Journal of Southeast University (English Edition) Vol. 28, No. 3, pp. 310 - 314 Sept. 2012 ISSN 1003—7985

Frequency response of a new kind of silicon nanoelectromechanical systems resonators

Yu Hong Yuan Weimin Liu Chunsheng Yue Dongxu
Wu Shijie Gu Yong Chen Zhiyuan Huang Qing'an

(Key Laboratory of MEMS of Ministry of Education, Southeast University, Nanjing 210096, China)

Abstract: Diffraction effects will bring about more difficulties in actuating resonators, which are electrostatically actuated ones with sub-micrometer or nanometer dimensions, and in detecting the frequency of the resonator by optical detection. To avoid the effects of diffraction, a new type of nanoelectromechanical systems (NEMS) resonators is fabricated and actuated to oscillate. As a comparison, a doubly clamped silicon beam is also fabricated and studied. The smallest width and thickness of the resonators are 180 and 200 nm, respectively. The mechanical oscillation responses of these two kinds of resonators are studied experimentally. Results show that the resonant frequencies are from 6.8 to 20 MHz, much lower than the theoretical values. Based on the simulation, it is found that over-etching is one of the important factors which results in lower frequencies than the theoretical values. It is also found that the difference between resonance frequencies of two types of resonators decreases with the increase in beam length. The quality factor is improved greatly by lowering the pressure in the sample chamber at room temperature.

Key words: nanoelectromechanical system; resonant frequency; over-etching; nano-beam

doi: 10.3969/j.issn.1003 - 7985.2012.03.010

Nanoelectromechanical systems (NEMS) resonators are of growing interest, since they have very high fundamental resonance frequencies, minuscule active masses, and extremely low power consumption[1-2]. They can be applied in fields such as RF signal generation and ultrasensitive detection of displacement, force, and mass[3-10]. NEMS resonators in doubly clamped beam type made of SiC with fundamental resonance frequencies ranging from very high frequency (VHF), ultrahigh high frequency (UHF) to microwave frequency were fabricated successfully in 2005[3] and 2008[10], and later the generation of high frequency was realized by doubly-clamped silicon nanowires, which were fabricated by a developed hybrid process[4-5]. The highest frequency silicon nanocantilever with an oscillating frequency of 1.04 GHz was reported in 2008[11]. It is expected that the resonant frequency will increase moreover when the dimension of a resonator beam keeps decreasing into several nanometers. In nanoelectromechanical mass detection, the first demonstration of mass spectrometry based on single biological molecule detection was reported in 2009[6]. The mass sensitivity of the sensors is described as $\delta m \approx 2M_{\mathrm{eff}}\delta\omega/\omega_0$, which means that the effective vibratory mass of the resonator M_{eff} and the minimum resolvable frequency shift $\delta\omega_{\min}$ by the measurement circuitry determine the ultimate mass sensitivity $\delta m_{\min}$[2]. Therefore, the realization of smaller structures with smaller mass and higher frequency is highly desired either in high frequency signal processing or in ultra-sensitive mass detection.

However, when the dimensions of the beam, say the width and the thickness, shrink down to the deep submicron, it brings about some problems and challenges for actuating and detecting the motion of the beam. For example, it becomes more difficult to detect the vibration of the beam resonator by optical detection, since the photo current in the photo detector is proportional to the reflection light, i.e. $I_{\mathrm{ac}} \propto \sqrt{I_{\mathrm{m}}}$[12]. If the size of the beam is too small, the reflected light will be too weak to be received by the detector. On the other hand, the strong diffraction effects emerge as the relevant NEMS dimensions are reduced beyond the optical wavelength[13], and the detection sensitivity will be determined not only by the width of the resonant beam but also by the gap between the suspended beam and the substrate. Moreover, for the electrostatically actuated beam, the force may not be large enough to actuate the nano-resonant beam, since the force is proportional to the dimension of the beam. To maintain the beam dimension in nano-scale without degradation of measurement results of optical detection, and to actuate the vibration of the beam more easily, a new kind of NEMS resonators in another shape needs to be proposed. The first of the H-type micromechanical structure was proposed to be used in pressure sensors with a high Q value of 3×10^5 in a sealed vacuum cavity[14]. But because the dimension of the beam was in tens of micrometers, the resonant frequency was only about several hun-

Received 2012-01-06.

Biography: Yu Hong (1966—), female, doctor, associate professor, h_yu@seu.edu.cn.

Foundation item: The National High Technology Research and Development Program of China (863 Program) (No. 2007AA04Z301).

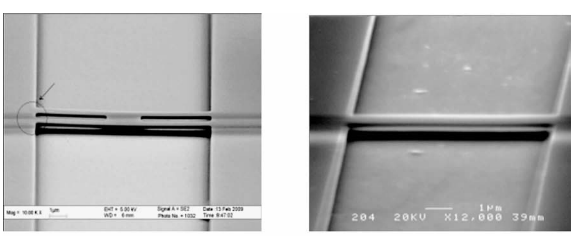
Citation: Yu Hong, Yuan Weimin, Liu Chunsheng, et al. Frequency response of a new kind of silicon nanoelectromechanical systems resonators[J]. Journal of Southeast University (English Edition), 2012, 28(3): 310 - 314. [doi: 10.3969/j.issn.1003 - 7985.2012.03.010]

dred kHz. The H-beam of a smaller size made of Si_3N_4 was modeled to have a high resonant frequency of 18 MHz[15] because of the higher Young's modulus of the material. In this paper, the NEMS resonator in nano-scale in H-type with one paddle between two supporting doubly clamped nano-beams is designed and realized. The thickness and width of the beam can be as small as 200 and 180 nm, respectively. The dynamic oscillation performance of this kind of resonators is explored experimentally. The resonant frequency ranges from 6.8 to 20 MHz. As a comparison, doubly clamped nano-beams are fabricated on the same wafer, and their dynamic responses are studied in the experiment as well.

1 Fabrication

The fabrication process has been described previously[16-17]. A silicon-on-insulator (SOI) wafer made of (100) mono crystalline silicon is used to fabricate the resonator. The wafer consists of a 200 nm top layer of silicon, a 200 nm buried oxide layer, and a 350 μm substrate. The pattern of the NEMS resonator is first defined onto the SOI wafer by optical lithography. Then the Si layer and silicon dioxide sacrificial layer are dry-etched by RIE. A heavily doped p-type layer is then formed in the anchor region, followed by sputtering an Al layer of 600 nm. Finally, the silicon dioxide sacrificial layer is undercut by a buffered oxide etcher (BOE).

Two kinds of beams, doubly clamped beams and H-type beams, are designed to be as NEMS resonators with dimension ranges from 180 nm to 3 μm in width, and 8 μm to 20 μm in length. The paddle dimensions of H-type beams are from 1 μm × 1 μm to 2 μm × 1 μm. Since the sizes of the beams are very small, when the sample is placed into the ethanol solution and dried after the wet oxide etching, the surface tension of the liquid can pull the suspended structure down to the substrate, resulting in sticking of the structure. Therefore, structure releasing becomes one of the key steps in the whole process. In order to reduce the adhesion of structures, a supercritical point drying technique is used[18]. The SEM photographs of the completely released H-type beam and the doubly clamped beam are shown in Fig. 1.



(a) (b)

Fig. 1 SEM of resonators. (a) H-type beam; (b) Doubly clamped beam

The above process provides us with suspended structures that are electrically isolated from the substrate. Then Au wires are bonded to the anchor and to the underlying substrate. To actuate vibration of the resonator, a voltage signal is applied between the beam and the substrate.

2 Experiment

A laser Doppler scanning vibrometer (Polytec MSV-400M2-20) is used to measure the vibration performance of the NEMS resonators. The schematic diagram of the experiment is shown in Fig. 2.

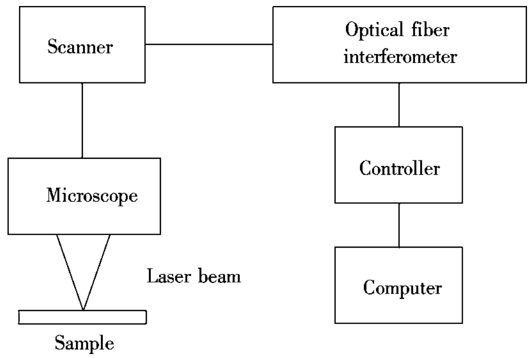


Fig. 2 Schematic diagram of measurement system

A sample of nano-beams (resonators) actuated by a signal voltage is placed on the sample stage. Incident He-Ne laser beam ($\lambda = 632.8$ nm) on the center of resonator's surface passes through a microscope adapter and a 50 × microscope objective lens. When the resonator is driven to vibrate, the vibration information is superimposed on the laser beam and reflected back to the laser interferometer. Then the laser beam is received by the detector and transmitted to the computer to be processed. The vibrometer controller sends a signal to control the motion of the scanner. The scanning image of the measured structure is captured by charge-coupled device (CCD) and can be shown on the computer screen.

The dynamic characteristics of NEMS resonators with different dimensions are studied experimentally. Because of the central paddle, it is easier to measure the performance of the H-type resonator. All measurements are performed at room temperature. Fig. 3(a) shows the mechanical response of one H-type resonator with two supporting doubly clamped beams of 10 μm in length and the paddle with a dimension of 1 μm × 1.5 μm. It can be seen that a peak response appears at 6.8 MHz. The vibration spectrum response of a doubly clamped nano-beam with a beam length of 10 μm is shown in Fig. 3 (b). It can be seen that the apparent peak is at 8.05 MHz, higher than 6.8 MHz. It is notable from Figs. 3(a) and (b) that the signal-to-noise ratio of the response for the doubly clamped beam is lower than that for the H-type beam, because the effect of diffraction for the doubly clamped beam is stronger than that for the H-type beam.

The relationship between the fundamental resonance frequency of the resonator and its length is shown in Fig. 4.

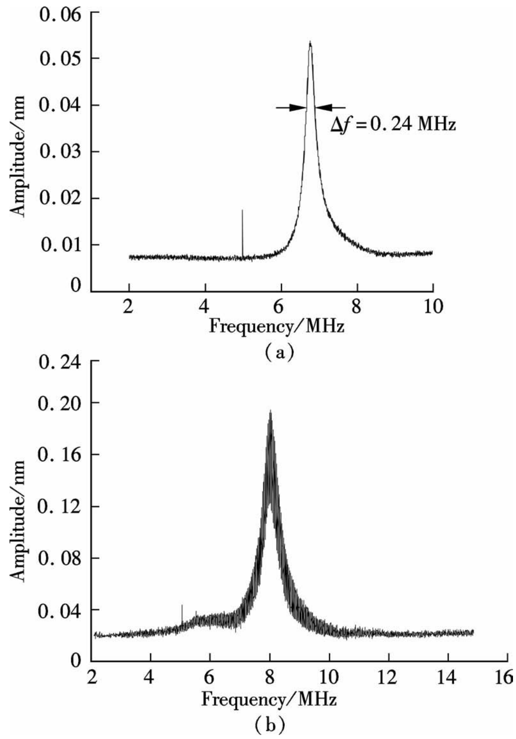


Fig. 3 Mechanical response of resonators. (a) H-type resonator with two supporting beams of 10 μm in length and the paddle with a dimension of 1 μm × 1.5 μm; (b) Doubly clamped nano-beam with 10 μm beam length

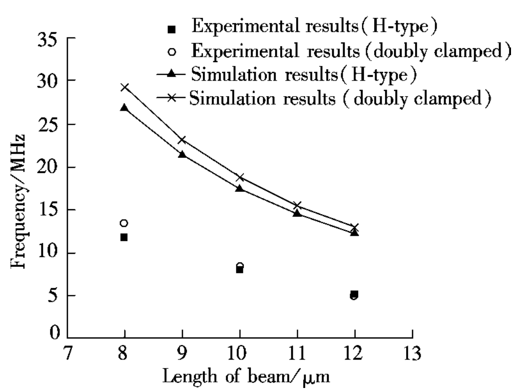


Fig. 4 Resonance frequency of the nano-beams with different lengths

It is found that the resonance frequency follows an inverse-length law; i. e., the fundamental frequencies of two types of nano-beams decrease with the increase in the beam lengths. In addition, the resonance frequency of the H-type beam is lower than that of the doubly clamped beam even though they have the same beam length. The difference between two resonance frequencies increases with the decrease in beam length. With the increase in beam length, the resonance frequency of the H-type nano-beam gets close to that of the doubly clamped nano-beam.

It is noticeable that resonant frequencies of two kinds of NEMS resonators are much lower than the simulation values by Ansys software. To give a reasonable explanation, the releasing process is monitored and the samples are checked carefully. It is found that the sacrifice layer under the anchor is partially etched by the buffered oxide etcher, which is circled as shown in Fig. 1(a). It means that the anchor is over-etched. Therefore, the shapes of the beams are different from the H-type and the doubly clamped type. By considering the influence of the over-etched part of the anchor, the resonant frequency is simulated by Ansys software again for two types of nano-beams. The results are shown in Fig. 5. It can be seen that over-etching does lower the resonant frequency for both types of beams. The experimental results are in agreement with the simulation results with over-etched depths of 3 and 4 μm. Therefore, over-etching is considered to be one of the main factors decreasing the oscillation frequency of the nano-resonator.

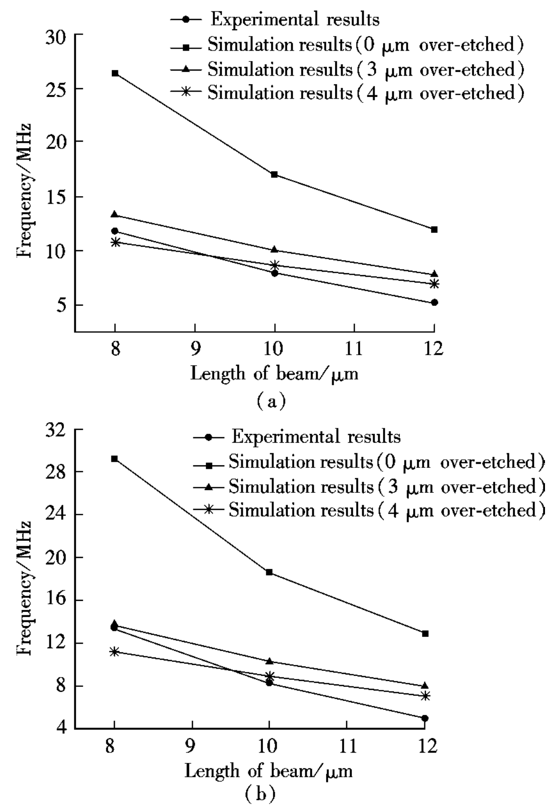


Fig. 5 Comparison of experimental results and simulation results by Ansys with and without over-etching. (a) H-type beams; (b) Doubly clamped beams

As we all know, the quality factor Q is a figure merit of the energy dissipation of the system, and it can be impacted by the temperature and the pressure surrounding the sample, because the thermo-elastic damping plays a very important role in the energy dissipation. The Q factor can be obtained by the formula $Q = f_0/\Delta f$ experimentally, where f_0 is the resonant frequency and Δf is the full width at half maximum power. It can be seen that the Q factor is about 30 in Figs. 3(a) and (b). To obtain higher Q, samples are placed into a chamber in which the pressure is about 5 066 Pa. The frequency response of one sample is shown in Fig. 6. The Q value is about 2 000, 70 times the Q value when the sample is placed in the air. It is expected that the Q factor will be improved moreover when both the pressure and the temperature become lower[19].

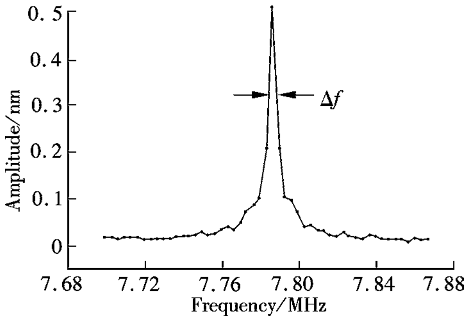


Fig. 6 Frequency response of the H-type beam with 10 μm beam length under 5 066 Pa

3 Conclusion

In summary, H-type NEMS resonators and doubly clamped resonators in nanometer scale are fabricated successfully by using the SOI wafer. Although the H-type resonator has a lower resonant frequency than that of the doubly clamped beam with the same length, it is easier to detect the vibration by a laser Doppler scanning vibrometer, because the central paddle can reflect more light power back to the detector. The difference between the resonance frequencies of the two types of resonators decreases with the increase in beam length.

The oscillation frequency of the nano-scale resonator is lower than the expected value and the simulation results since it is over-etched during the wet etching process. Therefore, the beam shapes are not the exact H shape and doubly clamped shape. The releasing process should be improved in the future. When the pressure is lowered, the Q factor is improved greatly.

Acknowledgements Authors would like to thank Mr. Pu Xianyong in SMIC and Yu Zhengyin in SIMIT for their discussion and help.

References

[1] Craighead H G. Nanoelectromechanical systems [J]. *Science*, 2000, **290**(5496): 1532 - 1535.

[2] Ekinci K L, Roukes M L. Nanoelectromechanical systems [J]. *Review of Scientific Instruments*, 2005, **76**(6): 061101 - 0611013.

[3] Huang X M H, Feng X L, Zorman C A, et al. VHF, UHF and microwave frequency nanomechanical resonators [J]. *New Journal of Physics*, 2005, **7**(1): 247 - 261.

[4] Feng X L, He R R, Yang P D, et al. Very high frequency silicon nanowire electromechanical resonators [J]. *Nano Lett*, 2007, **7**(7): 1953 - 1959.

[5] He R R, Feng X L, Roukes M L, et al. Self-transducing silicon nanowire electromechanical systems at room temperature [J]. *Nano Letts*, 2008, **8**(6): 1756 - 1761.

[6] Naik A K, Hanay M S, Hiebert W K, et al. Towards single-molecule nanomechanical mass spectrometry [J]. *Nature Nanotechnology*, 2009, **4**: 445 - 450.

[7] Li M, Tang H X, Roukes M L. Ultra-sensitive NEMS-based cantilevers for sensing, scanned probe and very high-frequency applications [J]. *Nature Nanotechnology*, 2007, **2**: 114 - 120.

[8] Yang Y L, Xia X Y, Gan X H, et al. Nano-thick resonant cantilevers with a novel specific reaction-induced frequency-increase effect for ultra-sensitive chemical detection [J]. *Journal of Micromechanics and Microengineering*, 2010, **20**(5): 055022 - 055027.

[9] Yu H T, Li X X, Gan X H, et al. Resonant-cantilever bio/chemical sensors with an integrated heater for both resonance exciting optimization and sensing repeatability enhancement [J]. *Journal of Micromechanics and Microengineering*, 2009, **19**(4): 045023 - 045033.

[10] Feng X L, White C J, Hajimiri A, et al. A self-sustaining ultrahigh-frequency nanoelectromechanical oscillator [J]. *Nature Nanotechnology*, 2008, **3**: 342 - 346.

[11] Liu N, Giesen F, Belov M, Losby J, et al. Time-domain control of ultrahigh-frequency nanomechanical systems [J]. *Nature Nanotechnology*, 2008, **3**: 715 - 719.

[12] Shagam M Y. Nanomechanical displacement detection using fiber optic interferometry [D]. Boston: College of Engineering, Boston University, 2006.

[13] Kouh T, Karabacak D, Kim D H, et al. Diffraction effects in optical interferometric displacement detection in nanoelectromechanical systems [J]. *Applied Physics Letters*, 2005, **86**(1): 13106 - 13109.

[14] Zook D J, Herb W R. Polysilicon sealed vacuum cavities for microelectromechanical systems [J]. *Journal of Vacuum and Science Technology A*, 1999, **17**(4): 2286 - 2294.

[15] Liu B, Liu Z W, Wang C W, et al. Research progress of RF-MEMS devices [J]. *Nanoscience and Technology*, 2005, **5**: 35 - 38.

[16] Yue D X, Yu H, Yuan W M. Nonlinear characteristics of sub-micro cantilever beam resonators actuated by statical electricity [J]. *Optics and Precision Engineering*, 2011, **19**(4): 783 - 788. (in Chinese)

[17] Yu H, Yuan W M, Yue D X. Measurement of frequency mixing characteristics of H-type submicro beams [J]. *Nanotechnology and Precision Engineering*, 2011, **9**(4): 305 - 309. (in Chinese)

[18] Lee M Y, Do K M, Ganapathy H S, et al. Surfactant-aided supercritical carbon dioxide drying for photoresists to prevent pattern collapse [J]. *Journal of Supercritical Fluids*, 2007, **42**(1): 150 - 156.

[19] Liu C. *Foundations of MEMS* [M]. Translated by Huang Q A. Beijing: China Machine Press, 2007: 65 - 66. (in Chinese)

一种新型纳机电硅谐振器的频率响应特性

于　虹　袁为民　刘春胜　岳东旭　吴士杰　顾　勇　陈志远　黄庆安

（东南大学 MEMS 教育部重点实验室，南京 210096）

摘要：对于静电驱动的亚微米及纳米尺度的谐振器，衍射效应将会使其驱动及振动频率的光学检测变得更加困难，为克服衍射效应的影响，设计、制作了新型纳机电谐振梁——H 型梁，使其产生高频振荡. 并制作了双端固支谐振器以进行比较. 2 种谐振梁的最小宽度和厚度分别为 180 和 200 nm. 对这 2 种结构的机械振动特性进行了实验研究. 谐振器的基波振荡频率在 6.8～20 MHz 之间，远低于理论预估值. 通过模拟仿真发现，过腐蚀是导致振动频率低于理论值的重要原因之一. 实验还发现：2 种谐振器的谐振频率之差随着梁的长度增加而下降；在室温下减小样品腔的压强后，谐振器的品质因数可以大大提高.

关键词：纳机电系统；谐振频率；过腐蚀；纳米梁

中图分类号：TP212.13