National Key Laboratory for Electronic Measurement Technology, North University of China, Taiyuan* 030051; 2. *State Key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instruments and Mechanology, Tsinghua University, Beijing* 100084, *China*)

Abstract: A design and fabrication method for a silicon micromachined resonant accelerometer based on a zinc oxide (ZnO) nanowire is reported. The key and sensitive element of the accelerometer is a nanowire-based resonator with a single ZnO nanowire suspended across two micromachined Cr/Au electrodes. A dielectrophoresis technique is used to assemble the ZnO nanowire onto electrodes, then a Focused Ion Beam (FIB) is employed to deposit Pt on the contact between the nanowire and electrodes to clamp the nanowire and eliminate the Schottky barriers at the interfaces. When an external acceleration is applied, the inertial force generated by the proof mass imposes a stress on the nanowire through the beams that support the suspended proof mass. Consequently, the acceleration is associated with the shift in the resonant frequency of the nanowire. By its quasi-digital output, the trouble in detecting feeble analog signals from most MEMS devices could be averted. Experimental results show

---

Received date: 2009-01-20; **Revised date:** 2009-04-30.

Foundation item: Supported by the National Natural Science Foundation of China Project (Grant No. 50575113) and the Program for NCET

that the sensitivity of the accelerometer increases dramatically with the decrease of the nanowire's thickness. In the design, nanowire with a thickness of 500 nm is selected for the theoretical analysis, and the sensitivity of the acceleration sensor is estimated to be more than 2.5 kHz/g.

Key words: ZnO nanowire; MEMS; accelerometer; oscillator; dielectrophoresis

1 Introduction

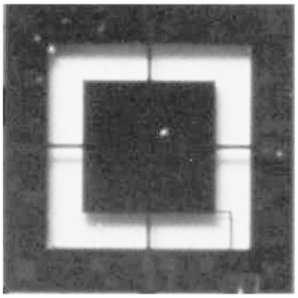
Silicon micromachined accelerometers have been developed and widely used in many applications due to their small size, batch fabrication and low cost[1]. The micromachined accelerometers can cover a wide measurement range from sub-gravity to tens of thousands gravities. Accordingly, the wide application fields of the micromechanical accelerometers include automotive air bags, vehicle stabilization systems, navigation and guidance systems, seismometry for oil exploration, earthquake prediction, shock and vibration detection, etc.

Micromachined accelerometers can be categorized into piezoresistive accelerometers, capacitive accelerometers and resonant accelerometers based on sensing principles. Piezoresistive accelerometers have the advantages of simple structure and low cost but have poor resolution accuracy and sensitivity to temperature variations. Capacitive accelerometers are insensitive to temperature variations, easy for interfacing with circuits and have better resolution and accuracy than piezoresistive ones. In this paper, a novel silicon micromachined resonant accelerometer by using ZnO nanowire-based resonators is presented. Resonant sensors have excellent performance[2], such as wide dynamic range, the quasi-digital nature of the output signal and the inherent continuous self-test capability. Furthermore, the upper bound of the dynamic range is limited by the measurement time, and increasing the measurement time automatically results in a larger dynamic range. The digital output signal can be directly connected to digital signal processing electronics. Therefore, the resonant sensing method can be a good candidate to implement a high resolution accelerometer for a navigational application.

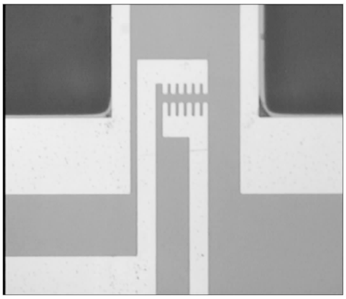
2 Design of accelerometer structure

In this paper, a novel micromachined resonant accelerometer based on zinc oxide (ZnO) nanowires with a quad-beam and a proof mass is reported, as shown in Fig. 1 (a). The sensitive element of the accelerometer is a nanowire-based resonator with a single ZnO nanowire suspended across two micromachined Cr/Au electrodes, which are located at the root of the silicon beams where the stress induced by the acceleration of the mass are maximal, as shown in Fig. 1(b) and (c).

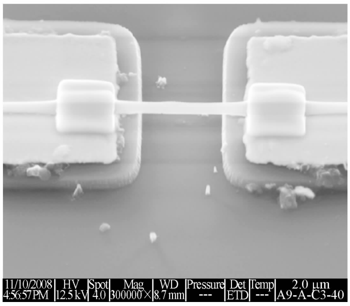
The nanowire is electrostatically driven into a motion using the alternating electrostatic interaction with the gate electrode underneath the nanowire. The driving signal frequency ω is swept and the vibrational motion of the nanowire will reach resonance if the driving frequency ω catches the fundamental frequency ω_0 of the nanowire. When an external acceleration is applied, the inertial force generated by the proof mass imposes a stress on the nanowires through the beams that support the mass. The stress will change the resonant frequency of the nanowire, and thus the acceleration is associated with the shift in the resonant frequency of nanowire.



(a) Fabricated accelerometer



(b) Enlargement of electrodes on beams



(c) SEM image of nanowire-based resonator

Fig. 1 Micromachined resonant accelerometer

3 Stress analysis and parameter design

The relationship between the structure parameters and the stress in the beam is theoretically analyzed, and therefore the sensitivity of the sensor depending on the structure parameters is obtained. When an external acceleration is applied, the beam bends. The bend induces a strain along the beam, which is transferred to the nanowire, and thus produces a stress in the nanowire. According to the mechanics theory, the stress T in the nanowires can be deduced as:

$$T=\frac{3mal_1E}{4b_1h_1^2E_1}b_2h_2, \tag{1}$$

where m is the mass; I_1, b_1, h_1 are the length, width and thickness of the silicon spring beam respectively; b_2, h_2 are the width and thickness of the nanowire respectively, Young's modulus $E=210$ GPa for a ZnO nanowire; $E_1=160$ GPa for the silicon spring beam. The fundamental frequency of the suspended nanowire is[3-4],

$$\omega_0=\sqrt{\frac{\beta^4EI+0.549\,9T\beta^2}{\rho A}}, \tag{2}$$

where ρA is the nanowire mass density ($\rho=5.606\times10^3$ kgm^{-3} for a ZnO nanowire), EI is the nanowire's bending rigidity, $I=b_2h_2^3/12$, $\beta=4.73/l_2$, and l_2 is the length of the nanowire. Thus the sensitivity of the accelerometer is given by

$$\Delta f=\frac{0.454\,8ml_1E}{4b_1h_1^2h_2E_1}\sqrt{\frac{1}{\rho E}}. \tag{3}$$

The results show that the sensitivity is directly proportion to the size of the proof mass and the length of the spring beam, and inverse proportion to the width, the square of the thickness of the spring beam and the thickness of the nanowire, as shown in Fig. 2.

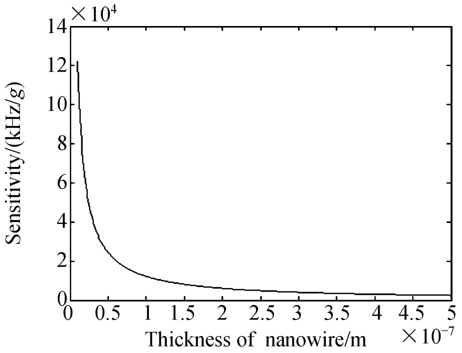


Fig. 2 Relationship between thickness of nanowire and sensitivity

From the figure, we can see that when the thickness of the nanowire is less than 500 nm, the sensitivity of the accelerometer will increase dramatically with the decrease of the nanowire's thickness. The nanowires are mostly with a length of $1-15$ μm and a thickness of 10-500 nm, so the thickness of 500 nm is chosen for the theoretical analysis, and the sensitivity of the sensor is estimated to be 2.5 kHz/g.

Modeling and simulating results of the quad-beam resonant accelerometer are gained by using ANSYS. By the theoretical analysis and simulation, the structural parameters are optimally designed. Finally, the accelerometer structural parameters are shown in Tab. 1.

Tab. 1 Structural parameters of accelerometer

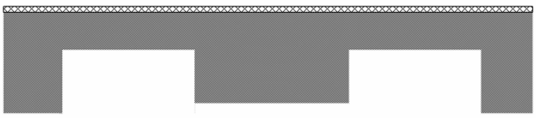
	parameters(μm)		
	length	width	thickness
proof mass	3 000	3 000	340
spring beam	750	120	40

4 Fabrication process and assembly of accelerometer

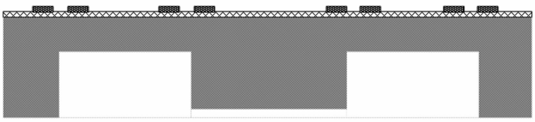
The fabrication process flow for realizing the accelerometer is shown in Fig. 3. The micromachining process is used to form the supporting beams and the proof mass of the accelerometer, also used to form the electrodes which are constructed similarly as a field effect transistor (FET) configuration. Firstly, a phosphorus-doped (P-doped) silicon is used as the substrate, and a shallow trench and a deep trench from the backside of the substrate are etched to form the proof mass structure. The depth of the shallow trench is defined by the thickness of the proof mass, and the depth of the deep trench is defined by the thickness of the beam. Secondly the silicon is covered by a SiO_2 layer formed by thermal oxidization. Thirdly, a Cr/Au film is sputtered

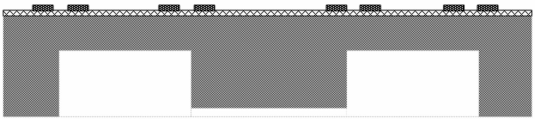

(a) Shallow trench etching

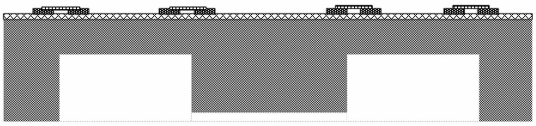

(b) Deep trench etching


(c) Thermal oxidization


(d) Sputter Cr/Au film


(e) Mask and etch Cr/Au film to form electrodes


(f) ICP etch to form supporting beams


(g) Assembly of zinc oxide nanowires

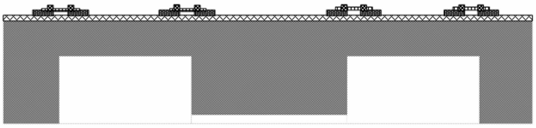
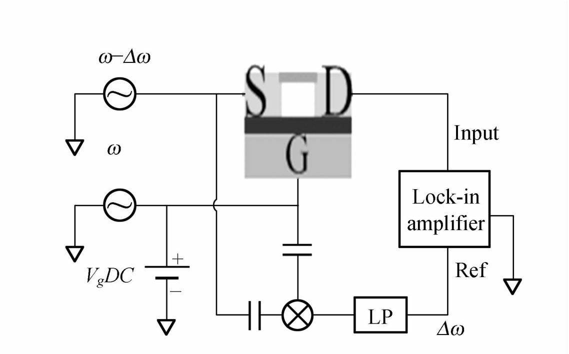

(h) Pt deposition

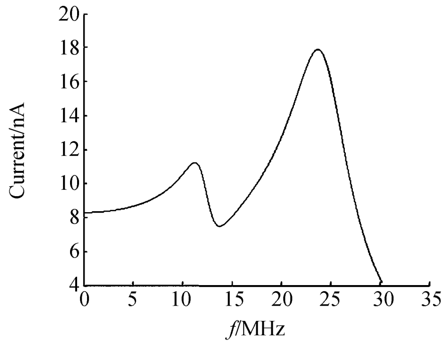
Fig. 3 Fabrication process flow of the accelerometer onto the SiO_2 layer, and then it is masked and etched to form the top two electrodes that are a pair of comb-like electrodes with multiple face-to-face narrow fingers. Finally, the silicon wafer is etched out from the front side using a ICP method to form the beam structure. Up to now the basic structure of the accelerometer is formed. Using a field effect transistor (FET) terminology, the top two electrodes are defined as the source and drain and the bottom silicon substrate as the gate. The following important step is the assembly of zinc oxide nanowires. The ZnO nanowires used in the device are synthesized by thermal evaporation of ZnO powders under controlled conditions without the presence of a catalyst[5]. The dielectrophoresis technique is used to assemble ZnO nanowires onto electrodes[6]. A drop of the nanowire-containing solvent is dispensed onto the prepared wafer with the electrodes and the appropriate alternating (AC) voltage is applied to the two top electrodes. An electric field is generated by the voltage between source and drain, and then it generates a dielectrophoretic force to trap and align a single nanowire on the electrodes. Here the alternating (AC) voltage 15 V at a frequency of 10 MHz is used. After the assembly, focused ion beam (FIB) is employed to deposit Pt on the contact between the nanowire and electrodes in order to clamp the nanowire and eliminate the Schottky barriers at the interfaces[7]. A near Ohm-contact is formed between the ZnO nanowire and the Au electrode by this post-treatment. The fabricated accelerometer and the scanning electron microscope (SEM) of the nanowire-based resonator are shown in Fig. 1.

5 Measurement set-up of oscillator

The oscillator is electro-statically driven into a motion. A combination driving signal of a static voltage (DC) V_gDC and a time varying voltage (AC) δV_g at a high frequency of ω is applied to the gate electrode underneath the nanowire. Here which induces an electrostatic force on



(a) The measurement set-up of the resonator (An AC voltage with frequency ω is applied on the gate electrode to drive the nanowire into motion. Another AC voltage with frequency $\omega-\Delta\omega$ is applied to the source electrode; it mixes with the alternating change in the conductance of the nanowire that is induced by the motion to generate an alternating current at $\Delta\omega$ and is detected by the lock-in amplifier through the drain electrode.)



(b) Theoretical current response of resonator

Fig. 4 Schematic and theoretical current response of resonator the nanowire, the frequency ω is swept from 1 MHz to 30 MHz in our experiments. The vibrational motion of the nanowire is self-detected by using the FET configuration frequency mixer and a lock-in detection method[8]. The frequency mixer detection helps to avoid the complication due to capacitive currents between the gate and the drain/source electrodes. An alternating voltage δV_{sd} with the high-frequency of $\omega-\Delta\omega$ is applied to the top source electrode at a frequency offset from the gate voltage $\delta V_g(\omega)$ by an intermediate frequency $\Delta\omega$. A frequency of 30 kHz is used in our experiments. The signal $\delta V_{sd}(\omega-\Delta\omega)$ mixes the conductance change of the nanowire which is proportional to the induced charge in the nanowire due to its motion. The lock-in amplifier picks up an AC current with the frequency of $\Delta\omega$ which is induced from the frequency mixer, as shown in Fig. 4(a). According to the research of the nanowire oscillator[9], the nanowire motion goes into resonance at two driving frequency points of $\omega_0/2$ and ω_0 theoretically, as shown in Fig. 4(b). An experimental measurement on the fabricated accelerometer is still in progress.

6 Conclusions

Due to the quasi-digital output of the frequency shift of the nanowire associated with the acceleration, the trouble in detecting feeble analog signals from most MEMS devices could be resolved. For the nanowires mostly with a length of 1—15 μm and a thickness of 10—500 nm, the thickness of 500 nm is chosen for the theoretical analysis, and the sensitivity of the accelerometer sensor is estimated to be 2.5 kHz/g.

References:

[1] ROYLANCE L M, ANGELL J B. A batch-fabricated silicon accelerometer [J]. *IEEE Trans. On Electron Devices*, 1979,26:1911-1917.

[2] ZACHARY J, WINNIE S, ANJA B. Design, fabrication and testing of a novel MEMS resonator for mass sensing applications [J]. *Microelectronic Engineering*, 2007,84:1601-1605.

[3] USTUNEL H, ROUNDY D, ARIAS T A. Modeling a suspended nanotube oscillator[J]. *Nano Lett*, 2005(5):523-526.

[4] BAO M H. *Analysis and Design Principles of MEMS Devices* [M]. Elsevier, 2005.

[5] PAN Z W, DAI Z R, WANG Z L. Nanobelts of semiconducting oxides [J]. *Science*, 2001, 291: 1947-1949.

[6] WANG D Q, ZHU R, ZHOU Z Y, *et al.*. Controlled assembly of zinc oxide nanowires using dielectrophoresis [J]. *Applied Physics Letters*, 2007,90:103-110.

[7] ARNOLD M S, AVOURIS P, PAN Z W, *et al.*. Field-effect transistors based on single semiconducting oxide nanobelts [J]. *Phys. Chem*, 2003,107: 659-663.

[8] SAZONOVA V, YAISH Y, USTUNEL H, *et al.*. A tunable carbon nanotube electromechanical oscillator [J]. *Nature*, 2004,1431:284-287.

[9] ZHU R, WANG D Q, XIANG S Q, *et al.*. Modeling and experimental study of nanoelectromechanical oscillator using single zinc oxide nanowire [C]. *IEEE International Conference on Micro Electro Mechanical Systems* (*IEEE MEMS*), 2008: 746-749.

Authors' biographies:

CHEN Guo-wei (1983－), male, conducts research at the National Key Laboratory for Electronic Measurement Technology, North University of China. His research interests are nanowires and MEMS/NEMS devices. **E-mail**: chenguowei.cool@163.com

ZHU Rong(1968－), female, Ph. D., professor of the State Key Laboratory of Precision Measurement Technology and Instruments, Department of Precision Instruments and Mechanology, Tsinghua University, her research interests are Nano/MEMS sensors and systems, navigation and control. **E-mail**: rong_zhu@263.net

---

●下期预告

Hα 和白光望远镜的热光学试验

吴明长[1,2],杨世模[1],陈志远[1],古学东[1],王 慎[1]

(1.中国科学院 国家天文台,北京 100012;2.中国科学院 研究生院,北京 100049)

Hα 和白光望远镜(HWT)是中国空间太阳望远镜(SST)有效载荷之一,为研究 HWT 的光学性能受温度环境的影响,在进行地面观测工况下温度场测量和数值模拟的基础上,确定了热光学试验的温度控制工况。建立了一套热真空状态下的光学性能检测系统,该系统由被测光学系统、真空系统、温度测量和控制系统以及波前检测系统组成。研究了系统中光楔镜结构、副镜结构、主镜结构、准直镜结构和成像镜结构这 5 个关键部位在不同温度控制工况下的系统光学性能。试验结果表明,在副镜结构温度不高(低于 40 ℃)的情况下,HWT 望远镜在地面观测工况下的光学性能约为 λ/8,可以满足 λ/6 的设计要求。以 HWT 为研究对象,实施了 Hα 和白光望远镜的热光学试验过程,实现了对不同温度控制工况下的 HWT 系统进行光学性能检测的试验目标。本文探索的热光学试验思路和方法也适用于其它用于太阳观测的光学望远镜。