

# Novel Fabrication Method for Surface Micromachined Thin Single-Crystal Silicon Cantilever Beams

Amit Gupta, *Student Member, IEEE*, John P. Denton, *Senior Member, IEEE*, Helen McNally, *Senior Member, IEEE*, and Rashid Bashir, *Senior Member, IEEE*

**Abstract**—This paper describes a novel technique for the fabrication of surface micromachined thin silicon cantilever beams using merged epitaxial lateral overgrowth (MELO) of silicon and chemical–mechanical polishing (CMP). The objective is to demonstrate the feasibility of using this novel technique for the fabrication of arrays of ultrathin, low-stress, single-crystal silicon cantilever beams for use in ultrahigh sensitivity surface-stress or resonant-frequency-based chemical or biological detection schemes. The process flow used in this work will be described in detail and the issues that were faced during the fabrication will be discussed. Cantilever beams with thickness of 0.3–0.5  $\mu\text{m}$  that were 10–25- $\mu\text{m}$  wide and 75–130- $\mu\text{m}$  long were fabricated. Mechanical characterization of the cantilever beams were performed by measuring their spring constant using the “added mass” method, which also demonstrated the use of these initial structures to detect masses as low as 10–100 pg. Further work is underway to scale the thickness of these beams down to the sub-100-nm regime. [823]

**Index Terms**—Cantilever beam, chemical–mechanical polishing (CMP), merged epitaxial lateral overgrowth, silicon-on-insulator (SOI).

**AUTHOR:** Are you or your co-authors members of the ASME? If so, please provide membership status for verification with the ASME. Also, please provide author photos in tiff, eps, or ps formats with at least a resolution of 220 dpi.—ED.

## I. INTRODUCTION

IN recent years, micro- and nanoscale cantilever beams have become important micromachined structures that have found usage in diverse applications as sensors and actuators. Cantilever beams were first introduced to the nanotechnology field with their use as force sensors in atomic force microscopy (AFM) [1]. They have also been used extensively as probes in various other imaging techniques, involving different interactions between the probe and the sample, that are collectively described as scanning probe microscopy (SPM) [2]. In the

literature, numerous techniques have been reported which have modified the AFM setup to conduct highly innovative and powerful experiments to measure different phenomenon at the molecular level. An overview of the various areas in which the cantilever beam has been used as a micromechanical sensor can be found in [3].

This paper presents the use of selective epitaxial growth (SEG), epitaxial lateral overgrowth (ELO), and chemical–mechanical polishing (CMP) for the microfabrication of thin single-crystal silicon cantilever beams. This paper presents the details of the fabrication process flow as well as the mechanical characterization of the cantilever beams by measuring their resonance frequencies and spring constants. The present thin cantilever beams can be integrated into silicon-based micro-systems such as flow sensors, pressure sensors, biochemical sensors and the like. The present process can easily be extended to produce low-stress sub-100-nm thickness cantilevers for ultra-high sensitivity chemical and biological detection.

## II. CANTILEVER BEAMS WITH NANOSCALE THICKNESS

### A. Motivation

The basic impetus for decreasing the dimensions of the cantilever beams is their corresponding increase in the mechanical sensitivity to perturbations from the surroundings. Studies have been published that study the affect of cantilever dimensions on its performance as a force sensor [4], [5], surfaces stress sensor [6], [7] and mass sensor [8]. There will be different design rules for different types of sensing schemes. But generally speaking, decreasing the dimensions of the cantilever beams can improve the performance of the cantilever beams. The thickness of the cantilever beam is of more interest, as it is the hardest to control during fabricating. The thickness is also the dimension that most affects the mechanical sensitivity of cantilever beams [9].

### B. Reported Nanoscale Cantilever Fabrication

Single-crystal materials are preferred materials to make sensor elements due to their high mechanical quality factor [10]. Silicon is usually preferred for fabricating sensor elements due to advantages such as low stress and controlled material quality, using currently available VLSI circuit fabrication facilities, miniaturization of devices, high control of dimensions, and the economical advantage of batch fabrication. In addition, if piezoresistive detection modes are preferred, especially due to the need for arrays of cantilevers and detectors, then silicon provides the capability to realize such resistors to detect

Manuscript received February 28, 2002; revised September 3, 2002. This work was supported by the National Science Foundation under NSF Career Award ECS-9984199. Subject Editor G. K. Fedder.

A. Gupta and H. McNally are with the School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907 USA (e-mail: agupta@ecn.purdue.edu; mcnallyh@ecn.purdue.edu).

J. P. Denton is with the Electrical Engineering Technology Department, School of Technology, Purdue University, West Lafayette, IN 47907 USA (e-mail: jpdenton@tech.purdue.edu).

R. Bashir is with the School of Electrical and Computer Engineering and Biomedical Engineering Department, Purdue University, West Lafayette, IN 47907 USA (e-mail: bashir@ecn.purdue.edu).

Digital Object Identifier 10.1109/JMEMS.2003.809974

deflections. Various methods for the fabrication of ultra-thin cantilever beams have been reported. Among the works that reported fabricating silicon cantilever beams, virtually all of them employ an SOI wafer as the starting material [4], [11]–[13]. Where it has been reported, the SOI wafers used in these processes were obtained from SIMOX (Separation by ion implantation of oxygen) process [11], [12]. Work has also been reported on fabricating nanosized cantilever beams using other materials such as silicon nitride [14] and metals [15].

### C. Selective Growth of Silicon

The cantilever beams in this work were fabricated using merged epitaxial lateral overgrowth (MELO) and CMP of silicon. MELO can be regarded as an extension of selective epitaxial growth (SEG) and epitaxial lateral overgrowth (ELO). SEG is a form of vapor phase epitaxy (VPE), and is a variation on the conventional full wafer epitaxy process. Fig. 1 shows a cross-sectional SEM of single crystal silicon grown selectively from a seed-hole region on a silicon wafer. A description of the various forms of selective silicon growth that can be accomplished can be found in [16].

The fabrication method described in this work is a novel technique that allows for fabricating all-silicon structures without any oxide layer being present under the silicon anchor of the cantilever beam [17]. This eliminates any mismatch in material properties between the silicon and silicon dioxide material that exists when using SOI as the starting material. The cantilever beams have to be stress free in order to avoid curling of the cantilevers that hampers their proper operation. Residual stresses in cantilever beams are also a source of vibrational energy loss [10]. The present fabrication method has the potential of fabricating arrays of cantilever beams with varying length, width, and thickness dimensions on the same substrate. This can also allow the fabrication of arrays of cantilever beams with a range of mechanical resonant frequencies and sensitivities. In addition, it is also important to note that the techniques described herein lay the ground work for the use of confined lateral epitaxy or tunnel epitaxy to fabricate sub-50-nm-thick cantilevers for single molecule detection applications.

### III. THIN CANTILEVER FABRICATION PROCESS USING SELECTIVE SILICON GROWTH

The process begins with growing a layer of silicon dioxide followed by photolithography and buffered hydrofluoric (BHF) wet etching of the oxide to define the cantilever shapes. In order to get the best SEG silicon material quality with the minimum density of defects, it is preferred that the patterns be aligned along the  $\langle 100 \rangle$  direction [18]. Another oxidation step is performed to grow a thinner layer in order to obtain the buried oxide layer as shown in Fig. 2(a). The step in the oxide thickness defines the cantilever thickness. (Different cantilever beam thickness can be achieved on the same substrate by performing a series of selective masking, etching and oxidation over the buried oxide layer in order to get different oxide step heights). This is followed by reactive ion etching (RIE) of oxide using  $\text{CHF}_3/\text{O}_2$

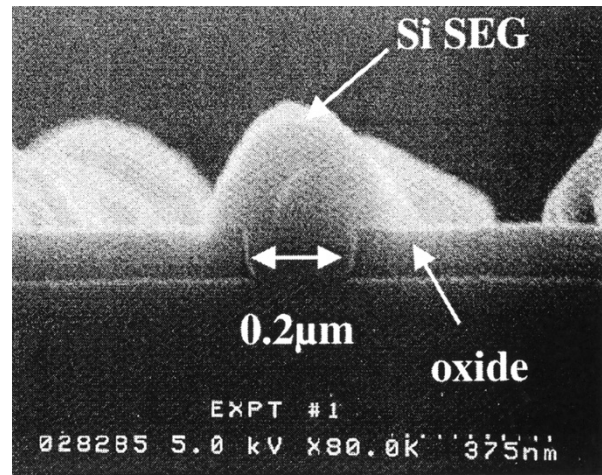


Fig. 1. Scanning electron micrograph (SEM) of single crystal SEG and ELO silicon on  $\langle 100 \rangle$  surface with patterns aligned to the  $\langle 100 \rangle$  direction.

to open the seed windows, as shown in Fig. 2(b), from where silicon is grown epitaxially. A sacrificial oxide is grown and wet etched to anneal the damage caused by the RIE step.

The selective epitaxial growth is done in a Gemini I pancake type reactor at  $T = 970^\circ\text{C}$  and  $P = 40$  torr using hydrogen ( $\text{H}_2$ ) as the carrier gas, dichlorosilane (DCS) as the source and  $\text{HCl}$  to maintain selectivity over the oxide. Fig. 2(c) shows the top view and cross-sectional diagram at this step. CMP was performed using a combination of slurries NALCO 2350 (for a faster etch rate) and NALCO 2355 (for finer etching) to etch the overgrown silicon to a flat surface using oxide as an etch stop, as shown in Fig. 2(d). It was necessary to polish the silicon down to the wafer flat surface, otherwise, the silicon forming the anchor of the cantilever beams would have been completely etched away when releasing the cantilever beams, as explained below. A thin layer of oxide ( $\sim 30$  nm) was grown to act as an etch stop against tetra-methyl-ammonium-hydroxide (TMAH) and an etch window was opened in the oxide layer using RIE with  $\text{CHF}_3/\text{O}_2$ , as shown in Fig. 2(e). TMAH, (25 wt. % in water) at  $T = 90^\circ\text{C}$ , was used to etch the surrounding silicon and release the cantilever beams. The wells formed beneath the cantilevers can also be used to form microfluidic channels in the substrate. After etching the surrounding silicon using TMAH and releasing the cantilever beams, as shown in Fig. 2(f), the oxide surrounding the beams was etched away using BHF to result in the final released cantilevers as shown in Fig. 2(g).

Even though the wells underneath the cantilevers were about  $14\text{--}16\ \mu\text{m}$  deep, the problem of stiction was encountered following each of the above two stated wet etching steps, since the cantilevers were thin ( $0.3\text{--}0.5\ \mu\text{m}$ ) and long ( $70\text{--}200\ \mu\text{m}$ ). Slightly different stiction prevention steps were performed following each of the two wet etching steps. After the TMAH etch of silicon to release the cantilevers, the structures were rinsed in deionized (DI) water for 10 min, followed by treatment in methanol in three steps of 10 min each. The structures were finally air-dried.

Surface modification by coating with hydrophobic self-assembling monolayers (SAMs) films was used to minimize stiction after the BHF etching of the oxide surrounding the cantilevers. The series of process steps were adapted from [19]. In

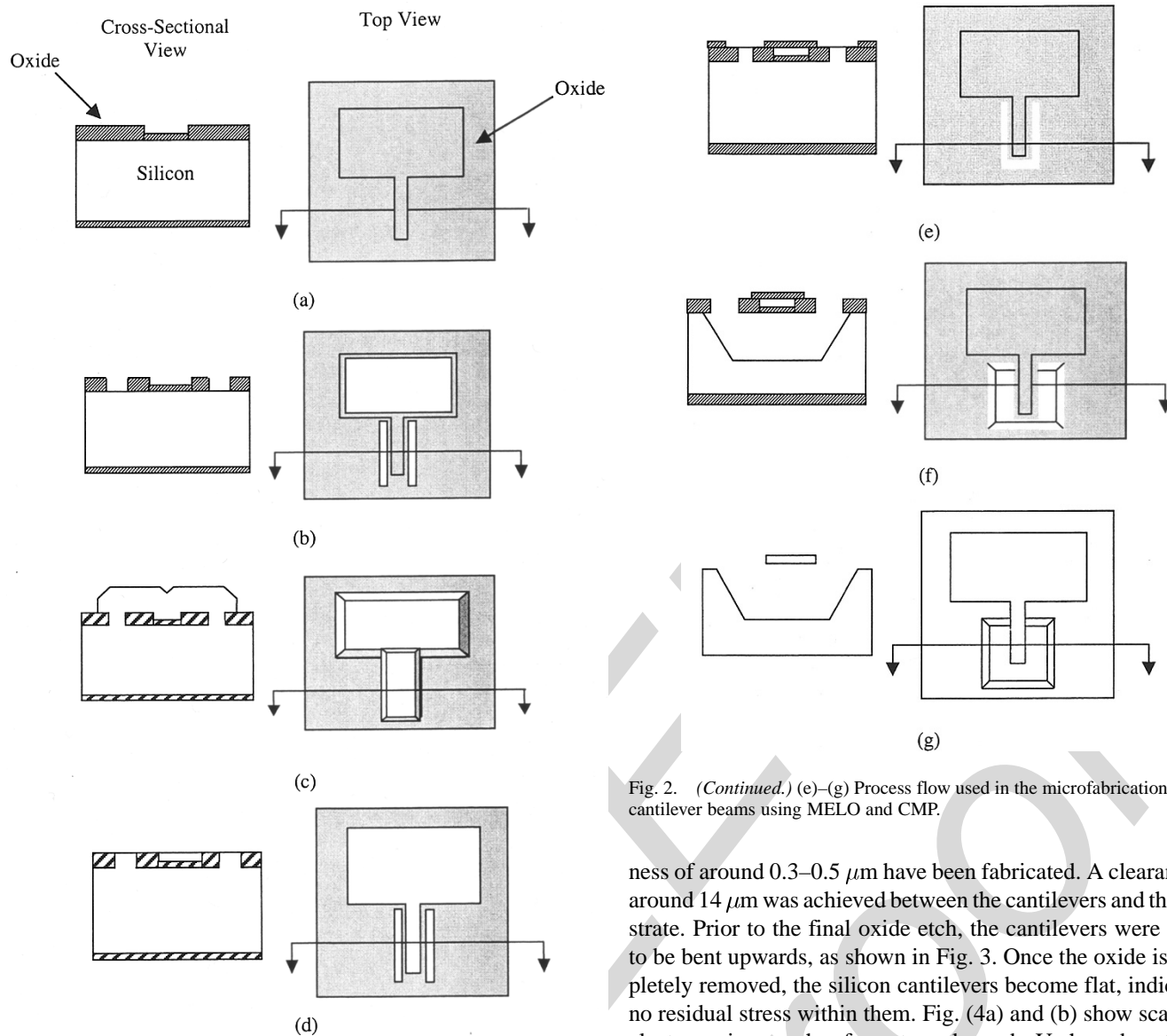


Fig. 2. (a)–(d) Process flow used in the microfabrication of thin cantilever beams using MELO and CMP.

this work, 1.0 mM of octadecyltrichlorosilane (OTS) in 2,2,4-trimethylpentane (isooctane) as the solvent was used to form the SAM coatings. The structures were etched in BHF for 20 min, followed by a 10 min rinse in DI water. The structure was then treated with hot hydrogen peroxide ( $\text{H}_2\text{O}_2$ ) for 10 min in order to obtain a very thin oxide layer on the structures. The structures were then rinsed in DI water for 10 min. Following the DI rinse, the structures were rinsed with 2-propanol (isopropyl alcohol) and then with isooctane for 10 min each. The structures were then treated with OTS for 10 min. The structures were then re-rinsed in fresh isooctane, 2-propanol and DI water for 10 min each and finally air-dried.

#### IV. RESULTS AND DISCUSSION

##### A. Processing Issues

A total of three masking steps were needed in the fabrication process. In the present work, cantilever beams with thick-

Fig. 2. (Continued.) (e)–(g) Process flow used in the microfabrication of thin cantilever beams using MELO and CMP.

ness of around  $0.3\text{--}0.5\ \mu\text{m}$  have been fabricated. A clearance of around  $14\ \mu\text{m}$  was achieved between the cantilevers and the substrate. Prior to the final oxide etch, the cantilevers were found to be bent upwards, as shown in Fig. 3. Once the oxide is completely removed, the silicon cantilevers become flat, indicating no residual stress within them. Fig. (4a) and (b) show scanning electron micrographs of a rectangular and a U-shaped cantilever obtained using this process. Cantilever beams of lengths  $78\ \mu\text{m}$  and  $129\ \mu\text{m}$ , and widths of  $13\ \mu\text{m}$  and  $23\ \mu\text{m}$ , were fabricated and released. The width of cantilevers produced is a function of the distance that the lateral epitaxy has to be grown before it merges from the growth front from the other side. If the selective growth is performed for too long of a time, an undesirable level of nucleation can be produced, resulting in an overall poor material quality. Using the HCl/DCS ratio reported earlier, we limited growth to about  $15\ \mu\text{m}$  so that  $20\ \mu\text{m}$  wide cantilevers could be comfortably produced.

The merging of the growth fronts is also an important factor to consider and optimize. In general, the slope of the sidewall facets decreases with decreasing HCl/DCS ratio [20], which is desirable in order to produce defect-free merged regions. However, as the HCL ratio is decreased, the selectivity of the silicon growth on oxide also decreases, resulting in a worsening of material quality. Data from literature from prior works can provide a process window for achieving high quality merged regions. It should also be pointed out that narrower structures with just one-sided growth could also be formed eliminating any issues with the merged silicon region.

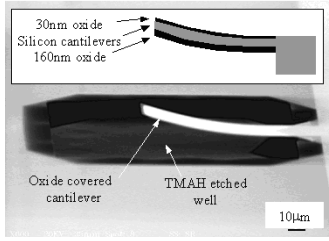
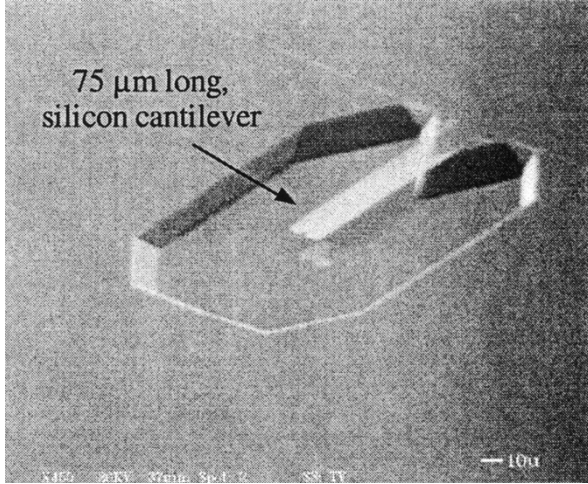
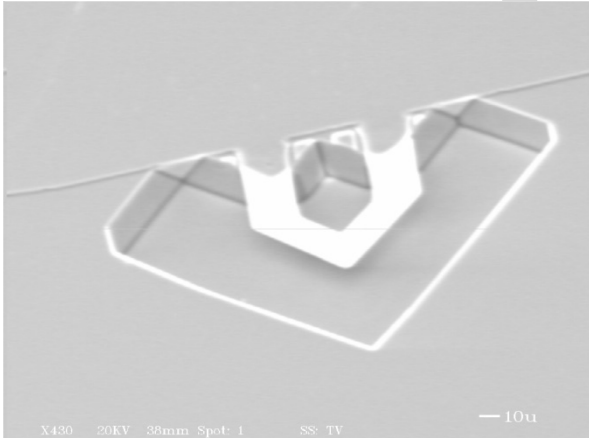


Fig. 3. An angled view of a silicon cantilever beam (prior to the final oxide etch) curling upward. The inset shows the oxide thickness expected from the process used in this work.



(a)



(b)

Fig. 4. SEMs of (a) released rectangular shaped cantilever beam and (b) released U-shaped cantilever beam.

### B. Mechanical Characterization of Cantilever Beams

The resonant frequency was measured in order to perform the mechanical characterization of the cantilever beams. Thermal mechanical noise is sufficient to oscillate the cantilever beams whose deflections can be detected by an AFM [21]–[24] that employ the optical lever technique [25]. The advantage of this method over driving the cantilever using a piezoelectric is that it does not excite other stiffer, higher mechanical resonance modes such as that of the cantilever holder. In the present set-up, the cantilever deflection signal was extracted from a Dimension 3100 SPM [26], using the DI signal access module, and then

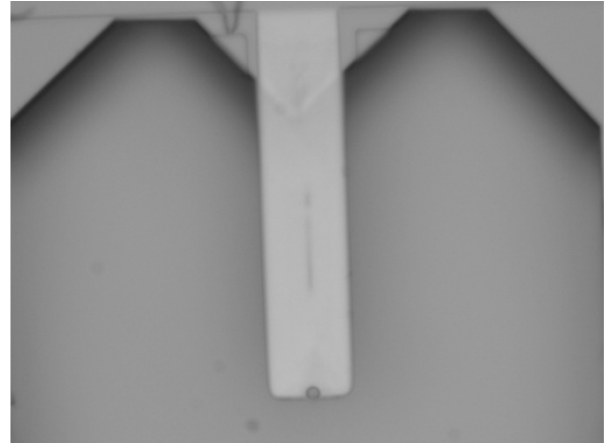


Fig. 5. Top view of cantilever 1 showing spherical polystyrene bead of diameter  $3.6 \mu\text{m}$  and mass  $26 \text{ pg}$  attached at the free end of cantilever.

digitized. The power spectral density (PSD) of the signal was then evaluated using MATLAB software. The thermal spectra data was fit to the amplitude response of a simple harmonic oscillator (SHO) [23]

$$A(f) = A_{dc} \frac{f_o^2}{\sqrt{[(f_o^2 - f^2)^2 + \frac{f_o^2 f^2}{Q^2}]}} \quad (1)$$

where  $f$  is frequency in hertz,  $f_o$  is the resonant frequency,  $Q$  is the quality factor, and  $A_{dc}$  is the cantilever amplitude at zero frequency. The resonant frequency of a spring system is given as

$$f_o = \frac{1}{2\pi} \sqrt{\frac{k}{m^*}} \quad (2)$$

where  $k$  is the spring constant and  $m^*$  is the effective mass.

In order to determine the stiffness (or spring) constant of the cantilever beams, the added mass (or Cleveland) method [21] was used. In the present study, polystyrene spherical beads [27] were placed at the ends of the cantilever beams using a micro-manipulator (see Fig. 5). Spherical beads of diameter of around  $5.48 \mu\text{m}$  and  $3.18 \mu\text{m}$  were used. Using the density of polystyrene of  $\rho = 1.05 \cdot 10^3 \text{ kg/m}^3$ , the masses of the beads were calculated to be in the range of  $90.5 \text{ pg}$  and  $17.7 \text{ pg}$ , respectively. Due to variation in the diameter of individual beads from the stated specifications of the manufacturer's values, the diameter was measured using an optical microscope. The change in resonant frequency,  $f_1$ , due to addition of a single mass,  $M_1$ , (see Fig. 6) can be used to calculate the spring constant,  $k$ , as well as the effective mass,  $m^*$ , of the cantilever beam [21]. The spring constant can be evaluated using

$$k = (2\pi)^2 \frac{M_1}{\left(\frac{1}{f_1}\right)^2 - \left(\frac{1}{f_o}\right)^2} \quad (3)$$

while the effective mass can be evaluated using

$$m^* = M_1 \frac{f_1^2}{f_o^2 - f_1^2}. \quad (4)$$

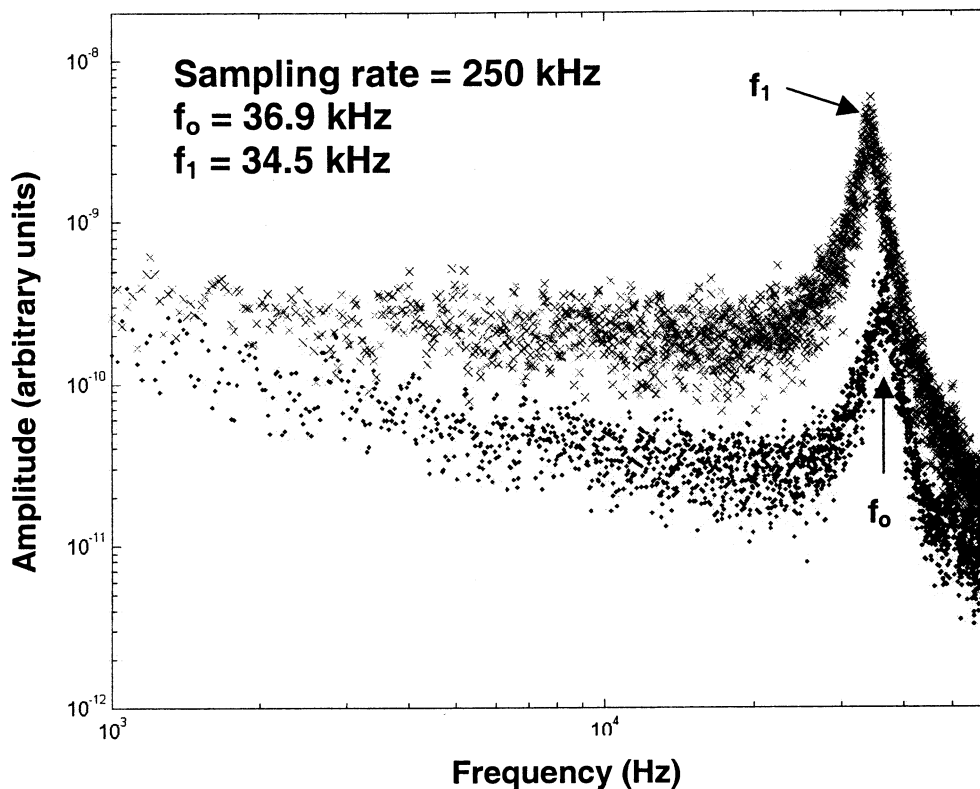


Fig. 6. Resonant frequency change of cantilever 3 after adding a single spherical polystyrene bead of size  $5.6 \mu\text{m}$  and mass  $97 \text{ pg}$ , where ( $\blacklozenge$ ) is the unloaded resonant frequency and ( $\times$ ) is the loaded resonant frequency.

TABLE I  
PLANAR DIMENSIONS OF CANTILEVER BEAMS WITH MEASURED RESONANT FREQUENCY AND  $Q$

Cantilever Designation	Length, $l$ ( $\mu\text{m}$ )	Width, $w$ ( $\mu\text{m}$ )	Resonant Frequency (kHz)	$Q$
1	78	23	85.6	56
2	93	13	70.6	41
3	129	24	36.2	23

Table I shows the planar dimensions of the cantilever beams and their measured resonant frequencies and  $Q$ . For one of the cantilevers (cantilever 1), a series of four different masses were added in order to get a linear plot of added mass versus  $(2\pi f)^{-2}$ . This gives a straight line, as shown in Fig. 7, with the slope giving the spring constant and the y-intercept yielding the effective mass. This can be seen if (2) is rearranged assuming that the masses are added right at the apex of the cantilever beam [21], giving

$$M = k(2\pi f)^{-2} - m^* \quad (5)$$

where,  $M$  is the total added mass. For the other cantilever beams only a single mass was added to calculate the spring constant

and effective mass using equations (3) and (4). From the data obtained, it was possible to determine the mass sensitivity of the cantilever beams given as frequency change per unit mass. Table II presents the values of the measured spring constant, effective mass and mass sensitivity for cantilever beams 1 and 3.

Table II also presents the values of the extracted thickness of the cantilever beam and the Young's modulus of the silicon material. The planar dimensions of the cantilever can be determined using an optical microscope. Using the planar dimension values and taking density of silicon as  $\rho_{\text{Si}} = 2.33 \cdot 10^3 \text{ kg/m}^3$ , the thickness of the cantilever can be determined by using the effective mass measured using the added mass method. The Young's modulus can, in turn, be determined from the spring

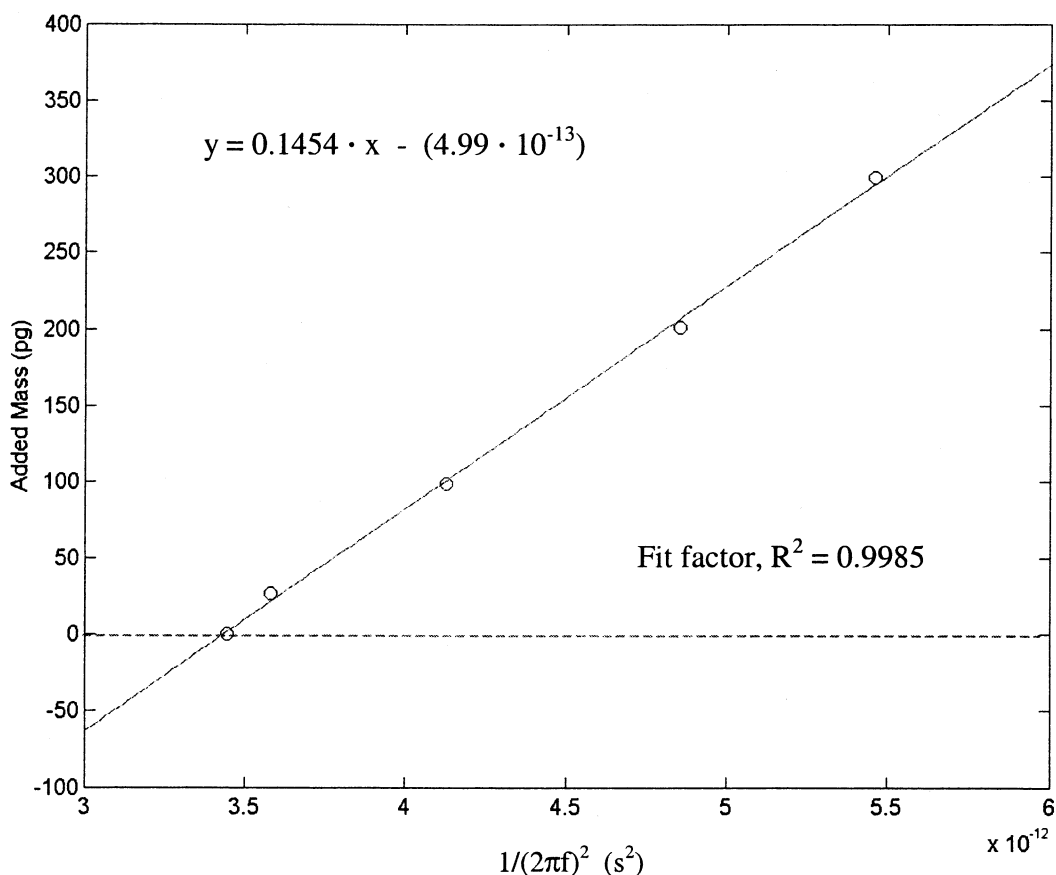


Fig. 7. Linear plot of added mass versus  $(2\pi\nu)^{-2}$  for cantilever 1 with the slope giving the spring constant and y-intercept the effective mass. (Note: The equation displayed in the inset is written assuming that the added mass is in kg).

TABLE II  
PLANAR DIMENSIONS AND MEASURED VALUES OF SPRING CONSTANT, EFFECTIVE MASS, AND MASS SENSITIVITY. ALSO LISTED ARE THE EXTRACTED THICKNESSES FROM THE EFFECTIVE MASS AND THE EXTRACTED YOUNG'S MODULUS FROM THE SPRING CONSTANT (ASSUMING THE GIVEN PLANAR DIMENSION) FOR CANTILEVER BEAMS 1 AND 3

Cantilever Designation	Length, $l$ Width, $w$	Measured Spring Constant, $k$ (N/m)	Measured Effective Mass, $m^*$ (kg)	Mass Sensitivity (Hz/pg)	Extracted Thickness, $t$ ( $\mu\text{m}$ )	Extracted Young's Modulus, $E$ (GPa)
1	$l = 78 \mu\text{m}$ $w = 23 \mu\text{m}$	0.145	$4.99 \cdot 10^{-13}$	65	0.49	100
3	$l = 129 \mu\text{m}$ $w = 24 \mu\text{m}$	0.0443	$9.56 \cdot 10^{-13}$	20	0.54	97.4

constant by inserting the planar dimensions and the thickness into the equation for the spring constant of a rectangular shaped cantilever beam given as [28]

$$k = \frac{Et^3w}{4l^3} \quad (6)$$

where  $E$  is the Young's modulus,  $t$  is the thickness,  $w$  is the width, and  $l$  is the length of the cantilever beam. From the table, it is seen that Young's modulus of the silicon material is different from that of regular silicon ( $E = 130$  Gpa, [29]). This could

be due to defects that might have been introduced during the growth and merging process of MELO. However, the extracted value of Young's modulus is found to be between 80–110 GPa, and is certainly within the range of the bulk reported value of single-crystal silicon. There was also uncertainty in the thickness values due to the uncertainty that entered in the measurement of the length using an optical microscope, on accounting of the silicon pedestal that was left under the cantilever beams as seen in the SEM micrographs in Fig. 4. This probably caused a layer of oxide to be left beneath the cantilever beam, when

the oxide surrounding the cantilever beam was being etched, causing the effective length of the cantilever beam to be less than that measured using an optical microscope.

## V. CONCLUSION

A novel microfabrication technique has been presented that is a viable process for fabricating ultra-thin cantilever beams in single crystal silicon with no stress. Cantilevers with thickness ranging from 0.3 to 0.5  $\mu\text{m}$ , maximum length of around 130  $\mu\text{m}$  and widths of around 20  $\mu\text{m}$  and 10  $\mu\text{m}$  were fabricated using surface micro-machining techniques presented in this paper. Mechanical characterization was performed by measuring the resonance frequency using the thermal noise method and by adding known micro-sized particles. Young's modulus, extracted from the added mass approach was found to be in the range of 80–110 GPa and the mechanical quality factor was measured to be in the range of 20–50 in air. Such cantilevers can also be scaled to thickness of less than 100 nm and can be integrated into micro-fluidic channels within the substrates for a wide variety of chemical and biological detection applications.

## ACKNOWLEDGMENT

The authors would like to thank T. Miller, D. Lubelski, and W. Crabill of the microfabrication laboratories of Purdue University, West Lafayette, IN, for their valuable technical assistance. The authors would also like to thank Prof. G. W. Neudeck for valuable discussions throughout this work, R. Gomez for assisting in curve fitting, and B. F. Robinson for helping in the resonant frequency measurements.

## REFERENCES

- [1] G. Binnig, C. F. Quate, and CCh. Gerber, "Atomic force microscope," *Phys. Rev. Lett.*, vol. 56, pp. 930–933, Mar. 1986.
- [2] H. K. Wickramasinghe, "Progress in scanning probe microscopy," *Acta Materialia*, vol. 48, no. 1, pp. 347–358, Jan. 2000.
- [3] R. Raiteri, M. Grattarola, H.-J. Butt, and P. Skladal, "Micromechanical cantilever-based biosensor," *Sens. Actuators, B Chem.*, vol. 79, pp. 115–126, Oct. 2001.
- [4] T. D. Stowe, K. Yasumura, T. W. Kenny, D. Botkin, K. Wago, and D. Rugar, "Attonewton force detection using ultrathin silicon cantilevers," *Appl. Phys. Lett.*, vol. 71, pp. 288–290, July 1997.
- [5] K. Y. Yasumura, T. D. Stowe, E. M. Chow, T. Pfafman, T. W. Kenny, B. C. Stipe, and D. Rugar, "Quality factors in micron- and submicron-thick cantilevers," *J. Microelectromech. Syst.*, vol. 9, pp. 117–125, Mar. 2000.
- [6] H. Ibach, "Adsorbate-induced surface stress," *J. Vacuum Sci. Technol. A*, vol. 12, pp. 2240–2245, July/Aug. 1994.
- [7] H.-J. Butt, "A sensitive method to measure changes in the surface stress of solids," *J. Colloid Interface Sci.*, vol. 180, pp. 251–260, June 1996.
- [8] P. I. Oden, "Gravimetric sensing of metallic deposits using an end-loaded microfabricated beam structure," *Sens. Actuators, B Chem.*, vol. 53, pp. 191–196, Dec. 1998.
- [9] S. Timoshenko and S. Woinowsky-Krieger, *Theory of Plates and Shells*, 2nd ed. New York: McGraw-Hill, 1965, p. 1.
- [10] G. Stemme, "Resonant silicon sensors," *J. Micromech. Microeng.*, vol. 1, pp. 113–125, June 1991.

- [11] J. A. Harley and T. W. Kenny, "High-sensitivity piezoresistive cantilevers under 1000 Å thick," *Appl. Phys. Lett.*, vol. 75, pp. 289–291, July 1999.
- [12] J. Yang, T. Ono, and M. Esashi, "Mechanical behavior of ultra-thin micro-cantilever," *Sens. Actuators, A Phys.*, vol. 82, pp. 102–107, May 2000.
- [13] D. Saya, K. Fukushima, H. Toshiyoshi, G. Hashiguchi, H. Fujita, and H. Kawakatsu, "Fabrication of single-crystal Si cantilever array," *Sens. Actuators, A Phys.*, vol. 95, pp. 281–287, 2002.
- [14] M. B. Viani, T. E. Schaffer, A. Chand, M. Rief, H. E. Gaub, and P. K. Hansma, "Small cantilevers for force spectroscopy of single molecules," *J. Appl. Phys.*, vol. 86, pp. 2258–2262, Aug. 1999.
- [15] A. Chand, M. B. Viani, T. E. Schaffer, and P. K. Hansma, "Micro-fabricated small metal cantilevers with silicon tip for atomic force microscopy," *J. Microelectromech. Syst.*, vol. 9, pp. 112–116, Mar. 2000.
- [16] J. J. Pak, A. E. Kabir, G. W. Neudeck, and J. H. Logsdon, "A bridge-type piezoresistive accelerometer using merged epitaxial lateral overgrowth for thin silicon beam formation," *Sens. Actuators, A Phys.*, vol. 56, pp. 267–271, Sept. 1996.
- [17] A. Gupta, J. Denton, G. W. Neudeck, and R. Bashir, "A novel micro-fabrication technique of thin single-crystal silicon cantilever beams for scanning probe microscopy applications," in *Proc. International MEMS Workshop 2001*, Singapore, July 4–6, 2001, pp. 748–752.
- [18] L. Jastrzebski, J. F. Corboy, J. T. McGinn, and P. Pagliaro Jr., "Growth process of silicon over SiO<sub>2</sub> by CVD: epitaxial lateral overgrowth technique," *J. Electrochem. Soc.*, vol. 130, pp. 1571–1580, July 1983.
- [19] U. Srinivasan, M. R. Houston, R. T. Howe, and R. Maboudian, "Alkyl-trichlorosilane-based self assembled monolayer films for stiction reduction in silicon micromachines," *J. Microelectromech. Syst.*, vol. 7, pp. 252–260, June 1998.
- [20] D. R. Bradbury, T. I. Kamins, and C.-W. Tsao, "Control of lateral epitaxial chemical vapor deposition of silicon over insulators," *J. Appl. Phys.*, vol. 55, pp. 519–523, Jan. 1984.
- [21] J. P. Cleveland, S. Manne, D. Bocek, and P. K. Hansma, "A nondestructive method for determining the spring constant of cantilevers for scanning force microscopy," *Rev. Sci. Instr.*, vol. 64, pp. 403–405, Feb. 1993.
- [22] J. L. Hutter and J. Bechhoefer, "Calibration of atomic-force microscope tips," *Rev. Sci. Instr.*, vol. 64, pp. 1868–1873, July 1993.
- [23] D. A. Walters, J. P. Cleveland, N. H. Thomson, P. K. Hansma, M. A. Wendman, G. Gurley, and V. Elings, "Short cantilevers for atomic force microscopy," *Rev. Sci. Instr.*, vol. 67, pp. 3583–3590, Oct. 1996.
- [24] J. E. Sader, J. W. M. Chon, and P. Mulvaney, "Calibration of rectangular atomic force microscope cantilevers," *Rev. Sci. Instr.*, vol. 70, pp. 3967–3969, Oct. 1999.
- [25] G. Meyer and N. M. Amer, "Novel optical approach to atomic force microscopy," *Appl. Phys. Lett.*, vol. 53, pp. 1045–1047, Sept. 1988.
- [26] Digital Instruments, Santa Barbara, CA.
- [27] Spherotech, Inc., Libertyville, IL.
- [28] S. Timoshenko and G. H. MacCullough, *Elements of Strength of Materials*. New York: Van Nostrand, 1949, pp. 163–184.
- [29] W. A. Brantley, "Calculated elastic constants for stress problems associated with semiconductor devices," *J. Appl. Phys.*, vol. 44, pp. 534–535, Jan. 1973.



**Amit Gupta** (S'93) was born in Durg, Chattisgarh (formerly part of Madhya Pradesh), India, in 1975. He received the B.S. degree in electrical engineering in 1998 and the M.S. degree in electrical and computer engineering in 2000, both from Purdue University, West Lafayette, IN. He is currently working toward the Ph.D. degree.

His current interests are in novel microfabrication techniques, microelectromechanical sensors and actuators, and bioMEMS.

**John P. Denton** (M'94–SM'97) received the B.S.E.E. and M.S.E.E. degrees from Purdue University, West Lafayette, IN, in 1983 and 1986, respectively, where in 1986, he worked as a Research Assistant in the solid-state electronics area. He received the Ph.D. degree also from Purdue University in 1995.

From 1983–1984, he worked at the Naval Avionics Center, Indianapolis, IN, as a Project Engineer in the area of hybrid microelectronic design and manufacture. In 1987, he worked for Alpha Industries in Woburn, MA as a Product Engineer for the manufacture of Hi-Rel GaAs parameter amplifiers and p-i-n mesa diodes. He joined the professional staff at Purdue University in 1987 as a Research Engineer in the area of silicon research, which included the fabrication of unique three-dimensional device structures using the selective epitaxial growth of silicon. His research was in the fabrication of silicon-on-insulator (SOI) islands and the creation of dual-gated fully depleted SOI MOSFETs using the selective epitaxial growth of silicon. From 1996 to 2002, as a Principal Research Engineer, he worked in the area of silicon device research using the selective epitaxial growth of silicon. He is the author or coauthor of over 25 journal publications, 45 conference papers, and 2 technical reports. He is currently an Associate Professor in Electrical Engineering Technology at Purdue University with interests in teaching and RF electronics.

**Helen McNally** (M'92–SM'02) received the engineering physics degree from Murray State University, Murray, KY, in 1986 and the M.S. degree in radar systems from Southeastern Institute of Technology, Huntsville, AL, in 1989. She received the Ph.D. degree in electrical engineering from Arizona State University in 1997.

She worked in industry for the Kwajalein Missile Range in support of the ballistic missile defense program and for NASA working on space lab programs. She has performed research in the molecular electronics area at Arizona State and Purdue Universities. She is currently at Purdue working in the area of Bio-MEMS/NEMS, to apply microfabrication and nanotechnology techniques to medical and life sciences applications.

Dr. McNally is a Member of the American Association for the Advancement of Science (AAAS), the International Society for BioMEMS and Biomedical Nanotechnology, and the Society of Women Engineers. She has been a National Science Foundation Fellow and was awarded the U.S. Army Achievement Medal for Civilian Service and the U.S. Army Civilian Performance Award.

**Rashid Bashir** (S'90–M'92–SM'01) received the B.S.E.E. from Texas Tech University, Lubbock, as the highest-ranking graduate in the College of Engineering in December 1987. He received the M.S.E.E. and Ph.D. degrees from Purdue University, West Lafayette, IN, in 1989 and 1992, respectively.

From October 1992 to October 1998, he worked at National Semiconductor in the Process Technology Development Group as a Senior Engineering Manager. His group worked on developing state-of-the-art bipolar and BiCMOS process for high voltage, analog and RF applications, SiGe HBT devices, SOI-bonded wafers, and MEMS technologies. He is currently an Associate Professor of Electrical and Computer Engineering at Purdue University since October 1998 and Courtesy Associate Professor of Biomedical Engineering at Purdue University since June 2000. He has authored or coauthored over 70 journal and conference papers and over 25 patents. His research interests include biomedical microelectromechanical systems, applications of semiconductor fabrication to biomedical engineering, advanced semiconductor fabrication techniques, and nanobiotechnology.

Dr. Bashir received the NSF Career Award for his work in Biosensors and BioMEMS in 2000. He also received the Joel and Spira Outstanding Teaching award from School of ECE at Purdue University, and the Technology Translation Award from the 2001 BioMEMS and Nanobiotechnology World Congress Meeting, Columbus, OH.