SANDIA NATIONAL LABORATORIES

UNIVERSITY ALLIANCE DESIGN COMPETITION 2009

CHARACTERIZATION/RELIABILITY/NANOSCALE PHENOMENA

TRIBOGAUGE FOR ON-CHIP AND *IN-SITU* CHARACTERISATION OF NANO-TRIBOLOGICAL PHENOMENA

TEXAS TECH UNIVERSITY

ABSTRACT

Microelectromechanical Systems is an emerging technology field that deals with the development of chip-based machines for sensing or actuation applications. A sound understanding of pertinent nano-tribological phenomena and their origins constitute an essential component for the development of a broad spectrum of MEMS devices. In this paper we discuss the design and implementation of a MEMS based "*Tribogauge*" to quantify nano-scale tribological phenomenon including stiction, friction and wear in electrostatic and electrothermal actuated MEMS devices. Contacting sidewall surfaces on the SUMMiT Poly3 level are employed for this study. The Tribogauge consists of an orthogonal arrangement of actuator-sensing assemblies. One of the assemblies is used to apply varying normal loads between the contacting surfaces, while the other is used for inducing sliding motion between the contacting surfaces. The actuation is achieved by either using an electrostatic comb-drive actuator or an electrothermal bent-beam actuator, while the comb-drive assemblies are used to capacitively sense the displacements. Off-chip capacitance measurements with resolution in 10s of aF will be used to monitor the change in capacitance. The device will be put in use for in-process monitoring of nano-scale coatings produced in a Molecular Vapor Deposition (MVD) chamber. Also, the device will be used under varying controlled environmental conditions to study the effect of temperature, humidity, and nano-coatings (anti-stiction, ALD coatings) on the rate of accrual of stiction, friction, and wear.

OBJECTIVE

The objective of this project is the development of a design for an on-chip micro-system to be used for *in-situ* study and quantification of nano-tribological phenomena like stiction, friction, and wear in MEMS. The device will be used as an *in-process* gauging tool inside a Molecular Vapor Deposition (MVD) system. The motivation for this is to better understand the coating process as it is happening as well the ability to monitor the performance of devices within an environment that contains a replenishment source of chemicals. The device will also be utilized towards understanding the effect of environmental factors such as temperature and humidity on accrual of stiction, friction, and wear on MEMS surfaces for different surface coatings. Another important goal for this device is to understand the effect of high temperatures (~500^{o}C) associated with electrothermal actuators on the surface coatings and nano-tribological phenomena. The results and finding from this device will help us develop better technique for defending against stiction, friction, and wear that are chief concerns for the reliability and lifetime of MEMS devices.

INTRODUCTION

Microelectromechanical systems capable of performing complicated functions of sensing and actuation have been developed over the past decade. To effectively advance them into the commercial realm, a multi-disciplinary approach utilizing the different aspects of electrical, mechanical, and chemical engineering was required. Some of the commercially successful

MEMS products available are Texas Instrument's DMD and the Analog Devices' ADXL series accelerometers.

Typically, the performance and useful life of many micromechanical structures is limited by their susceptibility to nano-scale phenomena such as stiction, friction, and wear occurring at contacting or sliding micro-surfaces [1]. The approaches for mitigation of these nano-scale tribological phenomena falls under two categories, physical and chemical. The underlying objective of the physical approach is aimed at changing the surface topography by selective etching procedures [2],[3],[4] or selective texturing of the surface by constructing a periodic array of small supporting posts called dimples. However, these methods are severely restricted by the unsuitability for devices with flat surface contacts and sidewall contacts [5]. Stiction reduction by chemical treatment of the contacting surfaces is a popular and effective method [6]. The limitations of the physical approach are overcome by the tailoring of the contact surfaces with low energy compounds which can be integrated with the standard fabrication procedures. One of the most important methods of chemical modification is the deposition of monolayers of low energy compounds on high energy metallic or oxide surfaces. Self assembled monolayers (SAMs) are molecular assemblies formed spontaneously and are capable of significantly lowering the surface energy of the adsorbed surface [7], [8].

In-situ measurement systems are important to effectively characterize the tribological phenomenon and develop effective passification techniques. Mastrangelo *et* al. [9] were the first to measure stiction forces between structural layers using bent cantilever beams. Patton *et al.* [10] tested a lateral output motor inside an environmental chamber that varied relative humidity over a wide range at a constant temperature. For this device, an interesting conclusion was reached that said that moderate humidity levels provided the necessary conditions for the best performance. de Boer *et al.* used a specially designed "hinge-pad test structure" to determine sliding friction [11]. A wobble motor was used to obtain the magnitude of the friction force by monitoring the actuation voltage required for inducing the motion of the motor by Lim *et al.* [12] and Mehregany *et al.* [13]. Prasad *et al.* [14] and Sneft and Dugger [15] were amongst the first to measure the dynamic friction on sidewall surfaces only. Sneft and Dugger used optical techniques to obtain the dynamic friction coefficient from thier devices. de Boer *et al*.'s version of the MEMS tribometer, the "Nanotractor", was used to obtain the static friction coefficient for varying normal loads. It was used for comprehensive tests with different coating materials [16]. One of the more recent work in MEMS tribometers came from Spengen *et al.* [17] that had some design similarities with the device developed by Sneft and Dugger, but a major improvement came in the form of a fast, sensitive electronic readout system that was utilized to monitor the position of actuated comb drives with high accuracy.

In this work we present the design of a Tribogauge to electronically quantify sidewall stiction, friction, and wear on surfaces at the SUMMiT Poly3 level. The gauge is divided into two sections; one utilizes electrostatic actuators while the other uses the electrothermal actuator to apply normal loads between the contacting surfaces. The lateral force for inducing sliding between the surfaces in contact is applied by electrostatic actuators in both the cases. The different classes of actuators (electrostatic and electrothermal) are used in this Tribogauge to understand the relevant tribological issues in both of these popular classes of MEMS actuators. In this design, we use capacitance based displacement sensing to implement an electronic readout system to obtain quantified values of stiction (adhesion) forces and dynamic friction coefficient between the contacting surfaces.

DEVICE DESCRIPTION

The AutoCAD layout of the MEMS Tribogauge is shown in Figure 1. In this layout Section A represents the electrostatic part, while section B represents the electrothermal part of the Tribogauge. The comb-drive assemblies used in this design are imported from Sandia's actuator library provided as part of Sandia's design tool plug-ins for AutoCAD. Figure 2 gives a 3D modeler view for one bank of this comb-drive. These high performance comb-drive actuators (HPCD) utilize all the mechanical layers of polysilicon for the comb-drive fingers, the central shuttle, and the supporting spring assemblies. The Poly1 and Poly2 layers are laminated together to provide a 2.5 µm bottom layer for the comb-drive fingers, while the 2.25 µm thick Poly3 and Poly4 layers form the middle and upper layer of the comb fingers. The central shuttle is designed in Poly3 while the support springs are designed in Poly4 and Poly1-2 and connected through a cut made at the Poly3 layer. The detailed explanation of the suspension system is provided by Rogers *et al.* [18]. The stationary combs are anchored to the substrate using cuts on the SacOx1 layer. Each comb bank consists of 20 pairs of comb fingers. The banks are arranged symmetrically about the central shuttle assembly with one end of movable comb frame connected to the central shuttle. Figure 2 shows a 3D modeler view of an arrangement of 4 comb-banks with 2 arranged symmetrically on each side of the central shuttle.

A detailed 3-D modeler view of Section A i.e., the electrostatic Tribogauge is presented in Figure 3. This design consists of two sets of orthogonally arranged comb-drive based actuation and sense assemblies. The actuation and sense assemblies both use 8 comb-banks. The movable combs on both the axis are connected to the ground potential while the fixed combs are sectioned and connected to the actuation and sense bond pads. The push-end of the comb-drive assembly in the Y-axis is connected to a beam on Poly3 and Poly4 using an adapter frame. The tip of this beam on Poly3 is used as one of the reference surfaces for gauging the tribological phenomena. The other reference surface (on Poly3) is held on a beam in the X-axis comb-drive assembly. The X-axis comb-assembly is broken into two parts and joined through a beam connected to the push head of one assembly at one end and pull head of the second assembly on other end. The normal load between the references surfaces used for measurements is applied by the Y-axis assembly while the lateral force to initiate sliding between the surfaces is applied by the X–axis assembly.

Figure 4 shows a 3D modeler view for the section B of the Tribogauge. As can be noted from the figure, this section of the device uses an electrothermal bent-beam actuator assembly on poly3 and poly4 to apply normal loads between the contacting surfaces. The bent beam actuator assembly consists of 10 legs connected to a central shuttle. The tip of this shuttle hosts one of the reference surfaces for tribological studies. The central shuttle is also connected to the sensing comb-assembly through a Poly4-3 beam. The lateral sliding motion between the surfaces is initiated by a comb-drive assembly similar to the one used in the Section A.

The working principle of this design is presented in the next section. A detailed discussion about the performance of the actuator and sensing assembly is provided in the modeling section of this paper.

Educational Outreach

The Tribogauge device will be used as a demonstration system for educating undergraduate and graduate students in various engineering and science fields in regard to the concepts of micro/nano-scale tribology. A typical educational module in this area would only contain theoretical equations and possibly a few 2D images. To actually help students *experience* the surface interactions and kinesthetics at the micro and nano scale, we will connect the control of the device to a haptic. Haptics are being used primarily in gaming and medical applications to provide tactile response to the user based on either measured or simulated forces. A commercially available gaming haptic will be interfaced with the proposed Tribogauge. The 2-axis motion of the microstage will be controlled by the joystick-like haptic controller. Force feedback for both axes, provided by capacitive sensors, will be sent to the haptic that will utilize its internal motors to provide resistance to the user's motion. The concepts of stiction and friction will be introduced to the students by allowing them to feel a scaled version of these nano-scale forces (van der Waals, capillary, electrostatic, etc) through the haptic feedback when surface-surface interactions occur.

This system we also be used to demonstrate the role nano-scale lubrication systems have on surface interactions. First an un-coated device will be used, wherein the student will be able to feel the relatively high levels of interaction between the native surfaces. Then, a device coated with a lower-surface energy material will be used to show how the stiction forces subside. This interactive system will harness the power of MEMS to teach important fundamental concepts in micro and nanotechnologies in an accessible way.

PRINCIPLE OF OPERATION

In this section we will first discuss the working principle of the device for *in-situ* study of stiction, friction, and wear between the reference surfaces. Then, the intended experiments to be implemented by using this device will be presented.

The working principle of both sections of the tribometer will be the same, with the difference being in the actuator used for applying the normal load. In Section A we use an electrostatic comb-drive actuator to apply the normal load between the contacting surfaces, while in Section B, an electrothermal actuator in the form of a bent beam actuator is used to apply the normal load between the contacting surfaces. This difference in the actuator types will help us in understanding the tribological issues when contacts happen during the operation of two of the most popular classes of actuators. The actuator assembly can be used in one of the three modes to obtain quantified information on stiction, friction, and wear between the surfaces.

The use of the tribometer for the quantification of stiction is illustrated in Figure 5. For this, the Y-axis actuation assembly is exclusively used while the X-axis assembly is left un-actuated. The comb-drive assembly in the Y-axis will be actuated to create contact between the test surfaces with a pre-determined normal load. The displacement of the central shuttle assembly will readout using the capacitive sensors attached to the shuttle. Based on the approach and retract curves we will get a measure of stiction between the surfaces. Friction measurements will be carried out by first actuating the Y-axis comb-drive assembly to apply a pre-determined normal force between the contacting surfaces, and then using the X-axis assembly to initiate the sliding between the surfaces. The difference in the position of the surface connected to this assembly when not in contact; to when in contact with the other surface will provide us with the vital information on the dynamic friction coefficient between the surfaces. A schematic representation of this technique in presented in Figure 6. For the study of wear between the surfaces, the surfaces will be brought in contact with a pre-determined normal load, and then a periodic signal will be applied to the X-axis comb-assembly to create a continuous sliding between the two surfaces. The contact area will be examined visually under a SEM after a fixed time intervals to look into debris formation due to the wear between the polysilicon surfaces. A schematic representation for the utilization of tribometer for study of wear on the polysilicon surfaces is shown in Figure 7.

We will use this device for *in-situ* characterization of nano-tribological parameters on MEMS surfaces while inside the MVD chamber. The motivation for this is to better understand the coating process as it is happening as well as the ability to monitor the performance of devices within an environment that contains a replenishment source of chemicals. Another important application where the device would be put to use is for, tribological characterization under controlled conditions of temperature and relative humidity. Experiments will be conducted at high, medium, and low temperature and relative humidity regimes providing a variety of conditions to analyze the behavior of nano-scale surface interactions under different nano-scale surface lubrication schemes.

DEVICE MODELING

An overview of modeling and analysis of key components of the device is presented in this section. The components have been broken down into Actuators and Sensors and discussed separately.

1. Actuators

Two different classes of actuators have been utilized in this design: electrostatic comb–drive actuators and electrothermal bent-beam actuators.

1.1. Comb-drive actuators

The force required for positioning the reference surfaces is accomplished by the actuation of the electrostatic comb drive actuators. These actuators consist of movable comb fingers and fixed comb fingers. A voltage difference is applied to create electrostatic forces in the x-direction as shown in Figure 8. The force experienced by the movable finger in the direction of motion is given as

$$F_x = \frac{N\varepsilon t}{g} V^2 \tag{1}$$

where N is the number of comb drive electrode fingers; ε is the permittivity constant of the dielectric (in this case air); t is the thickness of comb electrodes; g is the gap between the electrode fingers; and V *is* the driving voltage. The central shuttle is connected to movable combs of all the comb drive banks allowing larger forces to be produced at the end of the shuttle.

In this design, the comb drive used for actuation consists of 8 banks of combs, which are placed symmetrically about the central shuttle connecting all the movable comb electrodes. Each of these comb banks contains 20 fingers. The total number of fingers N is 160. The thickness t is the total thickness of all the mechanical layers utilized in the comb-drive actuator that is *Poly1-2* + *Poly3* + *Poly4*, equals 6.75 µm. The gap between the teeth is 0.5 µm. A graph showing the force vs. voltage for the comb-drive actuator is presented in Figure 9.

A simple DC run of the actuators will be conducted to quantify the displacement of the central shuttle as a function of voltage. This would help to determine the spring constant of the return spring by applying Hooke's law (as the force generated by the actuator as a function of voltage is already known).

1.2. Bent-beam actuators

Another type of actuator used for this design is the bent-beam actuators. These electrothermal actuators consist of V shaped beams arranged parallel to each other, the legs of the V shaped beams are anchored to the substrate. When a potential difference is applied between the legs of the actuator, they heat and expand (joule heating). The mutually constrained thermal expansion of the two symmetric legs will result in linear motion due to a combined bending of the beam [19].

Complete three-dimensional actuation of the device is modeled using the ANSYS FEA package [20]. The model is a coupled-field electro thermal model with conductive heat flow due to the Joule heating and displacements due to the thermal expansion calculated. The geometry of the device used in this modeling is provided in Figure 10. Figure 11 shows displacement vector sum at a potential difference of 3 V applied between the legs of the actuators. The material properties reported by Baker *et al.* [21] were employed in this model (though we did not take the temperature dependence of these properties in our model).

To construct an accurate and computationally efficient model, it is necessary to identify which mechanisms govern heat flow. Generally, these may include conduction, convection and radiation. Estimates of the relative magnitudes of these components are done, and show that conduction is dominant. Treating the thick silicon substrate as a heat sink, the anchor-pads were held at ambient temperature. All other surfaces are insulated, following the assumption of negligible convection and radiation. A detailed analysis of temperature, displacement and output force were done and the results are shown in Figure 12-14.

2. Sensor

In order to sense the displacement of the reference surfaces used for study of the nano-tribological phenomena in this device, a capacitance based sensing for displacement is employed. A similar configuration of comb-drive as discussed above is used for sensing. The comb-drive capacitance can be calculated by assuming a parallel plate type geometry, for which the equation is given as,

$$C = \frac{2n\epsilon tl}{g} \tag{2}$$

The factor 2 in the above equation comes from the fact that both side of the comb finger forms a parallel plate capacitor with the fingers next to them. In this equation, n is the number of comb drive electrode fingers, ε is the permittivity constant of the dielectric (in this case air), t is the thickness of comb electrodes, g is the gap between the electrode fingers, and l is the length of overlap. The change of the capacitance with respect to the displacement of the central shuttle of this drive is shown in Figure 15.

SUMMARY

We have designed a Tribogauge for on-chip and in-situ characterization of pertinent nano-tribological phenomena in electrostatic and electrothermal devices. The experiments will be carried out between two sidewall surfaces on the Poly3 layer. The device has been equipped with capacitance based sensing capabilities to implement off-chip electronics to get readout of stiction and friction between the test surfaces. The Tribogauge will be used for in-process characterization of nano-coatings (self-assembled monolayer, atomic layer deposition) in a Molecular Vapor Deposition (MVD) system. The device will provide us with an unique opportunity to develop an in-depth understanding of the effect of nano-coatings (self-assembled monolayers, atomic layer deposition) and ambient environment on the key reliability issues; stiction, friction and wear. The results of the experiments, conducted with the proposed device, will help us design defense mechanisms against the tribological concerns, and thus help advancing a range of complex MEMS devices into realms of commercial products. There are a number of interesting educational components that will provide access to the micro and nanoscale in an interactive way.

APPENDIX I – FIGURES

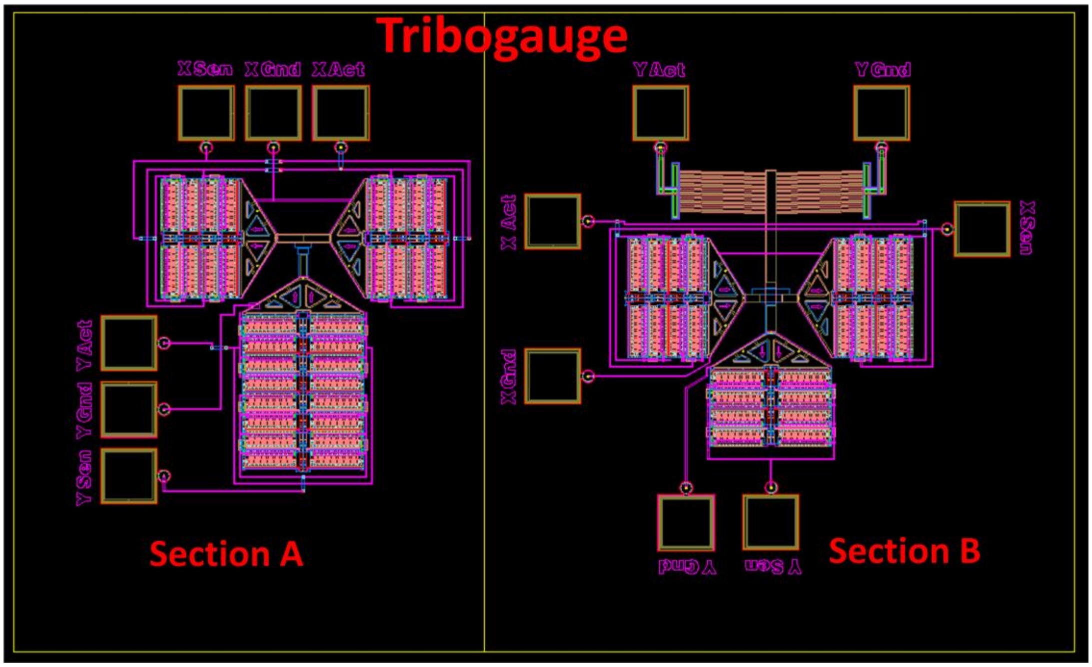


Figure 1. AutoCAD 2D layout of the *Tribogauge.*

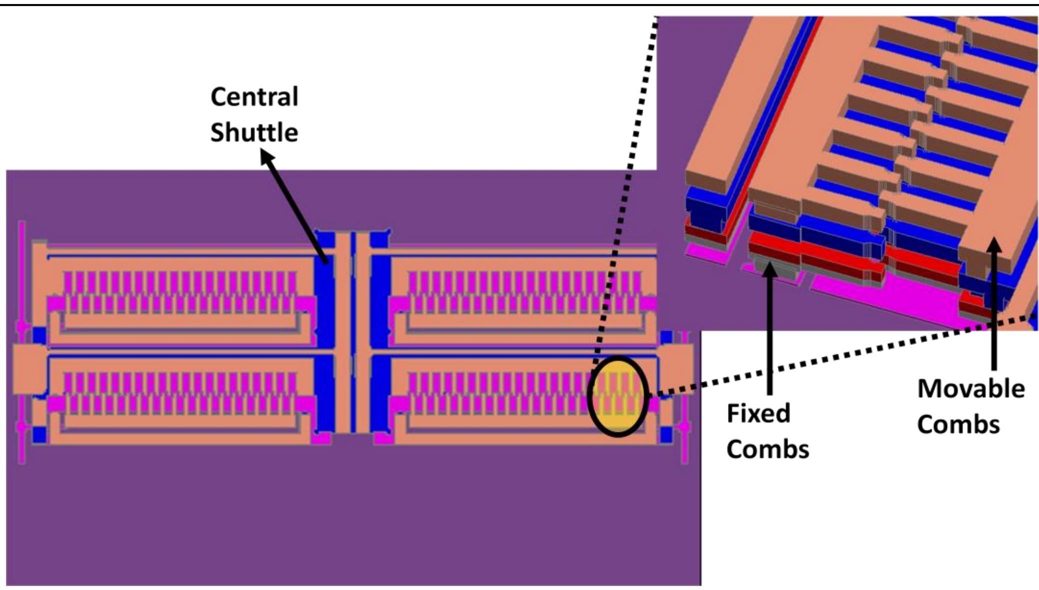


Figure 2. A 3D modeler view of 4 comb-bank and central shuttle assembly.

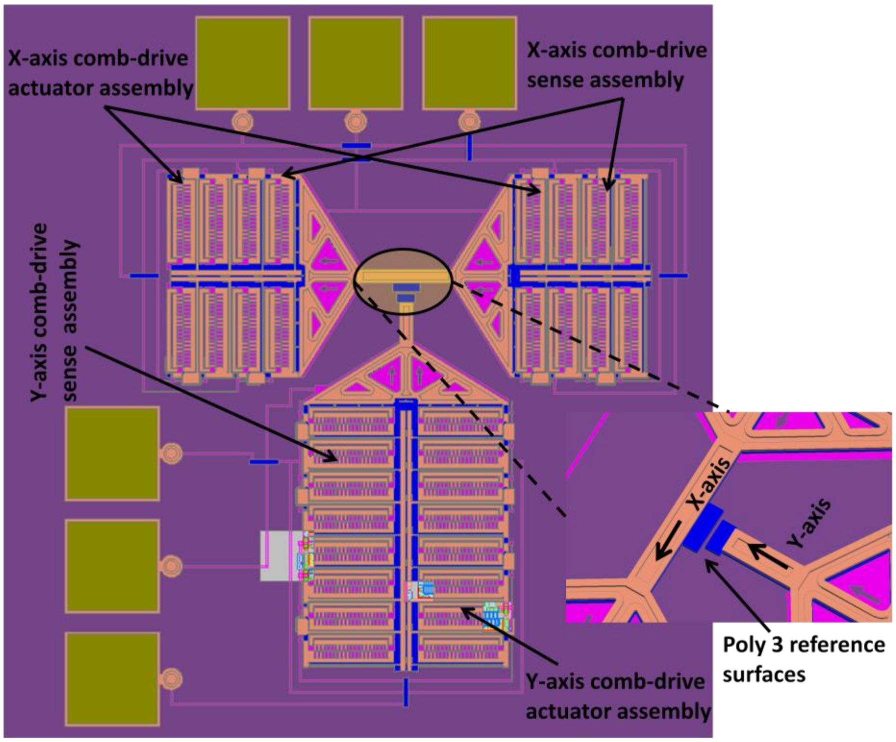


Figure 3. A detailed 3D view of Electrostatic Tribometer.

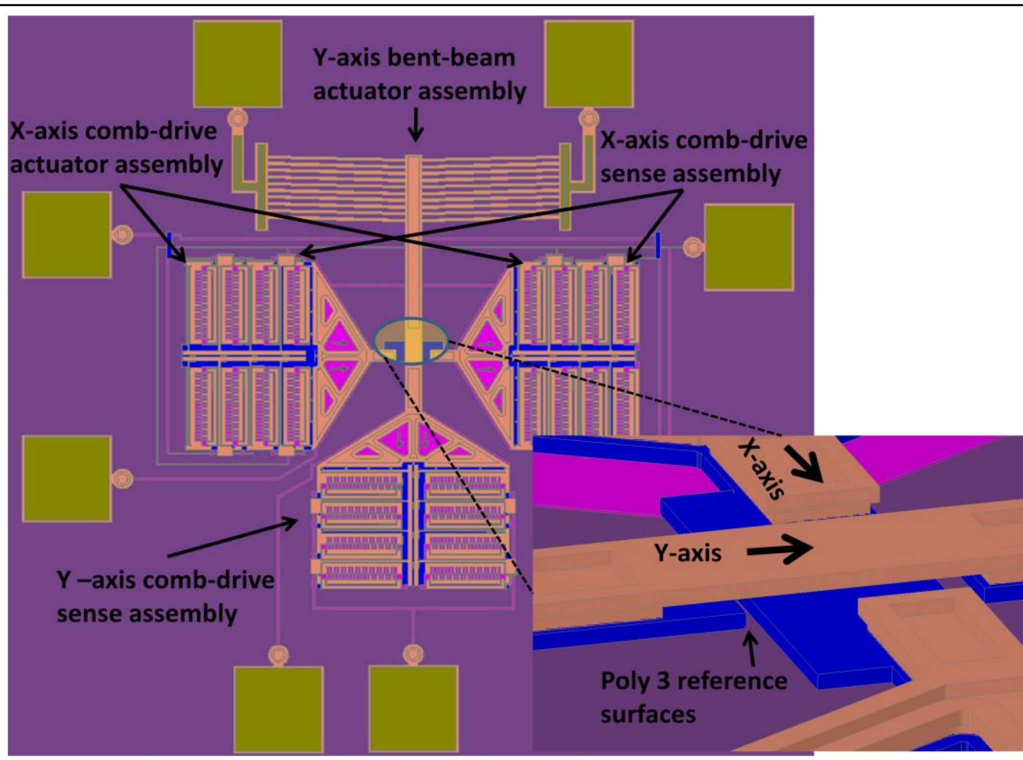


Figure 4. A detailed 3D view of Electrothermal Tribometer.

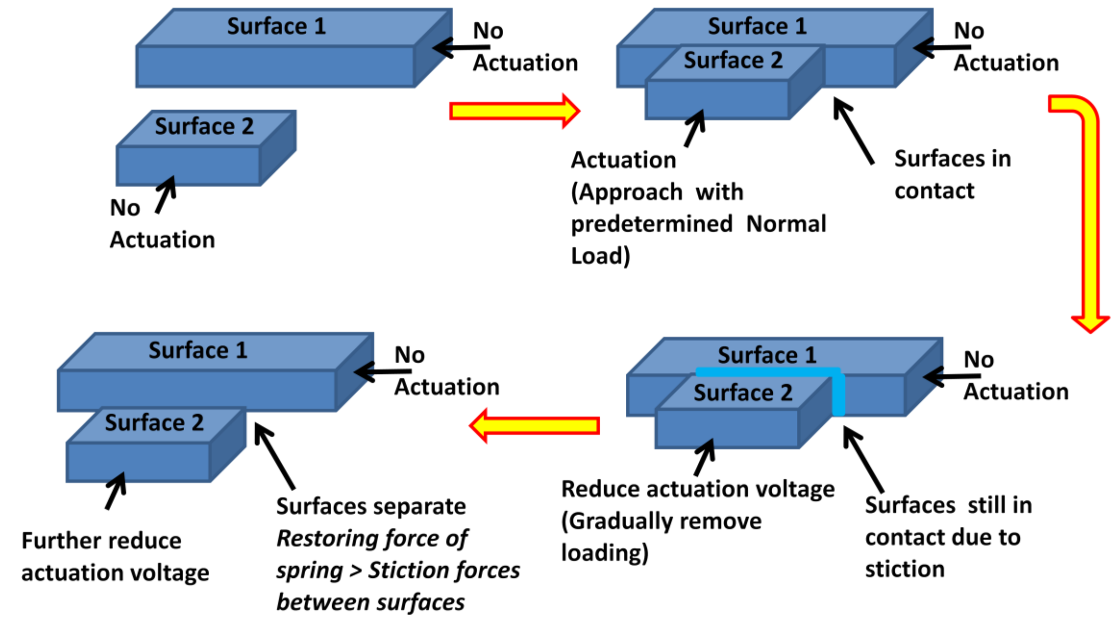


Figure 5. A schematic representation for study of stiction using Tribometer

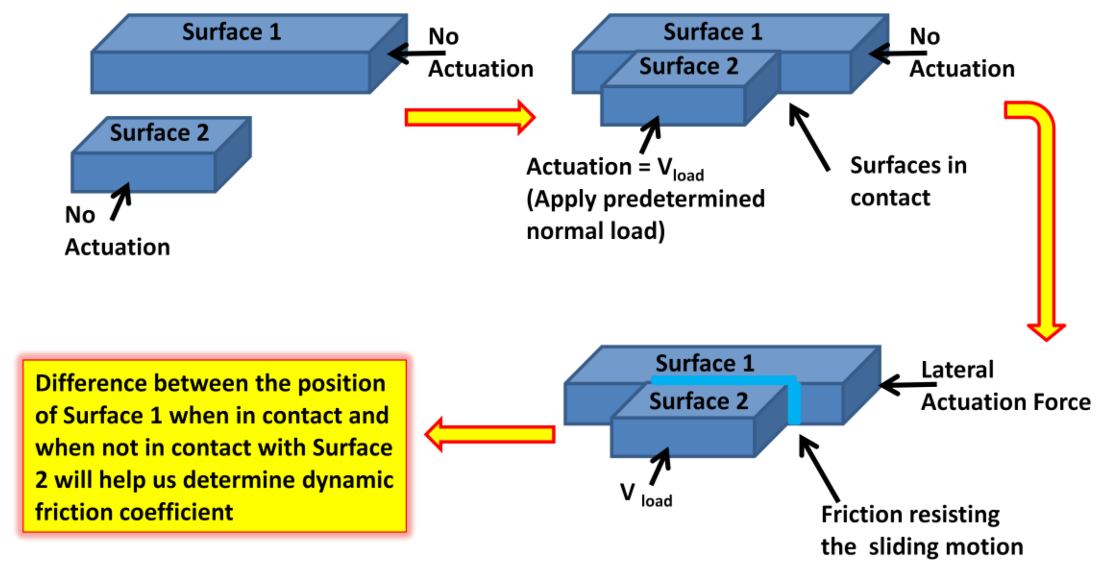


Figure 6. A schematic representation for study of friction using Tribometer

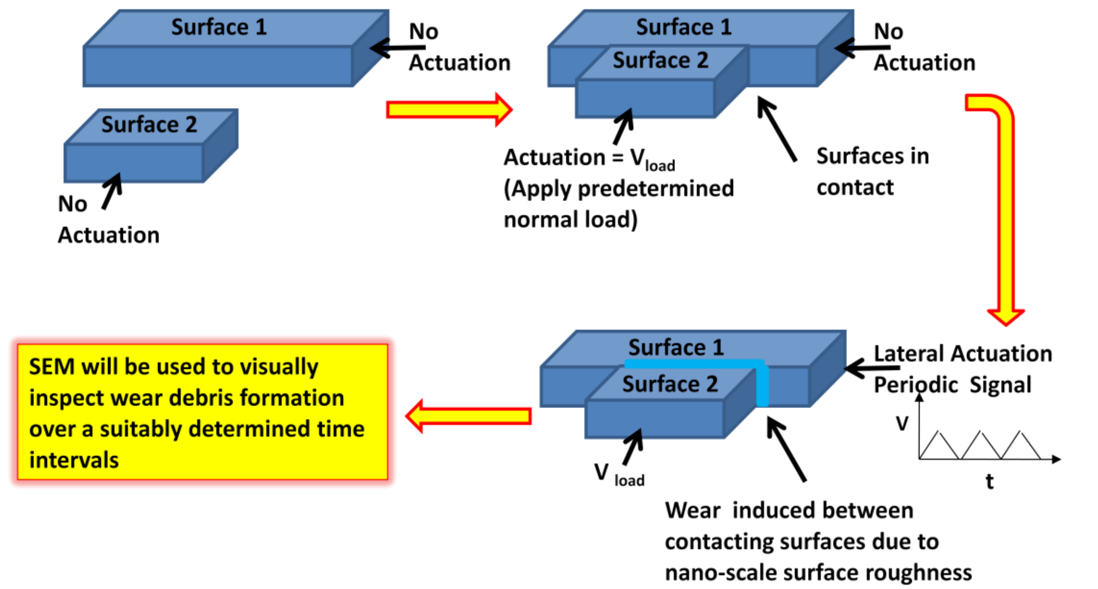


Figure 7. A schematic representation for study of wear using Tribometer

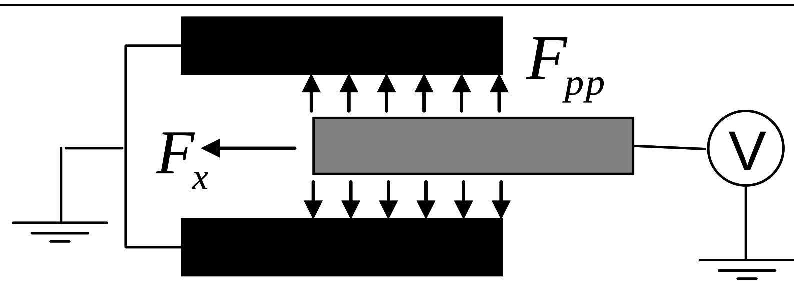


Figure 8. Schematic representation of forces acting on comb-drive actuators under applied voltage.

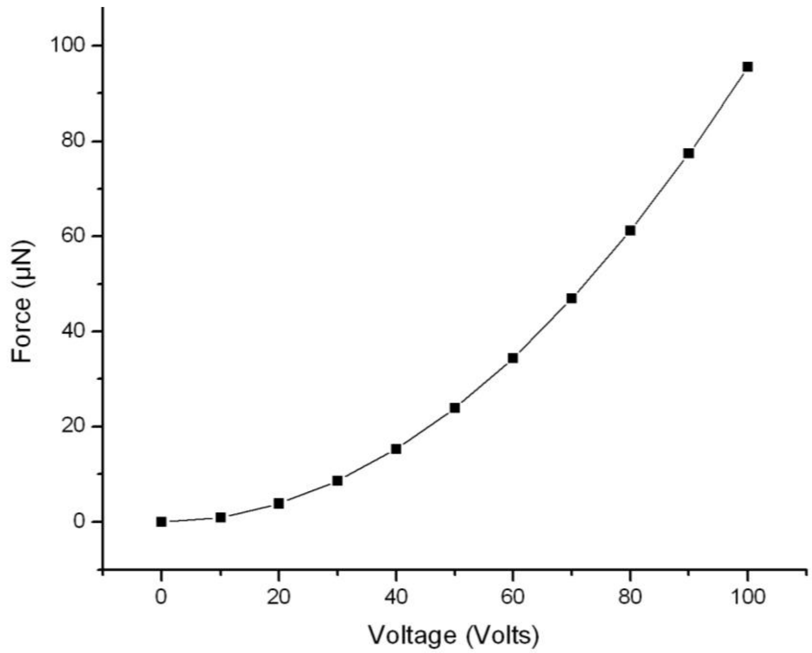
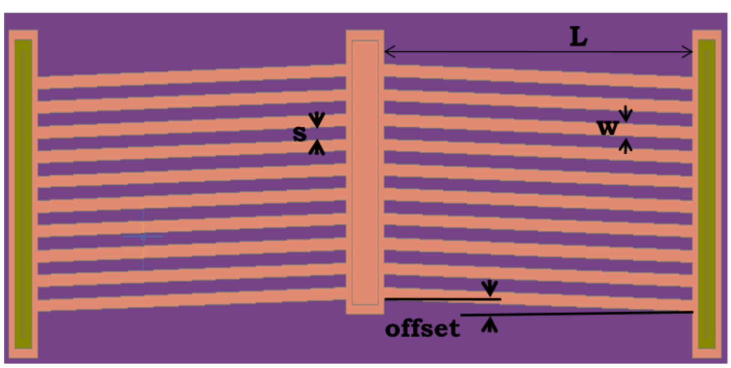
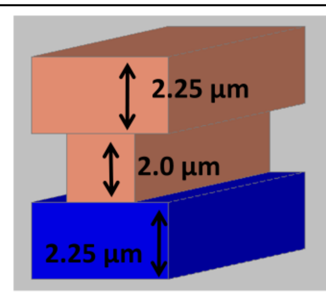


Figure 9. Graph depicting the relationship between the force and applied voltage for electrostatic comb-drive actuators used in the tribometer.





Parameters	Dim. (µm)
w	4
L	160
offset	4
s	4

Figure 10. Specifications on Bent beam actuator used for normal loading in Section B of the tribometer.

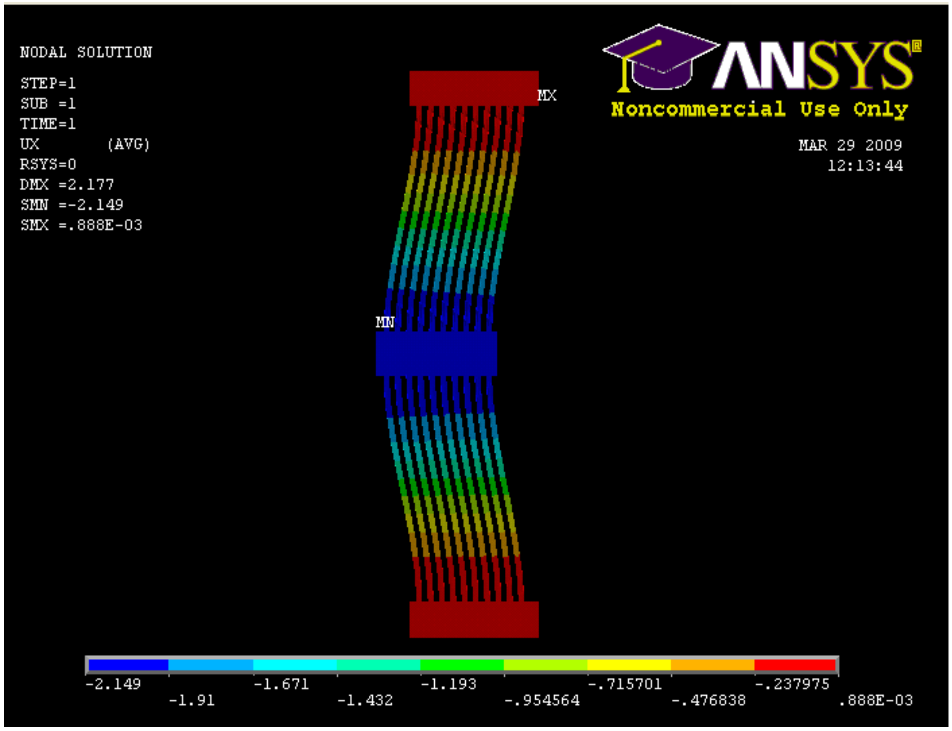


Figure 11. FEA simulation showing displacement along X-axis of device with maximum input voltage of 3V.

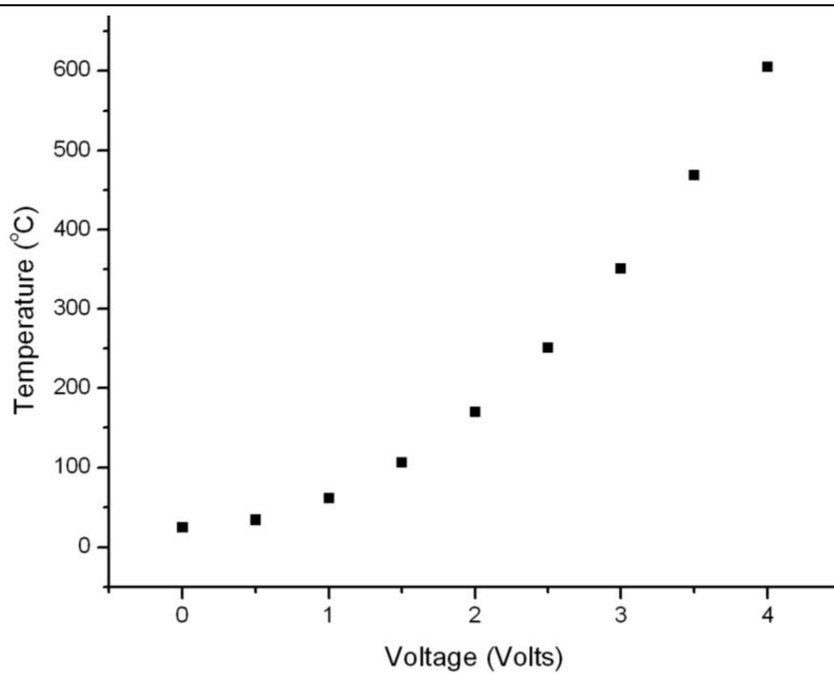


Figure 12. Variation of temperature as a function of voltage on the tip of the bent beam actuator used in Section B of the tribometer.

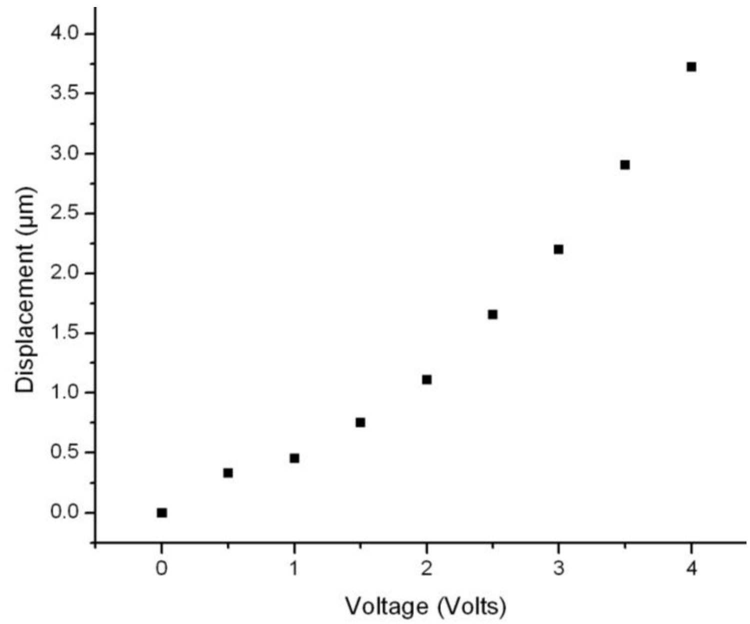


Figure 13. Variation of displacement as a function of voltage on the tip of the bent beam actuator used in Section B of the tribometer.

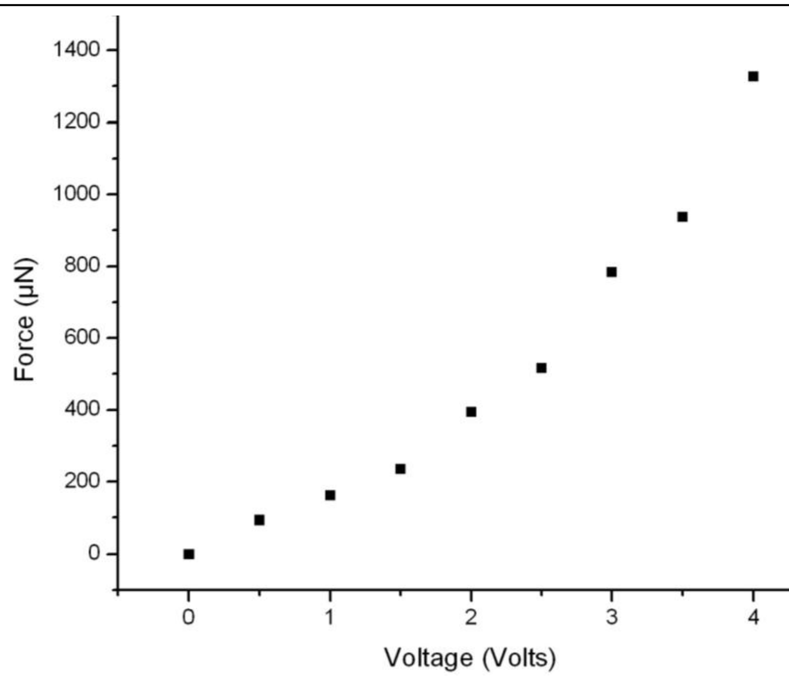


Figure 14. Variation of force as a function of voltage on the tip of the bent beam actuator used in Section B of the tribometer.

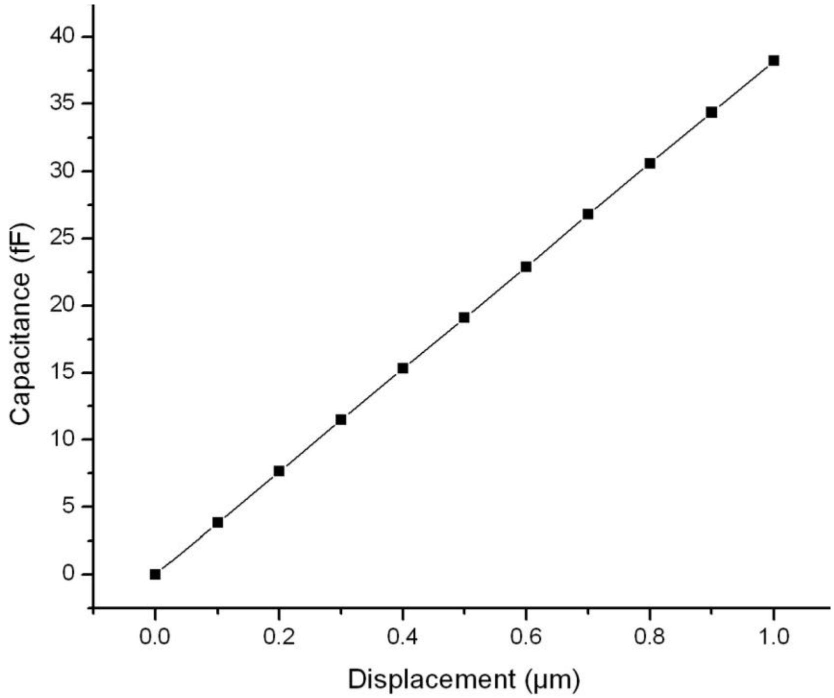


Figure 15. Variation of capacitance as a function of displacement of sense capacitance assembly.

APPENDIX II -REFERENCES

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