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Application of InAs Free-Standing Membranes for Electromechanical Systems

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1. Introduction

The electrical and mechanical properties of micro- and nano-electromechanical systems (MEMS/NEMS) are of growing interest not only from technological standpoint [1-7] but also from fundamental science, such as macroscopic quantum tunneling and quantized phonon transport [1,8-11]. Previous studies have used Si/SiO_2 on SOI substrates [1-4,6], silicon nitride [11], GaAs [8], GaAs/Al(Ga)As [5,6,9] and InAs/AlSb [9] heterostructures grown on (001) substrates to fabricate free-standing membranes. We have fabricated and characterized several number of freestanding InAs beams and cantilevers processed from InAs/GaAs heterostructures grown on GaAs (111)A surfaces, where the InAs thinfilm grows in layer by layer mode despite of the large lattice mismatch of 7 % [12].

InAs-based structures have the advantage that the position of the surface Fermi level is pinned in the conduction band [9,13], in contrast to other semiconducting materials where the level is pinned in the band gap. This unique property of InAs provides the possibility of fabricating much thinner conductive membranes than with other semiconductors, where the surface Fermi level pinning in the band gap causes a problem of carrier depletion for thin membranes. Preliminary experimental studies and a self-consistent model calculation have shown that the InAs thickness can be reduced to even less than 10 nm with sufficient electric conduction without any intentional doping [14]. This advantage in terms of reduced scale in device size can lead to an increase in operation frequency or high-sensitivity.

2. Experimental

We grew the samples using conventional solid-source MBE. We have already described the growth procedure in detail elsewhere [12]. Despite the large lattice mismatch of about 7% between InAs and GaAs, uniform InAs films can be grown on GaAs (111)A surfaces because more than 90% of the misfit strain is released by the formation of a dislocation network at the InAs/GaAs interface [15]. We grew undoped InAs films with thickness from 50 and 150 nm on semi-insulating GaAs (111)A substrates (Fig.1(a)). We defined the lateral device dimensions by employing a conventional photolithographic technique with wet chemical etching using $H_2O/H_2O_2/H_2SO_4$ solution (Fig.1(b)). We then selectively removed the GaAs under the InAs thin film by wet etching using $H_2O/H_2O_2/NH_4OH$ solution (Fig.1(c), (d)). We measured the thickness of the fabricated InAs membranes using SEM observation and found that the InAs was etched by less than 10 nm and the selectivity sufficiently high.

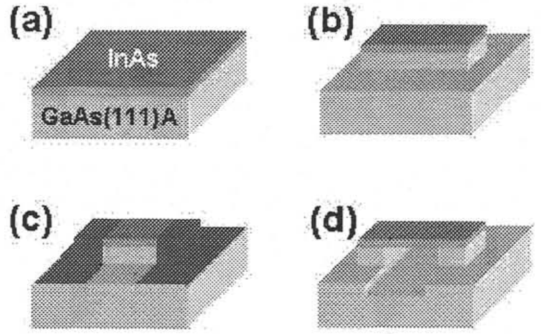

Fig. 1 Lithographic processes used to fabricate the freestanding structures. (a) The InAs/GaAs(111)A heterostructures. (b) The first photolithographic patterning and mesa etching to define the lateral dimension of the structures. (c) Second lithographic patterning. (d) Removal of GaAs sacrificial layer.

3. Experimental Results

Figure 2 shows the SEM images of typical freestanding InAs structures with the thickness and the width of 100-300 nm and 10μm, respectively. All the membranes are electrically conductive and deflected downward to relax the residual strain of about 0.5% in the InAs films. The Hall measurements proved that the freestanding InAs membranes show much higher electron concentration and mobility than as-grown heterostructures samples (i.e. InAs/GaAs) [16]. This is probably because the relaxation of residual strain in InAs layer reduces the deformation potential. As the results, the increased carrier concentration improves the electron mobility by screening effects. The removal of dislocation networks at the InAs/GaAs interfaces can also be responsible for the improvement in the mobility.

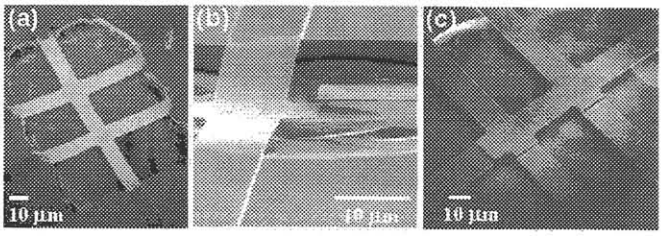

Fig. 2 Fabricated InAs Freestanding structures. (a) Hall bar (100 nm-thick), (b) single and (c) coupled cantilevers (300-nm-thick). The structures in (b) and (c) were fabricated by applying FIB manufacturing to similarly fabricated Hall bar structures.

To fabricate cantilevers, focused ion beam was applied to cut the beams making a vacuum gap (Fig.2(b)). By applying the bias voltage across the gap, the mechanical motion of the cantilever was electrically activated. The mechanical resonance characteristics of a similarly fabricated 300 nm-thick coupled cantilever structure (Fig2(c)) have been studied. Applying an AC voltage, with a magnetic field (1-8T) perpendicular to the current through the coupling part of the cantilever, the induced Lorentz force actuates the oscillatory motion. This motion induces the resistive voltage to the current and the mechanical resonance can be electrically detected as the change in the AC resistance of the devices [1]. At about 25 kHz, we confirmed clear resonance, whose peak height was proportional to the square of magnetic field intensity. The quality factor has the range of 2000-3500 depending on the bias voltage and the magnetic fields. With strong magnetic fields and large applied voltages, we clearly observed a hysteresis. By applying a non-linear Duffing equation, this bi-stability can be explained by the non-linear elastic response of the InAs membrane, which becomes significant with large deflections of the coupled cantilever.

4. Conclusions

We have fabricated freestanding InAs membranes made from InAs/GaAs(111)A heterostructures with the thickness of 50-300 nm and the typical length of several ten micrometers. Without any intentional doping, the membranes show clear conductivity which is promising for the application for MEMS/NEMS devices. By applying focused ion beam processes for freestanding Hall bar structures, single and coupled InAs cantilever were fabricated. The mechanical motion was electrically activated and resonance with showing non-linear elastic response of the membrane was clearly observed.

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