Compound Semiconductor Micro/ Nanomechanics

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Abstract

We are studying the fusion of semiconductor quantum nanostructures and micro/nanomechanical systems. Mechanical systems are extremely sensitive to applied force and this feature can be used to achieve new functionality in semiconductor quantum nanostructure devices. Here we report displacement detection using a quantum mechanical electron interferometer and the fabrication of nanoscale conductive semiconductor cantilevers.

1. Introduction

Technology using microelectromechanical systems (MEMS) has made rapid advances in the last few years. MEMS are miniature devices with fine structures that have mechanical functionalities. They are fabricated using state-of-the-art semiconductor microfabrication technologies. They are already used in practical systems, such as in the accelerometers of automobile airbag systems and in digital micromirror devices used in projectors connected to personal computers.

We are studying the fabrication and characterization of compound semiconductor nanostructure devices. The aim is to introduce new quantum mechanical functionalities into semiconductor systems to develop a novel category of nanostructure devices. We have recently succeeded in introducing mechanical functionality into semiconductor nanostructure devices by combining semiconductor heterostructures and mechanical cantilevers. The ultimate challenge is the fusion of semiconductor nanotechnology and MEMS technology. This kind of new research field, called "nanomechanics", has recently started fundamental studies at leading research institutes around the world. The fusion of these technologies promises to bring about a revolution in the application of semiconductor fine-structure devices.

In this paper, we report our recent approaches to combining semiconductor nanostructures and mechanical cantilevers. Section 2 covers the piezoelectric properties of micromechanical cantilevers fabricated from InAs/AlGaSb heterostructures with nanometer-thick InAs films. Section 3 describes the strong enhancement of detection sensitivity induced by quantum interference effects. Section 4 presents a novel fabrication technique for nanoscale semiconductor cantilevers using self-assembled growth.

2. Fabrication of InAs/AlGaSb heterostructure displacement sensors

Highly sensitive detection of ultrasmall cantilever displacement is one of the most important functions of MEMS devices. Various quantities, such as magnetic moment, electric charge, force, and acceleration, can be sensed with high resolution by detecting the displacement of micromechanical cantilevers. For displacement sensing, both optical and electrical methods are widely used. Optical methods, such as optical levers and laser interferometers, offer higher detection sensitivity than electrical ones. However, an optical system with lasers and detectors requires a sufficient volume of space for its construction. Downscaling to nanometer sizes is also problematic because it is difficult to collimate the laser beam onto nanoscale cantilevers. In contrast, electrical methods are advantageous for downscaling and also for specialized experiment, such as a low-temperature scan-

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ning probe microscope, where the volume of space is strictly limited.

For downscaling, we have proposed InAs-based mechanical systems. Compared with structures made from commonly used material systems, such as Si/SiO_2 [1] and GaAs/AlGaAs [2], InAs-based structures have the advantage that the surface Fermi level is pinned in the conduction band [3]. This makes it possible to fabricate piezoresistive cantilevers that are much smaller than those based on other semiconductors [4], [5]. We have successfully fabricated piezoresistive InAs/AlGaSb cantilevers, which can be downsized to the nanometer scale.

The layered heterostructures were grown by molecular beam epitaxy. To obtain uniform InAs/$Al_{0.5}Ga_{0.5}Sb$ films on a semi-insulating GaAs substrate, we used the (111)A substrate surface orientation, along which a highly uniform two-dimensional film can be grown despite the large lattice mismatch of about 7% [6]. The total thickness of InAs/$Al_{0.5}Ga_{0.5}Sb$ film was kept at 300 nm, and the top InAs thickness was varied from 20 to 8 nm. After defining the lateral structure by standard photolithography and subsequent dry etching using BCl_3, we etched the sacrificial GaAs layer with an NH_4OH solution, as shown in **Fig. 1**. A scanning electron microscope (SEM) image of a typical fabricated device is shown in **Fig. 2**. Ti/Au was deposited on the InAs surfaces for non-alloy ohmic contacts.

Figure 3 shows the measured room-temperature sensitivity, $\Delta R/R$ per unit displacement Δz, and the minimum detectable displacement, i.e., the noise density in the unit of displacement, at 1 kHz. The piezoresistance increases greatly with decreasing InAs thickness as a result of a quantum effect. When an electron system is thin enough, quantum mechanical effects allow electrons to have only limited val-

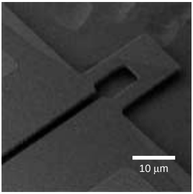

Fig. 2. Fabricated InAs/$Al_{0.5}Ga_{0.5}Sb$ piezoresistive cantilever.

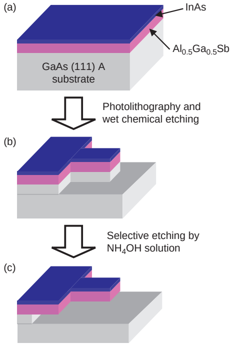

Fig. 1. InAs/AlGaSb piezoresistive cantilever fabrication processes.

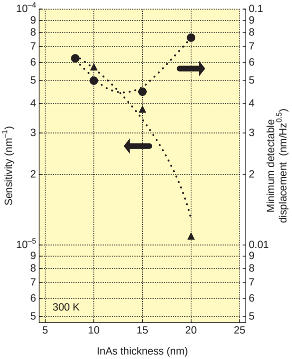

Fig. 3. Sensitivity and minimum detectable displacement of fabricated devices.

ues of energy. At the quantum mechanical resonance position, i.e., when the surface Fermi energy coincides with one of the quantum levels formed in the InAs film, the device conductance becomes highly sensitive to the strain caused by deflection of the cantilever.

However, the minimum detectable displacement had its minimum value at the InAs thickness of 15 nm. This is because the noise density also increased with decreasing InAs thickness and the best sensitivity-to-noise ratio was obtained in a 15-nm-thick device.

Because the noise density shows a typical 1/f dependence on the frequency in the lower frequency region, the fabricated devices showed much better sensitivity at higher frequencies. **Figure 4** shows the frequency spectrum of a 10-nm sample placed in a vacuum chamber. The signal induced by the thermal vibration of the cantilever is clearly observed. From the quality factor Q, the effective spring constant $k_{eff} \approx 0.1$ N/m, as directly measured with an atomic force microscope (AFM) and the resonance frequency f_0 of 345 kHz, the thermal displacement noise density δ_{therm} at the resonance frequency f_0 can be roughly estimated to be $\delta_{therm} \approx (k_B TQ\ /2\pi f_0\ k_{eff})^{1/2} \approx 10^{-2}$ nm/Hz$^{1/2}$. In this frequency range, the 1/f noise is sufficiently reduced and displacement of less than 1 Å can be clearly detected.

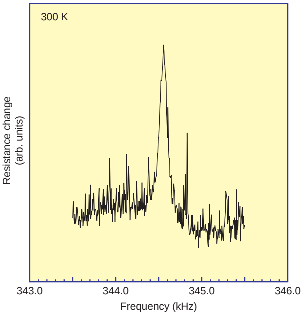

Fig. 4. Cantilever thermal vibration at 300 K detected by the resistance change in a fabricated InAs/$Al_{0.5}Ga_{0.5}Sb$ piezoresistive cantilever.

3. Displacement detection using electron interferometry

At low temperatures, electrons exhibit wave-like behavior, so they can be used for highly accurate sensing just like the photons in a laser interferometer. We have succeeded in detecting the displacement of a micromechanical cantilever by using electron interference [7]. The device used was an InAs/AlGaSb pieozoresistive cantilever with InAs thickness of 15 nm. The resistance change induced by the cantilever deflection was measured at various temperatures and under a magnetic field. First, the sample temperature dependence of the mechanical resonance characteristics was studied. The sample was mounted on a piezoelectric actuator and mechanically driven by applying an alternating voltage to the actuator. It was placed in a vacuum chamber and the resistance change induced by the mechanical displacement of the dc-biased cantilever was measured as a function of the drive frequency using a network analyzer. **Figure 5** shows the frequency responses obtained at (a)

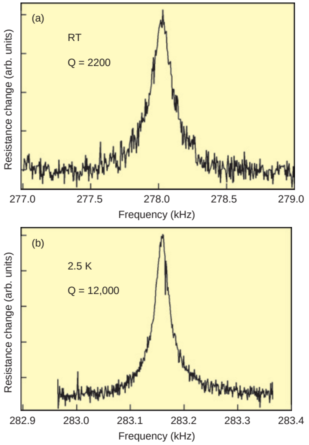

Fig. 5. Frequency responses obtained at (a) room temperature and (b) 2.5 K.

room temperature and (b) 2.5 K. The resonance frequency shifted to a higher value at 2.5 K due to the increase in the elastic constant (i.e., Young's modulus). In addition, the quality factor (Q) at 2.5 K was 12,000, which is much higher than that at room temperature (2200). This is probably because the internal friction is strongly suppressed at low temperatures.

Next, the magnetic field dependence was measured to study the effect of quantum interference. **Figure 6** shows the measured sensitivity, two-terminal resistance (R), and its derivative (dR/dB) as functions of magnetic field (B). The sensitivity has a strong and aperiodic B dependence, which was reproducible in repeated measurements. This B dependence is very similar to that for dR/dB, which shows quantum interference oscillations at the narrow parts of the cantilever. At 6.67 T, the sensitivity had a maximum value, which was nearly one order of magnitude larger than that at zero magnetic field. This clearly demonstrates the possibility of highly sensitive quantum mechanical displacement sensing, which is promising for future MEMS/NEMS*1 applications.

*1 NEMS: nanoelectromechanical systems

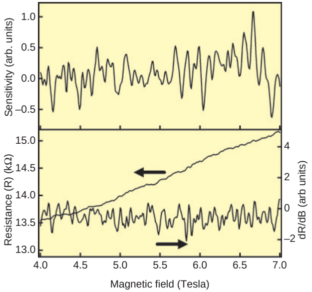

Fig. 6. (a) Measured sensitivity as a function of magnetic field. (b) Two-terminal resistance (R) and its derivative (dR/dB) measured for the same device as functions of magnetic field.

4. Fabrication of nanoscale InAs cantilevers using self-assembled growth

Surface step distributions during molecular beam epitaxy can be controlled for the fabrication of semiconductor low-dimensional structures. In particular, multistep structures formed via step bunching during growth are frequently applied for the growth of semiconductor quantum wires. This fabrication technique is a clean process and does not rely on electron-beam lithography, which often degrades crystalline quality. We have demonstrated, for the first time, the application of this "bottom-up" technique to the fabrication of semiconductor nanomechanical structures [8], [9].

We used preferential growth of InAs wires on bunched monomolecular steps formed on the growing GaAs surface [10]. **Figure 7** schematically illustrates the fabrication process for InAs nanoscale cantilevers, which are typical mechanical components in nanomechanical devices. The substrates were GaAs (110) wafers misoriented toward the (111)A direction. The growth of a GaAs buffer layer and then a five-period GaAs/$Al_{0.5}Ga_{0.5}As$ (30-nm-thick each) superlattice formed regular multi-step structures on the growing surface (Fig. 7(a)). The subsequent growth of InAs resulted in the formation of InAs wires along the steps (Fig. 7(b)). After mesa trenches were formed perpendicular to the InAs wire direction by photolithographic patterning, the sacrificial GaAs and AlGaAs layers were selectively etched to form

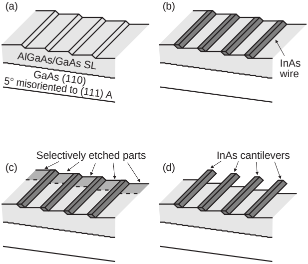

Fig. 7. Fabrication processes for InAs nanocantilevers using self-assembled growth.

the InAs cantilevers (Figs. 7(c) and (d)). **Figure 8** is a SEM image of typical fabricated nanoscale cantilevers. They are 50–300 nm long, 20–100 nm wide, and 10–30 nm thick.

The elastic properties of the InAs cantilevers were then characterized by viscoelastic imaging by contact-mode AFM. We detected the change in the vibration amplitude of the AFM tip scanned over the sample surface while performing sample-height modulation with a z-piezo-translator. The spring constants of the fabricated InAs cantilevers at a distance of 100 nm from the support ranged from 0.5 to 10 N/m, depending on the size of the cantilevers (**Fig. 9**). These spring constants showed good agreement with ones calculated from the elastic parameters of InAs. The resonance frequency of mechanical vibration is expected to reach 500 MHz for the smallest structure, pointing to the possibility of high-speed nanomechanical devices.

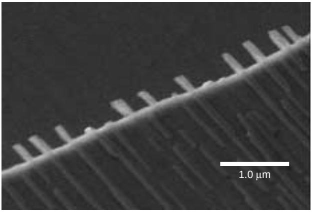

Fig. 8. SEM micrograph of fabricated InAs nanoscale cantilevers.

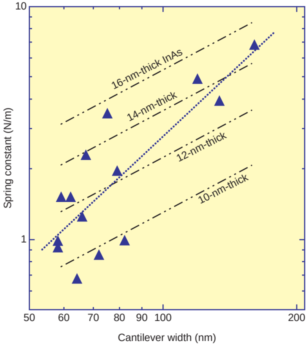

Fig. 9. Spring constants 100 nm from the clamped position evaluated for 14 different cantilevers. The dash-double-dotted line shows spring constants calculated from the cantilever dimensions and elastic constant of bulk InAs. The blue dotted line shows the least squares line fitting of obtained data.

5. Conclusion

The integration of semiconductor low-dimensional structures with mechanical cantilevers and the fabrication of nanoscale mechanical systems using semiconductor nanostructures promise to lead to novel semiconductor devices with mechanical functionalities. We have demonstrated the strong enhancement of displacement sensitivity using quantum mechanical interference in semiconductor nanostructures, and we expect that other kinds of nanostructrures, such as single electron transistors, quantum rings, and carbon nanotube transistors will enable further enhancement of displacement sensitivity.

Structure downsizing leads to a high resonance frequency and hence a fast mechanical response. In addition, it has recently been pointed out that the mechanical motion of cantilevers with nanometer-scale dimensions can be quantized [11]. Potential applications of this novel quantum effect include quantum nondemolition force and displacement measurements and the fabrication of solid-state quantum bits, which could be used as the elementary components for quantum computing. Extremely sensitive detection systems based on nanoscale high-speed mechanical structures might open the door to this new research field of quantum nanomechanics.

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