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Contents

Nanoindentation technique for characterizing cantilever beam style RF microelectromechanical systems (MEMS) switches*

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Abstract

A nanoindentation technique was used to mechanically actuate a radio frequency micro-switch along with the measurement of contact resistance to investigate its applicability to characterize deflection and contact resistance behaviors of micro-sized cantilever beam switches. The resulting load–displacement relationship showed a discontinuity in slope when the micro-switch closed. The measured spring constants reasonably agreed with theoretical values obtained from the simple beam models. The change in contact resistance during test clearly indicated micro-switch closure but it did not coincide exactly with the physical contact between two electric contacts due to a resistive contaminated film.

1. Introduction

The great stride in micro-fabrication techniques in recent years has helped microelectromechanical systems (MEMS) to become a rapidly growing and important technology. Radio frequency (RF) MEMS switches, in particular, have been developed to take advantage of superior RF performance over solid-state devices.[1] One key area during the application of a metal contact micro-switch is the availability or development of models or analyses for contact resistance and contact force to characterize their performance.[2–4] Therefore, it is also important to have or to develop simple tools for measuring micro-switch behavior to verify analytic models.

Nanoindentation technique has emerged as a powerful tool for characterizing small-scale mechanical behavior. Using this technique, mechanical properties (i.e. elastic modulus, hardness and fracture toughness) can be determined from the simple indentation load–displacement relationship at the micro- or nano-scale without imaging the indentation.[5] Further, the load–displacement relationship from a nanoindentation test can give valuable information about mechanical behavior of a small-scale device (i.e. bending test of micro-beam).[6–8] Thus, the nanoindentation technique has been adapted in many MEMS studies as an ideal tool for small-scale characterization.[9] In the present study, the nanoindentation technique was employed to mechanically actuate a micro-switch where the load–displacement relationship was simultaneously monitored along with contact resistance. Then, the results were compared with analytical solutions from a simple beam model to ascertain the applicability of this nanoindentation technique for investigating the performance of micro-switch devices.

2. Design and analysis

Figure 1 shows the RF MEMS switch used in the present study. This cantilever-style micro-switch with gold–gold (Au–Au) electric contact was fabricated on a highly resistive sapphire substrate using a custom fabrication process.[4] The cantilever beam is 250 µm long and 75 µm wide. The cantilever beam thickness was measured at 10 different locations, during device fabrication, across a 7.62 cm wafer using a Tencor P-10 surface profiler. The beam thickness, i.e. electroplated gold layer, varied from approximately 4 µm at the wafer's center to approximately 5 µm at the wafer's edge. The beams tested in this study were initially flat with no curling due to residual stress. The drive electrode and the lower electric contact are planar but the upper electric contact consists of two hemispherically shaped dimples. The diameter of each upper contact dimple is approximately 8 µm and the rounded dimples extend approximately 1 µm from the surface of the beam. It should be noted here that the upper contact dimples are not exactly hemisphere. The term 'hemisphere-shaped' is used to emphasize that the dimples are not flat-bottomed. The gap between the bottom of the beam and the lower electrode is 2.5 µm and the distance between the upper contact dimples and the lower contact is 1.5 µm. These distances are the average of ten measurements across a 7.62 cm wafer, measured using a Tencor P-10 surface profiler (standard deviation ~0.1 µm). The elastic modulus of the cantilever beam material (i.e. electroplated Au) was determined to be 80 GPa by nanoindentation tests.[10] A description of the fabrication process can be found in previous studies.[4,10]

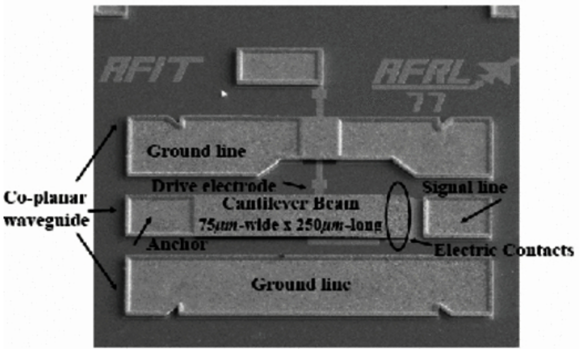

Figure 1. SEM image of an RF MEMS micro-switch.[10]

In actual operation, the switches are actuated electrostatically using the drive electrode. The initial closure of the micro-switch occurs when the micro-switch's actuation voltage reaches the pull-in voltage. At pull-in, electrical contact as well as physical contact is first established between upper and lower electric contacts, with the minimal contact force. As the actuation voltage increases, the contact area increases due to the material deformation caused by the increased contact force, which results in lower contact resistance. When the switch was electrostatically actuated, the measured pull-in voltage was approximately 58.6 V and the measured contact resistance at that instance was 4–6 Ω. The nanoindentation test simulated actual micro-switch operation mechanically as the indenter tip, positioned at the center of the beam, pushed the micro-switch's cantilever toward the drive electrode. This mechanical actuation of the micro-switch can be modeled using simple beam deflection models as described below.

2.1. Beam model

The micro-switch was modeled as a simple beam with the assumption that the micro-switch was flat. Prior to micro-switch closure, it was modeled as a beam with a fixed end at $x = 0$ and a free end at $x = l$ with a load F acting on an intermediate location at $x = a$ as depicted in figure 2(*a*). The deflection of the beam (*d*) under the load (i.e. at $x = a$) is

(1)

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

where a is the load position, E is the elastic modulus and I is the area moment of inertia.

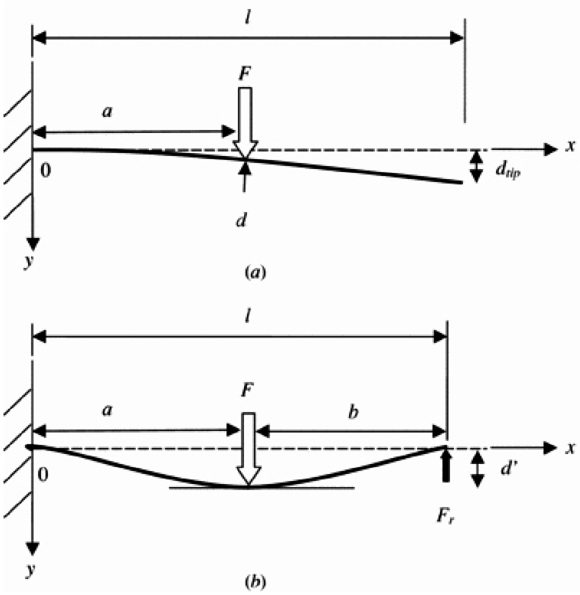

Figure 2. (*a*) Cantilever beam with a fixed end at $x = 0$ and a free end at $x = l$ with a load F acting at $x = a$. (*b*) Propped cantilever beam with a fixed end at $x = 0$, and a simply supported end at $x = l$ with a load F acting at $x = a$.

The micro-switch, after closure, was also modeled as a beam with a fixed end at $x = 0$ and simply supported end at $x = l$ with a load F acting at an intermediate location at $x = a$, as shown in figure 2(*b*). In reality, the end position at $x = l$ was slightly lower than the fixed position at $x = 0$ due to the anchor of the micro-switch but this was not accounted for in the present analysis since the gap between the upper contact dimples and lower contact electrode of the micro-switch was much smaller (~2 µm) than the length of the micro-switch beam (250 µm). The beam deflection of the beam under the load (i.e. at $x = a$) is

(2)

$$d' = \frac{-Fa^2 b}{12l^3 EI}[3l(b^2 - l^2) + a(3l^2 - b^2)]$$

where b is the length between the load position and the end of the beam. The reaction force F_r at the simply supported end is

(3)

$$F_r = \frac{Fa^2}{2l^3}(3l - a).$$

This reaction force is equal to the contact force (F_c) while the micro-switch is closed.

Further, the beam's spring constant k is defined using Hooke's law:

(4)

$$F_s = kd$$

where F_s is the mechanical restoring force of the beam. In equilibrium, spring constants at the load position can be obtained from equations (1) and (2) such that

(5)

$$k_1 = \frac{3EI}{a^3}$$

for an open micro-switch and

(6)

$$k_2 = \frac{12l^3 EI}{a^2 b[3l(b^2 - l^2) + a(3l^2 - b^2)]}$$

for a closed micro-switch.

2.2. Contact resistance model

The contact resistance from a closed micro-switch can be defined as

(7)

$$R = R_{\mathrm{c}} + R_{\mathrm{cf}}$$

where R_{c} is a constriction resistance due to contacting surface topography and R_{cf} is a contaminant film resistance. Contaminant films are normally present on all electric contact surfaces and thus should be mechanically or electrically cleaned prior to use. Assuming that current flow is only due to diffusive electron transport, the constriction resistance can be modeled analytically as[11]

(8)

$$R_c = \frac{p}{2r_{\mathrm{eff}}}$$

where ρ is the resistivity and r_{eff} is the effective radius of a circular contact area. If a contact material is plastically deformed by the applied contact force, r_{eff} becomes a function of contact force, resulting Holm's contact resistance equation:[11]

(9)

$$R_c = \frac{p}{2}\sqrt{\frac{H\pi}{F_c}}$$

where H is the contact material's hardness and F_{c} is the contact force.[11] This equation clearly shows that contact resistance decreases as the contact force increases.

3. Experiments

A direct measurement of micro-switch cantilever beam deflection was performed using a Nanoindenter XP (MTS, Oak Ridge, TN) using an experimental setup as shown in figure 3. The displacement and load resolutions of the equipment used in the present study are 0.01 nm and 50 nN, respectively. Prior to the test, the indenter tip was aligned over the target location on the micro-switch cantilever beam using an optical microscope. The deflection test began with the indenter tip approach 'segment' which brought it to the target point on the cantilever beam. The 'segment' is a part of the pre-programed nanoindenter software. In the approach segment, the surface of the cantilever was searched by sensing a change in the measured stiffness (i.e. slope of the load–displacement relationship). Since beam deflection could be initiated by a very small load (0.1 µN), a very small change of stiffness, about 2, was used to determine the cantilever beam's surface before starting the indentation load segment. This high sensitivity to stiffness change often resulted in false predictions of the cantilever beam's surface. These errors were corrected during data reduction by assuming that indentation load increased with increasing displacement after the contact between the indenter tip and the cantilever beam's surface. After the surface of the target point was determined, load was applied at a constant rate of 0.7 µN s^{-1} until it reached the maximum load of 0.1 mN. After a 2 s hold period at the maximum load, the unload segment proceeded until 90% of the maximum load was removed, at which time a second hold segment (10 s) was initiated for thermal drift correction. The test was completed with the final unload segment which removed the applied load entirely.

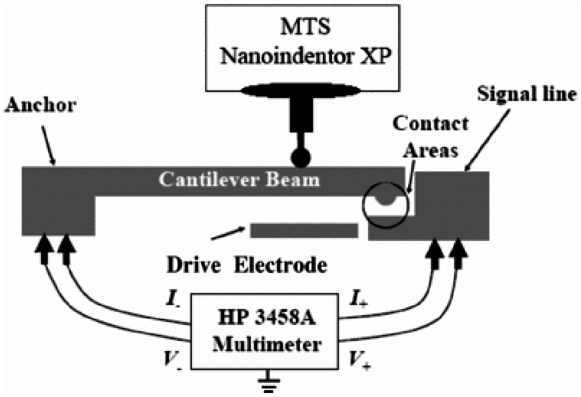

Figure 3. Experimental setup for the nanoindentation test on the micro-switch cantilever beam. A multimeter was also used to measure contact resistance.

A custom made, spherical diamond tip with a nominal radius of 25 µm was used as an indenter tip to minimize the effect of indentation of the tip into the cantilever beam surface. However, a shallow indentation due to the indentation of the tip into the soft electroplated Au still occurred during the test, especially after the micro-switch closure. The indentation depth into the electroplated Au as a function of load was determined by performing an indentation test on the unused portion of the micro-switch's co-planar waveguide (figure 1), which was made of the same material as the beam (i.e. electroplated Au), using the same test parameters as those of the deflection test. These results were then used to correct the data from the deflection tests by subtracting indentation depth from the measured displacement during the deflection test at each applied load level. The manufacturer of Nanoindenter XP (MTS, Oak Ridge, TN) did the calibration of load and displacement. However, the calibration was re-confirmed by the authors through indentation tests on the standard silica, using a Berkovich tip with a well-defined area function. These calibration indentation tests resulted in a consistent and expected elastic modulus of 72 GPa over indentation depths ranging from 20 to 2500 nm. Six micro-switch test specimens (i.e. individually wired micro-switches) were prepared by wire bonding the anchor and signal lines to a printed circuit board test fixture. The leads from the test fixture were connected to an HP3458A multimeter which was used to measure the closed switch resistance while actuating the device with the nanoindenter. Contact resistance was found by subtracting the measured beam resistance (1.0 Ω) from the closed switch resistance measurements. The resistance was measured using an HP3458A multimeter in a 4-wire (i.e. 4-point) configuration. The open circuit voltage of the multimeter was approximately 8.2 V and the current was limited to approximately 10 mA.

4. Results and discussion

Six deflection tests were conducted on six different pristine devices. Figure 4 shows a typically measured load and displacement relationship, which shows a bilinear behavior. The load was applied at 180 µm away from the anchor (i.e. *a* = 180 µm in figure 2). This figure also shows the corrected displacement after subtracting the indentation depth into the surface of the cantilever beam from the total measured displacement. Analytical load versus displacement using spring constants from the aforementioned beam models (k_1 and k_2 from equations (5) and (6), respectively) are also included in the figure to compare with the experimental measurement. A beam thickness of 4.3 µm, which was the average thickness of six beams estimated from SEM micrographs, was used for calculating the spring constants. The standard deviation of beam thickness was about 0.3 µm. From zero to approximately 1.42 µm displacement, the cantilever beam deflected through an air gap as the indenter tip pushed the cantilever beam downward. The measured spring constant (i.e. slope of the load–displacement curve obtained from the linear approximation) was about 12 N m^{-1}. At 1.42 µm, the micro-switch's dimples touched the lower electric contact causing the dramatic increase in the slope of the load curve. The measured spring constant after micro-switch closure was about 207 N m^{-1}. These two values were lower than the spring constants calculated using the beam models: $k_1 = 20$ and $k_2 = 318$ N m^{-1} for open and closed micro-switches, respectively, as shown in figure 4. When indentation depth of the tip was subtracted from the measurements, the 'corrected' load and displacement relationship, in figure 4, for the 'open' micro-switch did not show a noticeable change due to the lower values of applied load, while the measured spring constant for the 'closed' micro-switch increased significantly to 261 N m^{-1}, which agrees reasonably with the analytical counterpart, k_2. The experimental values of k_1 and k_2 are the average of the six measurements. The standard deviations for k_1 and k_2 values were 1.2 and 11.4 N m^{-1}, respectively.

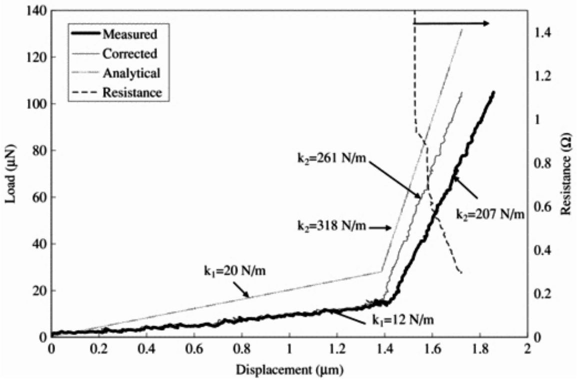

Figure 4. Analytical and measured load versus displacement of the indenter tip along with contact resistance versus displacement.

Overall, the measured spring constants were reasonably close to the calculated spring constants suggesting that the nanoindentation technique is an adequate and useful tool to characterize deflection behavior of micro-switches. Further, it is to be noted that the load–displacement curve for the 'open switch' condition in figure 4 is not linear but slightly curved in the very low load range. In addition, a sudden surge of load is observed right after the indenter tip touches the beam's surface. This might be due to the instability at the instant of first contact. After the indenter tip comes into contact with the beam's surface, it needs a little more load to start bending of the cantilever beam which could cause a surge in indentation load as well as nonlinearity in the very low load range in figure 4. Eventually, the load versus displacement curve becomes stabilized and shows a linear relationship after displacement of 0.2 µm. The difference in spring constants obtained from experiments and analyses might be attributed to several factors such as the resolution of nanoindenter load and displacement (especially at their lower values), uncertainty in the exact indentation position on the cantilever beam, overestimation of anchor stability, variations in the mechanical properties of the material and variations in micro-switch geometry (i.e. gap thickness, beam thickness, etc). In addition, the indentation behavior (indentation depth versus applied load) on the cantilever beam surface could be different from that of the co-planar waveguide which could also result in error. Direct measurement of the indentation depth resulting from tip penetration into the beam surface by techniques such as atomic force microscopy could significantly reduce this difference.

The measured contact resistance was used to verify micro-switch closure during the deflection test. The measured contact resistance during a typical nanoindentation test is also shown in figure 4, and it does not coincide with the micro-switch closure, which is indicated by the drastic slope change in the load–displacement curve (at displacement = 1.42 µm). Thus, the Ohmic contact between upper and lower electric contacts did not occur exactly when the micro-switch closed. This might be due to a contaminant film layer formed on the surface of the electric contacts. It is widely known that gold readily absorbs hydrocarbons, with oxygen, nitrogen and carbon, forming an insulating contaminant film layer (typically 2–4 nm thick) on the surface.[12,13] Therefore, actual contact resistance is affected by both contaminated film and surface topography as expressed in equation (7).

Contact force can be calculated using equation (3) as a function of applied load. However, an indentation load of ~16 µN was initially applied before the first contact between the upper and lower electric contacts as shown in figure 4. Thus, this amount of load was subtracted from the indentation load for the applied load *F* in equation (3), which ensured zero contact force and zero applied load when the first contact occurred. Figure 5 shows the calculated contact force, and measured contact resistance and displacement. It can be seen that the first Ohmic contact occurred at a contact force of 11 µN. This indicates that the contaminant layer might have ruptured after the application of contact force of 11 µN. After Ohmic contact was established, contact resistance gradually decreased with the increase in contact force due to the effect of constrictive resistance as shown in equation (9). A more systematic investigation is needed to characterize the complete contact resistance behavior (e.g. the minimum contact force to establish Ohmic contact); however, the present study shows that the nanoindentation method could be used for this purpose also.

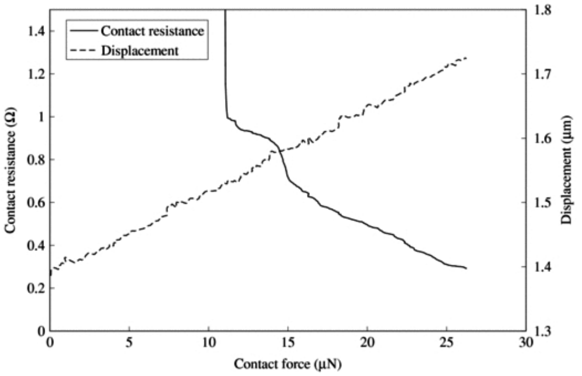

Figure 5. Contact resistance and displacement as functions of contact force.

5. Conclusions

A nanoindentation technique was utilized for the direct measurement of micro-switch cantilever beam deflection. Results of the nanoindentation test clearly showed two different regions, open and closed micro-switch. The measured spring constants from the indentation tests were reasonably close to those calculated using the simple beam models. The measured contact resistance does not coincide exactly with the closure of the micro-switch implying the existence of a contaminant layer. The result of the present study, however, clearly shows the capability of the nanoindentation technique to characterize the mechanical behavior of MEMS switches along with their contact resistance behavior.

Footnotes

*The views expressed in this paper are those of the authors and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the US Government.

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