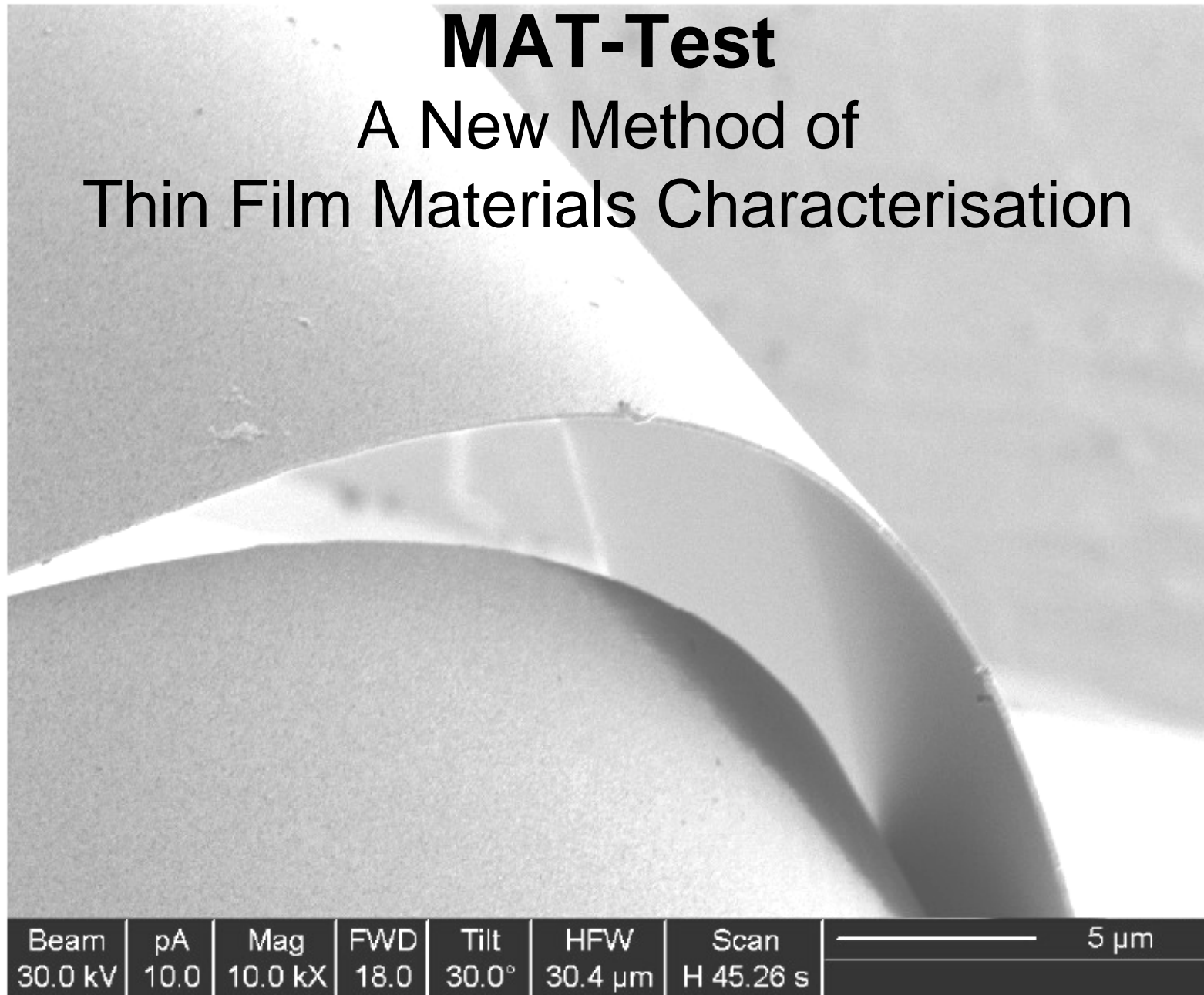


MAT-Test

A New Method of Thin Film Materials Characterisation



UNIVERSITY OF
CAMBRIDGE

LPCVD silicon nitride film bent through 90°



DEPARTMENT OF
ENGINEERING

Introduction

Measurements of Thin-Film Materials Properties

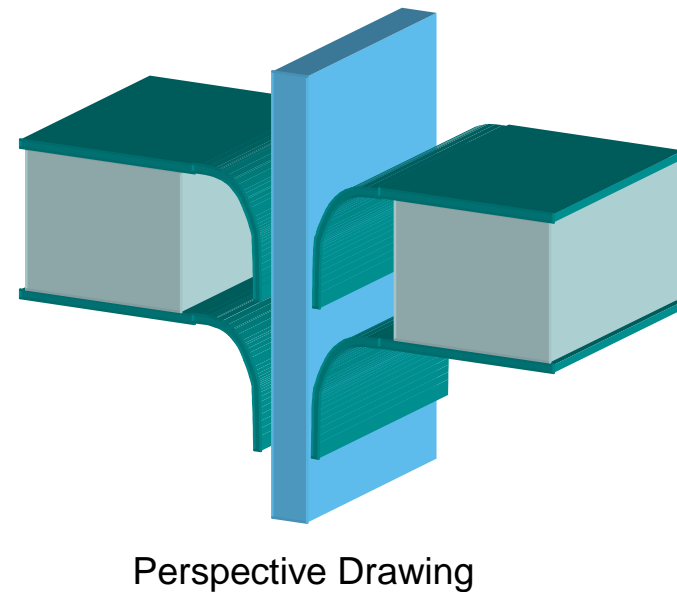
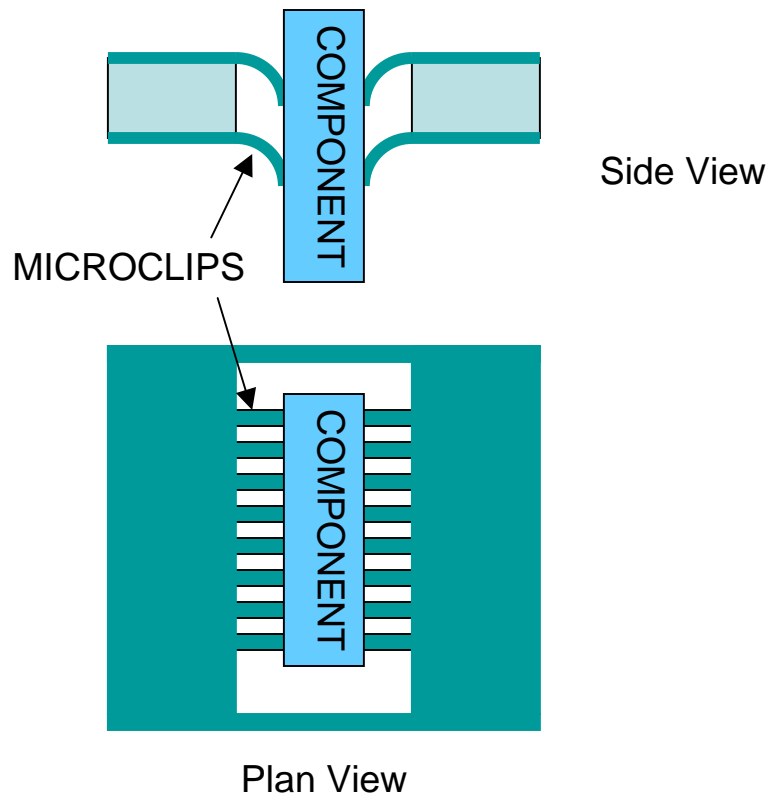
- There is a present and growing need for mechanical characterisation of thin films used in MEMS devices.
 - Accurate design of MEMS devices
 - Design for product-grade reliability
- Current measurement methods vary widely, have limited application, and produce different results.
- MAT-Test is a test method for evaluating the Young's modulus and breaking stress of thin films.
- MAT-Test is widely applicable and requires only common laboratory equipment.

Motivation: Microclips for Packaging

Proposed Microclip Packaging

- Create a slot through a substrate with overhanging interdigitated cantilevers around the edges. These microbeams are “Microclips”.
- When a component is inserted in the slot, the microclips deflect and hold the component in static equilibrium.

Proposed Microclip Packaging



Toward Microclips...

To implement these exciting packaging ideas, we need to develop the knowledge and tools to design microclips.

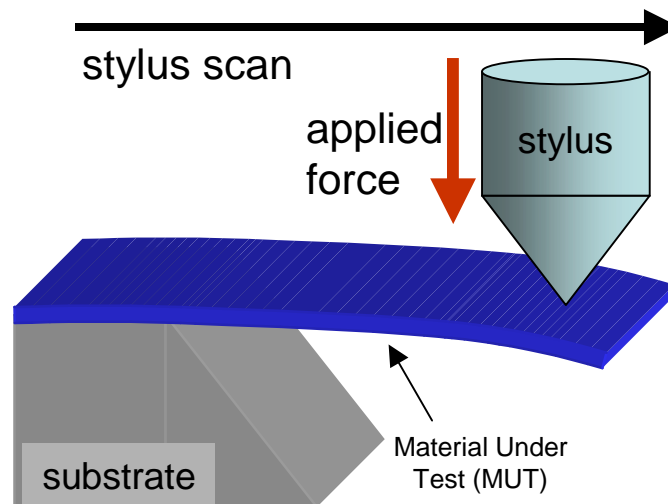
Effective microclip design requires:

- **Mechanical characterisation of thin films**
- Simulation of microbeams
- Modelling of microclip systems
- Fabrication of microclips

Thin Film Characterisation: MAT-Test

MAT-Test

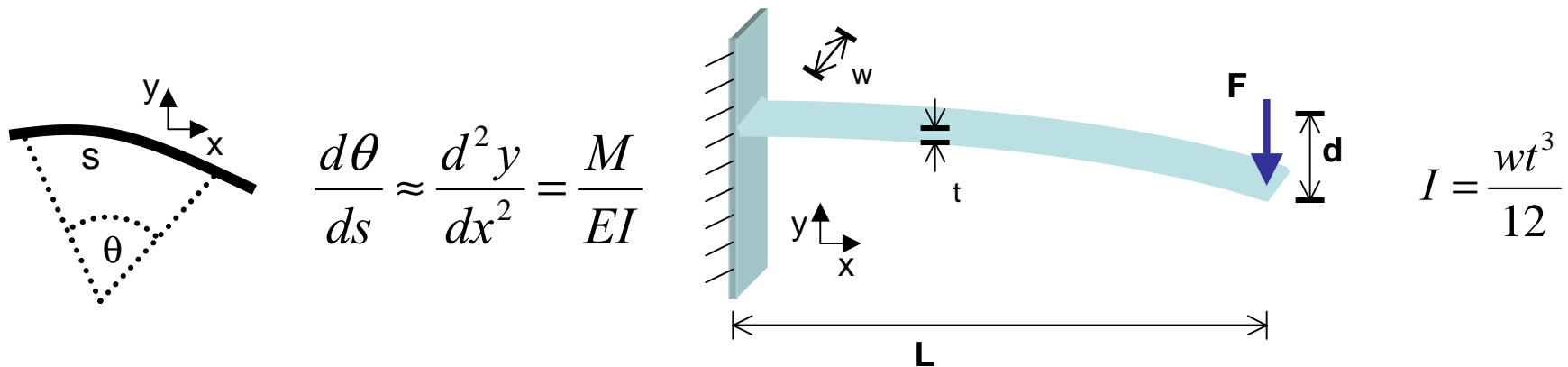
- MAT-Test is a method for determining some key mechanical properties of thin-films. MAT-Test is based on beam-bending:
 - The Material Under Test (MUT) is patterned into cantilever beams. The substrate material is removed, typically wet etched.
 - The cantilevers are deflected with a surface profilometer. The measured deflection is a function of the length of the beam, the force applied by the stylus, and the stiffness of the beam.
 - Young's modulus and breaking stress of the MUT can be extracted from the deflection data.



MAT-Test Analysis I: Foundation

Small-Deflection (Euler) Beam Theory

- If a prismatic beam is deflected by a normal force applied at the free end of the beam by an amount that is small compared to the length of the beam, the Euler Approximation can be used to predict the magnitude of the deflection:



- The expression for the deflection of a cantilever with a concentrated load is derived by solving the differential equation. The solution has the general form:

$$d = C_4x^3 + C_3x^2 + C_2x + C_1$$

- For $x=L$, the solution is:

$$d = \frac{FL^3}{3EI}$$

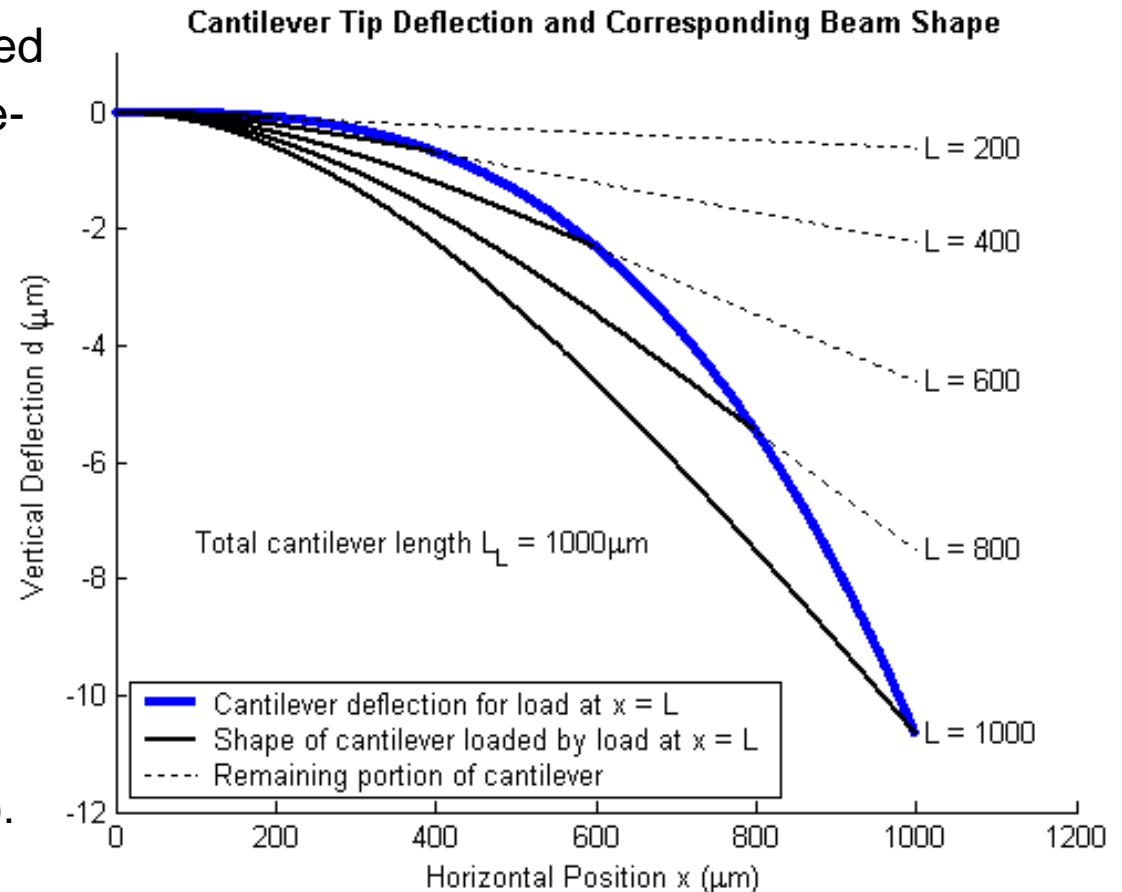
MAT-Test Analysis II: The Measured Data

Contact Surface Profilometer Scan Data

- The data collected by the surface profilometer is a plot of deflection at the tip of a cantilever loaded by the force applied by the surface profilometer stylus.
- The data can be thought of as a plot of the tip deflection of hundreds of cantilevers of increasing lengths; so that $x=L$.
- It can therefore be considered as a plot of the Euler small deflection equation, which gives d as a function of L^3

Of course, the measured deflection does not follow the Euler Equation exactly...

Figure: Cantilever tip deflection (blue) plotted with the corresponding cantilever shape (black).



MAT-Test Analysis III: Non-ideal Deflection

Measured Deflection vs. Predicted Deflection

- There are numerous “error effects” that cause the measured deflection of a cantilever to deviate from the predicted deflection, even when the conditions for small-deflection operation are met.

<u>Source of Deflection Error</u>	<u>Function of L</u>
• Shear Deformation	L
• Torsional Deformation (Twist)	L^3, L
• Tip Indentation	(n/a)
• Local Deflection	(n/a)
• Root Rotation (undercut)	L^2, L
• Root Deflection (undercut)	L^2, L
• Beam Stiffening	L
• Applied Force Direction	L
• Sample Horizontal/Vertical Misalignment	L
• MUT Internal Stress Gradient	L^2
• Beam mass	L^4
• Horizontal Data Offset	(n/a)

MAT-Test Analysis IV: Extracting Young's Modulus

Curve Fitting

- If we perform a third-order polynomial fit to the measured deflection data, we get a function that looks like:

$$d = YL^3 + UL^2 + SL + T$$

- Where:

$$Y = \frac{F}{3EI}$$

- And so Young's modulus, E , is given by:

$$E = \frac{F}{3YI}$$

- **The various error effects do not alter the value of the cube term coefficient, so we do not need to worry about calculating their magnitudes, and the test result is insensitive to these errors.**
- The remaining coefficients U , S , T , are a result of the error factors identified previously. They are difficult to classify, although we are considering whether additional information can be extracted from them.

MAT-Test Analysis V: Breaking Stress

Breaking Stress

- The stress, σ , in a bending cantilever is a function of the distance to the applied load:

$$\sigma = \frac{6F}{t^2 w} L$$

- If the surface profilometer is used to deflect a beam until it breaks, the distance L at the occurrence of failure is known. The point of failure, L_σ , is determined with a subsequent scan, and the breaking stress, σ_b , can be calculated. Repeated measurements are required to achieve statistical significance.

$$\sigma_b = \frac{6F}{t^2 w} L_\sigma$$

MAT-Test Simulation

Finite Element Method (FEM) Simulation

- FEM simulation results support the MAT-Test analysis: third-order polynomial curve fits to the simulated deflection data produce the expected values.

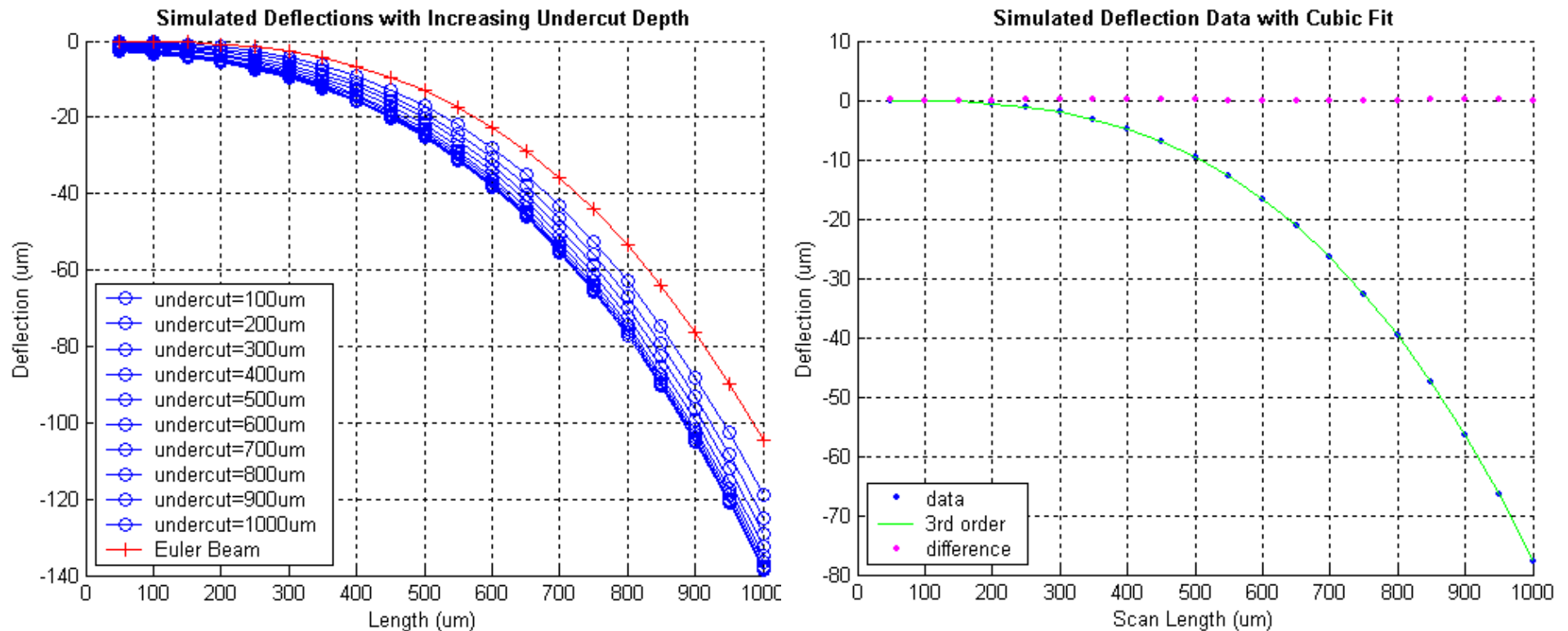


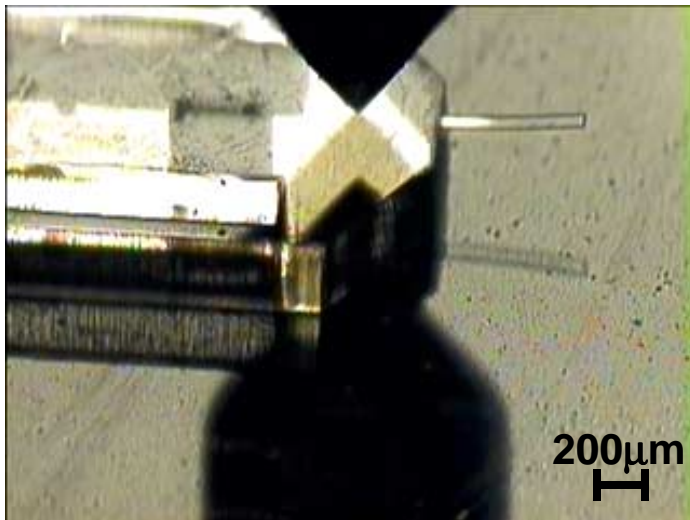
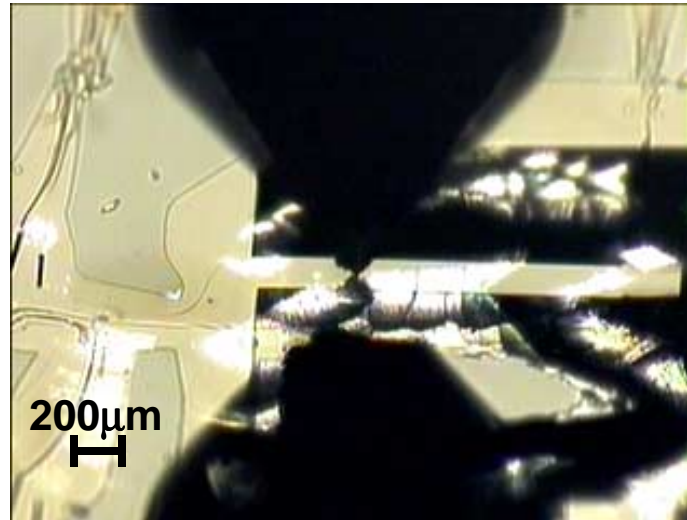
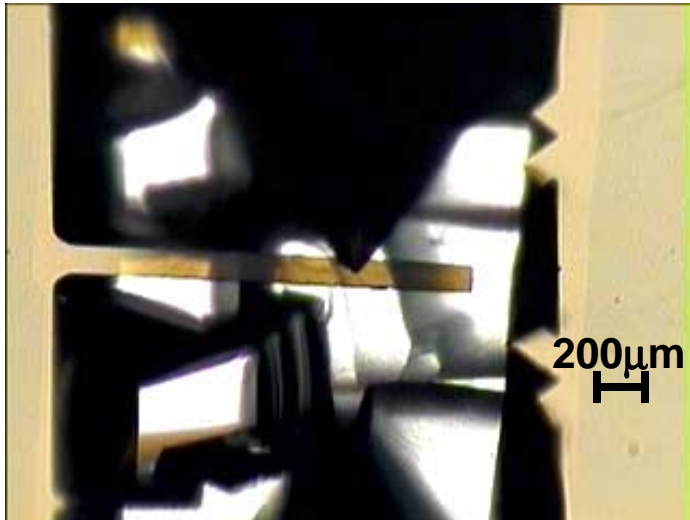
Figure: (*left*) Simulated profilometer data from a non-ideal cantilever (blue) and ideal cantilever (red). (*right*) Third-order polynomial fit (green) to the simulated data (blue) and difference between the polynomial fit and the simulated data (purple).

- FEM Simulations performed using FEMLAB, a FEM package for MATLAB.

MAT-Test Measurements

Measurements

- Silicon Carbide, Silicon Nitride, and SU-8 samples have been measured.



Photographs: (*clockwise from upper left*):

- 1) SiC cantilever being measured.
- 2) SiN cantilever being measured.
- 3) SU-8 AFM cantilever being measured.

The large black triangle in all of the pictures is the cantilever stylus. It enters from the top of the picture and casts a shadow below it.

MAT-Test Results

Analysis and Results

- The deflection data is analysed using the MAT-Test software, 'mt'.
- For the samples shown on the previous slide:
 - Silicon Carbide:
 $E: 436.7 \text{ GPa} \pm 23.1$
 - Silicon Nitride:
 $E: 263.6 \text{ GPa} \pm 27.4$
 - SU-8:
 $E: 2.7 \text{ GPa} \pm 0.1$

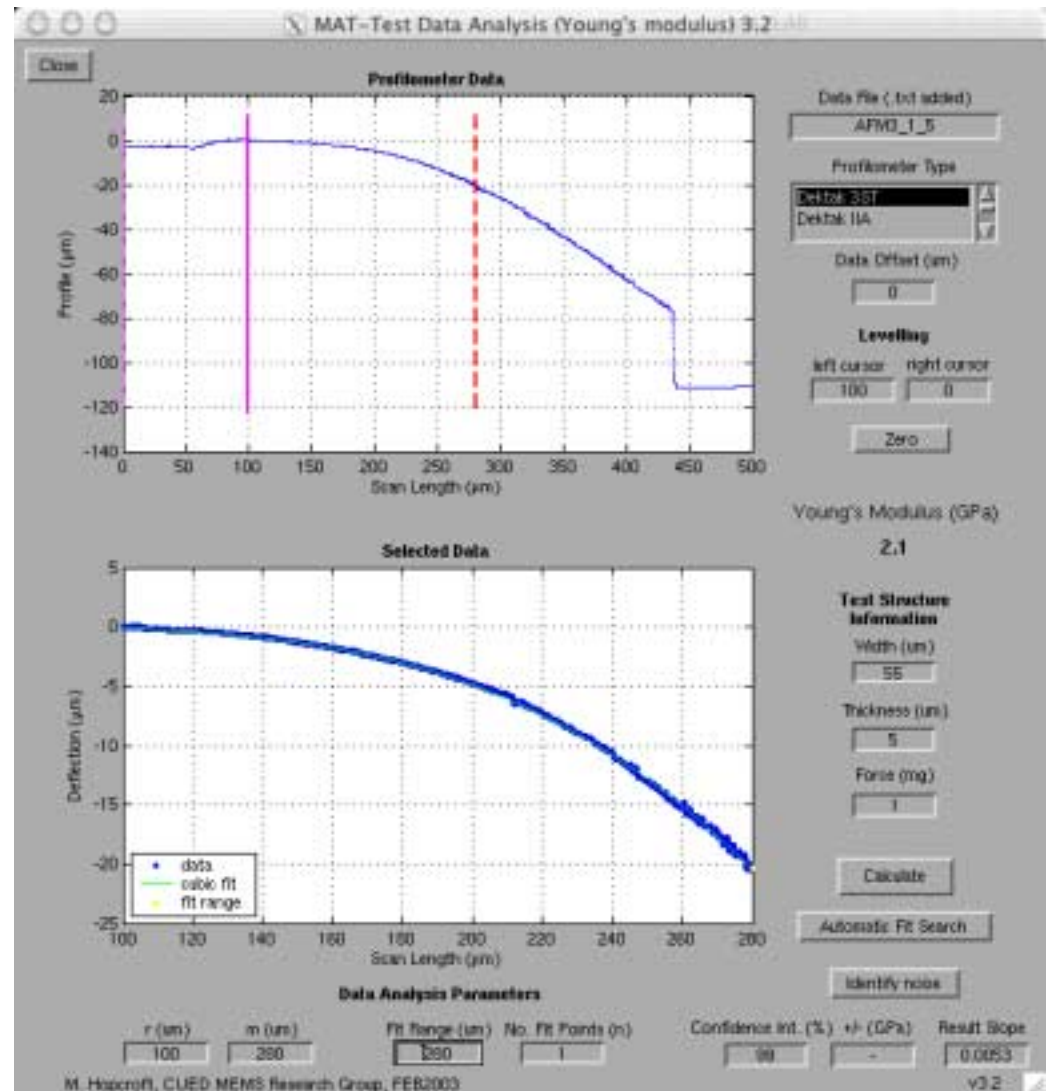


Figure: A screenshot of the MAT-Test data analysis software, mt.

Relationship to Previous Work

Deflection Analysis

- There is a significant body of previous work concerned with beam-bending methods for extracting material properties.
 - Nix (Stanford)
 - Senturia (MIT)
 - Schweitz (Uppsala, Sweden)
 - many others...
- All of the previous work relies on comparisons of load and deflection for a 'known' length.
- Material data extraction from these measurements relies on precise quantification of the components of the measured deflection. Significant effort has been devoted to investigating the deflection error effects.
- The equipment used is either expensive and rare (Nanoindenter), imprecise (micro-manipulator), or of limited applicability (electrostatic actuation).
- Other techniques (tensile test, frequency measurements, etc) have similar limitations.

Advantages and Limitations

Advantages

- Simple, fast, and cheap sample fabrication and test procedure.
- Requires only common test equipment (contact surface profilometer).
- Widely applicable: can be applied to all types of films, regardless of conductivity, deposition method, internal stress gradient, etc.
- Insensitive to common test errors.

Limitations

- Results are sensitive to film thickness and uniformity:

$$E \propto \frac{1}{t^3} \quad \sigma_b \propto \frac{1}{t^2}$$

- Requires relatively thick films: typically $>3\mu\text{m}$ (depends on E).
 - [Can be addressed using bilayer structures]
- Fracture stress test results may be limited by thin-film effects or processing issues (e.g. laser heating).

MAT-Test Applications

Research and Design

- Characterisation and comparison of unknown materials
- Materials selection for design

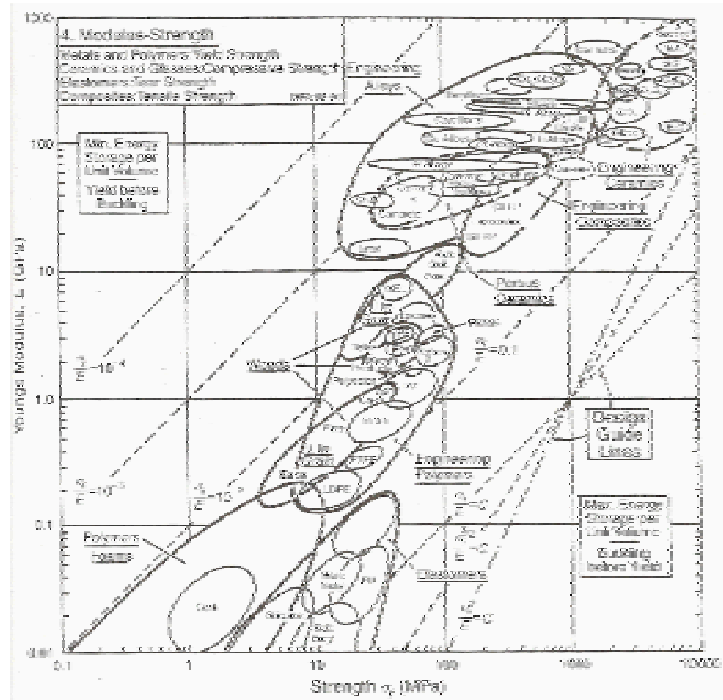


Figure: A macro-scale materials selection chart for modulus and strength (Ashby, Cambridge)

Commercial Production

- Process quality control for commercial thin-film fabrication: the Intermediate Quantities Y and L_σ can be monitored to detect process variation over time.

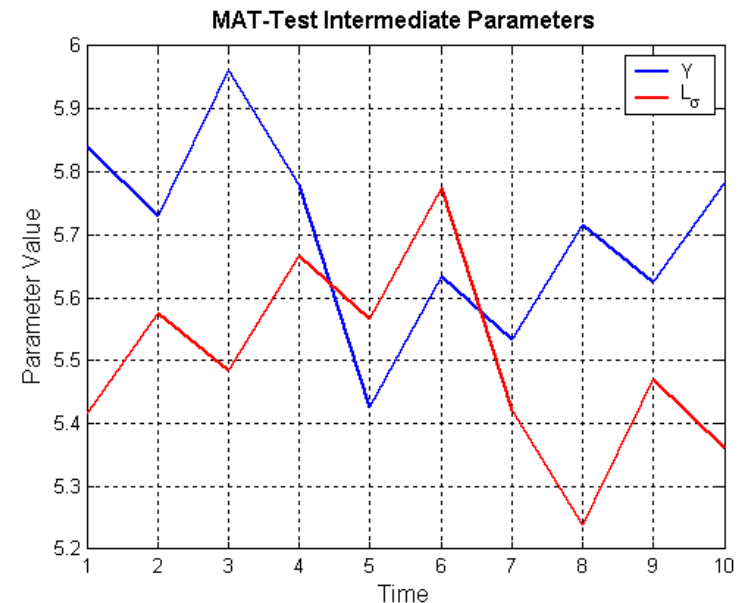


Figure: Example chart of MAT-Test Intermediate Quantities monitored over time for a fabrication process.

MAT-Test

A New Method of Thin Film Materials Characterisation

