A Technique for Force Calibration MEMS Traceable to NIST Standards

K. Abbas and Z. C. Leseman*
University of New Mexico, Albuquerque, NM
*Corresponding Author: MSC01-1150
Albuquerque, NM 87131: zleseman@unm.edu

ABSTRACT
Characterizing the mechanical properties of materials and biological systems at the nanoscale requires accurate measurement of forces on the order of 10’s of μN and less. Many times custom fabricated MEMS actuators and load cells are employed to apply these forces. Force response of these devices may be very different from their anticipated response due to fabrication induced effects. This makes it necessary to develop a method for their calibration that can be traced back to the National Institute of Standards and Technology (NIST). Due to the scale of the measurements and size of the instrumentation, calibration of nanoscale devices presents a new challenge in metrology. We have developed a novel method to calibrate a MEMS actuator with force resolution on the order of 1 μN using the tried-and-true deadweight method, but on the microscale. Calibrations are performed by suspending weights (traceably weighed sapphire spheres) from the MEMS device using the surface tension of water. The displacement was measured by measuring changes in capacitance and verified using a co-fabricated vernier. Measurements have been made using this method. Comparisons between our traceably calibrated force–displacement curves to a non-linear theoretical prediction, errors as great as 29% are revealed.

1. INTRODUCTION
Measurement of small forces (fN to nN) are the cause of numerous scientific breakthroughs in the last few decades. The vast majority of force measurements made below a µN are for the purpose of determining material properties. Examples are: measurement of single ligand-receptor interactions (~fN–pN) using the Surface Force Apparatus (SFA) [1], measurement of the mechanical properties of nanostructures (nN–mN) using Nano / Microelectromechanical Systems (NEMS/MEMS) [2-4], and a plethora of measurements have been made on the range of pN to nN using the Atomic Force Microscope (AFM). These measurements are becoming increasingly common, yet there is no traceable method of calibrating this full range of forces [5].

Traceable force calibrations are necessary to allow for the measurement of the mechanical properties of materials. More specifically, it is essential that measurements of mechanical properties be made using standardized methods with International System of Units (SI) traceable equipment. Without standardized testing methods and SI traceable equipment, bridges and building would fall and pressure vessels would explode as a result of improper design.

Consider the elastic modulus of gold, an element that is particularly important to the semiconductor industry. The bulk value, measured using standard methods and SI traceable equipment is 77 GPa [6], whereas samples with cross-sectional dimensions under 1 micron have values that vary considerably. For example, Wu et al. report values for elastic moduli of gold between 45 and 107 GPa [7], while Espinosa reports that \( E_{\text{gold}} \) is “consistently” between 53-55 GPa [8], and Leseman et al. found that the \( E_{\text{gold}} \) was 76 GPa [2].

It may be that all measurements were correct, but in order to remove all doubt use of standard testing methods and SI traceable equipment should be undertaken. Again, shrinking dimensions to the nanoscale will change the behavior of materials and systems, thus establishing standard testing methods and utilizing SI traceable equipment with proper force resolution is necessary. Because of the vast number of different methodologies of material growth, and geometries to which they conform, it will be some time before standard testing methodologies are developed for every material type and geometry. Therefore, because of the ingenuitive growth methods for materials, it can only be asked that researchers’ equipment be SI traceable and not force them to conform to standard testing methodologies. This is the more realistic and attainable short-term goal. Therefore for the purpose of this study two comb drive actuators with different spring elements were fabricated and calibrated...
by employing a recently developed method traceable to NIST standards [9]. Various parameters responsible for
the deviation of their response from their modeled response were identified.

2. EXPERIMENTAL SETUP
The calibration setup consists of two components, the MEMS actuator mount and the alignment setup. The
actuator mount is prepared by cleaving the substrate just below the lamp-shade shaped feature on the actuator.
The actuator is then carefully adhered to a glass microscope slide using double sided adhesive tape. In order to
measure the capacitance change between the comb fingers wirebonds are made from the bonding pads on the
actuator to the copper tape on the glass, Figure 1. The leads from the Agilent 4980A precision LCR meter were
later connected to the mounted actuator.

![Connection to LCR meter](image1.png)

**Figure 1.** MEMS actuator mounted on the glass slide

The alignment setup consists of set of precision linear translation stages and a goniometer, Figure 2. The
actuator was mounted onto a fixture that translates in the z-direction with a goniometer that allows for rotation
around the x-axis. The alignment of ball lenses was carried out by mounting them on another set of x-y linear
translation stages. A tube microscope with a CCD camera was also mounted on a separate set x-y-z linear
translation stages for the ease of observation. An observation microscope with a CCD camera is mounted on
separate x-y-z stages which makes it independent from the rest of the setup. The complete setup is shown in
Figure 3.

![Goniometer](image2.png)

**Figure 2:** Glass slide mounted on the goniometer and independent linear stage for movement in z-direction
3. PROCEDURE
Calibration of the actuators is accomplished by recently developed calibration technique [2, 9]. In order to calibrate known weights are hung from the portion of the actuator that extends beyond the cleave line of the wafer. After hanging the weight the change in capacitance between the comb fingers is measured with the LCR meter. Capacitance measurement provides displacement measurements with a tolerance of ±100nm. Hanging the weights, not surprisingly, requires extreme care. The weight is first properly aligned to the load cell using linear translation stages and goniometer. Weights were adhered to the load cell by using "secondary forces" and adhesives.

The calibration weights are commercially available sapphire ball lenses. These ball lenses are manufactured to tight specifications that allow great confidence in the weight of each sphere. The manufacturer’s specification for density, \( \rho \), is 3.98 ± 0.01 g/cm\(^3\). Tolerances on all diameters was ±2.54µm. Independent verification was performed on several samples, through the use of a precision balance that is traceable to the National Institute of Standards and Technology (NIST), and it was found that all samples tested fall within the manufacturer’s specifications.

To attain a centrally loaded structure, proper alignment between the actuator and the ball lenses is necessary. This was accomplished through the use of three linear translation stages and a goniometer (Figure 2). The actuator was mounted onto a fixture that translates in the z-direction with a goniometer that allow for rotation around the x-axis (axis perpendicular to the plane of the die). The ball lenses were mounted onto a custom stage that allowed for the rigid temporary attachment of the ball lens to the x–y linear translation stages. Upon proper alignment of the actuator and ball lens to gravity the ball lens was adhered to the load cell.

A non-linear force–displacement response for the fixed-fixed beam structure was anticipated, thus a range of weights was hung from each load cell to capture the load cell’s non-linear response. For ball lenses measuring, 300 and 500 µm in diameter, it was possible, when the humidity was relatively low, to attach the balls using static electricity. When the humidity was relatively high, it was possible to attach the balls using water menisci formed by the condensed water from the humidity. Figure 4 shows an optical micrograph of a 790 µm sapphire ball lens attached in this manner to the load cell. Images of spheres attached by static electricity are similar. Detachment of these smaller spheres was possible through the use of surface tension. A droplet of water was placed onto a substrate and the sphere was brought near. When the sphere was placed into contact with the water, the water quickly pulled the ball from the actuator without damage.
At the extreme end of our load range the large diameter spheres (1000 µm, 1500 µm) were attached using photoresist as an adhesive. These spheres were attached by dipping the load cell’s tip into a droplet of photoresist Figure 5. The photoresist wicked into the load cell’s specially designed ‘lamp-shade’ tip, this ‘wet’ tip was then lowered into contact with a large diameter sapphire sphere. Solvents quickly escape the small volume of resist needed to adhere the ball lens to the load cell, especially under the intense light of the microscope. It was possible to detach the spheres by vibrating the load cell. This was done at some risk though, as some devices were damaged in this process. An alternate method of removal of the ball lens and photoresist was performed by placing a dish of acetone under the load cell and ball lens assembly. The acetone vapor quickly weakens the positive photoresist because of the large dose of light it has received from the focused light of the microscope. Submersion of the ball lens and device was not necessary for ball lens removal.

It should be noted at this point that the weight of the member from which the weights hang and the liquids used for attachment never total to greater than 0.1% of the minimum weight hung from the load cell. Therefore, this additional weight can be safely neglected.
4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Compressive Residual Forces
After the fabrication was completed, physical inspection of the wafer was conducted under the optical microscope. Buckling was observed on almost all of the flexure beams. It is believed that this buckling is due to the compressive residual forces. These residual forces could not have been induced during the device fabrication due to lack of high temperature processing. These forces are believed to be intrinsic to the wafer itself, induced during its production perhaps during the oxide growth or bonding with the handle layer.

In order to quantify the buckling several strain gauges were purposefully designed on the masks. It was observed that these compressive residual forces vary from location to location on the wafer and hence buckling on the beams depended on the location of the device on the wafer. These strain gauges consisted of fixed-fixed beams of various lengths with a vernier at the center, the point that would be point of inflection after the buckling. It was observed that the deflection on 800µm beam (the same length as that on the fixed flexure) was approx 1.5µm near the edges of the wafer and approx 5µm at the centre of the wafer. Figure 6 below shows the buckled strain gauges at the center of the wafer. In an unbuckled beam both the verniers would have been aligned, the fact they are not means that the residual stress in the wafer increased the critical stress value for the beams and caused buckling. The displacement at the center of the beam is related to the compression by Saif et. al. in [4].

![Image of optical micrograph of strain gauge at wafer center]

Figure 6: Optical micrograph of the strain guage at the centre of the wafer

These residual stresses were not accounted for in any of the models and with the beams buckled the actual response is different from what is expected. It was observed that the devices with fixed-fixed flexure and folded flexure were still usable but the effect of compressive residual stresses on the devices with the serpentine flexure was so large that it had rendered the devices unusable.

4.2 Side Instability Voltage
The parameter that is most affected by the existence of the residual forces and buckling is the side instability voltage. The presence of uneven compressive residual forces and the buckled beams generates moments which brings the side instability voltage down from hundreds of volts to on the order of 10 volts in most cases. The observed value of side instability voltage on the actuators with fixed-fixed flexures is 15-18V, while for the actuators with folded flexure is 5-7V. As the side instability voltage depends on the amount of the compressive residual stresses in the wafer it varies for each kind of actuator depending upon its location on the wafer. This low side instability voltage severely affects the maximum force that can be applied and the maximum allowable comb displacement of the MEMS actuators.
4.3 Calibration

There are number of factors that can affect the response of the actuators. The first source of uncertainty is the dimensional uncertainty. The designed values of the spring and comb finger widths and on the mask is 2 +/- 0.2\(\mu\)m, assuming that photolithographic process was meticulously fine tuned and dimensions transferred on the wafer are exactly the same as that on the mask then the width of the springs in the flexure can be anywhere between 1.8 - 2.2\(\mu\)m. Similarly the comb finger gap can be anything between 1.6 - 2.4\(\mu\)m. The wafer tolerance on the handle layer thickness was 20 +/- 0.5 \(\mu\)m, which means that the height of the structure after it has been released could vary between 19.5 - 20.5 \(\mu\)m.

The second source of uncertainty is the uncertainty in the material properties of the silicon. The value for the Young’s Modulus for the Single Crystal Silicon (SCS) varies between 62 - 179 GPa \[10\]. The elastic modulus depends on the crystal orientation and type and amount of doping. The moduli expected for these devices, which correspond to \{110\} plane varies between 150-170 GPa \[11\]. These variations in dimensions and physical properties of the silicon lead to uncertainty in the actual response of the actuator.

\[ [12]\] A general method to deal with the propagation of uncertainties is given by Taylor \[12\][12]. Suppose if ‘R’ is function of variable \(x, y, z\) with uncertainties:

\[
R = f(x, y, z)
\]  

(1)

Then the uncertainty in ‘R’ due to \(x\) alone would be:

\[
\Delta_r R = f(x + \Delta x, y, z) - f(x, y, z)
\]  

(2)

Where \(\Delta x\) is the uncertainty in \(x\), similarly the uncertainty in ‘R due to \(y\) and \(z\) will be:

\[
\Delta_y R = f(x, y + \Delta y, z) - f(x, y, z)
\]  

(3)

\[
\Delta_z R = f(x, y, z + \Delta z) - f(x, y, z)
\]  

(4)

Therefore the net uncertainty is calculated as a square root of the sum of squares of the individual contributions:

\[
\Delta R = \sqrt{(\Delta_r R)^2 + (\Delta_y R)^2 + (\Delta_z R)^2}
\]  

(5)

The formal justification for this statement comes from the theory of statistical distributions and assumes that the distribution of successive variable values is described by the so-called Gaussian distribution. Note that this general method applies no matter what functional relationship between \(R\) and the various variables. It is not restricted to additive and multiplicative relationship as are the usual simple rules for handling uncertainties.

The above uncertainty analysis can be used to calculate the uncertainty in the device response due to the variation in the physical dimensions and material properties of the MEMS device. But there is a third and unpredictable source of uncertainty, the residual stresses in the wafer. These residual stresses induce residual forces in the device and make the response from each device unique. Modeling these residual stresses also presents a challenge. And even if they are accurately modeled, the combined uncertainty of all the three sources of variation will be very large making the accurate prediction of the actuator response impossible.

In order to eliminate this huge uncertainty in the calculated response each MEMS device can be individually calibrated by the method described in the previous chapter. It not only gives a very accurate response (very small uncertainty) for the device but also the calibration method can be traced back to the NIST standards ensuring that the results from different experiments can be compared.
4.4 Fixed-fixed flexure
A MEMS actuator with fixed-fixed flexure was calibrated using the method described in the previous chapter. Force vs. Capacitance change was noted. Later, the same device was measured in a SEM. Using the measured dimensions the capacitive measurements were transformed to the equivalent displacement using Equation 6.

\[ C = \frac{2\pi\varepsilon_0}{g} \]  

(6)

Figure 7 gives Force versus displacement curve for the calibrated fixed-fixed flexure.

![Force vs. Displacement Curve for Fixed-fixed Flexure with 800µm Long Beams](image)

**Figure 7: Calibration curve for the fixed-fixed flexure**

The error bars on the displacement (x-axis) are due to the measurement uncertainty and are equal to +/- 100nm. The uncertainty on the force (y-axis) is very small to display on the chart above. Table 1, below, gives the uncertainty on force for each diameter sphere. This uncertainty is due to the manufacturing tolerance of +/- 2.542µm on the diameter of the sphere.

**Table 1. Sapphire spheres' uncertainty for calibration of fixed-fixed flexure**

<table>
<thead>
<tr>
<th>Sphere Diameter (µm)</th>
<th>Force (µN)</th>
<th>Force Uncertainty (µN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>790</td>
<td>10.07</td>
<td>+/- 0.09uN</td>
</tr>
<tr>
<td>1000</td>
<td>20.42</td>
<td>+/- 0.15uN</td>
</tr>
<tr>
<td>1500</td>
<td>6.8.92</td>
<td>+/- 0.35uN</td>
</tr>
<tr>
<td>1580</td>
<td>80.55</td>
<td>+/- 0.38uN</td>
</tr>
</tbody>
</table>
Figure 8 shows the uncertainty in the response of the actuator due to the dimensional variations for elastic modulus of 150GPa and 170GPa. The uncertainty increases with higher modulus.

Figure 8: Range of uncertainty in actuator response with elastic modulus 150 – 170 GPa

Comparison between the calibrated response of the MEMS actuator and the modeled uncertainty is shown in Figure 9.

Figure 9: Comparison between the calibrated response and the uncertainty due to dimensional variation

It can be seen on the curves above that there exist an uncertainty of 1-2µm at large deflections. Also despite the residual stresses on the wafer the response of the MEMS actuator closely follows the predicted curves for very
small deflections. Making this type of the actuator ideal for testing metals where maximum required elongation is less than 0.5 µm.

4.5 Folded flexure
A MEMS actuator with folded flexure was also calibrated and the analysis similar to the one described in the section above was performed. Figure 10 gives Force versus displacement curve for the calibrated folded flexure.

![Force vs. Displacement Curve for Folded Flexure](image)

**Figure 30: Calibration curve for the folded flexure**

The error bars on the displacement (x-axis) are due to the measurement uncertainty and are equal to +/- 100nm. The uncertainty on the force (y-axis) is very small to display on the chart above. Table 2, below, gives the uncertainty on force for each diameter sphere. This uncertainty is due to the manufacturing tolerance of +/- 2.542µm on the diameter of the sphere.

<table>
<thead>
<tr>
<th>Sphere Diameter (µm)</th>
<th>Force (µN)</th>
<th>Force Uncertainty (µN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.55</td>
<td>+/- 0.01uN</td>
</tr>
<tr>
<td>500</td>
<td>2.55</td>
<td>+/- 0.04uN</td>
</tr>
<tr>
<td>790</td>
<td>10.07</td>
<td>+/- 0.09uN</td>
</tr>
</tbody>
</table>

Table 1. Sapphire spheres' uncertainty for calibration of folded flexure

Comparison between the calibrated response of the MEMS actuator and the modeled uncertainty is shown in Figures 12 and 13.
Figure 4: Range of uncertainty in actuator response with elastic modulus 150 – 170 GPa

Figure 5: Comparison between the calibrated response and the uncertainty due to dimensional variation

It can be seen on the curves above that there exist a huge uncertainty at all deflections. Therefore use of this type of flexure for any kind of testing would give misleading results unless the actuator is calibrated and its response is noted and accounted for prior to testing. This kind of flexure can be used for applications with very large deflections thus making it a good candidate for testing polymers or biological materials.

5. CONCLUSIONS
Traceable force calibration results for two types of MEMS actuators, fixed-fixed and folded flexures, have been presented. Traceable calibrations were performed using the dead-weight method of hanging fixed weights from the actuators. Calibration curves of force versus displacement were presented and compared to theoretical predictions. In all cases, theoretical predictions deviated from the calibration curves thus emphasizing the importance of traceable force calibrations of MEMS actuators.
REFERENCES


