Nanotribology

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This project studies the friction between extended contacts on the nanometer length scale. The aim is to develop our understanding of the now well-characterised tribological behaviour of point contacts into length scales and geometries which are more relevant for the emerging technologies of MEMS and NEMS. Our primary goal is to address the fundamental aspects of friction at these length scales, but applications and devices are an important motivating aspect. The principal method uses a semiconductor nanowire, pushed on by the tip of an atomic force microscope while it interacts mechanically with a substrate. By measuring the shape adopted by the nanowire we can deduce the forces which acted on it during the manipulation. These can include many different phenomena, but by careful choice of manipulation procedure we can isolate the effect of friction. We have studied the friction between nanowires and various substrates, and have found an interesting mixture of behaviours associated with macroscopic friction and that characteristic of atomic-scale point contacts.

1. Background and Motivation

Friction at the macroscopic level is seductively simple, and yet frustratingly hard to understand in fundamental terms. Since the invention of the Atomic Force Microscope (AFM), studies of the interactions between an AFM tip and different substrates have produced major advances in our understanding of friction at the atomic scale, but connecting that understanding to the mesoscopic and macroscopic length scales is still problematic.

In our work we have measured the frictional drag on InAs nanowires pushed laterally across surfaces by an AFM tip. In this system the contact length in the direction of movement is of the order of a few tens of nanometers, and is thus comparable to that found in many point-contact studies. However, perpendicular to the motion the wire is several microns in length. We are therefore able to measure an aggregate friction for the wire that lies in the mesoscopic regime, with a geometry that closely models proposed MEMS structures and devices.

2. Problem

In the process of miniaturizing mechanical devices, friction becomes of overriding importance and numerous problems have been encountered in practical nanomechanical devices. In nanoscale systems with moving parts, friction, adhesion and wear strongly influence our ability to conduct basic and applied science.

A considerable amount of theoretical and experimental work exists in the field of Nanotribology, but this work addresses either macroscopic effects, or the behaviour of point-contacts a few atoms or tens of atoms in size. It has been difficult to investigate the intermediate zones between the atomic and the macroscopic scale or even to determine where the boundaries are. It is not yet clear how the progress in understanding atomic-scale friction can be useful when scaling the results to the mesoscopic scale. One major difficulty is the inability to control the contact geometry. Despite impressive progress in the field of nanofabrication, it is not yet possible to replicate local contact geometries with the necessary degree of accuracy. Thus, every nanodevice becomes a special case and has to be measured separately.

Our work suggests a way to address this problem and to understand how friction is affected as objects become larger than a few atoms in dimension. Our measurements have proven to be a useful technique for studying the friction experienced by a particular class of nano-objects, but they also allow us to address basic questions about the nature of friction at these length scales.

3. Application Scenarios

We have studied InAs nanowires (NWs) on three different substrates: Si/SiO_2, silanized Si/SiO_2 and Si_3N_4/Si, which are typical surfaces widely used when making micro and nanoscale devices. The wires are up to a few microns long with diameters in the range 20-80 nm. They are grown by Chemical Beam Epitaxy (CBE) and transferred onto the substrates by a wipe on-wipe off technique. AFM imaging is done in Tapping mode, and manipulation is performed by turning off feedback and applying an offset to the measured trace height on the retrace scan.

The shape of the wire after bending is determined by an equilibrium between elastic forces and friction with the substrate. From the radius of curvature of the bent nanowire we can calculate the friction force per unit length using standard elasticity theory. The wires are hexagonal in cross section, and AFM and SEM measurements confirm that they lie with one flat of the hexagon facing the surface. Thus even in the presence of tip-sample convolution, the contact geometry between the wire and the substrate can easily be determined from the apparent height of the wire.

4. Results

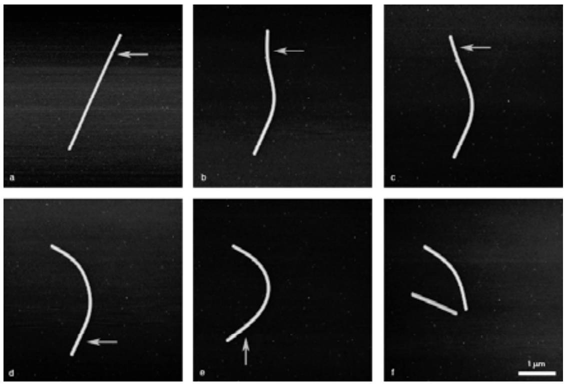

Figure 1 AFM manipulation of an InAs nanowire on Si_3N_4. The wire is 54 nm in diameter and about 4 µm long.

By a suitable choice of manipulation we are able to measure static or sliding friction. In a static friction experiment the nanowire is pushed at one end only and the rest of the nanowire is fixed. Multiple pushes bend the wire into successively tighter curves, until it either translates as a whole, or breaks. A typical example, including one push that breaks the nanowire, is shown in Figure 1. In a sliding friction experiment the nanowire is pushed in the middle so the entire wire moves with a uniform velocity and its final shape is determined by sliding friction alone (Figure 2).

Figure 3 shows the measured static and sliding friction force per unit length for a range of nanowire diameters on all three substrates. For larger wires there is a clear difference between sliding and static friction of two to three orders of magnitude. The very low values for sliding friction are characteristic of atomic-style contacts. For wires below around 40 nm the sliding friction jumps to become equal with the static friction, which we interpret as a transition to stick-slip motion.

The static friction values increases strongly with nanowire diameter. This may be due to a change in the

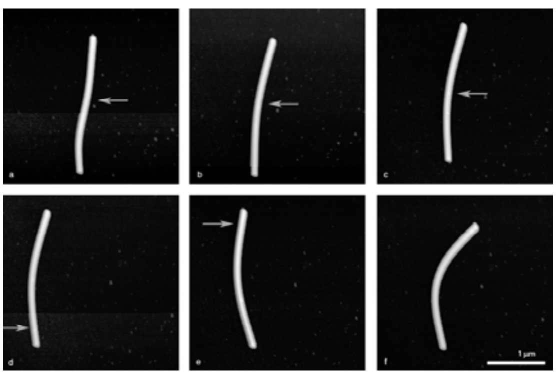

Figure 2 Sliding and static friction experiments performed on a single InAs NW on Si_3N_4. This wire was 49 nm in diameter and about 2.5 µm in length. First the whole wire is translated uniformly by pushing at its mid-point. Then it is bent into a tighter curve by pushing on one end at a time.

contact pressure with the Van der Waals force holding the nanowire onto the substrate: a type of friction usually associated with macroscopic objects.

Our main focus currently is to clarify whether the

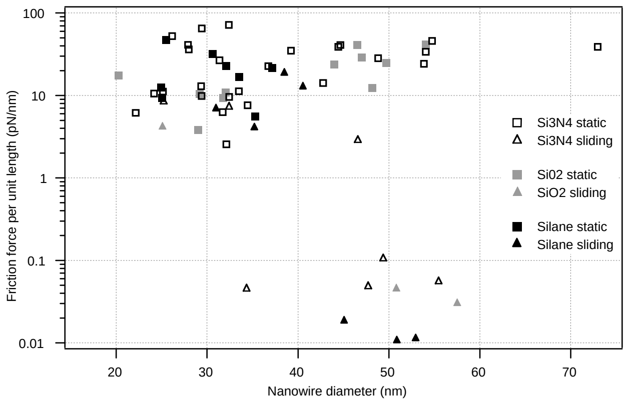

Figure 3 Friction force per unit length vs. the NW diameter for three different substrates.

nanowire-substrate contact behaves like a macroscopic one, in which differences between the 'true' and 'apparent' contact areas play a key role, and friction varies linearly with the applied normal force, or whether they are more like atomic-scale point contacts, where more fundamental processes dominate and friction often is independent of the normal force.

We are studying for example the way that the friction between InAs nanowires and an insulating silicon nitride layer on a conductive silicon substrate varies when a DC voltage is applied to the AFM tip during manipulation. The tip charges the capacitor formed by the wire and the grounded silicon back contact, giving rise to attractive Coulomb forces and thus increasing the contact pressure between the wire and the silicon nitride. In this way we can vary the normal force on the sliding surfaces using a single wire, with a constant structure and contact geometry.

Publications

"*Shear Stress Measurements on InAs nanowires by AFM Manipulation*"
M. Bordag *et al*
Small **3**, 1398-1401 (2007).

"Friction measurements of InAs nanowires on silicon nitride by AFM manipulation"
G. Conache *et al*
Small **5**, 203-207 (2009)