Contact Mechanics Description of Inelastic Displacement Response of a Nano-Positioning Device

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Abstract – **A classical mechanistic model was developed to capture the existence of pre-sliding tangential deflection (PSTD) in contacting polysilicon and coated polysilicon surfaces. For the purposes of modeling asperity friction, experiments have shown, and been supported through detailed finite element analyses, that frictional forces developed through tangential sliding scale linearly through a material parameter known as the junction strength. A junction strength model coupled with a discrete quasi-static contact mechanics analysis, using contacting surface descriptions sampled by AFM from actual polysilicon surfaces, predicts inelastic tangential displacements that are qualitatively consistent with observed PSTD response. The simulations imply that the existence of PSTD depends not only on the spatial characteristics of contacting surfaces, but also on the local loading characteristics.**

I. INTRODUCTION

Early researchers observed empirically that the friction (tangential) force between two surfaces is proportional to normal force and independent of the apparent contact area. Today it is well known that this observation is not valid if the nominal and true contact areas are the same (as in friction force microscopy or surface force apparatus measurements). Determination of the laws of friction that exist for MEMS surfaces is the focus of much current research. The characterization of MEMS-scale friction is important for the purpose of evaluating wear properties, durability, and reliability of MEMS devices.

A recently developed MEMS actuator called the "nanotractor" has leveraged its high-performance, bidirectional capabilities to serve as a friction test structure. The nanotractor, shown in Figure 1, is capable of measuring friction over a wide normal force and velocity range.

During characterization of the nanotractor, slipping of the device was observed to occur despite the fact that the static friction force was not surmounted. The observation that there are small-scale deflections before the static friction event has been made in tribology literature and is termed "pre-sliding tangential deflections" (PSTD). PSTD was observed to occur when the contacting surfaces of the nanotractor were coated with both FOTAS, an 8-carbon chain monolayer lubricant, and OTS, an 18-carbon chain monolayer lubricant. In both cases, the characteristic deflection length of PSTD is approximately 200 nm, substantially larger than the length scale of the individual asperity contact radius.

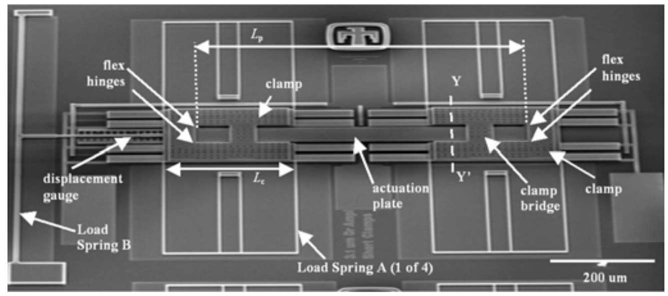

Fig. 1. An SEM image of the nanotractor friction test structure.

Since the physics that govern PSTD are not obvious, a mechanics model was developed to simulate the quasi-static response of the nanotractor during a friction test.

II. CONTACT MECHANICS MODEL

A. Static Friction Test

A simple static friction test was performed in which direct observations of PSTD could be made. The nanotractor was displaced a distance against the load springs and electrostatically clamped against the test substrate. Figure 2 shows an SEM cross-section of the clamp. The clamp actuation voltage is incrementally decreased and the position of the nanotractor is measured using Moiré grating. As long as the frictional force generated at the clamp is large enough to hold off the tangential force of the load springs, the nanotractor is expected to remain in place. The nanotractor is then expected to start sliding when the static friction force drops below the tangential force. The results from a FOTAS coated nanotractor is shown in Fig. 3.

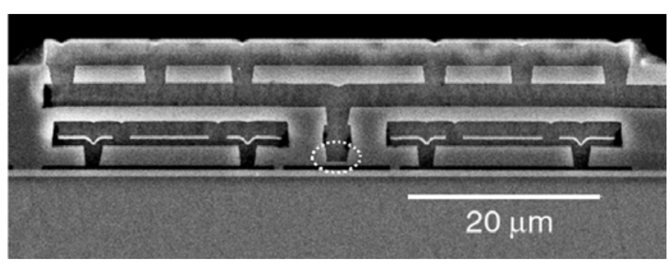

Fig. 2. SEM cross-section of the nanotractor clamp. The circled area comes into intimate contact with the substrate when the actuation voltage is applied.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

Proceedings of the 2005 International Conference on MEMS, NANO and Smart Systems (ICMENS'05)
0-7695-2398-6/05 $20.00 © 2005 **IEEE**

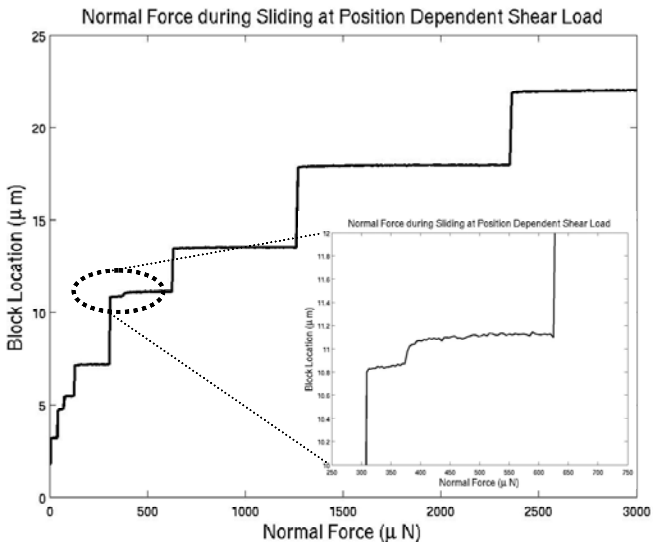

Fig. 3. A static friction test from a FOTAS coated nanotractor. The enlarged region shows the characteristic PSTD response of an apparently static deflection immediately preceding the sliding instability.

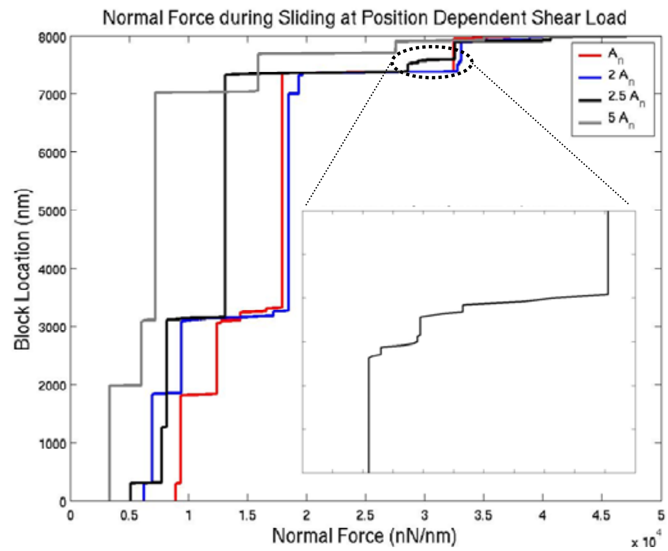

Fig. 4. A model simulation of silicon-on-FOTAS contact exhibits PSTD-like response. The appearance of PSTD in only one instance implies a complex dependence on surface topography and local contact mechanics.

B. Friction Simulation

The friction simulations were designed to parallel the static friction experiments during a PSTD event. The model does not include inertial effects, however, PSTD occurs during stable phases of tangential displacement and that is precisely the regime in which the model accurately reflects the inherent physics.

A Hertzian contact analysis was employed under assumed silicon-on-silicon contact, where the appropriate moduli were, elastic modulus, E = 161 GPa and Poisson's ratio ν = 0.23. The junction model was used to calculate friction force through

$$F_{friction} = \tau * A, \quad (1)$$

where A is true contact area and τ* is the material junction strength deduced from experiments. For the simulations, a calculated value of τ* = 195 MPA was employed.

The profiles of the contacting surfaces were sampled directly from an AFM scan of a polysilicon surface. Both the substrate and the clamp counterface were sampled randomly from a 10 μm x 10 μm (1024 x 1024 pixels) scan of a 2.7 nm rms polysilicon surface. The surfaces were then pressed into contact until the sum of the local contact forces was equivalent to that of the experiment (2.2 mN/nm). The simulation proceeded in the same manner as the experiment, using the same load spring restoring force calculated from the experiments.

Figure 4 shows the results from a series of simulations performed in which the substrate profile was held constant, but the apparent contact area was varied. The response curve with the largest apparent contact area has approximately the same number of contacting asperities as expected in the experiments and does exhibit a PSTD event of approximately 80 nm. The figure also shows that the response curve of each simulation was qualitatively similar; however, PSTD events did not occur in each of the simulations.

III. CONCLUSION

The phenomenology of the PSTD mechanism most likely cannot be determined *a priori* through independent investigation of the two intimately contacting surfaces. Analysis of the simulations pictured in Fig. 4 did however uncover some features common to PSTD events. During PSTD, the number of contacting asperities remains constant, but perhaps more interestingly, the true contact area also remains constant. This provides further support for the stochastic nature of PSTD events.

ACKNOWLEDGMENT

The authors would like to acknowledge the helpful discussions with and comments from Maarten de Boer of Sandia National Laboratories.

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