Invited paper

Nano Fabrication and Metrology for Nano ElectroMechanical Sensing Devices

Sunao Ishihara, Shin'ichi Warisawa and Reo Kometani

The University of Tokyo, Tokyo, Japan

Abstract – Nano electromechanical systems (NEMS) work in conjunction with nanomechanical resonators. Owing to their ultra-small size, nanomechanical resonators have extremely high fundamental resonance frequencies and quality (Q) factors. When operating in the resonant mode, they show outstanding performance in sensing and signal processing, realizing ultrafast and ultrasensitive sensors.

In this review, the technological challenges in nanostructure fabrication, metrology, and application to sensing devices are described. After the fundamental properties of nanomechanical resonators are reviewed, two key technological studies are described: 1) nano-vibration measurement and resonance characterization using an electron beam (EB) and an atomic force microscope (AFM) probe, and 2) nanofabrication technologies to make three-dimensional (3D) nanomechanical structures using an EB and a focused ion beam (FIB). Technologies to increase the Q-factor are considered the key to successful fabrication. Finally, the fabrication and demonstration of several sensing devices is described.

Keywords: Nanomechanical resonator, 3D nanofabrication, resonance property characterization, sensing device

1. Introduction

In the modern world, almost every system, piece of equipment, device, and material has had its structure size decreased in a bid to improve performance. A typical example is the Si semiconductor LSI. Driven by microfabrication technology, circuit patterns have been continuously miniaturized to the size of several tens of nanometers. In a simultaneous evolution, micro electromechanical systems (MEMS) composed of mechanical 3D structures fabricated using such microfabrication technologies have been widely developed and used for high performance sensors and actuators.

From the late 1990s, several scientific works on extreme resolution sensing have been reported, including nano-scale mechanical resonators with quite high resonant frequency and Q-factor [1], ultra-small charge detectors with nanomechanical structures [2], and femtometer resolution displacement measurements [3]. These studies demonstrated that the excellent mechanical properties of small-size resonators could be quite useful for ultra-high sensitivity sensing devices. This has resulted in the development of nano electromechanical systems (NEMS), and the general micro/nano-systems called MEMS/NEMS.

This paper reviews recent NEMS research activities focusing on nanostructure fabrication, nano-vibration measurement, and mechanical property characterization and how they can be applied to sensing devices.

2. Dynamic property of nanoresonators [4]

NEMS have excellent potential to realize ultimate sensing or actuation performances. As shown in Fig. 1, nanomechanical resonators made of semiconductors, ceramics, or nano-carbon materials have a size of tens to hundreds of nanometers [5–9]. They are mostly operated in resonant modes and perform extremely high fundamental resonance frequencies due to their small mass and significantly high Q-factors in the range of 10^3–10^5. These attributes are technically suitable for applications to high-sensitivity sensors, fast actuators, signal processing, and so on.

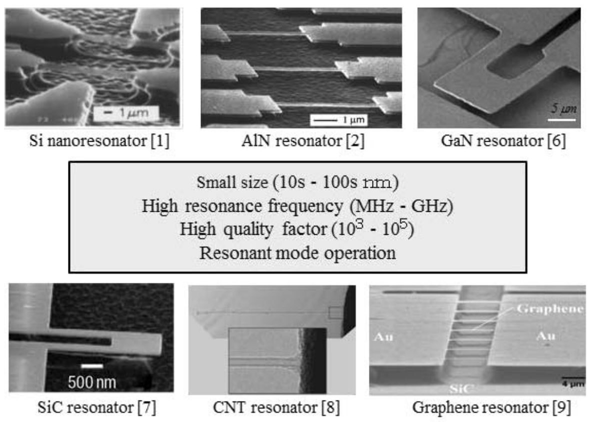

Fig.1. Resonance properties of nanomechanical resonator [4].

Figure 2 shows the basic configuration of a nanomechanical resonator sensing device. When a disturbances affects the resonating vibrator, the resonant characteristics (such as peak frequency) will change. In this case, a "disturbance" is considered an "input signal", and the device works as a sensor to detect displacements, masses, forces, flowing charges, pressure, temperature, and so on by monitoring changes of the resonance characteristics. Typical characteristics useful for sensing are resonance frequency f_0, vibration amplitude A_0, and *Q-factor* $f_0 / \triangle f$. The Q-factor is a performance index indicating resonance sharpness determined by various energy losses in a resonance system. It is the dominating factor for achieving high sensitivity.

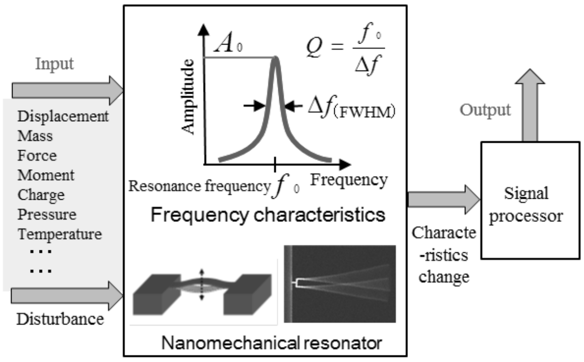

Fig. 2 Schematic of NEMS sensing device [4].

The resonance features of nanomechanical resonators described above show that the essential research tasks to realize fast, highly sensitive sensors using nanomechanical resonators are 1) to measure nano-scale vibrations and characterize their features, 2) to develop 3D nanostructure fabrication technology, and 3) to design and fabricate highly sensitive sensing devices.

3. Nano-scale vibration measurement

Laser interferometry is typically the most widely used technique for vibration measurement. However, in the case of measuring the behavior of NEMS components, optical methods have difficulty probing very small samples, mainly because of the optical diffraction limit. When the dimension of the vibrating elements is much smaller than the size of the laser spot, an interferometer can barely catch or distinguish between the reflected lights from the samples. Several nano-scale vibration measurement techniques using electron beams or atomic force microscopy have therefore been investigated.

An electron beam (EB) is suitable for probing very small structures due to its own small spot size, which is just a few nanometers. The schematic of a vibration measurement system using EB is shown in Fig. 3 [10]. When an EB is irradiated to a vibrating structure across the beam spot, secondary electrons (SEs) emitted from the resonator surface are modulated to an on-off signal by the vibration, and detected by the SE detector. The network analyzer then obtains the resonance characteristics in the frequency domain by sweeping the actuation frequency and analyzing the modulated signals [11].

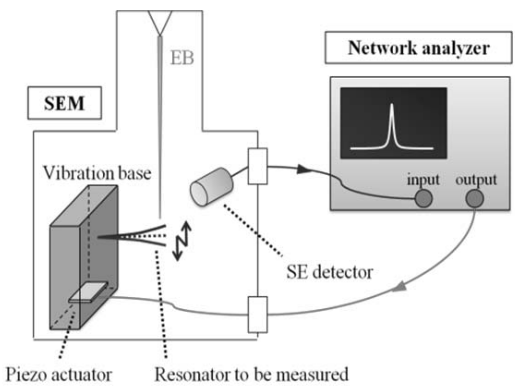

Fig. 3 Electron beam vibration measurement [10].

If a different irradiation direction is adopted, the measurement performance can be considerably improved. For example, when the EB is irradiated parallel to the vibrating plane with the appropriate inclination, the detection signal is also modulated by the SE emission dependency on the tilting angle of the resonator. These EB measurement methods can detect sub-nanometer amplitude at frequencies of up to several MHz. Moreover, in the latter case, very accurate resonance frequency identification and vibration amplitude evaluation can also be performed [10, 12].

In order to evaluate the dynamic characteristics of a nano-resonator, a vibration measuring technique using an atomic force microscope (AFM) was developed. As shown in Fig. 4, a GaAs membrane resonator is actuated with Coulomb force generated by AC voltage applied between the resonator and the probe. Simultaneously, the vibration amplitude is detected as height data of the AFM operating in the dynamic mode, resulting in the detection of the envelope of resonance. By sweeping the actuation frequency, the AFM output draws the frequency characteristics, as shown in the figure [13]. An added advantage of this method is that the resonance profile can be measured by using AFM scanning.

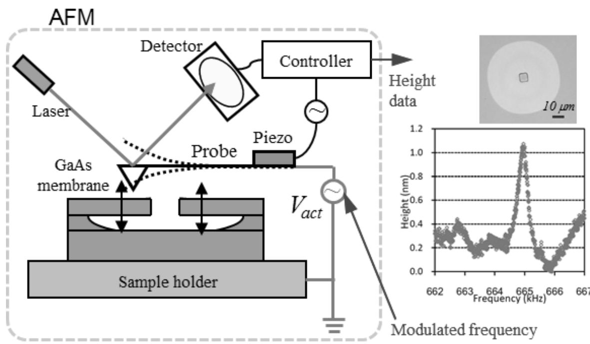

Fig. 4. Frequency characteristics evaluation using AFM [13].

4. 3-D nanostructure fabrication

Key materials in a nanomechanical resonator are semiconductors (Si, SiN, SiC, GaAs, or GaN) and carbons (DLC, CNT, or grapheme). When fabricating nanomechanical resonators, conventional micro/nano fabrication technologies for making semiconductor LSIs/MEMS that improve their resolution capability are typically used. Recently, bottom-up technologies based on self-assembly, crystal growth, and molecular deposition are also frequently being used. One of the very useful technologies for fabricating 3D nanostructures that we use in our own NEMS research is focused ion beam chemical vapor deposition (FIB-CVD).

As described above, the most attractive properties of nanomechanical resonators are their high resonance

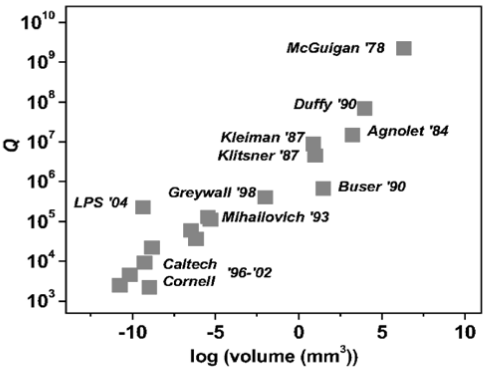

Fig.5 Size (volume) dependency of Q-factor of resonators [14].

frequency and high Q-factor. From the fabrication viewpoint, however, the Q-factor tends to decrease as the mass of the resonator decreases, as shown in Fig. 5 [14]. A key issue is therefore maintaining or even increasing the Q-factor when fabricating small size resonators.

One effective method of increasing the Q-factor is applying tensile stress/strain along the resonating structure. A typical example is shown in Fig. 6. The doubly clumped beam is made of a tensile strain-induced heterostructure fabricated with lattice mismatched heteroepitaxy. In this case, the Q-factor was increased by more than one degree of magnitude with 0.35% strain induce [15].

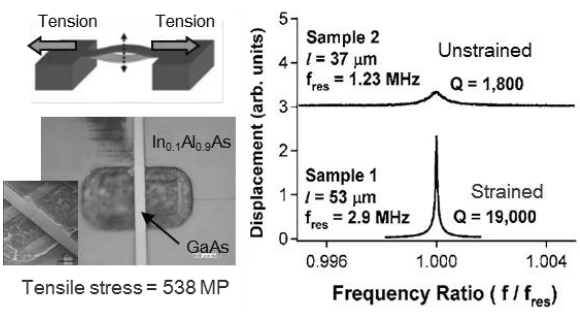

Fig. 6 Q-factor improvement by inducing stress into resonators. [15]

We examined a new lithography technique for 3D nanostructure fabrication to clarify its excellent lithography performance. As shown in Fig. 7, an ultra-thin strained carbon beam resonator can be fabricated using modified lithography and annealing processes. This new technique, which is called FIB/EB dual-beam lithography, utilizes the different penetration depths of the resist materials between ion and electron beams. In this process, a small penetration Ga+ ion exposes the vibration beam and a deep penetration EB exposes the supporting base. A beam resonator is then instantly developed, followed by curing and annealing to achieve a carbonization and hardening of the resist material. Tensile stress is simultaneously induced into the beam owing to the shrinkage of the supporting base [16, 17].

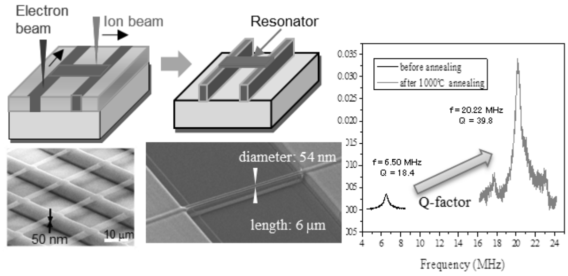

Fig. 7. FIB/EB dual-beam lithography and Q-factor improvement [16, 17].

Recently, carbon nanotubes (CNTs) and graphene have been widely applied to nanoresonators due to their outstanding mechanical properties [8, 9, 18]. We studied a graphene resonator to determine how to best make use of its extremely stiff and ultra-thin structure. In this study, the shrinkage property of the resist material is used to fabricate strained graphene resonators with a high Q-factor. As shown in Fig. 8, graphene resonators with several layers were fabricated on the trench of an SU-8 resist. The resonators were then clamped with diamond-like carbon (DLC) deposited by FIB-CVD and trimmed by FIB etching. Annealing was used to apply tensile strain to the graphene resonator by SU-8 drastic shrinkage. As shown in the figure, the Q-factor increased after annealing to over 7,000 at room temperature [19].

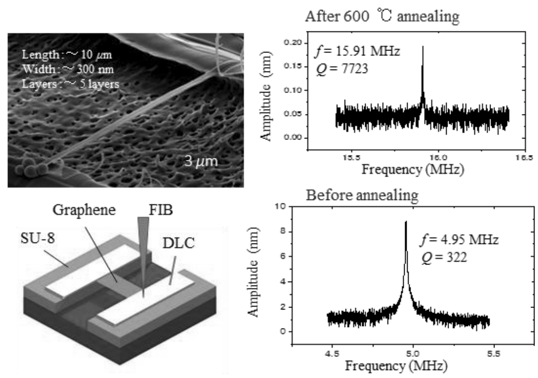

Fig. 8 Q-factor improvement of a graphene resonator [19].

5. Sensing device application

We made full use of the technologies for measuring and fabricating nanostructures mentioned in the previous section to fabricate sensing devices with micro/nanomechanical resonators. Here, two device making trials are described.

Figure 9 shows a high-sensitivity charge detection device using antisymmetric vibration in two coupled GaAs resonators. In this coupled beam resonator, the antisymmetric mode under in-phase simultaneous driving of the two beams disappears with perfect frequency tuning. The piezoelectric stress induced by a small gate-voltage modulation breaks the balance of the two resonators, leading to the re-emergence of the antisymmetric mode. Measurement of the amplitude

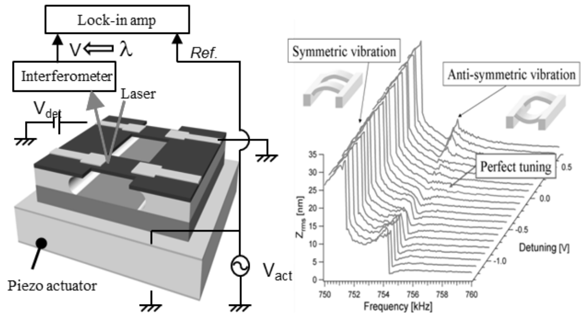

Fig. 9 Charge detctor using connected twin beam resonator [20].

change enables detection of the applied voltage or, equivalently, added charges. In contrast to the frequency-shift detection using a single resonator, this method enables a large readout up to the strongly driven nonlinear response regime, providing a high RT sensitivity of 147 e/Hz$^{0.5}$ [20].

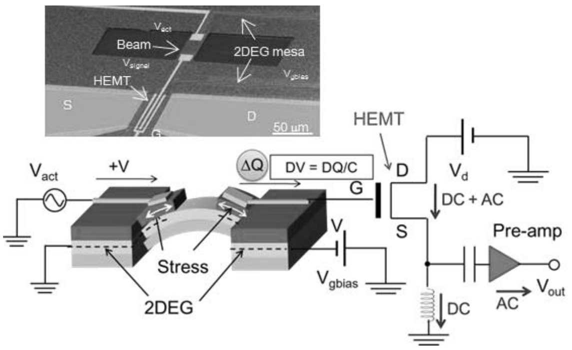

Fig. 10 Electromechanical displacement detector with on-chip HEMT [21].

Another trial is a highly sensitive displacement detection device using a GaAs-based electromechanical resonator integrated with high electron mobility transistor (HEMT). As shown in Fig. 12, piezoelectric voltage generated by the vibration of the resonator is applied to the gate of the HEMT, resulting in the on chip amplification of the signal voltage. This device achieved a displacement sensitivity of 9pm/Hz$^{0.5}$, which is one of the highest displacement detection schemes at room temperature [21].

6. Summary

The remarkable dynamic features of nanomechanical resonators make them promising candidates for the fabrication of extremely sensitive NEMS sensing devices. Extensive nanotechnology research on fabrication and metrology technologies for high Q-factor nanoresonators are currently being performed to enable the design and creation of such devices. Moreover, several sensing devices using micro/nanomechanical resonators have been made and demonstrate outstanding sensitivity at room temperature.

We expect there to be extensive further research conducted in this area.

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