# Micromechanical testing of SU-8 cantilevers

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**Abstract**: SU-8 is a photoplastic polymer with a wide range of applications in microtechnology. Cantilevers designed for a commercial Atomic Force Microscope (AFM) were fabricated in SU-8. The mechanical properties of these cantilevers were investigated using two microscale mechanical testing techniques: contact surface profilometer deflection, known as MAT-Test, and static load deflection using a specially designed test machine, the MFT2000. The Young's modulus values from the microscale test methods are approximately 2-3 GPa. These results are compared with results from macroscale tests of 4-5 GPa. The test methods and the results are discussed.

**Key words**: *SU-8, Young's modulus, microscale mechanical test, AFM cantilevers, surface profilometer, MAT-Test, MFT2000*

## 1. INTRODUCTION

The field of Microtechnology and Micro-Electro-Mechanical Systems (MEMS) has grown exponentially during the previous two decades. Recently, researchers are moving away from traditional silicon-based technologies and investigating alternative materials. One of the most promising candidate materials for new microsystem designs is a polymer called SU-8 [1]. SU-8 has several interesting and useful material properties, including photosensitivity, transparency to visible light, a low Young's modulus, and biocompatibility.

In order to design MEMS structures using SU-8, accurate material property data must be available. However, it is difficult to apply traditional macroscale mechanical test methods to microscale samples, so reliable *micromechanical* property data is scarce. In this paper, we present the design and fabrication of a cantilever for a commercial atomic force microscope (AFM) constructed from SU-8. This cantilever is then tested, using two different microscale test methods, in order to measure the stiffness of the cantilever and to determine the Young's modulus of the SU-8 material. The test results indicate that existing macroscale material test methods are not sufficient for MEMS design purposes and that reliable microscale test methods are required.

## 2. SU-8 CANTILEVERS FOR ATOMIC FORCE MICROSCOPES

Atomic force microscopes (AFM) have become an essential tool for surface analysis. In an AFM, a sharp tip attached to the end of a cantilever is scanned over the sample surface. The cantilever is deflected by features on the surface, and the deflection is detected using laser beam deflection techniques or other methods. This deflection measurement produces a profile of the sample surface with Angstrom resolution. Figure 1 illustrates the basic principle of AFM operation.

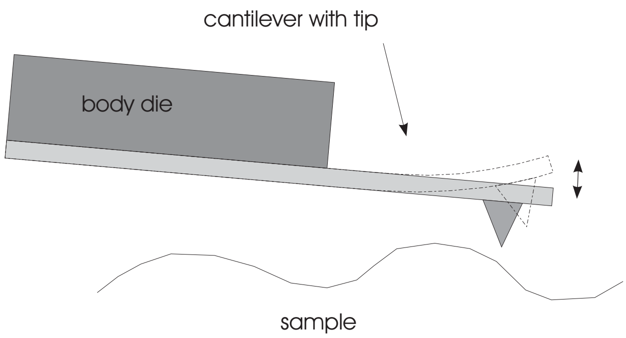


Figure 1. AFM operation

For effective operation, an AFM requires a cantilever with specific properties. It must have a high resonance frequency (>10kHz) and a low stiffness (0.1-1 N/m). Using conventional microfabrication techniques, it is difficult to fabricate a cantilever with a sufficiently low spring constant to achieve the very low contact forces that are required, as the thickness of the cantilever material becomes a limiting factor. Photoplastic polymers with a low Young's modulus (below ~5 GPa) present an interesting alternative, because they can be used to fabricate thick, robust cantilevers with the required properties [2].

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One of these polymers is the negative resist SU-8. With its highly cross-linked structure it is thermally and chemically stable and allows the realization of thick microstructures with high aspect ratios. The use of SU-8 also allows a simpler, cheaper and more versatile cantilever fabrication process based on surface micromachining. This makes the integration of additional functionality much easier and allows a variety of cantilever shapes to be designed. For example, SU-8 has recently been used to fabricate cantilevers with integrated piezoresistive sensors [3].

### 2.2. SU-8

The near-UV negative photoresist SU-8 was invented by IBM [1]. It is based on the EPON® Resin SU-8 from Shell Chemical. Layer thicknesses ranging from 750nm up to 300µm can be realized with conventional spin techniques, and structures of up to 2mm in height can be realized by using multiple coats. High-aspect ratio structures can be fabricated easily using thick layers of SU-8 and standard lithography tools. With its advantageous chemical and mechanical properties and the standard lithography compatibility, SU-8 is a promising candidate for many MEMS applications, including packaging, micromolds, microchannels, and many others. The characteristics of SU-8 have been described previously [1, 4].

### 2.3. Cantilever Fabrication

The complete SU-8 cantilever chip consists of a cantilever attached to a large body die. The cantilever fabrication process is illustrated in Fig. 2.

The SU-8 cantilevers were fabricated by spin coating SU-8 layers onto a silicon substrate [5]. Sotec 60/40 and 70/30 SU-8 solutions were used to achieve the different layer thicknesses [6]. The fabrication process began with a sacrificial layer of 200nm Cr and 500nm Al deposited on the silicon substrate. The first layer of SU-8 (Sotec 60/40) was then spun on and the cantilever patterns were exposed with UV lithography but not developed. The second layer of SU-8 (Sotec 70/30) was then applied and the body patterns were exposed. Then all of the unexposed SU-8 was developed and removed. Finally, the sacrificial layer was etched and the cantilever chips were removed from the substrate. To simplify the release of the cantilevers from the substrate, the different chips were attached to a SU-8 frame which held the chips together. The individual cantilever chips were then removed from the frame as needed. Figure 3 is a scanning electron microscope (SEM) image of a fabricated cantilever chip.

The cantilevers were designed with thickness 5µm, width 55µm, and lengths between 250µm and 475µm. The body die contains alignment features which were designed to match the alignment features used in a commercial AFM manufactured by Nanosurf AG [7]. The cantilevers shown here do not include an AFM tip.

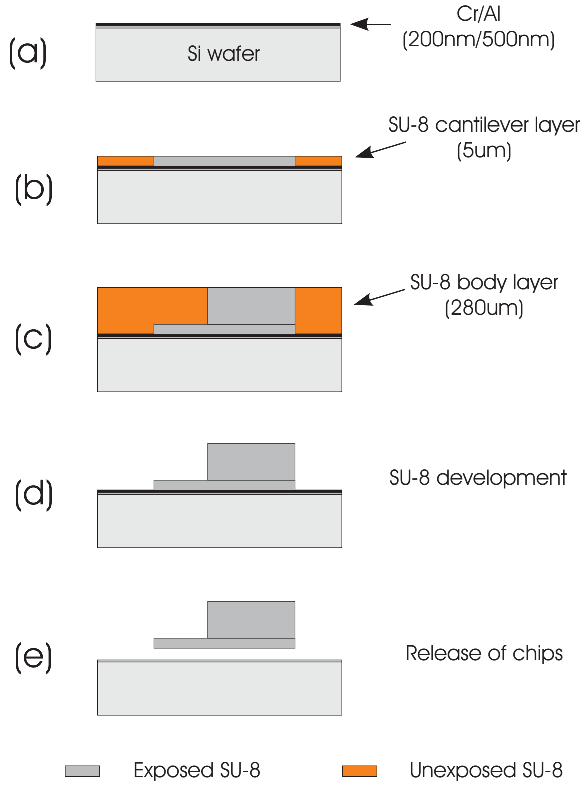


Figure 2. SU-8 cantilever fabrication
(a) a Cr/Al sacrificial layer is deposited on the silicon substrate (b) a 5µm layer of SU-8 is spun on and exposed to define the cantilevers (c) a 280µm layer of SU-8 is spun on and exposed to define the body (d) the SU-8 layers are developed (e) the sacrificial layer is etched and the cantilever chips are removed

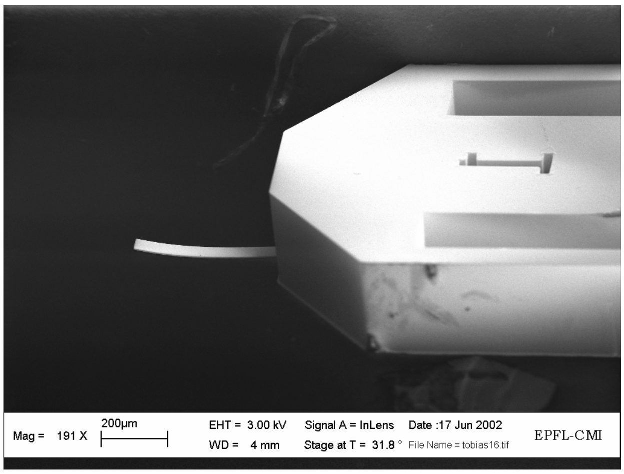


Figure 3. Fabricated SU-8 cantilever

## 3. MICROSCALE MECHANICAL TESTING I: SURFACE PROFILOMETER

Micromechanical property data is desired so that microsystems can be designed efficiently. However, traditional macroscale mechanical test methods are difficult to apply to microscale materials, due to the small size and fragility of the samples. Therefore, new microscale mechanical test methods are a focus of continuing interest and research [8-10].

Unfortunately, most of the work published to date describes test methods that are specific to a certain material, involve extensive fabrication procedures, are subject to errors, and/or require exotic test instruments. A new test method, called MAT-Test, which addresses all of these issues, was recently published [11, 12]. The name “MAT-Test” is an acronym for Materials Testing. MAT-Test achieves improvements in test quality through the use of a contact surface profilometer as the test instrument. This results in a test that is generally applicable to thin film materials, requires minimal test structure fabrication, is insensitive to potential test errors, and utilizes a test instrument (the profilometer) that is a ubiquitous, inexpensive piece of microfabrication laboratory equipment. Development of MAT-Test is ongoing, so the results presented here should be considered preliminary rather than definitive. Furthermore, the devices tested here are at the limits of the resolution of the test equipment. However, the results are instructive, both for the results of the test and for the test method.

A contact surface profilometer operates by dragging a small stylus across the surface of a sample while monitoring the height of the stylus. The stylus applies a constant force against the sample* as it follows the contours of the surface. The scan data that the profilometer records is the stylus height at each horizontal position. Plotting this scan data creates a two-dimensional profile of the surface of the sample. Surface profilometers are found in almost every microfabrication laboratory, where they are typically used to measure the thickness of deposited films.

### 3.1. The MAT-Test method

The MAT-Test test procedure is illustrated in Fig. 4. A contact surface profilometer stylus is scanned along the length of a suspended cantilever beam fabricated from the material under test (MUT). Because the stylus is applied to the sample with a constant force, the cantilever beam is deflected downwards. This deflection is reflected in the data trace recorded by the profilometer. This data set can be analyzed in combination with the geometry specifications of the test structure to determine the Young’s modulus of the MUT in a manner that is insensitive to potential errors in test structure fabrication, such as undercut of the cantilever root or residual stress in the MUT [11].

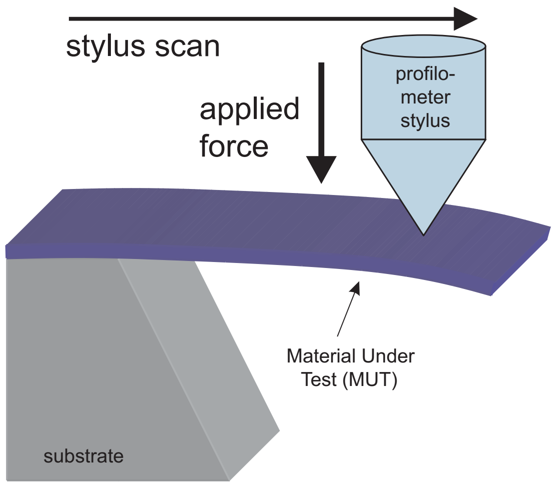


Figure 4. MAT-Test test procedure [11]

This test method is easy to perform and is widely applicable, as it can be used with any material system in which suspended cantilever structures can be fabricated. This applies to the most common material combinations used in microsystems currently, i.e., a thin film deposited on a substrate (e.g. silicon nitride on silicon). It can also be applied to more exotic materials, such as spin-coated polymers.

### 3.2. Results of SU-8 Tests

MAT-Test experiments were performed on the SU-8 cantilevers described in Section 2, using a Dektak 3ST contact surface profilometer, manufactured by Veeco, Inc. [13]. Figure 5 is a microphotograph of a cantilever being scanned in the Dektak.

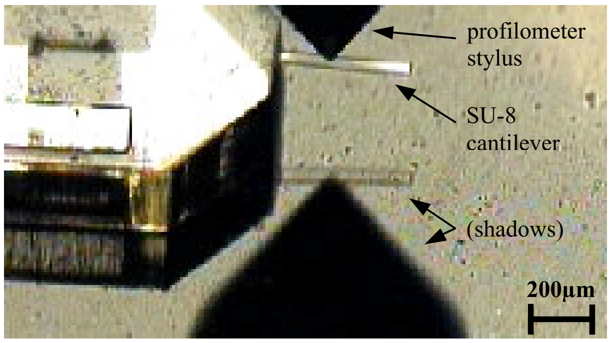


Figure 5. SU-8 Cantilever Test

The first requirement is to establish that the cantilever is being deflected only in its elastic region, and that no plastic deformation is occurring. Figure 6 shows the results of five successive measurements of the same cantilever plotted on the same figure. The sample orientation is that shown in Fig. 5, with the base of the cantilever at the left, and the sample was scanned from left to right. The small region of positive slope at the start of the cantilever is a topographical feature of the sample and does not represent bending of the cantilever. The measurements show no significant change from one to

* Not all contact surface profilometer mechanisms are capable of applying a constant force to the sample. Profilometers that cannot maintain a constant force are not suitable for MAT-Test.

the other, indicating that the material is not plastically deformed by the profilometer scan. Note that this procedure could be used to determine the yield stress of the material, simply by increasing the applied force until deformation is observed.

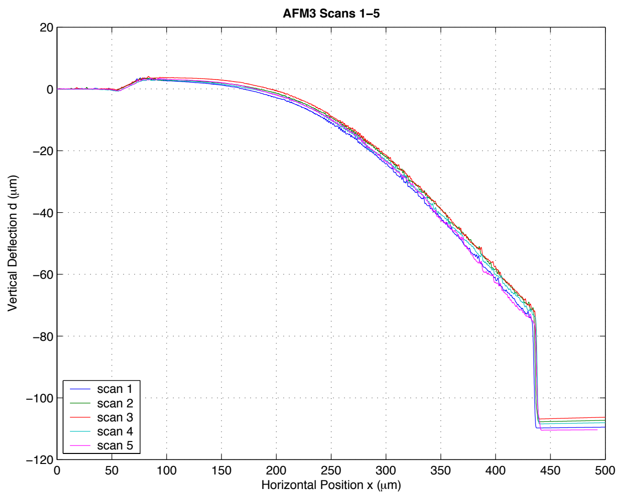


Figure 6. Repeated deformation of SU-8 cantilevers

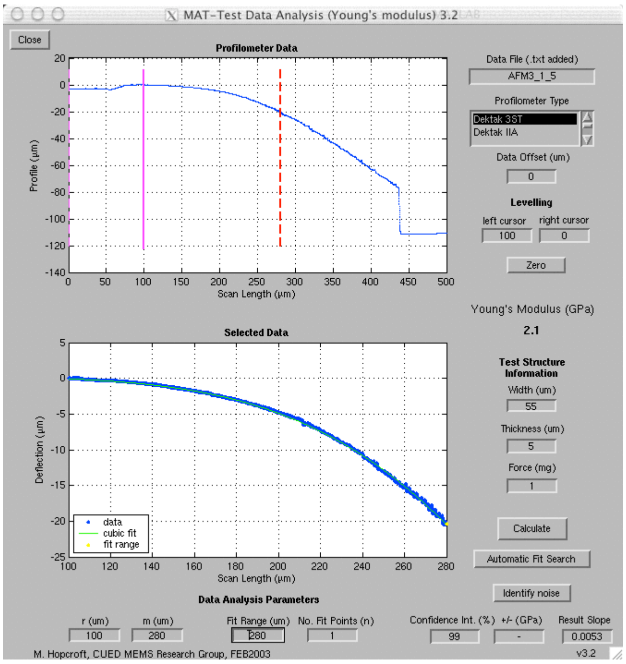


Figure 7. MAT-Test analysis software

Next, the data is analyzed. Figure 7 shows a screenshot of the MAT-Test data analysis software, which was written in MATLAB [14]. The software displays the profilometer scan data in the upper plot, and the operator selects the relevant region of the data for analysis, shown in the lower plot. In the case of the SU-8 cantilevers, this selection step is particularly important because the cantilevers are extremely compliant, so much so that the smallest force applied by the profilometer stylus causes the cantilever deflection to enter the large deflection regime. The most accurate analysis is achieved when the deflection of the sample can be accurately described by Euler small deflection:

$$d = \frac{FL^3}{3EI} \qquad (1)$$

where $d$ is deflection of the cantilever, $F$ is the applied force, $L$ is the length of the cantilever, $E$ is the Young's modulus of the cantilever material, and $I$ is the second moment of area of the cantilever cross-section. The Euler small deflection analysis yields acceptable results when the ratio of cantilever deflection to cantilever length, $d/L$, is less than approximately 0.1.

The average Young's modulus result from the SU-8 cantilevers using the MAT-Test technique was 2.7 GPa. It is not possible to give specific error bounds for this measurement without further investigation of the cantilever geometry.

## 4. MICROSCALE MECHANICAL TESTING II: MICROSCALE MECHANICAL TEST MACHINE

Static load bending tests on the SU-8 cantilever specimens from the same fabrication lot as those discussed in Section 3 were carried out using a specialized mechanical testing machine for micro-sized specimens, called MFT2000, which was developed at the Tokyo Institute of Technology. This test machine can apply both static and cyclic loads to micro-sized specimens, and tensile, compression and bending tests can be performed by changing loading and specimen fixtures. The load resolution of this testing machine is 10μN and the displacement resolution is 5nm. The loading position can be adjusted by a precision X-Y stage with a translation resolution of 0.1μm. Further details of the testing machine are described elsewhere [15, 16].

### 4.1. Results of SU-8 Tests

Bending tests on the SU-8 cantilevers were performed by loading the cantilevers at a fixed position and recording the resulting deflection. The loading position of the cantilever beam was set at 56μm from the fixed end of the specimen. Static load was applied to the specimen by a diamond tip with a radius of 5μm, which was connected directly to the actuator. Figure 8 shows the load-displacement curve obtained from loading the cantilever. A linear relationship between load and displacement was observed up to a displacement of 15μm. The bending test was stopped at a displacement of 50μm.

The load-displacement curve in Fig. 8 deviates from the linear relationship after a displacement of 15μm. Figure 9 shows a series of photographs taken during the bending test. As seen in Fig. 9(d), the position of the diamond tip appears to have slipped along the beam, and so it is thought that the deviation from the linear load-displacement relationship may be due to this slipping. It is interesting to note that the specimen was not broken even after a bending displacement of 50μm as shown in Fig. 9(d). Figure 9(e) shows the specimen after the bending test. The specimen exhibited slight plastic deformation after removal of the load and no cracking was observed with laser microscope inspection.

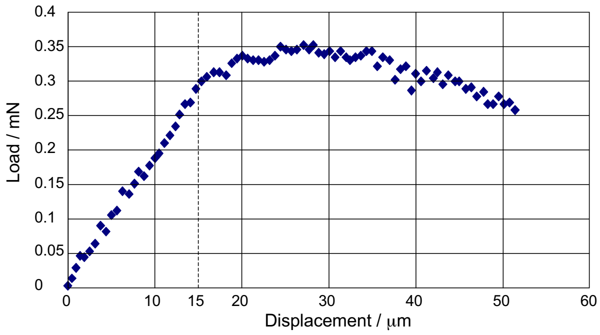


Figure 8. Load-displacement curve for SU-8 cantilever loading

The Young's modulus was calculated to be 1.9 GPa from the linear portion of the load-displacement curve of Fig. 8. As in Section 3, the measurement precision cannot be determined without precise measurement of the specimen dimensions.

## 5. DISCUSSION

An example application of SU-8 for AFM cantilevers was presented to illustrate the usefulness of alternative materials in modern MEMS design. SU-8 has a number of desirable material properties, and use of SU-8 is likely to increase for a broad range of MEMS applications, from cantilevers to fluid microchannels.

Examples of two different microscale material property test methods applied to SU-8 were also presented. MAT-Test uses a standard contact surface profilometer to perform a quick and accurate test that can be applied to a variety of materials. The MFT2000 test machine is a versatile instrument that can be used to perform a wide variety of mechanical tests on a microscale samples. The results of the Young's modulus tests with the two test methods compare favorably with each other, with results of approximately 2-3 GPa. These results are, however, somewhat different than previous results obtained using macroscale test methods of 4-5 GPa. This is not unexpected, as the behavior of materials at the microscale is often different from the macroscale. Furthermore, the material properties of many thin film materials vary considerably depending on their deposition and curing conditions.

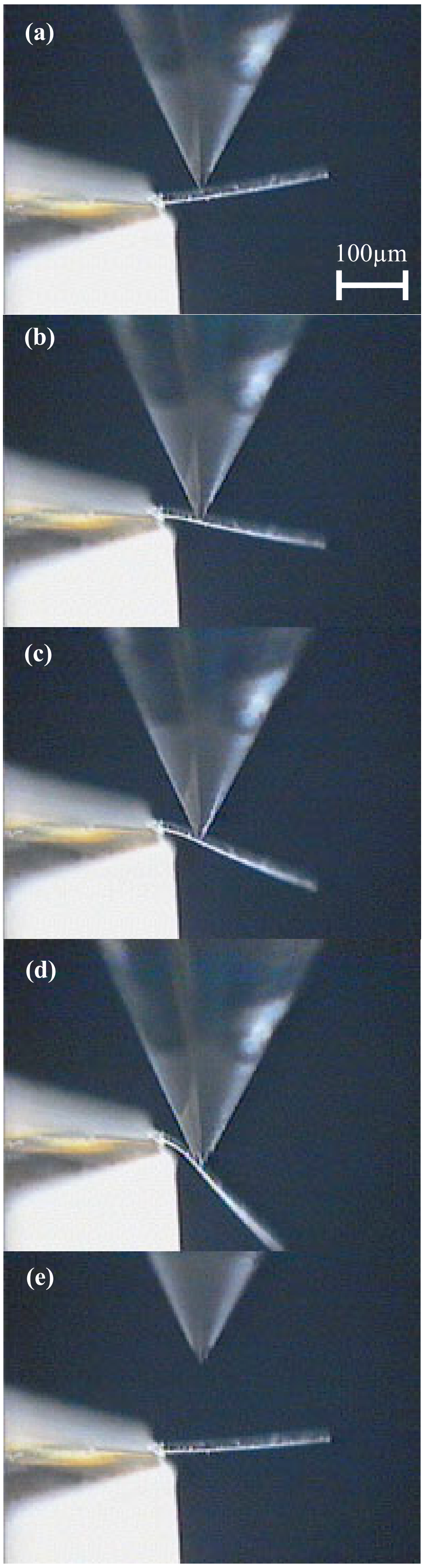


Figure 9. SU-8 cantilevers being tested
(a) before the test (b) 10 μm deflection (c) 20μm deflection (d) 50μm deflection; note that the stylus appears to have slipped along the beam to the right, as a consequence of the large deflection (e) after the test

Results such as these emphasize the need for reliable microscale material test methods for MEMS research and design. For example, the AFM cantilevers presented herein have a spring constant approximately half as stiff as intended, due to the use of macroscale test data in the design process. Microscale test methods must be introduced and certified as standards so that MEMS devices can be designed to known material specifications. This will enable widespread reliable, robust MEMS design for commercial products.

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