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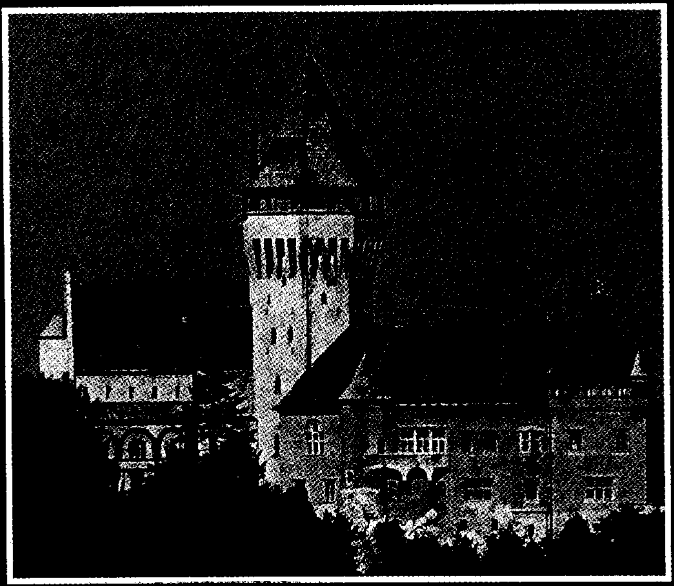

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Micro-Mechanical Characterisation for MEMS Thin Films by Bending μ-machined Cantilevers

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A simple, cost-effective, μ-mechanical characterisation process is developed. It can be applied to a wide range of materials, including non-conductive material. This technique is based on μ-machined beam bending. The beams of the material under test, are patterned by laser micromachining and released by alkaline etching. A surface profilometer stylus is then used to scan along the cantilevers, deflecting them and yielding position-displacement traces, from which the thin film's elastic modulus can be extracted. A consistent data analysis method is developed to extract the modulus from such traces. LPCVD SiN cantilevers are fabricated and the Young's modulus is extracted 155+/-20 GPa. Finite Element Modelling (FEM) is used to analyse the beam behaviour.

1. Introduction

Thin film mechanical characterization is of great interest for MEMS reliability and packaging [1,2]. Opto-electronics packaging by elastic clips requires good knowledge of Young's modulus. Thin film process development in IC and MEMS/NEMS requires simple and fast characterisation methods. Characterisation techniques such as tension tests, electrostatic pull-in tests, membrane-bulge tests, beam-bending tests [3, 4], micro-bridge tests, frequency-response tests and indentation tests are widely utilized [4, 5]. Most of these techniques are either too complicated to set up or too expensive for a straightforward industrial application. Moreover, analyses using these techniques are not robust and accurate enough. A survey by Schweitz [4] shows an uncertainty of ±30% for [110] single crystal Si Young's modulus with mean values ranging 120~220 GPa. We demonstrate an improved characterisation process to extract Young's modulus, using LPCVD SiN as an example.

2. Process and fabrication

Fig.1 shows the schematic process flow: 1) Laser micromachining [2] is used to pattern the beam on the thin film material under test, 2) An alkaline etch is used to release the cantilever, 3) Surface profilometer, e.g. Dektak, is used to scan along the cantilevers. 2.35 μm-thick LPCVD (Low Pressure Chemical Vapour Deposition) SiN samples, fabricated by MESA Research Institute, University of Twente, the Netherlands, called SiN-TM below, have been processed as above. It is cut by UV laser of a New-wave QuikLaze system with process parameters of 100 % Hi-power, 20 % X, 20 % Y (translating to 11 μm x 11 μm spot size), 50Hz- pulse, 25μm/sec-scan rate. **Fig.2(a)** shows the sample just after laser ablation. Tetramethyl ammonium hydroxide (TMAH) is used to release the beams. **Fig.2(b)** shows Si under SiN-TM is partly etched by 5 wt % TMAH for only 20 minutes at 85 °C. **Fig.2(c)** shows that SiN beams are released after TMAH etch for 4 hours.

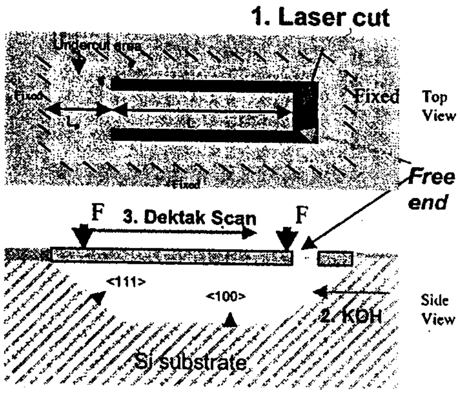


Fig.1 Process flow of extracting Young's modulus by bending thin film micro-machined cantilever

In order to measure the most important geometries factor – thickness, floating squares are designed as shown in **Fig. 2(b)**. Instead of using an air gun to dry the samples after etching, the samples are put in the oven or hot plate to dry to keep the 'squares' on the sample by surface adhesion, after cleaning with de-ionized water. **Fig. 2(d)** shows the floating SiN pieces for the thickness measurement, and mechanical scanning route for the profilometer to scan and bend the beam. This particular scan allows the film thickness $t = 2.35 \pm 0.03$ μm and the modulus to be extracted at the same time, because one floating square is on the beam.

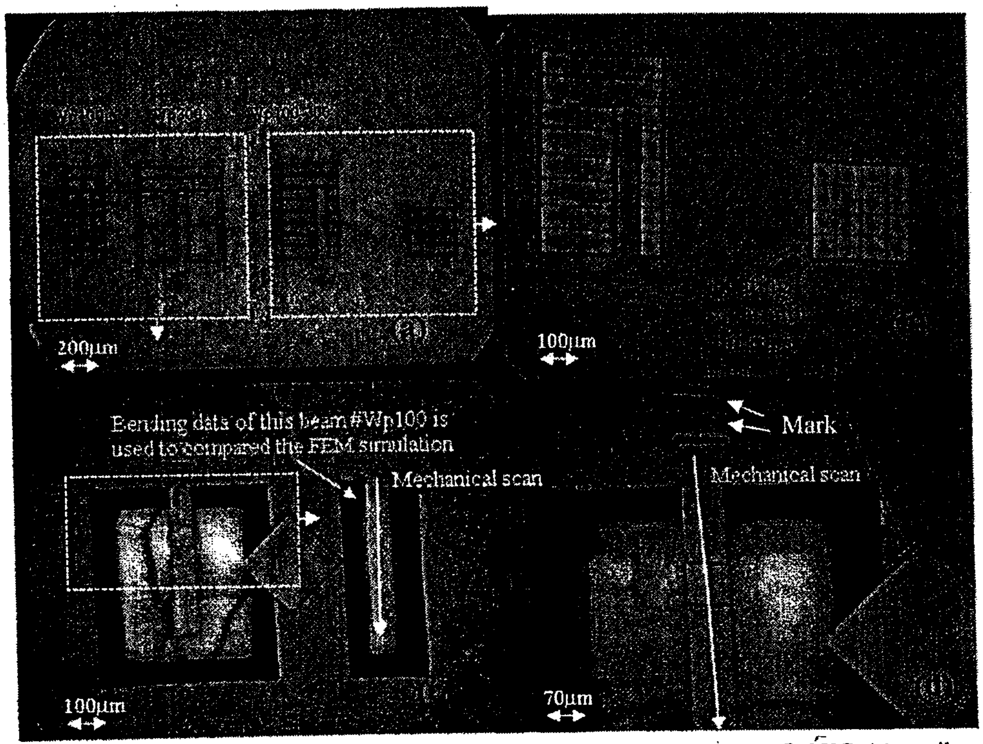


Fig. 2 LPCVD SiN (a) after UV laser cut before TMAH; (b) TMAH etch for 20 minutes @ 85°C, (c) cantilevers released after 4-hour TMAH etching, dry the sample in the oven without using an air gun to blow; #Wp100:L=580µm, W=92.7µm, t=2.35µm, (d) the floating squares on the beam or sample are designed for thickness measurement.

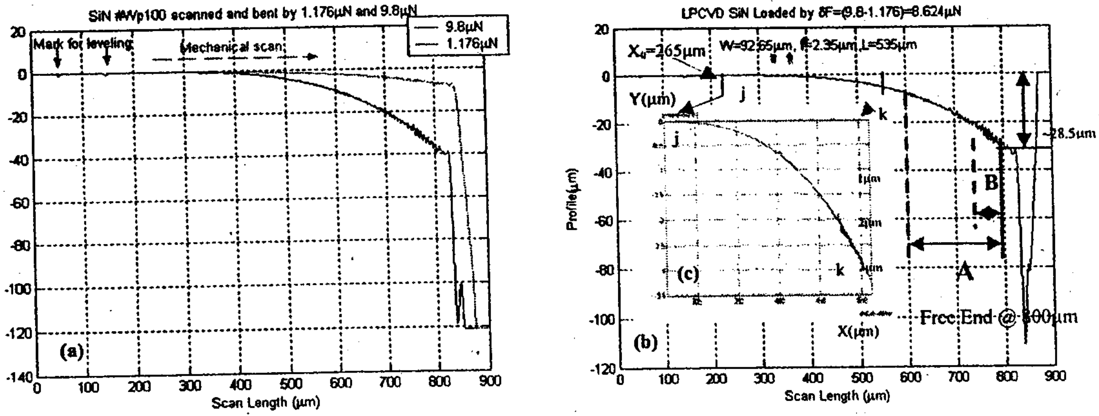


Fig. 3 (a) Scanning profile of Wp100 bent by 1.176µN and 9.8µN and (b) dF=8.624µN; (c) is part of profile (b)

3 Results and Analysis

Profilometer scans along the cantilever (right) SiN-TM #Wp100 shown in **Fig.2(c)**. Two forces 9.8 µN and a reference force 1.18 µN, have been used to scan and bend the beam as **Fig.3(a)** shown. The scan goes over two pits from the marks cut by laser shown in **Fig.2(c)**. They are used for levelling to avoid possible errors due to initial beam curvature. In **Fig.3(a)**, the 1st profile is subtracted from the 2nd profile to produce **Fig.3(b)**. It can be regarded as a profile bent by 8.62 µN, without the effect from initial bending. As a result, the deflection at the free end (X = 800 µm) is about ~28.5µm. This corresponds to the respective deflection difference of ~ 35.5 µm and ~ 7.0 µm in **Fig.3(a)**. Only the range between A and B in **Fig.3(b)** is used extract the modulus. Ranges larger than A could introduce bias from undercut error and anticlastic error, while ranges smaller than **B** could have too few data points for accurate analysis. **Fig. 3(c)** is the range j-k of **Fig.3(b)**,which won't be used for analysis.

4. Theoretical and data analysis

Fig.4 shows a cantilever beam of length L with a point load F at its end. The deflection of the cantilever beam can be described by the Euler constitutive relationship in Equ.(1). For small deflection, $dx \cong ds$, so $M \cong F(L-x)$ and $dy/dx \cong 0$, , after integration, the maximum deflection is obtained for $x = L$ as Equ. (2) shows. Detailed analysis can be found in [6, 7].

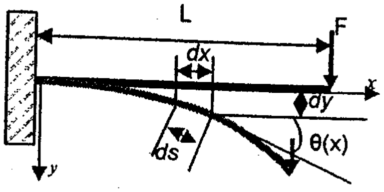


Fig.4 Two-dimensional beam bending model

$$\kappa = \frac{1}{R} = \frac{\frac{d^2y}{dx^2}}{[1+(\frac{dy}{dx})^2]^{3/2}} = \frac{-M}{EI} = \frac{F(L-x)}{EI}$$

Equ. (1)

$$y_{max} = \frac{FL^3}{3EI}$$

Equ. (2)

Equ. (2) can be used to extract the modulus in **Fig.3(b)** if it is an ideal beam without other effects, e.g. undercut. These errors add some additional terms to Equ.(2) [8] as below:

$$Y = AX^3 + BX^2 + CX + D$$

Equ. (3)

where $A = \frac{F}{3E'I}$, I = $wt^3/12$, and E' = E φ, w : width, t : thickness, φ : anticlastic correction factor. φ = 1 when the beam is long enough; φ = 1 / ($1-\upsilon^2$) when the width is much larger than the length. Polynomial cubic fitting (PCF) and other robust regression methods, with least-square or least-absolute fitting, have been tried to extract the cubic term A, and therefore Young's modulus E, but cube root fitting (CRF) yields the most consistent results [7]. CRF method is based on Equ.(4), taking cube root of Y from ranges between **A** and **B** in **Fig.3(b)** and plotting against X. Linear robust regression delivers the slope S and extract the modulus E'.

$$Y = \frac{F}{3E'I}(X+\varepsilon)^3,\ Y^{\frac{1}{3}} = \sqrt[3]{\frac{F}{3E'I}}X + \sqrt[3]{\frac{F}{3E'I}}\varepsilon = SX + C,\ E' = \frac{F}{3I \cdot S^3}$$

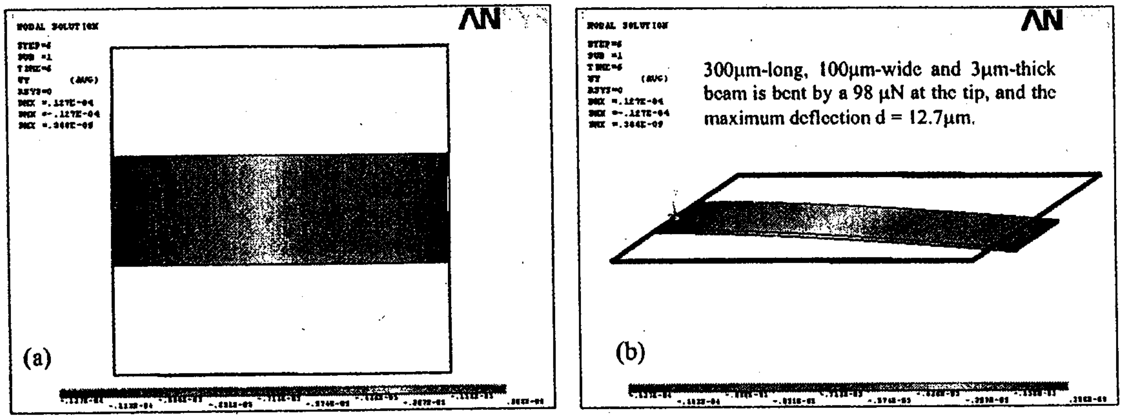
Equ. (4)

5. Finite Element Modelling (FEM) Analysis

We developed a new FEM model. ANSYS is used to simulate the anticlastic effect using 3D solid element Solid95. It determines where there is plate bending and where there is beam bending when the stylus scanning along the cantilever. **Fig.5** displays (a) top view and (b) 3D 45° side view of the contour plot of the deflection of a 300 μm long, 100 μm wide and 3 μm thick beam bent by a 98 μN force in the tip centre of the beam. **Fig.6** shows how the correction factor φ depends on length/width ratio with different Poisson's ratio v = 0.3 and v = 0.1. The v = 0.3 one is used to determine the modulus for ceramics materials, e.g. SiN-TM; for SiN-TM #Wp100, W / L < 0.17, the error is less than 2 %. It also indicates that the smaller the Poisson's ratio, the smaller the correction factor, which matches the literature [9]. **Fig.7** shows that experimental profiles are used to verify the FEM simulation results for a SiN-TM #Wp100 cantilever (W = 93 μm, L = 535 μm, Wp = 100 μm) with different extent of undercut of 5 μm and 30 μm respectively. They match each other very well if the error bar is considered, except some resonance near the free end of the beam.

6. Conclusion

We developed a simple micro-mechanical characterisation process including data analysis. After force calibration of the profilometer using a Si cantilever, we find that the actual force is 2 % larger than the nominal force on our machine. Testing Si-rich low stress LPCVD SiN-TM using this method we measure the elastic modulus to be 155 ± 20 GPa, which is comparable to literature values [10] and to the our nano-indentation testing result of 150 GPa. The detailed analysis and other works on electroplated Ni and other materials can be found in [7,11].



300μm-long, 100μm-wide and 3μm-thick beam is bent by a 98 μN at the tip, and the maximum deflection d = 12.7μm.

Fig. 5 Beam deflection by ANSYS when force is applied at the tip (a) Top view (b) 3D 45° side view

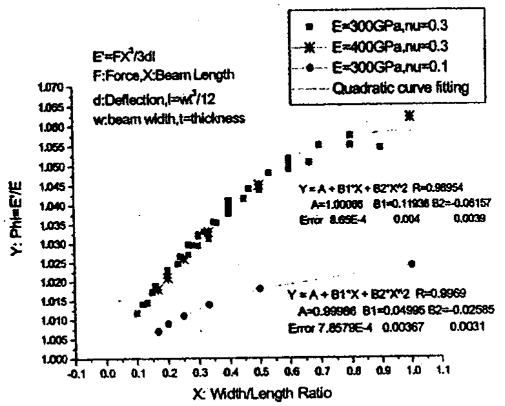


Fig.6 Correction factor map for Young's modulus with W/L ratio due to anticlastic effect by ANSYS

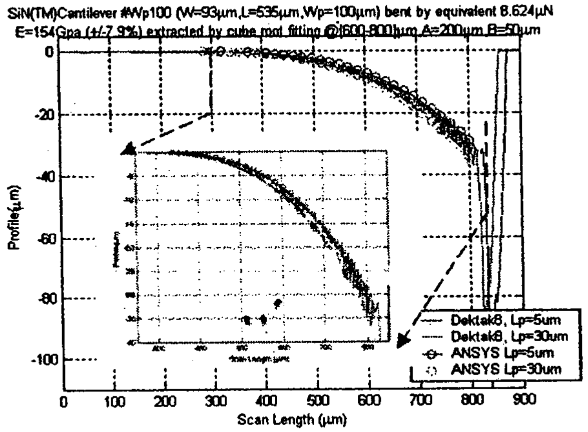


Fig.7 Simulation V.S. Experimentation of SiN-TM #Wp100 cantilever. Lp: undercut, The sample of Lp=30μm is the sample of Lp=5μm with 3-hour more TMAH etch.

Acknowledgement

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