Measuring and Modeling Electrostatic Adhesion in Micromachines

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SUMMARY

We measure deformations of electrostatically actuated cantilever beams adhered to a substrate, and compare results to numerical simulations. Beams are peroxide treated and either supercritically dried or coated with octadecyltrichlorosilane (ODTS). In air with relative humidity (RH) of about 30%, measured deformations are consistent with numerical results when an effective insulator thickness of 14 nm is assumed. This value is a measure of the roughness of the substrate. Deformations are generally reversible for voltages up to 2V. With RH of 75%, deformations of supercritically dried beams are dominated by capillary rather than electrostatic forces. The ODTS-coated beams exhibit less effect from the capillary forces, as expected for a hydrophobic coating.

Keywords: Interferometry, Electrostatic Adhesion, Stiction.

INTRODUCTION

Devices such as microbridge displays [1], distributed microactuators [2] and zip actuators [3], have been proposed or are in commerical use. These devices rely on electrostatic forces to bring one surface into contact with another. Ideally, there is no chemical adhesive bonding between the surfaces in contact, and an insulating layer prevents leakage between the surfaces. Typically, a nitride or oxide layer will act as the insulating layer. However, the adhesion of the actuated beam to this layer may vary with humidity, causing unwanted changes in deflections, or worse constraining the beam to the substrate when voltage is relaxed. A possible method to avoid this susceptibility is to coat the devices with a hydrophobic layer such as ODTS [4]. Previously, we showed that measured deformations of adhered cantilever beams agree well with beam theory predictions [5]. Furthermore, a single beam attached over a long length can be a preferable specimen for measuring auto-adhesion (e.g. stiction) compared to sampling an array of beams of different lengths. The purpose of this work is to investigate how the deformations of cantilevers in contact with the substrate depend on electrostatic forces, coating and humidity.

EXPERIMENTAL

We have constructed an environmental interferometric microprobing station which enables us to measure static z-deflections of beams under powered-up conditions to about 10 nm accuracy. As seen in Fig. 1, the apparatus consists of an optical microscope fitted with a Michelson interferometric attachment on the objective lens. Out of plane deflections in beams give rise to fringes. Using green light at 547 nm, a full oscillation corresponds to 273.5 nm. Images taken from a CCD camera were analyzed on a Power Macintosh 7600/120 computer using the public domain program "NIH Image" available on the Internet by anonymous FTP from zippy.nimh.nih.gov. Using the linescan function, pixel intensity vs. pixel position data is obtained, and a computer program then converts the data into z-deflection vs. x-position data.

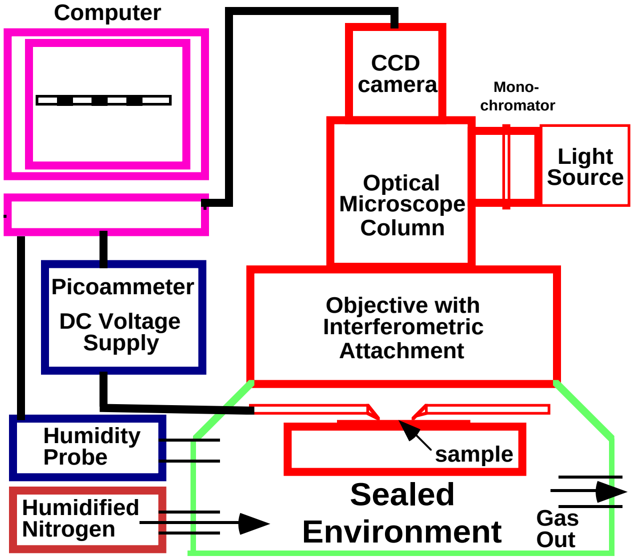

Fig. 1 Schematic of Environmetal Interferometric Microprobe Station

The measurements were conducted either in air or by environmentally isolating the microscope while flowing nitrogen bubbled through water into the chamber. RHs of 20-35% and 75% were respectively measured using a Vaisala HMP234 humidity probe.

The cantilever beam is schematically represented in Fig. 2 after ref. [6]. The thickness of the beam is t (2.4 µm here), the height of the step-up post is h (1.75 µm here), the displacement of the beam relative to the step up post is $z(x)$, and the beam length is L (varied from 600 to 1000 µm in 100 µm increments here). The angle which the beam makes with the substrate at its point of contact is θ, and the slope parameter m is defined by $\theta = m(h/s)$. The unadhered length is s. In Fig. 2 with 0V applied, deformation is due only to adhesion, and m=3/2 in Fig. 2a while m=0 in Fig. 2b. See ref. [6] for details and predicted deformations.

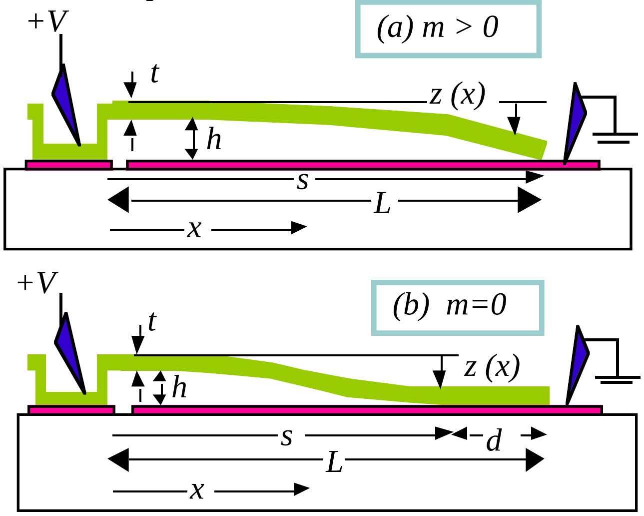

Fig. 2 Poly beam pulled in to poly pad
(a) Pulled-down beam, m>0.
(b) Pulled-in beam, m=0.

RESULTS AND DISCUSSION

(a) Results in Air

The m=3/2 condition is attained experimentally by first pulling the beam down from its unattached state at the pull-down voltage. Because beams were very nearly flat (1000 µm beams were curved up about 150 nm), the pull down voltage correlates well with theoretical predictions [7]. Because the beams were long (600-1000 µm), the voltage was small (2V-0.5V respectively) and minimal leakage current is measured after pull down. The voltage is then relaxed to 0V, and the beams remain adhered at their tip only because of the small pull-off force. This behavior for supercritically dried and ODTS-coated films was quite similar. From the 600 µm beam using Eq.(18) in ref. [6], we can calculate that the auto-adhesion of the surfaces is about 50 µJ/m^2, in reasonable agreement with ref. [8]. Measurements of $z(x)$ then agree well with predictions from ref. [6] for m=3/2 indicating that residual charges which may remain do not perceptibly affect the deformations. (For shorter beams, this sequence could not be applied. 500 µm long beams typically would pop off, while shorter beams required higher pull down voltage. Due to significant leakage, these would remain adhered at their tip only, and only large voltage changes induced further deformations.)

Beginning with the m=3/2 shape at 0V, voltage is gradually applied. The unadhered length s initially remains the same while m decreases. A typical deformed profile of a 600 µm beam with 1.0V applied is shown in the image of Fig. 3a. The pixel intensity data from the beam in Fig. 3a is plotted vs. x on the left hand axis of Fig. 3b. Three lines are plotted for the right hand axis of Fig. 3b. The two dashed lines, z (m=3/2) and z (m=0) are the beam theory in ref. [6] (no external forces applied).

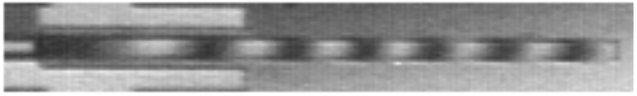

Fig. 3a Inteferometric image of a 600 µm beam subject to 1.0V and adhered only at its tip.

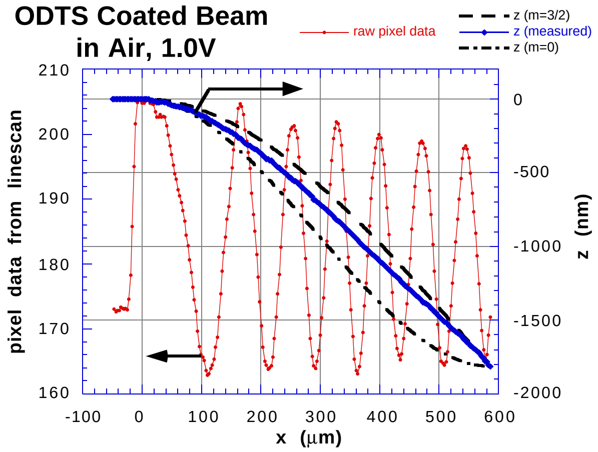

Fig. 3b Pixel data from linescan (left axis) and deformations (right axis) at 1.0V.

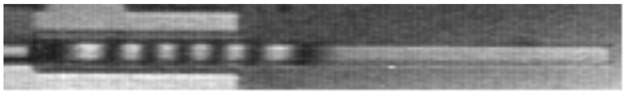

Fig. 4a. Optical inteferometric image at 1.8V.

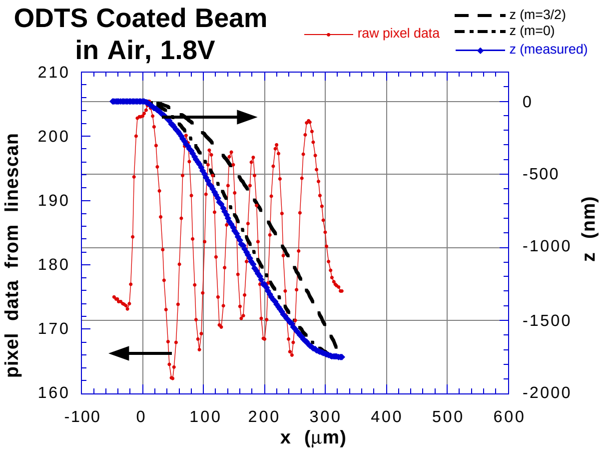

Fig. 4 Deformations at 1.8V.

Because the measured deformation, z (measured), is between these two lines, s has not yet decreased. At a slightly higher voltage of 1.16V, the beam pulls in to an m=0 condition. The value of s rapidly decreases to 400 µm. This is because of the $1/(h-z)^2$ increase near s in electrostatic force as the beam approaches the substrate. An instability results similar to the instability associated with pulling down a beam. The post critical equilibrium length of 400 µm is dependent on the beam stiffness which increases with $1/s^3$. With further increments in voltage, s

continues to decrease. Deformations at 1.8V are shown in Fig. 4. In Fig. 4b, the value of m=0, but the deformations are below the simple calculation represented by z (m=0) from ref. [6] which assumes no external forces. Only small differences in deformations were noted between supercritically dried beams and ODTS coated beams.

(b) Numerical Calculations

Because the external forces due to the electrostatic field depend on the deformation of the beam, an iterative technique is required to calculate the equilbrium state. While the problem is in principle three dimensional, relatively accurate results are attainable using a one dimensional model for the forces [7]. Here, we have used the finite element code ABAQUS [9] and applied the simple electrostatic force law at each node of the beam. In all calculations, the Young's modulus E=140 GPa, t=2.4 µm, h=1.75 µm, and the dielectric constant of air are used. Chemical adhesion is ignored, as will be justified later. Since the minimum insulating gap thickness g_{min} is unknown, the deformed shapes are calculated for different g_{min}.

We find best agreement with the measured deformations at g_{min}=14 nm. A free slip condition was assumed (a no slip condition was was also analyzed with no appreciable difference). Fig. 5 shows the comparison between measurements and calculcations at 1.4, 1.7 and 2.0 V. Possibly because of step-up post compliance, the measured deflections for small x are slightly greater than the calculated. Overall, the fit appears satisfactory. The deformations are very sensitive to the value of g_{min} assumed - at 17 nm, the data clearly did not match calculations.

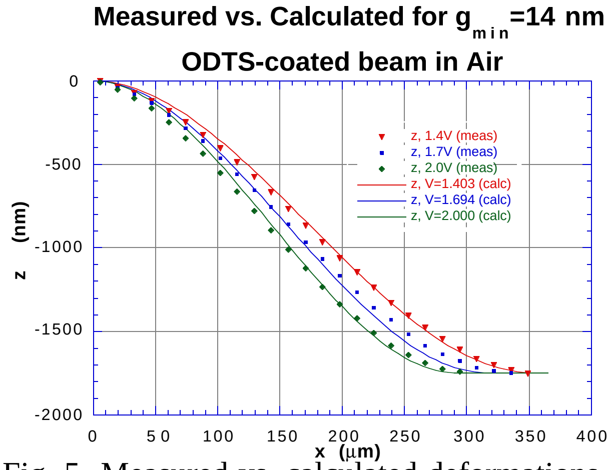

Fig. 5 Measured vs. calculated deformations at 1.4, 1.7 and 2.0V.

What is the expected value of g_{min}? The thickness of the oxide layer is about 1nm, while the thickness of the ODTS is about 2 nm. This will give a 6 nm separation (counting both beam and substrate). A contribution due to roughness, which prevents close approach of the surfaces, is expected as well. Roughness was measured by atomic force microscopy on both the underside of the polysilicon beam as well as on the polysilicon pad. Line profiles over 10 µm lengths indicated that the roughness, as defined by the difference in the maximum and the minimum heights, was 10 nm for each surface. Thus, the average separation should be about 10 nm assuming peaks contact peaks. Then, the expected g_{min} is 16 nm. Because the numerical result g_{min}=14 nm is close to this estimate, we can say that the z deformations are in effect a sensitive measure of the roughness.

Knowing g_{min}, an approximate adhesion due to electrostatics can be calculated from $\varepsilon V^2/2g_{min}$, where ε is the dielectric constant of air. At 1.2V, we obtain 455 µJ/m^2. Because this value is much larger than the 50 µJ/m^2 for the adhesion between the layers, our assumption of ignoring this adhesion in the deformation calculations is justified. At larger voltages, this assumption improves.

(c) Reversibility Tests in Air

Experiments were carried out to test the reversibility of the crack growth. The beam voltage was increased monotonically, and then reset to 0V. Fig. 6 shows an example of the deformations measured.

While results were somewhat variable, a general trend did appear. Up to 2 to 3 volts, s rapidly increased to the end of the beam once the

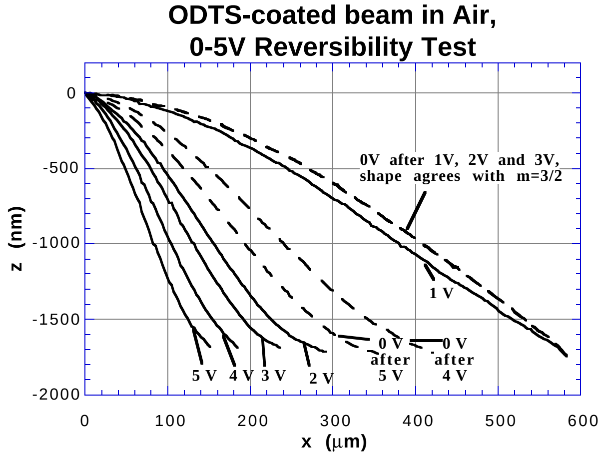

Fig.6a Dashed lines measured at 0V after 1-5V voltage applied.

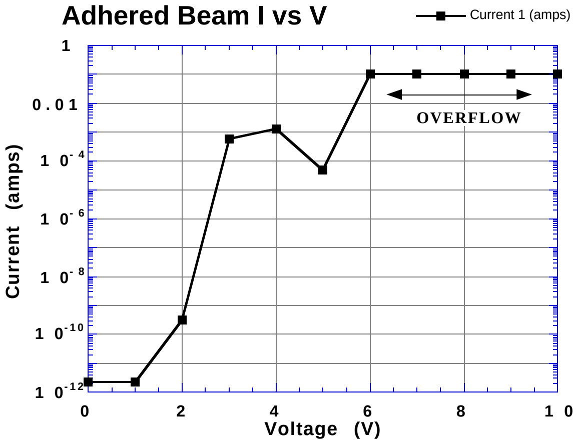

Fig.6b Current vs. Voltage measurements. Significant current flow begins after 2V.

voltage was relaxed, as seen in Fig. 6a. This would occur within a few video frames. Above 2 volts, significant current flow at the microamp level or above was observed as seen in Fig. 5b. At or soon after this onset, the crack usually did not propagate back to the end of the beam when the voltage was relaxed. In air, both the reversibility and the current breakdown data were qualitatively similar for the supercritically dried and the ODTS coated beams.

(d) Effect of Humidity

The reversibility test was next conducted in the high humidity environment of 75% RH. Deformations for the super critically dried films were now completely irreversible. Even for a 1000 μm long beam with a low pull down voltage of 0.7V, *s* immediately decreased to 200 μm. Upon relaxing the voltage, no change in *s* was observed. Indeed, at 0V, *s* was observed to gradually decrease to a length of 100 μm, commensurate with an adhesion energy of 100 mJ/m^2, as might be expected from the surface tension of water.

Reversibility of ODTS coated beams was also affected by the 75% RH environment. Because the ODTS forms a hydrophobic coating, humidity should have a reduced effect. Indeed, the effect on *s* was not as severe as in the supercritically dried case. Deformations were controlled by the voltage applied, similar to the observations in air. However, upon release of voltage, no increase of *s* to the beam tip was observed. We believe that the ODTS films should exhibit better behavior, and will continue this testing.

CONCLUSIONS

The electrostatic adhesion of polysilicon beams to a polysilicon substrate was investigated. These results are for beams with only a native oxide layer or with an additional 2 nm ODTS coating. For long beams, pull down voltage is low, so that leakage is prevented and electrostatic calculations satisfactorily model measured deformations. In air, the presence of the ODTS coating made only minor differences on the deformation behavior and leakage current. To model the deformations, a minimum gap of 14 nm was required. This correlates well with the roughness of the polysilicon as measured by atomic force microscopy. In air, deformations were generally reversible with voltage from 0 to 2V. When the beams were placed in a wet environment, the deformation of supercritically dried samples became dominated by forces on the order of the surface tension of water. ODTS-coated beams were not as severely affected.

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