Fabrication and characterization of 100-nm-thick GaAs cantilevers

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We describe a new process for making submicron, micromechanical cantilevers out of GaAs epilayers grown by molecular beam epitaxy. The extremely high aspect ratios of these cantilevers (typically 100 nm thick and 100 μm long) give spring constants as low as 10^{-4} N/m. We present characterizations of the cantilevers' resonant frequencies, quality factors, and spring constants. The ability to fabricate III–V GaAs-based mechanical microstructures offers new opportunities for integration with electronics for strain-sensitive force detection. © *1996 American Institute of Physics.* [S0034-6748(96)00509-6]

I. INTRODUCTION

The fabrication of very delicate mechanical cantilevers combined with sensitive displacement detection schemes has resulted in a number of remarkably powerful experimental techniques, including scanning force microscopies,[1] mechanically detected magnetic resonance,[2] and a new class of torque magnetometers.[3] In general, the force sensitivity of these techniques can be improved by lowering the spring constant k of the cantilever (thereby increasing the displacement per unit force) and increasing the resonant frequency ν_0 (decreasing the necessary averaging time). Since most semiconductors and metals have mass densities (ρ) and elastic moduli (E) within an order of magnitude of each other, the design parameters that afford the greatest opportunities for improvements are the physical dimensions of the cantilever. Specifically, since for a rectangular cantilever[4]

$$\nu_0 = 0.162\sqrt{\frac{E}{\rho}}\frac{t}{l^2} \quad \text{and} \quad k = \frac{Et^3 w}{4l^3}, \tag{1}$$

where t, l, and w are the thickness, length, and width of the cantilever, one can achieve small k and large ν_0 by simultaneously decreasing all the dimensions.

Typically, micron-scale cantilevers are fabricated from silicon, silicon oxide, or silicon nitride.[5] Fabricating cantilevers from the GaAs/$Al_xGa_{(1-x)}As$ materials presents challenges in designing new processes for the III–V chemistry. More importantly, it offers the advantages of integration with optical devices,[6,7] magnetic systems,[8] and strain sensing elements that utilize the piezoelectric properties of the GaAs to detect the cantilever displacement.[9] Cantilevers fabricated from the III–V semiconductors have usually contained Al-rich layers[6,7] (included as part of a laser structure), which simplify the fabrication of free mechanical structures by allowing the selective etching of the GaAs substrate out from under the Al-rich layers. In this article, we describe a process for making cantilevers from a single epilayer of GaAs grown by molecular beam epitaxy (MBE) on an AlAs etch stop layer on a [100] GaAs single crystal substrate. We have fabricated cantilevers 100-nm-thick, within an order of magnitude of the thinnest cantilevers fabricated from silicon[2] and much thinner than cantilevers previously fabricated from GaAs/AlGaAs.[6,7] This process allows easy access to both sides of the cantilever by etching a window through the entire thickness of the GaAs substrate, unlike previous GaAs/AlGaAs cantilever processes. We also present characterization of the resonant frequency, quality factor (Q) and spring constant of a 100-nm-thick GaAs cantilever fabricated in this fashion.

II. FABRICATION

To construct very thin cantilevers made of a single material (as opposed to GaAs/AlGaAs layers), we use MBE to grow a 100-nm-thick GaAs epilayer on a 300-nm-thick AlAs epilayer on a [100] GaAs substrate [Fig. 1(a)]. The GaAs epilayer will ultimately form the cantilever, and so its thickness determines that of the cantilever; the AlAs serves as an etch stop and a sacrificial layer. The lateral shape of the cantilever is defined by optical lithography in photoresist spun on the epilayers. In the present case, the pattern is of the form of a window with a cantilever extending into the window. This pattern provides protection to the cantilever against damage in later fabrication steps as well as in actual use. This pattern is then etched into the epilayers by a Cl_2 reactive ion etch. In order for the subsequent steps to be successful, it is crucial that the Cl_2 etches all the way through the GaAs epilayer but stops just inside the AlAs epilayer [Fig. 1(b)]. After removal of the photoresist mask, a fresh layer (~5 μm) of photoresist is spun on the now patterned epilayers and baked for 1 min at 95 °C to afford them protection during the subsequent steps. Next, 5–10 μm of photoresist is spun on the back of the chip and baked at 95 °C for 1 min. Using an infrared mask aligner, windows are patterned in the back mask directly beneath the cantilever patterns in the epilayers. The windows in the back mask define the region of the substrate that will be removed by a spray etch[10] in order to free the cantilever, and so this alignment is crucial. It is important to note that the etch profile will depend upon the orientation of the mask relative to the crystal axes of the substrate. This can easily be compensated for in the shape of the back mask window [Fig. 1(c)].

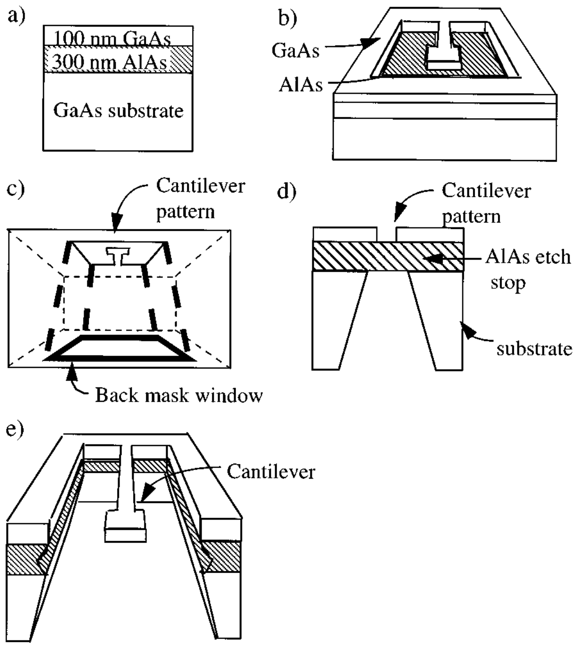

FIG. 1. Outline of processing steps: (a) MBE structure: 100 nm GaAs layer on 300 nm AlAs layer on a GaAs substrate. (b) Cantilever shape is defined in GaAs epilayer by Cl_2 reactive ion etching. (c) Patterning of windows on the back of the chip, directly beneath the cantilever shapes. The thick dashed lines show the profile of the spray etch, and the thin dashed lines correspond to the hidden surfaces of the chip. (d) Wet etch through substrate to AlAs etch stop. (e) Removal of AlAs etch stop with HF acid.

The photoresist is subsequently baked at 115 °C for 2 min. The chip is placed substrate up on a glass slide and held in place with wax. The slide and chip are mounted in a spray etcher with a 1:30 mixture (NH_4OH:H_2O_2). This mixture gives the maximum GaAs to AlAs selectivity and a GaAs etch rate of a few μm/min.[11] When the etch reaches the AlAs epilayer, the etched part of the chip will suddenly become transparent, and so when light can be seen through the sample, the spray etch is halted, the slide and sample removed and immediately rinsed in deionized water. To remove the AlAs epilayer, a few drops of 1:5 HF:H_2O are placed on the exposed AlAs epilayer for 5–10 s [Fig. 1(e)] Since the exposed AlAs layer is transparent to visible light, one can verify that it has been removed by looking for signs that the unexposed part of the AlAs layer has been partially etched by the HF. This can be seen under an optical microscope as a faint ring around the epilayer window.

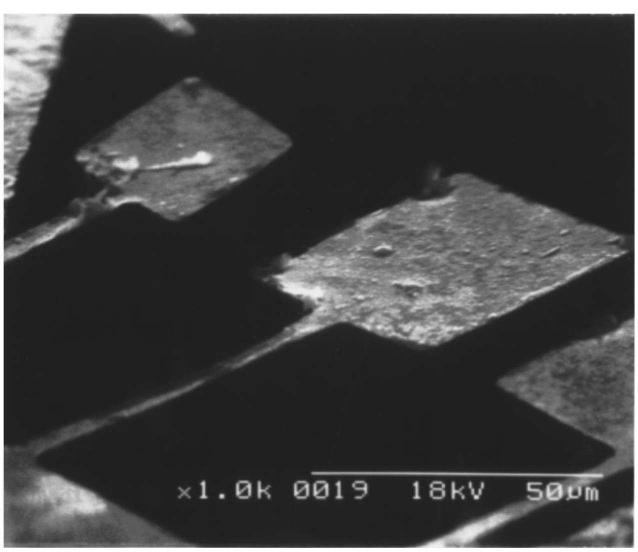

FIG. 2. SEM photograph showing 100-nm-thick spatula-shaped cantilevers. Spatula arm is 70 μm long and 6 μm wide. Spatula head of central cantilever is 30 μm square.

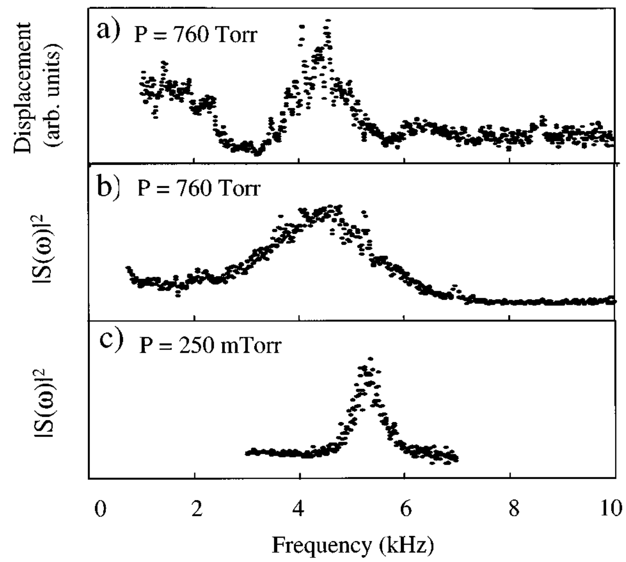

FIG. 3. (a) Frequency-dependent mechanical response of a 135 μm long by 30 μm wide by 100-nm-thick cantilever at room pressure and temperature shows $\nu_0=4$ kHz and $Q\sim 2$. (b) Spectral density $|S(\omega)|^2$ of thermal noise of under identical conditions. (c) Spectral density $|S(\omega)|^2$ of thermal noise cantilever at room temperature and $P=250$ mTorr shows $\nu_0=5.1$ kHz and $Q\sim 9$.

At this stage, the cantilever is free from the semiconductor material; it is only bound by the wax to the glass slide. The wax can be dissolved with acetone over an 8 h period, and the chip removed. However, removing the cantilever intact from the acetone bath is made difficult by the surface tension of the acetone, which tends to break the cantilevers. This problem can be circumvented by the use of a high pressure CO_2 critical point dryer. Figure 2 shows spatula-shaped cantilevers fabricated by this process. The lateral dimensions are defined by the first photoresist mask, and the vertical dimension by the MBE grown GaAs epilayer (100 nm in this case). Here, the center spatula arm is 70 μm long and 6 μm wide, and the head is 30 μm square. The apparent surface roughness is due to photoresist residue left from earlier processing steps, and does not appear to affect the mechanical properties of the cantilevers.

III. CHARACTERIZATION

The cantilevers were mounted on a piezoelectric crystal and driven over a range of frequencies in order to measure ν_0, k, and Q. Here we take $Q=(\Delta\nu/\nu_0)$, where $\Delta\nu$ is the full width at half-maximum of the cantilever response. Their displacement was measured using laser interferometry. The interferometer and cantilever were mounted on a small optical table to reduce spurious vibrations. Shown in Fig. 3(a) is the response of a 135-μm-long, 30-μm-wide, and 100-nm-thick cantilever as a function of the driving frequency. This curve was taken at room temperature and pressure and shows a resonant frequency of 4.5 kHz and a Q of $\sim$2. Figure 3(b) shows the absolute magnitude of the Fourier transform of the (undriven) noise in the interferometer. The technique of measuring the thermal noise of the cantilever has many advantages over the driving approach, in particular the fact that the spectral weight of the thermal noise tends to select the ''soft'' (small k) modes and reject the large k modes, which include the modes of the mounting itself, whereas the response of a mode to the piezo driving force is insensitive to the mode's k.[12] The thermal noise gives values of ν_0 and Q that are consistent with the piezo driven measurement. Although other damping mechanisms may be present, air damping strongly affects the Q because of the cantilevers' large aspect ratio and low mass. The thermal noise of the same cantilever at a pressure of 250 mTorr is shown in Fig. 3(c). Here, ν_0 has increased to 5.1 kHz and Q to $\sim$9. From this value of the resonance frequency and Eq. (1), we find $k \sim 10^{-4}$ N/m. Given a dc displacement sensitivity of 1 nm,[13] this results in a dc force sensitivity of $\sim 10^{-13}$ N. An order of magnitude estimate for the thermal noise of the cantilever based on a simple model[14] gives the peak value of $|S(\omega)|$ in Fig. 3(c) as $\sim 2\times 10^{-10}$ m/Hz$^{1/2}$, corresponding to a force noise of $\sim 2\times 10^{-14}$ N/Hz$^{-1/2}$.

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