New Optomechanical Technique for Measuring Layer Thickness in MEMS Processes

Janet C. Marshall

Abstract—**Dimensional metrology improvements are needed to achieve the fabrication of repeatable devices. This research presents a new optomechanical technique for measuring the thickness of a suspended material in two distinct microelectromechanical system (MEMS) fabrication processes. This technique includes design of test structure, choice of measurement tools, method of measurement, and computation of thickness. Two tools, the stylus profilometer and optical interferometer, are used to take measurements. Non-contact measurements are possible on structures as narrow as 5 μm. Local thickness measurements are achievable with combined standard uncertainty values of less than 10 nm. Benefits of using the new technique include greater likelihood of fabricating repeatable devices and more accurate measurements of material parameters. The proposed technique is also applicable for measuring layers that are thinner and made of materials other than the conventional suspended material used in this research. [533]**

Index Terms—**Integrated microelectromechanical systems (iMEMS), interferometry, microelectromechanical systems (MEMS), multiuser MEMS processes (MUMPs), polysilicon, profilometry, test structures, thickness.**

I. Introduction

THE first polysilicon microelectromechanical systems (MEMS)[1] device was fabricated in the early 1980's at the University of California, Berkeley [1]. The inspiration for using sacrificial layers to form microstructures (or surface micromachining) came from work done at Westinghouse in the 1960's, where a metal cantilever beam was used as a resonant gate for a field-effect transistor [2]. Since then, great strides have been made in the MEMS field. Perhaps the most widely known surface-micromachined commercial product to this day is the Analog Devices ADXL50[2], a fully integrated surface-micromachined accelerometer used as an automotive air bag sensor [3].

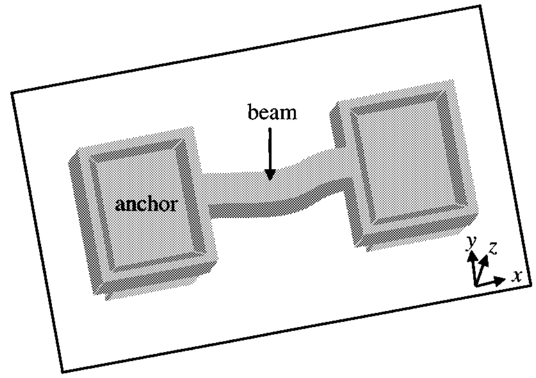

Fig. 1. 3-D view of a fixed-fixed beam test structure depicting out-of-plane curvature in the z-direction.

In 1992, Cronos Integrated Microsystems[3] offered the first MEMS fabrication process to the public. The fabrication process was financed by the Defense Advanced Research Projects Agency (DARPA). This was the first of many Multi-User MEMS Processes (or MUMPs) [4]. Another MEMS fabrication process currently available to the public is the Integrated Micro Electro Mechanical Systems (or iMEMS) process [3] provided by Analog Devices, Inc.

Test structures (such as the fixed–fixed beam shown in Fig. 1) are commonly used to characterize MEMS processes. These test structures are a valuable tool for designers, modelers, and processing engineers alike. Improved designs can be fabricated given the knowledge of the mechanical/dimensional parameters of the MEMS materials obtained via test structures. As a result, the number of design/fabrication iterations is reduced.

This paper presents a new technique for measuring the thickness of the mechanical, suspended layer that results from MEMS processes. Two tools, the stylus profilometer and optical interferometer, are used to take measurements. Non-contact measurements are possible on structures as narrow as 5 μm. Local thickness measurements are achievable with combined standard uncertainty values, u_c, of less than 10 nm. (The combined standard uncertainty is comparable to the estimated standard deviation of the result [5].)

The method for measuring layer thickness is described in detail and then applied to the MUMPs and iMEMS process. The resulting measurements of layer thickness are compared with the values provided by the two processing facilities.

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[1]MEMS are also referred to as microsystems technology (MST) and micromachines.

[2]Certain commercial equipment, instruments, materials, or products are identified in this paper. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the products specified are necessarily the best available for the purpose.

[3]Cronos Integrated Microsystems is currently owned by JDS Uniphase. In 1992, Cronos was known as the MEMS Technology Applications Center of MCNC. Six years later, it became a financially independent subsidiary of MCNC, as marked by its name change to Cronos Integrated Microsystems, Inc. In 2000, JDS Uniphase acquired Cronos.

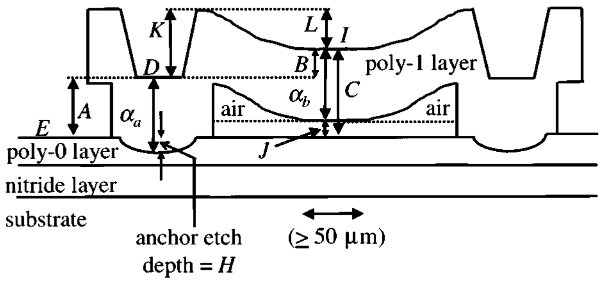

Fig. 2. A schematic illustration (not to scale) of a cross-sectional side view of a severely pegged fixed-fixed beam test structure fabricated in the MUMPs. J is typically on the order of 31 nm. In this research, it is assumed that $\alpha = \alpha_a = \alpha_b$.

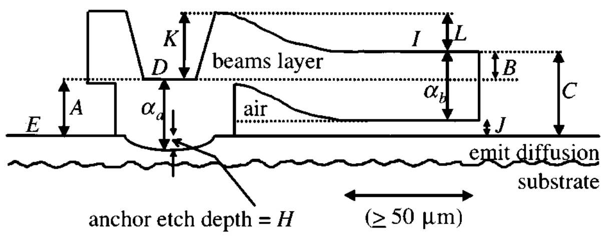

Fig. 3. A schematic illustration (not to scale) of a cross-sectional side view of a severely pegged cantilever test structure fabricated in the iMEMS process.

II. Optomechanical Technique

The new optomechanical technique consists of four parts: test structure design, measurement tool choice, measurement method, and thickness computation. Each part is discussed in the following subsections. To help describe the new optomechanical technique, Figs. 2–4 are used. Fig. 2 is a schematic cross-sectional side view of a fixed-fixed beam fabricated in the MUMPs. Fig. 3 is a schematic of a cantilever test structure fabricated in the iMEMS process[4]. In both these figures, the structure is considered to be severely pegged to the top of the underlying poly-0 layer (or emit diffusion). In these figures, the dimension J is specified with the component parts shown in Fig. 4.

There are four key dimensions: the minimum thickness A, the delta thickness B, the maximum thickness C, and the estimated thickness α. In this research, it is assumed that $\alpha = \alpha_{\mathrm{a}} = \alpha_{\mathrm{b}}$.

A. Test Structures

The minimum thickness measurement A and the delta thickness measurement B help describe the estimated thickness α. The common endpoint for the measurements of A and B is the top of the poly-1(or beams) layer in the anchor area (D). Figs. 2 and 3 depict these dimensions in the MUMPs and iMEMS process, respectively. For both processes, a single type of test structure can be used to measure both A and B. Figs. 5 and 6 depict the layer and dimensional recommendations associated with the designs. Note that the test structure design can be altered such that the thickness of other layers (e.g., the poly-2 layer in the MUMPs) can also be determined.

[4]Note that wherever the MUMPs is specified, application to the iMEMS process is possible if the fixed-fixed beam test structures are replaced by cantilevers, the poly-1 layer replaced by the beams layer, and the poly-0 layer replaced by the emit diffusion.

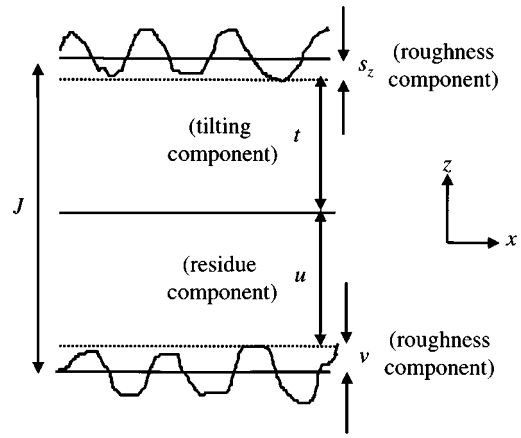

Fig. 4. A schematic illustration (not to scale) of the component parts of dimension J, which is shown in Figs. 2 and 3. This view is along the length of the structure, where it has adhered to the top of the underlying layer.

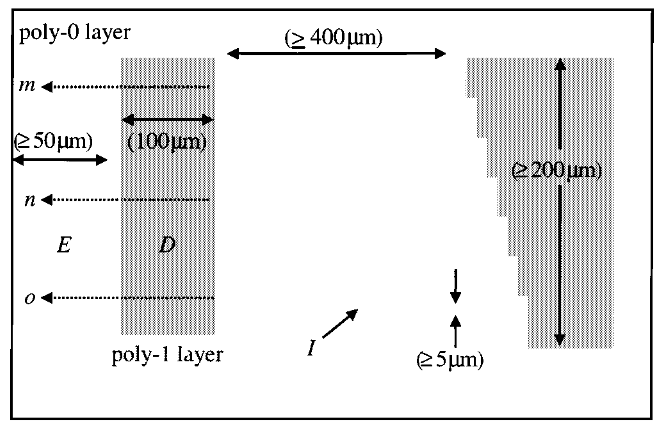

Fig. 5. Top view of a possible design of a subarray of fixed-fixed beam test structures for the MUMPs (not to scale). Several 2-D step height measurement traces (such as m, n, and o) are taken with a stylus profilometer to determine the minimum thickness measurement, A, as shown in Fig. 2.

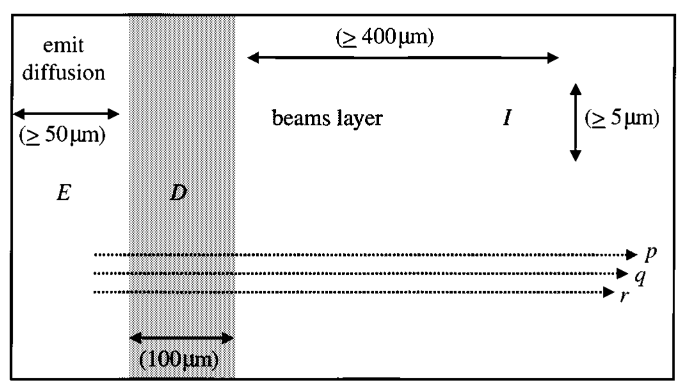

Fig. 6. Top view of a possible design of a portion of a subarray of cantilevers for the iMEMS process (not to scale). With the optical interferometer, several 2-D measurement traces (such as $p, q,$ and r) can readily be chosen on a severely pegged cantilever after the 3-D measurement is taken. The delta thickness measurement, B, as shown in Fig. 3, can be determined from these traces.

For the measurement of A, large anchors are recommended, since small anchors tend to fill in with extra polysilicon and therefore give an unrealistically thick value. Several two-dimensional (2-D) step height measurement traces (such as m, n, and o

in Fig. 5, or similar traces in Fig. 6) are taken with a stylus profilometer. Therefore, the poly-0 layer (or emit diffusion) must extend at least 50 μm beyond the anchor lip.

For the measurement of B, a severely pegged structure (e.g., a fixed-fixed beam or cantilever) is required. During fabrication, the sacrificial layer is removed. This creates suspended structures. Oftentimes, the suspended structure is pulled down to the layer beneath it and it stays there. It is from severely pegged structures that the delta thickness values are obtained. Severely pegged structures are adhered to the top of the underlying layer for a good portion along the length of the layer (at least 50 μm). On these structures, a three-dimensional (3-D), measurement is taken with the interferometer, from which several 2-D traces (such as p, q, and r in Fig. 6, or similar traces in Fig. 5) are chosen.

The type of test structure chosen for the measurement of B depends upon whether or not the suspended layer is under tension or compression. Although fixed-fixed beam test structures offer more desirable properties than cantilevers for thickness measurements, they are not suitable for a tensile strain polysilicon layer. Unlike cantilevers, it would be rare to see a fixed-fixed beam test structure under tension that has adhered to the top of the underlying layer.

Therefore, for a compressive polysilicon layer, as in the MUMPs, subarrays of fixed-fixed beams with large anchors are the recommended test structure for the measurements of A and B. For a tensile polysilicon layer, as in the iMEMS process, subarrays of cantilevers with large anchors are the recommended test structure for these measurements.

B. Measurement Tools

The optomechanical technique combines two measurement tools, the stylus profilometer and the optical interferometer. This combination of tools leads to more accurate, comprehensive measurements. The optomechanical technique is more accurate by at most 31 nm with a combined standard uncertainty, u_c, of 5 nm. This is the value for J (as shown in Figs. 2–4) obtained in this research. The optomechanical technique is more comprehensive due to the interferometer's 3-D measurements as opposed to the typical 2-D measurements obtained with a stylus profilometer.

A stylus profilometer is used for the measurement of A, as shown in Figs. 2 and 3, because the values for u_c [5] tend to be lower [6] than those derived from an optical interferometer for the given step height. The technique is also simple, straightforward, and reliable.

A major benefit of the optical interferometer is that it can be used to obtain peak-to-valley measurements (such as K and L shown in Figs. 2 and 3) without the tool contacting the suspended structure [7], [8]. The delta thickness value, B, is calculated from these measurements. A second benefit in using the optical interferometer for this measurement is the ability to measure narrow (5 μm) structures. A third benefit is the ability to readily choose 2-D traces after a 3-D measurement is taken. A fourth benefit of the optical interferometer (although not required for this research) is its ability to provide smaller error bars for the linear measurements in the xy-plane than an optical microscope [9]. The integrity of the interferometric data points, in the z-direction, must be maintained by properly analyzing any secondary sets of fringes, as discussed in the next subsection.

C. Measurement Methods

The two measurement methods (the minimum thickness method and the delta thickness method) associated with the optomechanical technique are described below.

1) Minimum thickness: For each profilometer sweep along the anchor (such as traces m, n, and o in Fig. 5, or similar traces in Fig. 6), the profilometer is operated such that the data is leveled with respect to the bottommost layer (e.g., the top of the poly-0 layer, E, as shown in Fig. 2). Then, two sections along each 2-D trace are selected by cursors, a section within the anchor area D and a section within E. The average height of the D section is compared to the average height of the E section. The difference in these two heights determines the minimum thickness measurement A.

2) Delta thickness: An optical interferometer is used for the delta thickness measurement. Secondary sets of fringes are a major concern with interferometry done on thin film samples. Each sample area under investigation needs to be examined carefully for secondary fringes and the effect they have on the measurement. The two sample areas of prime concern for the interferometry in this work are the anchor area D and the area of the pegged structure I, as shown in Figs. 2 and 3.

In this work, it is determined that the secondary set of fringes does not affect the data for either of the sample areas in either of the processes. This implies that the secondary fringe effect g is zero. (If g is not zero, it is used as a correction factor.) This may not be the case for subsequent processing runs (e.g., if the polysilicon layer is thinner). Therefore, verification for each processing run is recommended.

Once the value for g is determined, a 3-D measurement is taken with the interferometer. Several 2-D traces (such as traces p, q, and r in Fig. 6, or similar traces in Fig. 5) are selected from the 3-D measurement. For each trace, the peak-to-valley measurements (K and L as shown in Figs. 2 and 3) are obtained from which B is calculated ($B = K - L + g$).

D. Thickness Computation

Determination of the estimated thickness α depends upon the range ΔH of the anchor etch depth H provided by the processing facility.

Referring to Fig. 2 or 3, A is a minimum thickness value since the polysilicon in the etched area H is not included. C is a maximum thickness value because it includes the dimension J in addition to the complete thickness of the layer. The figures show that

$$A + B = C. \tag{1}$$

The estimated thickness α is between the minimum thickness A and the maximum thickness C

$$A < \alpha < C \tag{2}$$

and Figs. 2 and 3 show that

$$\alpha_a = A + H \tag{3}$$

and

$$\alpha_b = C - J. \tag{4}$$

Two assumptions are made in this research. First, it is assumed that

$$\alpha = \alpha_a = \alpha_b. \tag{5}$$

This assumption can only be made for test structures designed with large anchors as in this research. Small anchors tend to fill in with extra polysilicon. With large anchors, (5) can be assumed to be as accurate as the polysilicon thickness variations over the distances considered. This variation is compensated for by taking multiple measurements on different test structures at select locations. Therefore, the variations are included in the calculations of u_c. This assumption is used in the determination of J. If J cannot be explained by the sum of its parts, as shown in Fig. 4, then a correction factor is needed in (5).

The second assumption is that J is assumed to be the same for both processes (i.e., the MUMPs17[5] and iMEMS process[6]). In other words,

$$J = J_{\mathrm{MUMPs17}} = J_{i\mathrm{MEMS}} \tag{6}$$

where J accounts for the roughness of the underside of the poly-1 (or beams) layer in the z-direction, the roughness of the topside of the poly-0 layer (or emit diffusion), any residue present between these layers, and the tilting associated with the beam, as shown in Fig. 4. In other words,

$$J = s_z + t + u + v. \tag{7}$$

After examining each component of J, it is reasonable to assume (6) for the two processes. If a discrepancy exists, the equation can be modified accordingly.

III. Application to the MUMPs and iMEMS Process

The minimum polysilicon thickness, the delta thickness, the maximum thickness, and the estimated thickness values were obtained for the MUMPs17 and iMEMS process. These measurements were taken on one chip in the MUMPs17 and on one 150 mm wafer in the iMEMS process. The calibrated, numerical results are given in Table I and discussed below. Throughout this paper, the subscripts l, c, or w refer to local, chip, or wafer designations, except when used with the combined standard uncertainty, u_c. The estimated thickness values are compared with those provided by the two processing facilities.

A. Minimum Thickness

For the MUMPs17, minimum thickness measurements were taken on 14 anchors somewhat evenly spaced throughout a test chip. Three profilometer sweeps were taken along each anchor similar to traces m, n, and o in Fig. 5, for a total of 42 sweeps.

For the iMEMS process, three anchors on each of eighteen chips somewhat evenly spaced throughout a wafer were examined with three profilometer sweeps taken along each anchor, for a total of 162 sweeps.

TABLE I
Polysilicon Thickness Values for the MUMPs17 and iMEMS Process Using Optomechanical Technique

Polysilicon Thickness	MUMPs17	*i*MEMS® Process
Minimum value (*A*)	$A_c = 1.945\ \mu m$ $u_c = 6$ nm	$A_w = 1.745\ \mu m$ $u_c = 9$ nm
Delta value (*B*)	$B_c = 41$ nm $u_c = 3$ nm	$B_w = 259$ nm $u_c = 9$ nm
Maximum value (*C*)	$C_c = A_c + B_c$ $C_c = 1.986\ \mu m$ $u_c = 7$ nm	$C_w = A_w + B_w$ $C_w = 2.004\ \mu m$ $u_c = 13$ nm
Estimated value (α)	$\alpha_a = \alpha_c = A_c + H$ $\alpha_c = 1.955\ \mu m$ $u_c = 7$ nm	$\alpha_b = \alpha_w = C_w - J$ $\alpha_w = 1.973\ \mu m$ $u_c = 14$ nm

B. Delta Thickness and Maximum Thickness

For the MUMPs17, eighteen severely stuck beams were measured to obtain B_c. The maximum thickness value C_c is calculated using this value.

For the iMEMS process, at least one severely pegged cantilever was found on 6 of the 18 chips measured for the minimum thickness values. The maximum thickness value for the wafer C_w was calculated using B_w.

C. Estimated Thickness

For the MUMPs17, the anchor etch depth H is specified to be less than or equal to 20 nm. This implies that ΔH = 20 nm. This value for ΔH is small enough to choose an appropriate anchor etch depth H with a relatively small uncertainty. This enables the use of (3). If H is chosen to be in the middle of the 0 to 20 nm range, then the smallest uncertainty value results. Therefore, H is chosen to be 10 nm $\pm$ 10 nm and (3) is used to determine α.

For the MUMPs17, B = 41 nm and H = 10 nm. Therefore, J_{MUMPs17} = 31 nm according to (6) and the following equation

$$J = B - H. \tag{8}$$

This equation was derived from (1), (3)–(5).

For the iMEMS process, the anchor etch depth is between 0.1 μm and 0.4 μm (i.e., ΔH = 0.3 μm). This large value for ΔH prohibits the use of (3). Therefore, α is calculated using (4)–(6).

For both the MUMPs17 and iMEMS process, the local estimated thickness values α_l are obtained with values for u_c less than 10 nm. This was determined from calculations involving the raw data.

[5]MUMPs17 refers to MUMPs run number 17 with a design due date of January 13, 1997.

[6]To be more specific, the MCNCPC1 process (i.e., project chip 1 organized by MCNC and fabricated in the iMEMS process) was used. However, to avoid confusion with MCNC's MUMPs, the general iMEMS process will be specified.

D. Comparing α with the Value Provided by the Processing Facilities

As reported by the processing facility, the MUMPs17 thickness of the poly-1 layer $\alpha_{\mathrm{MUMPs17}}$ is 1.9739 μm with a standard deviation of 52.8 nm. Therefore, considering the value for α_c obtained with the optomechanical technique (i.e., 1.955 μm), Δ = 1.0% where Δ = $|(\alpha_{\mathrm{MUMPs17}} - \alpha_c)/\alpha_c| \times 100\%$. The values for α_c and $\alpha_{\mathrm{MUMPs17}}$ are 19 nm apart, which is well within the reported MUMPs17 standard deviation value of 52.8 nm.

The targeted value for fabrication of Analog Devices' polysilicon thickness is 2.0 μm, with a guarantee it is within 0.1 μm of this value. The value of α_w = 1.973 μm obtained with the optomechanical technique verifies that the polysilicon thickness is within the guaranteed range.

IV. Conclusions

The polysilicon thickness in two surface micromachining MEMS processes (the MUMPs and the iMEMS process) was determined with a new optomechanical technique. This technique includes design of test structure, choice of measurement tools, method of measurement, and computation of thickness.

With the new optomechanical technique, subarrays of fixed-fixed beams with large anchors are the recommended test structure for a compressive polysilicon layer, and subarrays of cantilevers with large anchors are the recommended test structure for a tensile polysilicon layer.

A stylus profilometer is recommended for the minimum thickness measurement A, as shown in Figs. 2 and 3. The minimum thickness is determined from the step height of the large anchors in the test structure. An optical interferometer is used to take delta thickness measurements, B, on severely pegged fixed-fixed beams or cantilevers in the subarrays.

The maximum thickness value, C, is then calculated as the sum of the minimum thickness measurement and the delta thickness measurement (i.e., $A + B = C$). The estimated thickness value α is between the minimum and maximum thickness values (i.e., $A < \alpha < C$). The determination of this value is based upon the range ΔH of the anchor etch depth H for the particular process. Local thickness measurements are achievable with values for u_c less than 10 nm. The estimate obtained for α_c for the MUMPs17 was well within one standard deviation of the value reported by the processing facility. For the iMEMS process, the estimate obtained for α_w is within the guaranteed range of expected values.

Benefits of using this new optomechanical technique include greater likelihood of fabricating repeatable devices and more accurate measurement of material parameters. This technique shows promise for measuring layers that are thinner and made of materials other than the conventional suspended material used in this research.

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