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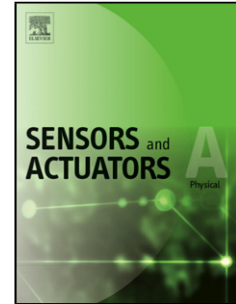

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Direct comparison of stylus and resonant methods for determining Young's Modulus of single and multilayer MEMS cantilevers

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Abstract

As microelectromechnical systems (MEMS) becomes more complex and are produced in even greater numbers it becomes increasingly important to have a full understanding of the mechanical properties of the commonly used MEMS materials. One of the most important properties for MEMS is the Young's modulus. This work describes the direct comparison of two methods often used for measuring the Young's modulus of thin film materials using micro-cantilever test structures: a load-deflection method and a resonant frequency method. The comparison was carried out for a range of materials, different cantilever geometries as well as for single and multilayer materials. It was found that both methods produce results that agree with each other and also agree with the values most often given in the literature.

Keywords: Young's Modulus, elastic modulus, MEMS, Micro-cantilevers, resonant frequency, load-deflection method, mechanical characterisation.

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1. Introduction

Microelectromechanical systems (MEMS) is the basis for a wide ranging and rapidly evolving field of research and industrial applications. MEMS technology is incorporated into a large number of different areas, from sensors and actuators to active RF components, from optics to energy generation [1]. Despite being still an emerging field the market for MEMS devices is huge with hundreds of millions of MEMS devices already shipped and being used in applications such as automotive sensing, computer games and smart phones, to name but a few. The combination of increasingly complex devices and industrial mass production makes it important to have a full understanding of the properties of the materials that are used to fabricate MEMS devices and determine their behaviour. Many of the materials used in MEMS devices have also been used in the microelectronics industry, and their electronic properties are well understood. However, the mechanical properties which are key in predicting the behaviour of MEMS devices have been less extensively studied. In the same way that the successful fabrication of integrated circuits requires the electronic properties for CMOS integrated circuits to be monitored and controlled, so must the mechanical properties of advanced MEMS structures. As with the electronic properties, the mechanical properties will vary with processing conditions [2]. It is therefore important to develop methods for accurately measuring the mechanical properties of MEMS materials during industrial fabrication.

The Young's modulus is one of the key parameters influencing the behaviour of MEMS structures. For such an important parameter the Young's modulus is surprisingly poorly understood for most MEMS materials. In their recent paper Hopcroft et al. [3] discuss the Young's modulus of single crystal silicon, noting the range of values that have been regularly quoted for the Young's modulus, ranging from 130 to 190 GPa, with MEMS designers regularly ignoring the effects of the anisotropy of the modulus of silicon. Single crystal silicon is the most widely used semiconductor material both for microelectronic and microelectromechanical systems. It has been extensively studied and is generally well understood. If the properties of such a well studied material can be subject to such uncertainties it follows that the other materials used in the fabrication of MEMS also suffer from such uncertainties. In fact the other materials may experience even greater uncertainty in the Young's modulus. Silicon is produced as single crystalline wafers whereas the other materials used in a MEMS process are produced

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by sputtering, thermal oxidation or chemical vapour deposition (CVD). The conditions in which the materials are fabricated can vary greatly and can effect the Young's modulus. Another factor which can influence the modulus is the level of doping and this can vary for different layers of the same material [3]. It is therefore important for a MEMS manufacturing foundry to accurately monitor the Young's modulus in order to supply their designers the information needed to develop advanced MEMS with high reliability and low failure of design. The measurement of the Young's modulus requires test structures to be included on the wafer. A common test structures for the Young's modulus of MEMS materials are micro-cantilevers; it is these devices that are studied here.

There are two methods for determining the Young's modulus of thin films using micro-cantilever test structures. Both of these can be applied in an industrial environment. The first of these is the load-deflection method in which the deflection of the cantilever is measured as a known force is applied along the length of the beam. This has been discussed in detail by Ericson [4] and Virwani [5] for single layer and multilayer structures. The second method is a non-contact method where the cantilevers are excited into mechanical resonance either by acoustic, thermal or electrical stimulation. The resonant frequencies of cantilevers of various lengths are measured from which the Young's modulus can be derived [6, 7].

Both these methods have been used previously for determining the Young's modulus. However, to the best of our knowledge, there has been no direct comparison made of the two methods using the same test structures. This work aims to provide this comparison between the two methods, with particular emphasis on their use in an industrial environment for rapid characterisation of deposited thin films. This will include consideration of ease of use, the possibilities of further automation as well as the accuracy and repeatability of the two methods.

The methods will be compared using a number of MEMS materials and cantilever structures. In the first instance, the methods are used to determine the Young's modulus of three sets of cantilevers fabricated using single layers: single crystal silicon, silicon carbide and amorphous silicon nitride. The use of single crystal materials such as silicon and silicon carbide allows direct quantitive comparison with the values given in the literature. The two methods are then expanded to include cantilevers consisting of multiple layers.

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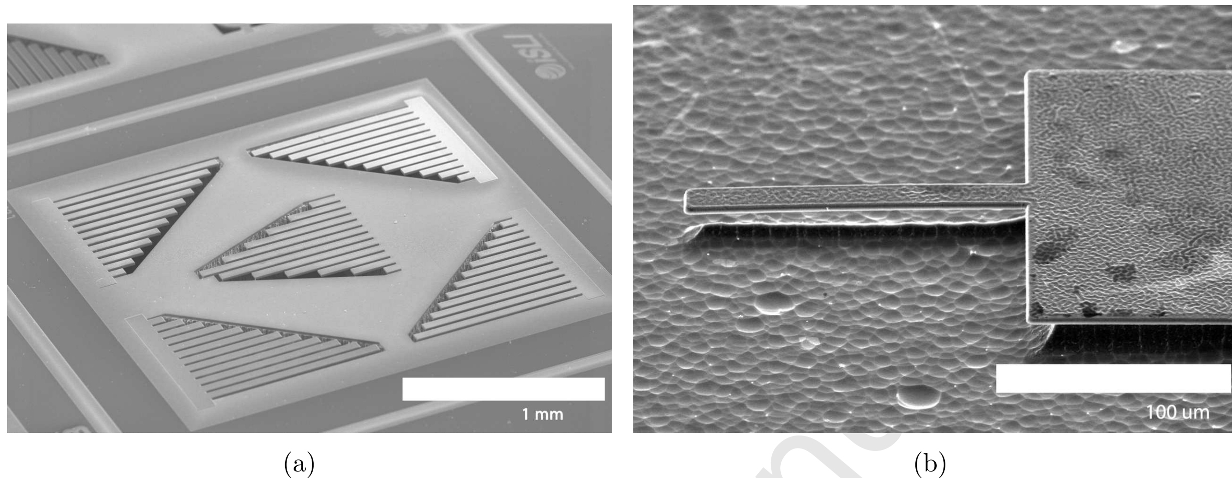

(a) (b)

Figure 1: Scanning Electron Micrographs of test structures.(a) CMOS MEMS test structure (b) SiC cantilever showing the undercut of the device layer at the base of the cantilever.

2. Design and Fabrication

This work used cantilevers of three designs. The test structure designs used for the silicon and multilayer experiments is shown in Figure 1(a). The first design consists of twelve single crystal silicon cantilevers ranging in length from 900 μm to 75 μm in 75 μm intervals. The width of the cantilevers is 50 μm with a thickness of 15$\pm$1 μm giving a range of resonant frequencies varying from 20 kHz to 1 MHz. The second design consists of silicon carbide cantilevers which were provided by the University of Edinburgh and have a slightly different geometry with four lengths ranging from 200 to 50 μm with a width of 30 μm. The SiC layer is much thinner, having a thickness of around 2 μm. The shorter length and larger Young's modulus leads to much higher resonant frequencies for the SiC structures, ranging between 150 kHz and 4 MHz. The third design was for silicon nitride cantilevers and was slightly different again, the cantilevers had a width of 20 μm and a thickness of 1 μm. The lengths range from 100 to 400 μm in 50 μm increments.

The multilayer cantilever test structures were fabricated by SEMEFAB [8]using their 3 μm MEMS process. (Illustrated in Figure 2) The structures were fabricated using silicon on insulator (SOI) wafers consisting of a 2-3 Ω cm N-type SOI layer above a 4 μm buried oxide layer grown on a 380 μm silicon handle wafer. The thickness of the SOI layer was given by the

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manufacturer as 15 $\pm$ 1 μm. The cantilevers were aligned parallel and perpendicular to the primary flat of the (100) handle wafer. The devices were fabricated using a deep reactive ion etch (DRIE) process, the first step is the definition of the pattern in the SOI layer. The top surface is patterned using photoresist and the SOI device layer is etched down to the buried oxide layer using a DRIE process. The backside of the wafer is then patterned with large windows aligned to the upper patterned layer which are opened up by a secondary DRIE process which etches all the way through the handle wafer, again stopping on the buried oxide layer. The cantilevers are then released by etching away the sacrificial oxide layer using an hydrofluoric (HF) acid wet etch. This leaves the free standing cantilevers as shown in Figure 1(a). The SiC devices are fabricated using a similar sacrificial oxide technique. The 2.4 μm thick silicon carbide layer was deposited on top of a silcon oxide layer by hot wall chemical vapour deposition. The SiC is then patterned and etched down to the oxide layer using a CF_4/H_2 reactive ion etch. The cantilevers are released by etching the sacrificial oxide layer using the lateral etching behaviour of hydrofluoric acid. The silicon nitride cantilevers were formed by the anisotropic wet etch of silicon using potassium hydroxide. To fabricate silicon nitride cantilevers, silicon (100) wafers were coated on both sides with a 1 μm thick layer of low stress Si_3N_4 by Low Pressure Chemical Vapour Deposition (LPCVD). This was patterned and etched down to the silicon layer using CHF_3/Ar RIE process. The cantilevers were released by etching the underlying silicon in 30% KOH:H_2O solution at 70 ℃.

The wet etch process used to release the cantilevers etches laterally as well as vertically, leading to an undercutting of the device layer at the root of the cantilever. (Figure 1(b)) The length of this undercut varies with the design and between fabrication runs. It is difficult to measure directly since the oxide layer is buried between the device layer and the handle wafer. This uncertainty in the length of the undercut has significant consequences for the behaviour of the beam structures, effectively increasing their length and reducing the resonant frequency. The following section will describe the analysis methods that will be used and the approaches used to overcome the problems of the undercut.

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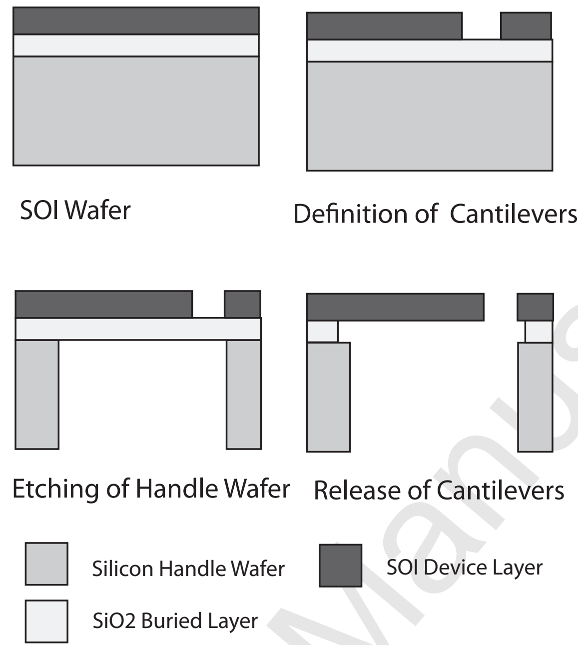

Figure 2: Illustration of fabrication process used to produce SOI cantilevers.

3. Theory and Analysis

The behaviour of a beam clamped at one end is described by the Euler-Bernoulli equation [9],

$$EI\frac{\partial^4 y}{\partial x^4} + \rho A\frac{\partial^4 y}{\partial t^4} = 0 \tag{1}$$

where E is the Young's modulus, I is the moment of inertia and ρ is the density. Equation 1 can be rewritten to describe the deflection of the beam

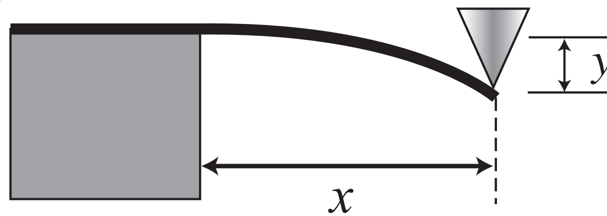

Figure 3: Illustration of deflection of a beam due to a point force applied at a position, L.

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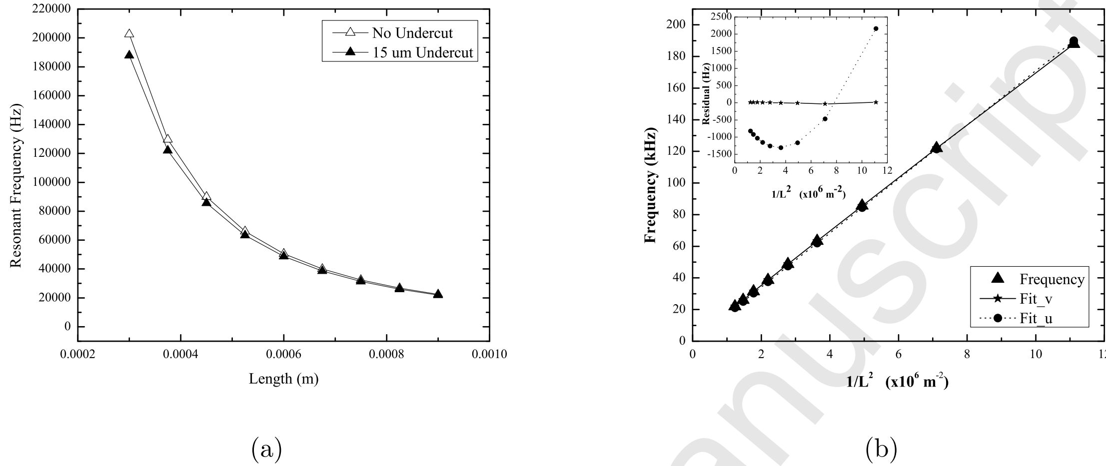

(a)

(b)

Figure 4: Simulation of the resonant mode of cantilevers of various length (a) Resonant frequencies with and without a 15 μm undercut (b) Cantilevers with 15 μm undercut fitted with two functions: $\frac{a}{L^2}$ and $\frac{a}{(L+\Delta L)^2}$

as illustrated in Figure 3 where y is the deflection at point x, where the force, F, is applied.

$$y = \frac{Fx^3}{3EI} \tag{2}$$

From this equation it is straightforward to calculate the Young's modulus for a particular force if the position, x, deflection, y, and the second moment of inertia, I, are known. However it is not possible to know the exact location of the base of the cantilever due to the undercut at the base of the cantilever. Hopcroft proposed solving this by considering the cubic behaviour of the position rather than the absolute position[10]. By fitting the deflection/position data to the third order polynomial it is possible to determine $\frac{F}{3EI}$ from the coefficient of the cubic term. From this, and with knowledge of the cantilever geometries, it then is straightforward to calculate the Young's modulus, E, without knowledge of absolute length.

3.1. Resonance Method

The resonant behaviour of a beam fixed at one end is also described by the Euler-Bernoulli equation. (Eqn. 1) [6, 11] This can be solved to describe

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the resonant frequencies of each bending mode of the cantilever of length, L.

$$f_n = \frac{\alpha_n^2}{2\pi\sqrt{12}} \frac{1}{L^2} \sqrt{\frac{EI}{\rho A}} \tag{3}$$

where α is the non-trival solution of

$$1 + cos\alpha_n cosh\alpha_n = 0 \tag{4}$$

Equation 4 can be solved numerically for α_n, the first four solutions corresponding to the first four modes are (1.8571, 4.694, 7.855, 10.996,. . .) If the geometry and the density of the beam are known it is possible to use equation 3, to calculate the Young's modulus. This can be done for each length of cantilever but will be subject to any random variation in the measured frequencies. The least squares fitting method is used to reduce this dependence. It is seen from Equation 3 that for a particular mode, the resonant frequency varies with the inverse of the length squared. By measuring a number of different lengths of cantilevers and fitting to

$$f_n = A\frac{1}{L^2} \tag{5}$$

it is possible to find the coefficient, A, and therefore the Young's modulus with a reduced dependence on the random variation in the measurements. This method also allows us to consider the change in resonant frequency due to the undercut at the base of the cantilevers. In the undercut region at the base of the cantilevers we might expect the resonant behaviour to be described best by considering the bending of a plate with a width greater than the length (w >L) rather than the beam that we have studied thus far. This would certainly be true if the undercut was large but in our case the length of the undercut is small compared with the width of the cantilevers. (typically less than half the width). Therefore the undercut can be adequately described by increasing the effective cantilever length by ΔL. By replacing L with (L+ΔL) in Equation 5 for a number of lengths it is possible to build a series of simultaneous equations which can be solved for ΔL [11]. The cantilever lengths in Equation 3 can then be corrected for the effect of the undercut and the accurate value for the Young's modulus determined.

The validity of this approach was studied using finite element modelling (FEM), the design shown in Figure 1(a) was modelled using ConventorWare

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FEM package. ConventorWare is widely used for the simulation of MEMS devices and libraries of materials for various foundry processes are included. The standard material library for MEMSCAP SOI Multi User MEMS Process (MUMPS) was used with layer thickness obtained from measured devices. The structure was simulated setting the boundary conditions at two positions, (a) at the base of the cantilever, and (b) set back 15 μm from the base giving an undercut. The boundary conditions used are those originally used to derive Equation 2 i.e. that the position is fixed in all directions. The results for various lengths are shown in Figure 4(a), as we would expect the resonant frequencies to be lower for the cantilevers with an undercut due to the increase in effective length. The change in frequency is not large but is still significant. Figure 4(b) shows the simulated resonant frequencies of cantilevers with a 15 μm undercut plotted against the inverse of the length squared, which results in a straight line. Two functions are then fitted to this line $\frac{a}{L^2}$ and $\frac{a}{(L+\Delta L)^2}$. This results in two gradients that are similar but which result in significant variation in the calculated Young's modulus. The quality of the fit is shown in the inset, it is seen that the quality of the fit is greatly improved by including the correction for the undercut, leading to residuals close to zero. The length of undercut determined from the fitting method was 12 μm, close to the true value of 15 μm used in the simulation. This method therefore allows us to take into account the effect of the undercut and also determine its value from measured resonant frequencies.

The method for determining the Young's modulus for cantilevers consisting of single materials is relatively straightforward. However, it is often desirable to determine the properties of materials that are either too thin or too weak to form cantilever test structures. In this case a multilayered structure is used where a thin layer of the material of interest is deposited on a supporting layer, for example a thin layer of polysilicon on a SOI cantilever. This multilayer situation is more complex and it becomes necessary to consider the average density and the moment of inertia of the multilayer beam as a whole. This is performed using the transformed section method described below.

3.2. Transformed Section Method

The transformed section is a method widely used for the study of composite beams and was previously used for micro-cantilevers by Voiculescu et al. [7]. This involves replacing the multilayer beam with a single beam of uniform Young's modulus. This is done by normalising the cross sectional

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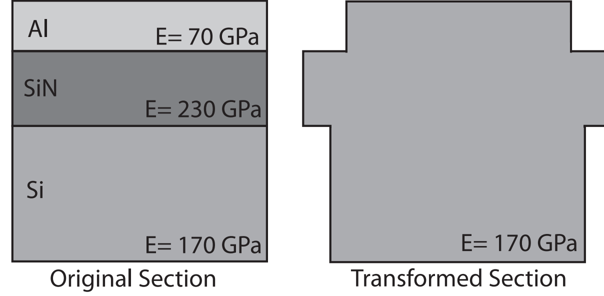

Figure 5: Diagram of the transformed section method for a three layer composite structure

area by the ratio of the Young's modulus (E_i/E_{ref} where E_i is the transformed layer and E_{ref} is the reference layer, in our case, the SOI layer). This is illustrated in Figure 5. The new transformed beam is equivalent to the original beam with its neutral axis in the same position. For a multilayer beam the bending stiffness is given by

$$\overline{EI} = \sum_{i=1}^{N} E_i I_i \tag{6}$$

The moment of inertia of each layer, I_i is given by

$$I_i = \frac{wt_i^3}{12} + A_i d_i^2 \tag{7}$$

where w is the beam width, t_i is the thickness of the layer, A_i is the transformed cross-sectional area, and d_i is the distance from the centroid axis of the composite beam to the neutral axis of the individual layer. For a single layer this reduced to $I = \frac{wt_i^3}{12}$ as we would expect. The position of the neutral axis is given by

$$d = \frac{\sum_{i=1}^{N} d_i A_i}{\sum A_i} \tag{8}$$

The composite density is given by

$$\overline{\rho} = \frac{\sum_{i=1}^{N} \rho_i t_i}{\sum_{i=1}^{N} t_i} \tag{9}$$

where N is the number of layers in the multilayer beam, ρ_i, is the density of each layer and t_i is the thickness.

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It is noted that in order to determine the density, ρ_i and the moment of inertia, I_i of each layer we need to know E for each layer, including the layer that we want to calculate. In order to do this we solve self-consistently using an initial estimate for E from the literature, repeating until the difference between iterations is less than 1 GPa.

4. Experimental

The experimental methods are relatively straightforward, however since the aim is to determine the Young's modulus in an accurate and repeatable fashion care has been taken to develop a robust measurement scheme that can be followed, and that eliminates as many sources of experimental error as possible.

4.1. Deflection Method

The deflection measurements were carried out using a KLA-Tencor Alpha Step IQ surface profiler. This profiler can measure deflections of up to 400 μm with a maximum vertical resolution of 0.24 nm. The force applied by the stylus can be varied manually and be measured accurately between the range of 1 and 99.9mg. The scan length and the scan speed can also be varied depending on the application.

There are a number of factors that must be considered to ensure accurate and repeatable measurements using this method. The bending equation that was given in equation 2 assumes that the applied force is acting vertically on the central axis of the beam. Any force that is applied off the central axis will cause torsional bending of the beam. This torsional bending (twisting) of the beam is reported by Hopcroft [10] to also follow a L^3 behaviour which would introduce errors in the calculated Young's modulus. To minimise this, the path of the stylus is aligned to the edges of the test cell die which lie parallel to the cantilevers. The start position of the scan is positioned as accurately as possible to the centre of the cantilever. However it should be noted that accuracy is limited by the optics of the system. For stylus profilers it is important that they are properly levelled i.e. they do not show an change in tip height over a flat scan. It is possible to correct this during the data analysis but ensuring a physically level system reduces any errors introduced. The stage is therefore carefully adjusted so that there is less than a 100 nm change in height over a scan length of 1 mm.

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Some of the multilayer cantilevers exhibit bending with zero force applied due to the initial stress in the films. This intrinsic bending can skew the results; in order to resolve this the scans are repeated with three forces and then subtracted from each other giving the deflection due to a differential force. The forces applied depend on the stiffness of the cantilevers under test so as not to exceed the elastic limit, and, in the case of the SiC cantilever to ensure that the deflected cantilever does not touch the underlying substrate. For the SOI and multilayer structures forces of 5 ,10 and 30 mg were used. Throughout the process, each measurement is repeated four times which allows the mean and standard deviation to also be calculated.

The scans are taken on only a single length of cantilever as the deflection behaviour of the beam is independent of the length of the cantilever, depending only on the measurement position with respect to the root of the cantilever.

The measurements are analysed using an automated Octave script (an open source equivalent to MATLAB). The script initially subtracts the deflection data of two forces. There are 4 repeats of each measurement giving 16 individual measurements for each differential force. Each of these is fitted to a third order polynomial using the least squares fitting method. The range over which the data is fitted is chosen to ensure that we are in the bending region of the scan, (i.e. on the cantilever rather than the substrate) and not at the very end of the cantilever. The length of scans that the polynomial was fitted over was 700 μm for Si and multilayer cantilevers and 300 μm for SiC cantilevers due to the different geometries available. After the coefficient of the cubic term is determined it is straightforward to calculate the Young's modulus. However, for accurate results it is necessary to have exact values for the geometry of the cantilevers. From equation 7 it is seen that the moment of inertia is a function of w and t^3 The thickness must therefore be known with a high degree of accuracy to prevent inaccurate values of Young's modulus being calculated. The height of the additional layers is straightforward to determine, either by using a stylus profiler or an optical surface profiler. The silicon layer was more difficult. Due to the fabrication methods used to release the cantilevers there is no structure where it is possible to measure the thickness directly. The thickness of the SOI layer provided by the wafer manufacturer was 15 ± 1 μm. However this is not accurate enough for our requirements and it is therefore necessary to directly measure the thickness. This was performed by sectioning the cantilevers in a scanning electron microscope. The sample was prepared by carefully breaking cantilevers off an

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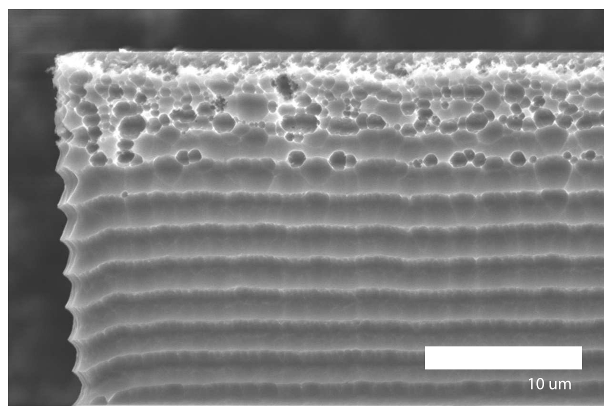

Figure 6: Cross Section scanning electron micrograph of Si cantilever. The scalloping of the edges is a feature of the DRIE process.

unused test structure close to the test site and transferring to a SEM sample holder. The Hitachi S-3000 microscope allows the sample to be rotated 360° and tilted through 60° which enables high resolution images of the cantilever cross section to be taken (Figure 6) from which accurate measurements of the thickness can be obtained. The thickness measured using this method was 15.6 μm. This value was then used to determine the Young's modulus as discussed below.

4.2. Resonant Method

There are a number of methods for exciting the resonant modes of cantilevers, thermally [6], electro-statically[7], and magnetically [12]. In this work we use two methods to excite the modes. A loudspeaker was used to acoustically excite the resonant mode of the longer cantilevers with resonant frequencies below 100 kHz. A piezoelectric transducer was used to excite higher frequencies of shorter cantilevers or higher order modes. The transducer was mounted directly on the back of the die. Both the loudspeaker and the piezo transducer are driven by sinusoidal voltage supplied by a TTi TGA 1230 signal generator amplified by a voltage amplifier to provide a peak to peak voltage of 10 and 5 volts for the speaker and piezo respectively. The movement of the cantilevers were monitored using a Polytec PFV 3001 vibrometer with OVD-02 velocity decoder, with a specified maximum detection frequency of 1.5 MHz. The resonant frequency of each cantilever is found by manually sweeping the frequency supplied by the signal generator

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Table 1: Density and measured thickness of thin films

Material	Density (g/cm^3)	Measured Thickness (μm)
Silicon	2.33	15.6
Silicon Carbide	3.16	2.4
Silicon Nitride	3.18	1.12
PolySilicon Two	2.33	0.4
PolySilicon One	2.33	0.405
Metal	2.7	1.275

Table 2: Determined Young's modulus for range of thin film materials using deflection and resonant frequency method.

Material	Stylus Method (GPa)	Resonant Method (GPa)
Silicon	172	169
Silicon Nitride	244	243
Silicon Carbide	438	435
Aluminium	58	89
Poly-Silicon One	150	149
Poly-Silicon Two	10	153

and monitoring the velocity of the cantilever using a Tektronix TDS2004B oscilloscope. The fast Fourier transform (FFT) of the velocity signal is used to determine the resonant frequency. The use of FFT is quicker and easier to determine the true resonance peak and so reduces uncertainties due to human error. This method allows the resonant frequency to be determined down to the order of a few Hz.

5. Results

The two methods presented in Section IV were used to determine the Young's Modulus of a range of materials and the results from the two methods are compared in Table II . As has been discussed above, the resonant method requires the assumption of the density of each layer. The values used in the calculations were taken from values given in the literature and are given in Table I. The measured thickness of each layer is also shown.

We shall first consider the cantilevers fabricated from a single layer of

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single-crystal silicon and silicon carbide. These are the most understood materials and provide the best means for determining the accuracy of the measurement methods. It is seen that the results from the two methods agree very well with a difference of less than 2% for both materials. The value of Young's modulus quoted in the literature has ranged from 120 to 190 GPa [13]. It is now accepted that the Young's modulus in the [110] and [$\bar{1}$10] directions is 169 GPa [3]. This value matches that determined by both our methods i.e. 172 and 169 GPa for the stylus method and the resonant method respectively. The standard deviation of the deflection method is found to be 3.8 GPa, matching the differences between our two measurements. The value of the Young's modulus normally quoted for silicon carbide is around 440 GPa [14, 15, 16] although this has been seen to vary with processing and doping concentrations. This published value also agrees well with both our methods, with less than a 1% difference between the two methods. The results for amorphous silicon nitride are also very good, the two method closely agree with each other with values off 244 and 243 GPa for the deflection and resonant methods respectively. As with silicon carbide the Young's modulus of silicon nitride is seen to vary depending on composition, in particular, the hydrogen content of the SiN films [17]. The values that have been quoted for nitride films deposited by LPCVD range from 178 to 290, [2, 18, 19] and our results lie at the centre of this range. Overall, the results for the silicon and SiC show that the two methods demonstrated are robust and are capable of accurately measuring the Young's modulus of a range of materials using a variety of test device designs.

The two methods were expanded using the transformed section method to enable the determination of the Young's modulus of thin films as part of multilayer cantilevers. Due to the more complex method and the low thickness of these layers relative to the silicon support layer, the results for the materials determined by the multilayer method display greater variation. The extracted values for the metal (aluminium) layer vary quite substantially between the two methods with the accepted value lying in the middle of this range. The Young's modulus of poly-silicon can range from 120 to 180 GPa depending on composition and doping. The values for the Poly-Silicon One layer show between close agreement with the values for the deflection and resonance method. The value of 150 GPa is in the middle of our expected range. The value of the Poly-Silicon Two determined by the deflection method was repeatably very low and is considered to reflect the limitations of this method when using thick SOI support layers.

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6. Conclusion

We have presented the direct comparison of two methods commonly used for the measurement of the Young's modulus of thin film using micro-cantilevers. The measurements for each method were performed on the same micro-cantilever test structures. The experiments were performed on a range of materials and cantilever geometries. For single layer cantilevers the results from the two methods matched and were in close agreement with the values of the Young' modulus found in the literature. Both methods were also extended to measure the Young's modulus of thin films within multilayer cantilever structures. Again the results were consistent between the two methods and within the expected range of values for each material. The results of the multilayer transformed section could be greatly improved by using thinner support silicon layers.

Since the results match so closely the performance is not the limiting factor. We must also consider factors such as the repeatability, the suitability for use in an industrial environment and possibly the scope for further automation. The deflection method uses relatively simple equipment that is commonly available in most commercial MEMS foundries. However, at present the method requires some degree of operator skill and care during the measurements. The need to take multiple scans to account for any residual stress makes the process relatively time consuming.

The resonant methods has a major advantage in the fact it is fast and non-contact. The measurement process is straightforward and it is possible to measure a number of devices quickly. The measurement of the resonant frequencies using FFT of the vibrating cantilevers velocity is rapid and accurate. The major problem with the method however remains that the density of the film must be known accurately in order to calculate the Young's modulus. The density of thin films can vary depending on the deposition conditions and is difficult to measure, which limits the usefulness of the resonant method. Therefore the load-deflection method using a stylus profiler is more useful as a stand alone method as it requires no addition material properties to be known. However due to the speed and simplicity of the resonant method it is ideally suited to be incorporated into a series of measurements where a range of mechanical properties, including density, are measured.

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