REVIEW

Micro/nano-mechanical sensors and actuators based on SOI-MEMS technology

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Abstract
MEMS (micro-electro-mechanical systems) technology has undergone almost 40 years of development, with significant technology advancement and successful commercialization of single-functional MEMS devices, such as pressure sensors, accelerometers, gyroscopes, microphones, micro-mirrors, etc. In this context of MEMS technology, this paper introduces our studies and developments of novel micro/nano-mechanical sensors and actuators based on silicon-on-insulator (SOI)-MEMS technology, as well as fundamental research on piezoresistive effects in single-crystal silicon nanowires (SiNWs). In the first area, novel mechanical sensors, such as 6-DOF micro-force moment sensors, multi-axis inertial sensors and micro-electrostatic actuators developed with SOI-MEMS technology will be presented. In the second area, we have combined atomic-level simulation and experimental evaluation methods to explain the giant piezoresistive effect in single crystalline SiNWs along different crystallographic orientations. This discovery is significant for developing more highly sensitive and miniaturized mechanical sensors in the near future.

Keywords: MEMS, mechanical sensor, electrostatic actuator, silicon nanowire

Classification numbers: 6.00, 6.12

1. Introduction

MEMS and NEMS stand for, respectively, micro-electro-mechanical systems and nano-electro-mechanical systems, which relate to micro/nano-electro-mechanical integrated devices fabricated by the extension of microelectronic fabrication technology, e.g. photolithography, thin film deposition and etching, with high accuracy and high throughput. While microelectronic devices are solid and mechanically immovable, MEMS devices have movable 3D microstructures, e.g. micro-cantilevers, micro-beams, membranes, etc. However, the significance of MEMS/NEMS is not only in mechanical motion, but also in miniaturization, multifunctional integration and mass production. Compared to LSI devices, which deal only with electrical signals, MEMS devices relate to conversion and integration of a wide variety of signal types, such as physical (electrical, mechanical, thermal, optical, etc), chemical and biological signals. Generally, silicon MEMS technology offers the possibility of low-cost, high-performance, and miniaturized multifunctional-integrated devices for use in a wide range of consumer and industrial applications, such as in the automotive, biomedical and telecommunication industries, defense, and so on.

The first ideas on MEMS/NEMS were proposed by the 1965 Nobel laureate Richard Feynman in 1959 [1]. However, MEMS devices were not demonstrated until the late 1960s and early 1970s when some silicon micro-devices
and structures, such as gas chromatography [2, 3], pressure sensors [4–6], force sensors [7], resonators [8], micromirrors [9], ink-jet nozzles [10], etc, were successfully developed. This landmark of MEMS device development was made possible because of the previous studies and success of so-called bulk silicon micromachining technology in the late 1960s and, subsequently, surface micromachining technology in 1986–1988. The former mainly features in wet isotropic etching [11, 12], wet anisotropic etching [13, 14], dry anisotropic etching (e.g. deep reactive-ion etching (D-RIE) [15, 16]), as well as wafer bonding techniques [17, 18], while the latter relates to selectively etching thin sacrificial layers underlying etch-resistant thin films from a multilayer sandwich of patterned thin films [19].

After decades of extensive study in both microfabrication techniques and material properties [20], silicon was considered to be the most appropriate and useful material for MEMS technology. Besides the fact that silicon is an excellent electronic material used in most integrated circuits, it also has excellent mechanical properties: high elasticity, stiffness, fracture and fatigue strength, thermal conductivity, thermal stability, etc. Furthermore, silicon has many properties extremely suitable for highly sensitive integrated sensor applications, such as piezoresistive effect [21], thermo-resistive effect, photovoltaic effect, and so on.

Over the past 40 years of research and development of MEMS, there have been significant changes in the field: huge improvements in the technology, extensive infrastructure in place, significant designs for commercialization (such as pressure sensors, accelerometers, gyroscopes, flow sensors, inkjet print heads, microphones, resonators, digital mirror displays, optical switches, etc), The MEMS devices market had reached US$7.1 billion in 2007, US$6.8 billion in 2008, and was estimated to reach US$6.9 billion and US$49 billion in 2009 and 2020, respectively [22]. MEMS technology has attracted the attention of worldwide research institutions to develop new industry, new applications and new markets. While MEMS have been successfully developed and commercialized, NEMS technology is still being fundamentally studied to elucidate new properties and effects of materials at the nanoscale to further enhance the performance and widen the application of micro-integrated devices, while reducing the overall size. Mechanical, electrical, optical, chemical and biological properties, and various sensing effects of nanomaterials such as nanodots, nanowires and nanosheets, are being investigated.

In this paper, we present our recent study on micro-devices based on SOI-MEMS, as well as using MEMS as a platform for studying the piezoresistive effect in single crystalline silicon nanowires. All devices have been fabricated using SOI (silicon-on-insulator) wafers. The term SOI refers to a silicon substrate with a single crystalline silicon device layer lying on a buried oxide layer which is set on top of a silicon substrate. This structure is widely used in MEMS because it provides reliable electrical insulation, excellent etching stop and sacrificial layer functions; therefore, it increases the fabrication accuracy, process simplicity and device performance. MEMS industry is boosting SOI wafer demand thanks to the market dynamism of products such as accelerometers or gyroscopes, which are now widely used in numerous consumer products and industry.

2. Micro-mechanical sensors and actuators

Here we introduce our typical SOI-MEMS micro-mechanical sensors and actuators, including a six-degree-of-freedom (6-DOF) force moment sensor, a 3-DOF micro-accelerometer, a dual-axis gyroscope and an electrostatically driven micro-transportation system.

2.1. 6-DOF force moment sensor

The sensing chip was designed to be able to simultaneously detect three components of force and three components of moment in three orthogonal directions (figure 1). Two-terminal and four-terminal p-type silicon piezoresistors were created by thermal diffusion of boron ions to suitable places on the surface of a crossbeam-shaped structure of (111) n-type silicon. The total number of piezoresistors is 18, much fewer than the previous piezoresistive-based 6-DOF force moment sensors known to the authors [23]. When a force or moment is applied to the sensor, the beams will be deformed; consequently, stresses will be induced at the piezoresistors, leading to a change of their resistance, thus changing the output of the corresponding bridge circuits. The sensor was fabricated based on IC compatible processes, e.g. photolithography, impurity diffusion, thin film deposition and etching, and silicon bulk micromachining technology, e.g. the deep-RIE etching process. The schematic of the fabrication process is shown in figure 2. The fabricated chip has dimensions of 3 × 3 × 0.5 mm² as shown in figure 1(b). The sensor has been applied in robotics as fingertip tactile

![Figure 1. 6-DOF force moment sensor (a, b) and tactile sensor for robotic application (c). (a) Simulation model, (b) fabricated force sensor chip and (c) tactile sensor.](image-url)
Step 1: Starting material, SOI (111) plane

SOI wafer:
- Device layer: 40 µm
- Box layer: 1 µm
- Handle substrate: 450 µm

- Si wafer washing
- Drying

Step 2: Oxidization

SiO₂: 0.3 µm

- Thermal oxidation

Step 3: Piezoresistor diffusion

Piezoresistor: 3 x 40 µm²

- Photoresist spincoating
- Piezoresistor patterning
- SiO₂ etching
- Boron ion diffusion
- B.O. removing
- Drive in

Step 4: Contact hole

Contact hole: 4 x 4 µm²

- Photoresist spincoating
- Contact holes patterning
- SiO₂ etching

Step 5: Wiring

Wire (W x T): 2 x 0.5 µm²

- Al evaporation
- Photoresist spincoating
- Wire patterning
- Al etching
- Annealing

Step 6: Crossbeam formation

Beam size: 500 x 100 x 40

- Al evaporating & patterning
- Backside etching by DRIE
- Buried SiO₂ etching by RIE
- Front side etching by DRIE

Figure 2. Fabrication process of the 6-DOF force moment sensor.

Figure 3. Simulation model (a) and photos of the fabricated 3-DOF micro-accelerometers (b, c).

sensors (figure 1(c)) [24], and in hydraulics to measure the fluid force acting on small particles in water flow [25].

2.2. Multi-axis micro-accelerometer

Inertial sensors refer to accelerometers and angular rate sensors (or gyroscopes). Several kinds of micro-accelerometers, such as piezoresistive accelerometers [26, 28], thermo-resistant accelerometers [27], have been developed. A recently developed accelerometer is shown in figure 3 [28]. This accelerometer can independently detect three components of linear acceleration along three orthogonal directions. The detecting principle is based on piezoresistive effects in single-crystal silicon. The sensing chip is made of single-crystal Si, with a seismic mass being suspended at the middle of the four surrounding beams, which are themselves fixed to the ‘rigid’ frame at the ends. Si piezoresistors are formed by diffusing boron ions to suitable places on the surface of the n-type silicon sensing beams. When an external acceleration is applied to the sensor, the seismic mass is displaced due to the inertial force. This movement of the seismic mass deforms the beams. As a result, the resistance of the Si piezoresistors is changed due to the piezoresistive effect. The change of resistance is converted to an output voltage by Wheatstone bridges. The fabrication process is illustrated schematically in figure 4, and an SOI wafer was used. The dimensions of the accelerometer chip are 1 mm x 1 mm x 0.45 mm (L x W x T). The sensitivities to the X-, Y- and Z-axis are 30, 30 and 23 µV g⁻¹, respectively, and cross-axis sensitivity is less than 5.5%. Thanks to the small size and high performance, the sensor can be applied to portable electronic devices, such as mobile phones or cameras to stabilize or automatically find the image orientation, or to remote game controllers, health monitoring sensors, etc.

2.3. Dual-axis angular rate sensor (gyroscope)

Figure 5 shows our recently developed 2-DOF convective angular rate sensor (gyroscope) [29, 30]. The sensor can detect two components of angular velocity based on the thermo-resistant effect of the low-doped silicon. The working principle is illustrated in figure 5(a). The gas flow generated by the piezoelectric diaphragm pump flows to the nozzle
orifice and creates a jet flow in the chamber. The gas flows toward the sensing element, and goes through the symmetric center of the four thermistors. As an angular rate is applied, the gas flow is deflected (figure 5(a)) due to the Coriolis effect. This deflection causes differential cooling between opposing thermistors and, as a result, the resistances of the two thermistors change in opposite directions. A Wheatstone bridge is used to convert these resistance changes to output voltage. Therefore, angular rates $\omega_x$ around the $X$-axis and $\omega_y$ around the $Y$-axis can be measured independently. The sensing chip is fabricated from the SOI wafer by applying a fabrication process similar to that shown in figure 2. The gyroscope was packaged at Tamagawa Seiki Corp. (figure 5(b)). The sensitivities of the gyroscope for the $X$- and $Y$-axis are 0.082 and 0.078 mV deg$^{-1}$ sec$^{-1}$, respectively. The cross-sensitivities between the two input axes are less than 0.26%; the nonlinearity was smaller than 0.5% F.S in the range of ±200 deg sec$^{-1}$.

Several applications of this high-performance gyroscope mentioned here include automotive, ship stabilization systems and aerospace.

2.4. Electrostatic micro-actuator

Silicon comb-drive electrostatic actuators are among the most frequently utilized in MEMS since they were first reported about 20 years ago [31]. The advantages of these actuators include the simple and mass fabrication process, accuracy, easy control and large displacement. In this paper, we propose novel ratcheting structures which allow converting reciprocating displacement of electrostatic comb-drive actuators to continuous, unidirectional, straight and turning movement of micrometer-scale objects. The working principle of the micro-transportation system is shown schematically in figure 6. Force induced from the electrostatic comb-drive actuator pushes the ratchet racks inward, causing the driving wings to move inward. As a result, the container (moved object) is moved forward. When the force is removed, the container will not move backward due to the ratchet mechanism of the anti-reverse wings. Figure 7 shows the silicon micro-transportation system [32, 33] made from SOI wafer by using D-RIE silicon etching and SiO$_2$ etching processes. The velocity of the object can be controlled by driving voltage and frequency. The maximum velocity was about 200 $\mu$m s$^{-1}$ at 100 V and 20 Hz driving voltage. This miniaturized transmission system can be used to transport small objects, such as biomedical samples, micro/nano-particles and carbon nanotubes (CNTs) from one place to another.

Another transmission system based on an electrostatic actuator and ratchet mechanism, called a gearing transmission system, was developed recently as shown in figure 8 [34]. The reciprocal movement of rotational comb actuators is converted to the unidirectional rotation of the gears through a driving mechanism as shown in the right SEM image of figure 8. The system was fabricated from SOI wafer using D-RIE and HF vapor etching processes. The angular velocity was changeable depending on the frequency of the driving voltage. The maximum angular velocity was about 40 deg s$^{-1}$ at 80 V and 50 Hz driving voltage. The gearing system can be used...
3. Fundamental study of the piezoresistive effect in silicon nanowire for mechanical sensing

In this section, we present our theoretical and experimental investigations of the piezoresistive effect of single crystalline silicon nanowires (SiNW), as well as a promising application of SiNW in the development of higher sensitive and miniaturized mechanical sensors in the near future. Firstly, the piezoresistive effect in SiNW is theoretically studied using atomic-level simulation, that is the first-principles calculation method, and then it is experimentally measured on the SiNW sample fabricated using electron-beam direct writing and RIE. Finally, the fabrication process of an ultra-small accelerometer having SiNW as sensing element is presented.

3.1. First-principles simulation

We have performed first-principles calculations based on density functional theory [35] with the generalized-gradient approximation (GGA) method [36]. We adopted the three-dimensional supercell approximation technique with norm-conserving pseudopotentials prepared according to the
Si nanowire models were composed of a fragment of optimized bulk Si with a one-dimensional periodic boundary, and all dangling bonds at the wire wall were terminated with H atoms. Figure 9 shows Si_{0.5}H_{0.5} (001) (wire diameter 2R = 2.21 nm) and Si_{0.5}H_{0.5} (110) (2R = 2.58 nm) Si nanowire models, where the longitudinal directions with one-dimensional periodic boundary are respectively set to [001] and [110].

A periodic boundary condition along the transverse directions, or perpendicular directions to the wire axis in the three-dimensional supercell, was given by inserting sufficient space between H-terminated Si nanowires with two large cell parameters perpendicular to the wire axis. On the condition that sufficient space in the Si nanowire model disturbs the interaction between the Si nanowires, the electronic band structure of the Si nanowire model can be reduced to one dimension, which is dependent on only one reciprocal coordinate, k_z. The effect of uniaxial tensile strain on structure was represented by partial optimization of bulk Si with a fixed coordinate, z. The effect of uniaxial strain on structure was represented by partial optimization of bulk Si with a fixed coordinate, z. The uniaxial tensile stress, which have been represented by a linear-response approximation according to the classical Hooke’s law, δ 

\[ \sigma = \frac{\epsilon}{\varepsilon_0} \]

where \( \epsilon \) is the strain and \( \varepsilon_0 \) is the elastic modulus.

For the relaxation time, we have adopted the approximation \( \tau = \frac{\hbar^2}{m^* k_B T} \)

where \( \hbar \) is Planck’s constant divided by 2π, m^* is the effective mass, k_B is the Boltzmann constant, T is the temperature, and \( \Delta \) is the change in carrier occupation.

The effective mass is given by \( m_j^* = \pm \hbar^2 \left( \frac{\epsilon^2 E_j}{\epsilon k_B T} \right)^{-1} \)

where \( E_j \) is the energy of the jth subband, \( \epsilon \) is the dielectric constant, and \( \epsilon \) is the strain.

The Si_{0.5}H_{0.5} (001) model has four VB subbands in the vicinity of the VB top as shown in figure 10. The highest VB subband of those without stress has a small hole effective mass, called the light-hole band, and by contrast, two of the second highest VB subbands in degeneracy have a larger hole effective mass, called the heavy-hole bands. The uniaxial tensile stress in the [001] longitudinal direction causes a sharp drop in the band energy of the light-hole band, leading to the alternation of the order of band energy levels between the light-hole band and the heavy-hole bands, and then most of the holes will be redistributed to the heavy-hole bands where hole effective mass is markedly raised due to the longitudinal tensile stress. This sudden change in the hole occupation with temperature T, where \( E_{j,k_z} \) is the intrinsic-semiconductor-state band energy of the jth band at the k_z point, \( w_{k_z} \) is the k-point weight for k_z, \( V \) is the volume of Si nanowire in the unit cell and \( k_B \) is the Boltzmann constant. In practice, we first have to set \( \Delta \) to an appropriate constant such as \( 10^{-n} \) (n = 2, 3 and 4), and then \( E_{j,k_z} \) in n-type and p-type carrier occupations can be solved according to equations (2) and (3), respectively [38–41].

The effective mass is generally given by a 3 × 3 tensor, but it can be defined simply as a scalar for one-dimensional SiNW models [38, 39]:

\[ m_j^* = \pm \hbar^2 \left( \frac{\epsilon^2 E_j}{\epsilon k_B T} \right)^{-1} \]

where \( E_j \) is the energy of the jth subband, \( \epsilon \) is the dielectric constant, and \( k_B \) is the Boltzmann constant.
Figure 10. Variations of valence-band diagrams, occupation ratios and effective masses due to 1% longitudinal and transverse tensile strains for the Si$_{89}$H$_{44}$⟨001⟩ SiNW model.

Figure 11. Piezoresistance coefficients of SiNW models with respect to carrier concentration $N$.

with Young’s modulus $Y_{lt}$ and tensile strain $\varepsilon_{lt}$, $\rho_0$ is the resistivity along the wire axis without stress, and $\Delta\rho_{lt}$ are variations in $\rho_0$ due to $\sigma_{lt}$. Young’s modulus of nanoscale low-dimensional Si materials [42] is somewhat smaller than that of bulk Si. According to the first-principles total energy calculation of tensile-strained models, we assumed $Y_{lt}$ to be 25% of the experimental values of Young’s modulus of bulk Si.

Figure 11 summarizes calculation results of the piezoresistance coefficients with respect to $\delta$. Obviously, the values of $(\pi_{<\langle001\rangle})_p$, longitudinal piezoresistance coefficients for the p-doped Si$_{89}$H$_{44}$⟨001⟩ model, are by far the largest in figure 11. We have obtained $588 \times 10^{-11}$ Pa$^{-1}$ for $(\pi_{<\langle001\rangle})_p$.
with $\delta = 10^{-4}$, i.e. two orders larger than that of the bulk silicon, and it is expected that p-doped (001) SiNW will have giant longitudinal piezoresistivity.

### 3.2. Measurement of the piezoresistive effect in SiNW

A giant piezoresistive effect has been theoretically found in single crystalline SiNWs using the first-principles calculation method. It is necessary to verify these results experimentally. Accordingly, SiNWs with a length of 2 $\mu$m, thickness of 35 nm and width ranges from 35 nm to 480 nm have been fabricated from SIMOX (separation by implanted oxygen) SOI wafer using electron beam (EB) direct writing and RIE etching [43, 44]. Figures 12(a) and (b) shows SEM images of the 35 nm width SiNWs array.

The width dependence of the longitudinal piezoresistive coefficient $\pi_{(110)}$ along the (110) crystallographic orientation at doping concentration of $1.2 \times 10^{18}$ atoms cm$^{-3}$ of SiNWs has been measured (figure 12(c)). The results show a strong increase of the longitudinal piezoresistive coefficient when the width of the SiNW becomes smaller than 150 nm. The increase of $\pi_{(110)}$ is up to 62.5% when the SiNW’s width decreases to 35 nm. This enhancement of $\pi_{(110)}$ can be qualitatively interpreted by introducing the one-dimensional (1D) hole transfer and the hole conduction mass shift mechanisms based on the 1D hole transport system, which might be expected to be induced in a nanowire p-type piezoresistor. This enhancement of the longitudinal piezoresistive coefficient is very significant for sensitivity improvement of piezoresistive-based ultra-small mechanical sensors, one of which will be presented in section 3.3.

### 3.3. Ultra-small accelerometer based on SiNW

The first demonstration of applying SiNWs as nanoscale piezoresistors to mechanical sensing was carried out. An ultra-small 3-DOF accelerometer utilizing Si nanowires as nanoscale piezoresistors was designed and fabricated. The model of the sensing chip is shown in figures 13(a) and (b). The seismic mass is suspended on four surrounding sensing beams, which are connected to the frame at the ends. Si nanowires are placed near the fixed ends on the surface of the sensing beams. When acceleration is applied to the sensor, the seismic mass will be moved due
to the inertial force. This movement deforms the beams; as a result, the resistance of the nanowires changes. The change of resistance is converted to a voltage change by a Wheatstone bridge. The overall size of the accelerometer chip is 500 × 500 × 400 μm³, (L × W × T). This accelerometer has been made from multi-layer SIMOX SOI wafer and fabricated by nano/micromachining technology, including EB lithography and RIE silicon etching [45]. The SiNW piezoresistor has dimensions of 128 nm × 50 nm (W × T). The resistance of these piezoresistors was measured to be 20 kΩ, and the calculated sensitivity for each axis is about 50 μV G⁻¹, and the resolution is 30 mG. (G is the gravitational acceleration, i.e. = 9.8 m s⁻²). Accordingly, by using SiNWs as piezoresistors, we can reduce the sensor’s size while increasing the sensitivity. Smaller chip size means more chips per wafer, higher productivity, and therefore lower cost per chip. Ultra-small accelerometers are important for portable devices, such as camcorders, mobile phones, navigation systems, entertainment devices, and so on.

4. Conclusions

This paper has briefly described progress in micro/nano-electromechanical systems (MNEMS) technology, as well as several research achievements of our group on SOI-MEMS mechanical sensors and electrostatic actuators. SOI wafers have been used because the buried oxide layer plays very important roles; for example, it is a reliable electrical insulation layer, an excellent etching stop layer and an ideal sacrificial etching layer. Therefore, it has become the principal substrate for MEMS/NEMS device fabrication. Furthermore, the cost per unit of SOI wafer is decreasing due to the rapid development of silicon wafer fabrication technology.

Over the past 40 years, single functional MEMS devices have developed rapidly and their consumer applications have spread widely in industries such as automotive, telecommunication, biomedical, security and defense, etc. Recently, MEMS have also become good platforms for studying nanotechnology. MEMS technology has lagged behind the IC industry, which came into production in the mid-1960s, by about 15 to 20 years. However, with significant technology improvement, strong development of MEMS infrastructure and strong demand for higher performance, multifunction integrated, low-cost and miniaturized devices, MEMS technology will continue to play an important role in industry and consumer applications. Future trends of MEMS devices will be toward multifunctional integration, nanoscale integration, integration with electronics, and new MEMS materials to create new and smart devices for not only traditional applications but also new purposes such as Environmental-MEMS, Energy-MEMS, Safety-MEMS, Health-MEMS, and so on.

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