Friction Measurements of InAs Nanowires by AFM Manipulation

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Abstract

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

We have studied InAs NWs on three different substrates, SiO$_2$, silanized SiO$_2$ and Si$_3$N$_4$. The wires are up to a few microns long with diameters in the range 20-80 nm. 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 in the wire and friction with the substrate. By measuring the radius of curvature of the bent nanowire we can calculate the friction force per unit length using standard elasticity theory.

We are able to measure both static and 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 finally the nanowire breaks or moves as a whole. In a sliding friction experiment the nanowire is pushed in the middle so the entire wire moves with a uniform velocity. In this case the final shape is determined by the sliding friction alone.

We have measured the static and sliding friction force per unit length for a range of nanowire diameters on all three substrates. Interpretation of the data is complicated by a range of unknowns, but the geometry invites analysis in terms of a distributed set of point contacts. The system displays behaviours typical of friction studies at other scales, such as differentiated sliding and static friction and a transition to stick-slip motion, the details being an interesting mix of those from both atomic-scale and macroscopic regimes. This system therefore represents a useful experimental test bench for studying friction on the mesoscopic scale.
Preface

I started my work here on an EC project on studying the forces between nanoobjects and nanofeatures on patterned substrates in order to create specially designed substrates which can trap and align the nanoobjects into the desired positions. The goals of the project were to achieve self-assembly with carbon nanotubes and semiconductor nanowires in order to mass-fabricate chemical sensors with sensitivity to different substances with high precision in positioning and high accuracy over a large area. While trying to perform AFM manipulation of CNTs and NWs we realized that a major obstacle in our study was the way friction would overwhelm the other desired interactions. I started to study friction in detail by performing many hours of AFM manipulation on a large number of nanowires. There are still numerous questions to answer but I discovered the fascinating field of nanofriction.

First of all I would like to thank to my supervisors, professors Lars Montelius and Håkan Pettersson who gave me the opportunity to work into this department and who guided and encouraged me during these years. Special thanks I would like to address to Struan Gray who supervised and encouraged me and for the nice moments while having non-scientific discussions as well as to his family. I would also like to thank to the NanoLab team: Aline Ribayrol, David Adolph, Ivan Maximov, Mariusz Graczyk, Lena Timby. Thanks to Linus Fröberg and Jessica Eriksson who have grown nanowires that I used in my experiments.

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List of papers


For this paper I participated actively to the AFM manipulation experiments.


For this paper I did the optical images for the identification of the NWs and the AFM manipulation experiments. I participated in the planning of the experiments and the analysis of the results. I wrote the paper.


For this paper I did the deposition of NWs from the growth substrate to the patterned substrate, I made the optical images for the identification of the NWs and I performed all the AFM manipulation experiments. I participated in the planning of the experiments, I did the analysis with the non-computerized method, I participated to the discussions for the interpretation of the results and I wrote most of the paper.

4) G. Conache, S. Gray, A. Ribayrol, L. E. Fröberg, L. Samuelson, H. Pettersson, and L. Montelius, “Friction measurements of InAs nanowires on SiO₂, silanised SiO₂ and Si₃N₄ by AFM manipulation”, in manuscript.

For this paper I did the optical images for the identification of the NWs and the AFM manipulation experiments. I participated to the planning of the experiments, I did most of the analysis with the non-computerized method, I participated to the discussions for the interpretation of the results and I wrote most of the manuscript.
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1. Introduction

Friction is omnipresent in everyday life. In many cases people use and exploit it to improve their quality of life. Actions like walking, lighting a fire or playing a violin are some good ways in which friction is manifested. But friction also has numerous less advantageous aspects, and it can be destructive, especially in the technological applications [1].

The study of friction, adhesion, and wear from a macroscopic perspective is known as tribology, but although this term is relatively new, friction has been studied for centuries. Most of the work has been done in the engineering field because of its important practical consequences. Examples from the transport industry alone include reducing energetic losses due to friction (helping a car engine work efficiently), using friction as an operation mechanism (car breaks), reducing material losses due to wear (longer-lasting tires) and optimizing lubricants (increasing the efficiency and lifetime of engine parts). All of these are important issues for a wide range of industrial applications with large effects in society [2]. Improved friction and wear properties would save the enormous amount of money that is currently invested to replace machines because of reduced performance or the destruction of component parts [3].

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

Up to now a considerable amount of theoretical and experimental work has been done, 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 more difficult to investigate intermediate zones between the atomic and the macroscopic scale or even to determine where the boundaries are. There are a number of excellent review articles in the field [1-6].

A related fundamental problem in MEMS or NEMS technology is to understand the mechanical properties of the objects from which the devices are built. The mechanical behavior of materials at the nanoscale is different from that at the macroscopic scale due to the increasing ratio of the surface to the volume. For nanostructural materials with a large ratio of the surface area to the volume, the surface effect can be substantial and can affect, for example, the Young’s modulus. In a new field of nanomechanics, an interesting problem is to determine how mechanical properties change on the nanometer-scale as the size varies. The dependence of the Young’s modulus with diameter and in particular an increase at smaller diameters has been determined previously for nanowires made of different materials [7-9]. Several cases in which the elastic modulus of nanowire of different
Materials or nanotubes is independent of diameter have been also reported [10-12], and no generally-applicable conclusions can at present be drawn.

Studies of friction began at least 500 years ago, with the work of Leonardo da Vinci on the laws governing the motion of blocks on a planar surface. However the first to published his work was Amontons in 1699. He reported that the friction force is proportional to the normal load, the proportionality coefficient being the coefficient of friction, and that the friction force is independent on the apparent area of contact. A more successful model was that of Bowden and Tabor in the twentieth century who modeled the contact between two surfaces as an array of micro-contacts, and who stated that the friction force is not proportional to the normal load but varies with the true area of contact, i.e. the sum of all the active micro contacts. The coefficient of proportionality is a fundamental interfacial quantity, the shear strength, which can be in some cases pressure dependent [13-14]. In the absence of precise measurement methods, continuum mechanics models have been proposed to derive the true area of contact. For an elastic contact between a sphere and a flat surface (single-asperity contact), there is a nonlinear area-load dependence. Greenwood and co-workers have shown that in the case of multiasperity contact, only for certain statistical distributions of the individual surface asperities, a linear relation between the true contact area and load can be found, so in such a case the two theories of Amontons and Bowden and Tabor are not in conflict [3].

Since the invention of the Atomic Force Microscope (AFM), considerable progress has been made in understanding friction at atomic scale thanks to studies of friction between AFM tips and different substrates. AFM has become an important tool in the new emerging field of nanotribology. By using an AFM tip, which can be modeled as a single-asperity, in contact with different substrates, it can be proven that at the nanometer scale the friction is indeed proportional to the true area of contact [15, 16]. It has been observed that the tip shape and composition are critical in determining the frictional behaviour in this type of experiments with the AFM. To eliminate the uncertainties due to the tip shape, another type of experiment has been performed with the AFM using its ability to modify surfaces, and to manipulate objects on substrates. Experiments have been performed in which islands of different materials or nanocrystals are pushed with the AFM tip so that they slide on the substrate, and the friction between them and their substrate has been studied [17-19]. These studies link the observed friction behaviour to the fundamental, atomic-scale properties of the contact surfaces: for example, it has been observed that friction can be much smaller for particular crystal orientations or when the two surfaces are in incommensurate contact, where there is a mismatch between the two crystal lattices [17, 20]. The environment (pressure, humidity) as well as the
The chemical nature of the substrate can also influence friction between the tip and the substrate [21, 22].

One of the most common everyday life experiences with friction at the macroscopic scale is the occurrence of static friction: the force required to initiate any motion is always larger than the force required to keep an object in motion. Static friction can be quite variable and can also depend for example on how long the two surfaces have been in contact. A closely associated phenomenon is stick-slip motion, when the movement can be described as repetitive steps of sticking and slipping at the interface, producing for example the screeching noises associated with car brakes or the sounds of bowed string instruments. Stick-slip motion has been observed on many length scales, including at the atomic-scale in the AFM, where the individual slips are the size of the atomic spacing in the crystal lattices [23] and are determined by atomic-scale processes. At the macroscopic level however stick-slip behaviour is determined by the dynamic elastic response of the bodies. Because they are governed by fundamentally different processes, atomic-scale and macroscopic stick-slip often operate at quite different velocities.

In contrast to macroscopic stick-slip, in atomic-scale friction the interface is atomically smooth, and for many solid materials wear does not occur at all. A theory of atomic-scale friction in the absence of wear has been suggested by Tomlinson in 1929, involving dissipative excitations such as phonons that are generated at the moving interface. Phononic mechanisms of friction were first proven to exist experimentally by sliding of monolayers over a substrate [3]. Recently further good evidence has been published based on the modification of friction by a change in the vibrational properties of a surfaces due to a change in the termination of the substrate from hydrogen to deuterium [24]. The possibility of involving electronic excitations as a loss mechanism has been proposed, an increase in nanoscale friction being reported in the case of pn junctions [25]. When a bias was applied to the sample, an increase in friction was observed in the p-doped region, but not in the n-doped region. The mechanism for this increase is not clear, but present estimates of the contribution due to electronic friction (the drag force that results when charge carriers move in an electric field) are far too low to explain the result.

In small-scale devices, especially those with sliding interfaces such as actuators, positioning devices, and microgears, wear considerably decreases their life-time and reliability, or in a worst case adhesion and capillary forces stop them from working at all. It is therefore important to find ways to control or reduce friction and some interesting progress has been made in recent years in the field of applied atomic-scale friction. It has recently been shown that friction can be reduced by more than two orders of magnitude in a nanometer-scale contact by exciting the mechanical resonances of the
sliding system perpendicular to the contact plane [26]. Also, a transition from stick-slip motion with dissipation to continuous sliding produced by the decrease in the normal load on the contact has been reported [27] and a concept of “superlubricity” has been introduced related to the regime when the stick-slip instabilities do not exist and extremely small friction is present.

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. It is not yet possible even with the impressive progress in the field of nanostructures to replicate the atomic-scale features that determine 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 bridge the gap between the fundamental understanding that now exists at the atomic scale and what happens as objects become larger. As an experimental technique, our measurements allow us to study friction at these important intermediate length scales for specific types of nano-object, but they also allow us to address basic questions about the nature of friction at these length scales.
2. Sample preparation

2.1 Nanowire growth

Semiconductor whiskers (tapered nanowires) have been grown in a controlled way since the ‘60s and their growth was explained using the vapor-liquid-solid (VLS) model proposed by Wagner et al. [28]. Due to the supersaturation of the growth species dissolved in a metal droplet lying in contact with a semiconductor surface the nanowires will grow at the surface-droplet interface. The diameter of the grown nanowires is dictated by the size of the particles. Whiskers from the material combinations II-VIs (CdSe, CdTe, CdS…), and III-Vs (GaAs, InAs, GaP..), as well as single elements from group IV (Si, Ge, SiC) were all grown in the ‘70s. The diameter of the whiskers decreased from the order of micrometer down to 10 nm in the ‘90s when Hiruma et al. used Metal organic vapor phase epitaxy (MOVPE) to grow these NWs [29]. Nanowires can also be grown by Chemical beam epitaxy (CBE). A schematic illustration of the NWs growth is shown in fig. 2.1 [30].

In our case size-selected Au particles with diameters in the 20-80 nm range are deposited on InAs(111)B substrates using an aerosol deposition technique [31]. The sample is then transferred into the CBE growth chamber. Before growth the sample is heated under an As pressure. In this process the oxide is removed and also an alloy is formed between the Au particle and the substrate constituents necessary for the NW growth. Then the temperature is lowered and the growth species are introduced into the chamber. The growth species are dissolved into the molten metal particle via the vapor phase until supersaturation is reached and growth starts. The supersaturation is then maintained by a constant flow of material into the alloy. For growing pure InAs NWs used in most of the experiments, trimethylindium and tertiarybutylarsine are used as sources of In and As respectively [32,33]. Our NWs have a length as grown of 3-4 µm.
Figure 2.1. Schematic illustration of the whisker fabrication process. a) Deposition of Au aerosol nanoparticles  b) annealing step c) precipitation, growth of the nano-whiskers.

2.2 Carbon nanotube samples

Single-wall carbon nanotubes (SWNTs) have been produced by Chemical Vapor deposition (CVD). Our network partners at the University Rovira I Virgili in Tarragona provided us with purified carbon nanotubes in solution. For the purposes of the project we needed to have well-separated individual carbon nanotubes deposited on suitable substrates, and several methods of deposition were tested.

We found that the spin coating technique gives the best results whereas other methods mostly produced meshes of entangled carbon nanotubes. These were concentrated in particular areas leaving large portions of the sample uncovered. With the spin coating technique a more uniform distribution of individual or small bundles of carbon nanotubes on the whole sample was found. By performing multiple depositions in this way the density of carbon nanotubes on the substrates was increased until in the end a suitable density for experiments could be obtained.

2.3 Substrate preparation and deposition

The substrates used for our manipulation experiments were silicon wafers, capped either by a 330 nm thick thermal oxide layer or with a 120 nm coating of silicon nitride deposited by plasma enhanced chemical vapor deposition (PECVD). In some experiments the silicon oxide was ‘silanized’ as described below. All the substrates were patterned using e-beam lithography with a mixture of gold dots and location markers to allow us to easily identify and repeatedly re-locate individual nanowires. Nanowires were transferred from their growth wafers using a dry deposition method,
consisting of wiping them off from the growth substrate with a piece of cleanroom wipe and brushing off the wipe onto the patterned substrates. In order to find nanowires of interest optical reference images of a large set of areas on the sample’s surface were taken of each new sample using an Zeiss Axio Imager optical microscope. By triangulating nanowire locations from the e-beam defined gold positioning markers, it was also possible to use the relatively poor resolution of the built-in alignment microscope on our AFM to return to individual nanowires to perform repeated experiments.

To produce silanized silicon dioxide samples a method proposed in [34] has been used. From nanoimprint lithography (NIL) technology it is known that the anti-adhesion properties of Si or SiO$_2$-based stamps can be improved by binding fluorinated silanes covalently to the surface, which show a very weak van-der-Waals interaction with the imprint polymer. For embossing 10 nm size features is essential to employ monomolecular anti-adhesion layers. A vapor phase deposition is advantageous when the stamp features are in the nm-size range. The molecule that we use is Tridecafluoro-(1,1,2,2)- tetrahydrooctyl-trichlorosilane, named shortly F$_{13}$-TCS. Chlorosilanes react spontaneously with hydroxylated silicon or SiO$_2$ surfaces under elimination of hydrochloric acid, the reaction mechanism being shown in fig. 2.2.

![Reaction mechanism for the condensation of F$_{13}$-TCS on Si or SiO$_2$ surfaces.](image_url)

It is important to perform the reaction in a water-free environment (in our case, inside a glove box), to avoid spontaneous polymerization. The sample is cleaned and dried and transferred into the glove box under nitrogen atmosphere. The wafer is placed on a hotplate into a Petri dish whose lid has an injection hole. After the hotplate is heated up to 250°C, some microlitres
of F$_{13}$-TCS are injected through the hole which afterwards is covered with a glass slide. The droplet starts to evaporate and a monolayer will be formed on the sample. After 2 hours reaction time the sample is washed off in hexane to remove the excess of F$_{13}$-TCS to avoid subsequent polymerization. The reaction setup is shown in fig. 2.3.

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{reaction_setup.png}
\caption{Reaction setup for the silanization process.}
\end{figure}

3. Characterization and manipulation of nano objects

3.1 Atomic force microscopy

Atomic Force Microscopy (AFM) is a technique that is part of the large family of Scanning Probe Microscopies. It was invented by Binnig, Quate and Gerber in 1986 [35]. The technique was proposed to surmount a drawback of the previously invented Scanning Tunneling Microscope [36] which could image sample surfaces with atomic resolution but which was limited to conductive samples. With the AFM new kinds of samples could be studied and in a variety of environments: air, liquid, and vacuum.

In AFM, a sharp tip mounted on an elastic cantilever beam is scanned over the sample surface using a piezoelectric scanner. A laser beam is reflected off the back side of the cantilever and falls on a quadrant photodetector. During scanning voltages are applied to the piezoelectric tube in order to move it in the direction normal to the surface and maintain a constant deflection of the cantilever. The displacements of the piezo tube at each (x,y) point are recorded and displayed on the computer as a topographical image (fig. 3.1). The microscope is typically run in one of two
modes: in contact mode where the tip makes a hard contact as it moves across the surface, or in intermittent contact mode ("tapping mode") where the tip oscillates vertically, and spends most of its time further away from the surface. Contact mode has the disadvantage that is not suitable for soft samples or for imaging particles that are weakly bound on the substrate because the cantilever is always in contact with the surface and the lateral forces can be very high. In intermittent contact mode the cantilever is oscillated by the piezo tube, with an amplitude in the range of 20 - 100 nm, and is in contact with the substrate only at one end point of the oscillation, thus minimizing the lateral forces.

![Schematic illustration of TappingMode AFM.](image)

**3.1.1 Stick- slip on the atomic scale**

One year later after the invention of the Atomic Force Microscope, the ability of the AFM to measure forces was applied by Mate et al. to image atomic-scale variations of the friction force as a tungsten wire scans over a graphite surface. Friction Force Microscopy (FFM) was thus born. In spite of the high load force applied, due to the dimensions and high spring constant of the probe wire, atomic resolution in the spatial variation of the friction force on a HOPG sample was obtained [37]. Figure 3.2 illustrates how the friction force changes as the sample is scanned back and forth in the
direction perpendicular to the long axis of the cantilever. The figure shows three friction loops measured at different applied loads.

![Friction force loops](image)

Figure 3.2. Friction force loops for three different loads for a tungsten wire scanned laterally over a graphite surface. The lower curve shows the stick-slip behaviour most clearly [23].

The friction loop can be explained in the following way. At the beginning of each scan the tip first “sticks” to the sample by static friction. The cantilever bends more and more due to the sample movement as the scan proceeds. While the lateral force is lower than the force needed to shear the tip-sample junction, it increases linearly with the scanned distance. At a certain critical point, the lateral force exceeds the holding force of static friction, the junction is sheared, the tip “slips” into a new equilibrium position, and the lateral force decreases. In the new position, the tip “sticks” once more until the critical force is again reached, followed by another “slip”. This process repeats itself as long as the scanning direction is not reversed. If the scanning direction is reversed the tip usually unbends, then “sticks” and bends in the new direction (so the signal changes polarity) until the critical force is reached. The stick-slip process is then repeated with the
opposite polarity being observed in the friction loop. The enclosed area has dimension of energy, and this area represents the energy dissipated during each scanning cycle. It is clear that the sliding process is not uniform, but instead the frictional force displays a corrugation with an approximate periodicity of 2.5 Å, the same periodicity as the honeycomb structures of the graphite surface. If an area of the sample is scanned, friction force images can be obtained, like the one shown in fig. 3.3 [23]. The dimension of the image is $2 \times 2$ nm and shows again the variation of the friction force corresponding to the atomic periodicity of the graphite surface.

![Friction force image](image.png)

Figure 3.3. Friction force image recorded with a tungsten wire on a graphite surface. The spatial variation of the lateral force has the periodicity of the HOPG surface [23].

### 3.2 Manipulation technique

The AFM used for the manipulation is Dimension 3100 from Veeco, equipped with Nanoscope IIIa controller. It is located in a clean room suite, which provides a humidity and temperature controlled environment. Since our AFM software does not include a manipulation option, several manipulation techniques were tried using the modes that were available. Eventually, a successful technique was found in close collaboration with the application scientists from Veeco. First the nano object of interest is found and an image is taken in intermittent contact mode. Then the position and orientation of the manipulation force is decided, and the scan adjusted so
that the tip is scanning back and forth across the wire at the correct place and angle. During the actual manipulation the scanning is performed on a single scan line, i.e. the image slow scan axis is disabled. A mode called “Retrace lift” is then set. This option is used for example in MFM (Magnetic force microscopy) and EFM (Electric force microscopy) in which the tip first acquires topographical information from the surface on the forward, “trace” scan, and then is lifted higher above the surface on the backwards, “retrace” scan while recording a magnetic or electric signal. This mode can also be used to avoid tip to sample contact during a retrace scan while coming back to the start point of a new line. In our modified method the tip scans in tapping mode on the trace scan, while in the retrace scan the oscillation is stopped, the feedback is turned off and the cantilever relaxes to an average position above the substrate. The controller moves the tip back along the same path as was measured on the trace scan, but with a vertical shift whose value is set in the “Lift scan height” parameter. By introducing a negative value in the “Lift scan height”, the tip is actually lowered towards the surface and thus presses harder into the surface for higher values of the parameter. As the tip scans back and forth along a single scan line, the negative lift scan height is increased in small steps, typically 0.1-0.2 nm, so that the force applied by the AFM tip increases until a shift in the “trace“ signal is observed which means that the nano object has been moved. An illustration of the manipulation procedure is shown in fig. 3.4. In most cases the manipulation force is increased until a significant displacement of the nanowire has been observed and then an image of the same area is taken in normal imaging conditions. To perform repeated manipulation experiments a new position where the force should be applied is set and the procedure is repeated. The scanning speed of the AFM tip during manipulation was typically of the order of 1-3 μm/sec.

This procedure has the advantage that the manipulation force is applied only in one direction and the object is not moved back and forth. It is also more “gentle” than the method of simply dragging the tip across the surface in contact mode [38] as the tip follows the same height contour as in the forward scan. Finally, the applied force can be increased in very small increments, with good visual feedback as to the position of the nanowire under manipulation. Although nanowires have been manipulated in a controlled way and with a high degree of delicacy, one disadvantage was that we could not determine the lateral force applied during manipulation. However the normal force applied by the AFM tip to the NW-substrate system could be determined from a force-distance curve performed close to the object of interest, knowing the nominal spring constant of the cantilever provided by the manufacturer. In these experiments we have used normal intermittent contact mode silicon probes with rectangular cantilevers from Veeco or Nanosensors, with a spring constant in the 20-40 N/m range.
Figure 3.4. Schematic illustration of the manipulation procedure
a) “trace” scan; b) “retrace” scan.

4. Results and discussion

4.1 Manipulation of carbon nanotubes

Individual or small bundles of Single-wall carbon nanotubes have been manipulated using the procedure described in section 3.2. Figure 4.1 a) shows an AFM image in “intermittent contact” mode of a single-wall carbon nanotube of about 1.4 nm diameter in the upper part of the image, while in the lower part of the image we can see a small bundle of single-wall carbon nanotubes with a diameter of about 4.8 nm. The individual nanotube has been manipulated with the AFM tip, the force being applied approximately in the center of the wire. The result of manipulation is shown in fig. 4.1 b). It can be seen that the nanotube has been bent into a sharp curve and a large portion of it has been dragged behind the tip like a rope.
We found that it was very difficult to manipulate single-wall carbon nanotubes in a controlled manner, because their diameter is much smaller (around 1-2 nm) than the diameter of the AFM tip (15-20 nm for a new tip). The behaviour that we saw for all single-wall carbon nanotubes was one which we later characterized for nanowires as “wet spaghetti” - as is described in section 4.2. This behaviour is identical to that observed for nanowires which are long, thin and relatively flexible. From this behaviour classification we concluded that friction with the surface dominates the manipulation of these nanotubes. It became obvious that successful experiments on carbon nanotubes would require an understanding of, and control over, friction which at that stage we did not have. We decided therefore to concentrate on manipulating semiconductor nanowires, where a much richer spectrum of behaviour could be observed, and quantitative results could be derived.

4.2 Friction properties of nanowires - a qualitative view

In this work approximately 150 InAs nanowires have been manipulated on three different substrates in one or up to 13 manipulation steps. In total around 500 push steps have been performed. The practical experience gained during this work was an important factor in performing controlled manipulation experiments as well as in understanding the nanowires’
behaviour and in the planning of new experiments from which new and valuable information could be extracted.

In fig. 4.2 is shown a well-controlled AFM manipulation experiment on a nanowire of about 40 nm diameter on a silicon dioxide substrate. Initially the upper end of the nanowire is in contact with a gold dot and its middle section lies alongside and in contact with a shorter nanowire fragment. In all the illustrations of manipulation shown here the arrow indicates the direction upon which the manipulation force is applied, the result of the manipulation being shown in next image in the series. In this case the NW is first separated from the smaller wire (step b), then the NW is passed smoothly over the top of two gold dots thus forming a bridge (step c), then it passes down onto the substrate again it bends more until finally it contacts another gold dot at the initially free end (step f). From this experiment we cannot extract quantitative information about the NW interaction with another nanowires or with the gold dots that was the main motivation for our project. However it could be seen that the NW-NW interaction is weaker than the friction between the NW and the substrate. It could also be seen in other experiments that there is an attractive interaction of the NW with the gold dots, however this interaction is in most cases overwhelmed by friction with the substrate, because the nanowires would adopt a very similar bent shape even in the absence of the gold dots.

Figure 4.2. Illustration of a manipulation experiment performed with a 40 nm diameter NW on silicon/silicon dioxide substrate.

Because friction with the substrate proved to be quite high on silicon dioxide we decided to perform manipulation experiments on silicon nitride
substrates and silanized silicon dioxide. Both of these were known to have lower macroscopic coefficients of friction with respect to different materials. Also, unlike the hydrophilic oxide and nitride surfaces, the silanized samples are strongly hydrophobic, and thus would allow us to study the influence, if any, of capillary forces from the always-present absorbed water layer on the nitride and oxide surfaces.

By performing measurements on wires of different length and diameter, a spectrum of four behaviours was found on all three substrates and with this conceptual framework the friction regime of operation of any experiment could be identified [39]. The first behaviour observed is the “rigid-stick” one, when the friction is relatively weak and the wire is comparatively stiff. Figure 4.3 shows this type of behaviour in which a short 26 nm nanowire is translated and rotated on a silicon dioxide substrate and does not perceptibly bend.

Figure 4.3. Illustration of the “rigid-stick” behaviour in a 26 nm diameter wire on silicon/silicon dioxide substrate.

The second behaviour is the one of a “not-so-rigid stick” in which the wire still moves as a body, but is flexible enough to allow friction with the substrate to induce some small bending of the wire. This behaviour is illustrated in fig. 4.4 in a 48 nm diameter wire on the oxide substrate. It can be seen that by applying the manipulation force in the middle of the wire, it can be made to translate with a constant shape (steps d and e), the ends being bent back behind the tip. We will come back to this phenomenon in
section 4.4.2. In the final step (f) it can be seen that the nanowire is slightly more bent when it is pushed against the gold dots. This is proof that as mentioned above, the gold dots provide some degree of pinning of the wire that resists elastic forces.

The third class of behaviour is that in which there is no overall motion of the wire, but only bending. Here the friction with the substrate is stronger (or, equivalently, the wire is less stiff). In this case pushing the wire near to one end will bend it in the direction of the push, but the other parts remain anchored on the substrate and do not move. If pushed in the middle a nanowire in this class usually breaks. The behaviour is illustrated in fig. 4.5 where a 54 nm diameter wire lying on a silicon nitride substrate is pushed at the ends. They will bend more and more forming an ever tighter curve until finally the nanowire is broken.

Figure 4.4. Illustration of the “not-so-rigid” stick behaviour on a 48 nm diameter wire on a silicon dioxide substrate. Two steps of manipulation have been omitted.
Figure 4.5. Illustration of the third behaviour in which the wire is bent without moving as a whole. This case is a 54 nm diameter wire on a silicon nitride substrate. Two steps of manipulation have been omitted.

The fourth behaviour of the spectrum is that which we call the “wet spaghetti” behaviour. Here the wires are extremely flexible and thus friction with the substrate dominates and only local bending of the wires can be produced by manipulation. The behaviour is shown in fig. 4.6 on a tapered wire of diameter ranging from 28 – 44 nm on a silicon nitride substrate.

Figure 4.6. Illustration of the “wet spaghetti” behaviour on a tapered wire with diameter ranging from 28 – 44 nm on a silicon nitride substrate.

The spectrum of behaviours is governed by several competing properties of the nanowire and the substrate, such as nanowire stiffness and friction between the nanowire and the substrate. Passing from the “rigid-stick” behaviour to the “wet spaghetti” behaviour the relative friction with the
substrate increases and the relative stiffness of the nanowire decreases. The relative stiffness of the nanowire can be tuned in two ways. First the intrinsic material stiffness can vary, as a less stiff material will show spaghetti-like behaviour at lower values of the surface friction. Second, and more interesting, we found that for any particular combination of material in the wire and substrate the behaviour is determined by the aspect ratio (length/diameter) of the wire. Low aspect ratio nanowires (short and thick) (see fig. 4.3.) show a rigid-stick behaviour, and are moved as inflexible units with friction playing only a minor role. High aspect ratio nanowires (long and thin) (see fig. 4.6.) are easily dominated by friction and only local changes in shape can occur, with the wire behaving like over-cooked spaghetti. A similarity in behaviour was observed between single-wall carbon nanotubes and long and thin nanowires, both of them being very easily dominated by friction (fig. 4.1. and fig. 4.6.).

In fig. 4.7 is shown a summary of the spectrum of behaviours.

<table>
<thead>
<tr>
<th>Rigid Stick</th>
<th>Not-so-rigid Stick</th>
<th>Local Bending</th>
<th>Wet Spaghetti</th>
</tr>
</thead>
</table>

Figure 4.7. Surface friction- summary.

The spectrum of behaviours passes from one extreme to another, from a behaviour in which the wire moves as a whole, translating and rotating on the surface due to a relatively high stiffness, to a behaviour in which the friction with the substrate dominates and only very local deformations of the wire can be induced. The spectrum can be traversed in three ways. First, by increasing the intrinsic material stiffness we can pass from the wet spaghetti behaviour to the rigid-stick one. Second, when using surfaces with very low relative friction any given wire will be more likely to move like a stick, while on high relative friction surfaces the same wire will be subject only to local bending. Finally, the aspect ratio of the wire can be varied, very small and thick wires (low aspect ratio) showing rigid stick behaviour while very long and thin ones (high aspect ratio) show more wet spaghetti behaviour.
We can thus predict that long and thin nanowires from a stiffer material will behave like short and thin wires from a more compliant material.

### 4.3 Quantitative measurements of friction and shear stress on nanowires – analysis method

We have developed a method to deduce the friction force per unit length and the shear stress between InAs nanowires and a silicon dioxide substrate by analysing AFM images of the bent nanowires. The method, which is described in ref. [40], is based on the fact that for a bent nanowire on a substrate there is an equilibrium between friction with the substrate and internal elastic stresses.

Figure 4.8 illustrates the analysis. As usual, the arrow indicates the place where the manipulation force was applied. By measuring the radius of curvature at the position where the wire is most strongly bent, the maximum friction force or shear stress can be determined using standard elasticity theory. Crudely, if the radius of curvature of the bent wire is small, the friction force must be large because the wire would otherwise straighten out. If the radius of curvature is larger then friction with the substrate must be smaller. Experimentally, measuring the strength of the friction force becomes a question of ensuring that we have bent the wire as much as possible without breaking it, or causing it to move as a whole.

![Figure 4.8](image)

**Figure 4.8.** Illustration of the method to measure the friction force per unit length and the shear stress on a bent wire with the AFM tip.  
a) Before manipulation  b) After manipulation.
The friction force is deduced as follows. The elastic energy $U$ stored in a wire is given by the formula

$$U = \frac{YI}{2} \int \frac{1}{R(z)^2} dz,$$

where $R(z)$ is the radius of curvature at a location $z$ along the wire, $I$ is the geometric moment of inertia, $Y$ is the Young’s modulus and the integral is performed over the length of the wire. For a hexagonal cross section, which is known to be the case for this type of nanowire [41], the moment of inertia is related to the diameter $D$ of the wire by the formula

$$I = \frac{5\sqrt{3}}{144} D^4,$$

where $D$ is defined as being the distance between two parallel edges of the hexagon. Assuming a global-most bent state in which the wire forms a circle, the formula (4.1) gives

$$U = \frac{\pi YI}{R}.$$

The force acting over the whole length of the wire can be calculated by differentiating (4.3) with respect to $R$ and taking the minus sign. From that the force per unit length can be determined as

$$F = \frac{YI}{2R^3} = \frac{5\sqrt{3}YD^4}{288R^3}.$$

From equation (4.4) the force per unit length measured in units of pN/nm can be rewritten using appropriate dimensions as

$$\frac{F}{(\text{pN/nm})} = \frac{5000\sqrt{3}}{288} \frac{Y}{\text{GPa} \ (\text{D/nm})^4}.$$

The diameter of the nanowires is determined from the height profiles obtained by AFM. The radius of curvature in the most bent state has been determined from the AFM micrograph of the wire after manipulation taking the radius of the inner and outer circle positioned in the most curved part of the nanowire, as it is illustrated in fig. 4.8. The radius $R$ was taken to be the mean value of the radii of the inner and outer circles. Because to date the elastic constants of these wurtzite-structure InAs nanowires have not been
measured, we have assumed in our analyses a value for the Young’s modulus of $Y=58$ GPa, which is the value for bulk zinc-blende InAs.

The shear stress $\sigma$ can be obtained by dividing the expression in (4.5) with the transversal contact length of the nanowire, which is $D/\sqrt{3}$. It was assumed that the nanowire is lying with the flat side on the substrate after AFM manipulation. Support for this assumption comes from observations of the substrate surface after manipulation of nanowires which have been allowed to oxidize on the silicon dioxide substrate, the period of time from the deposition on the substrate to the manipulation experiments being of a few months. Figure 4.9 shows a 42 nm diameter nanowire which has been bent in the usual way. In the black-and-white version in fig. 4.9 c) can be seen two faint traces on the surface corresponding to the position where the nanowire lay on the surface before manipulation. The separation between these faint traces of oxide, 1-2 nm in height, is comparable to the calculated width of one side of the hexagonal wire, and they are due to oxide formed at the edges of the nanowire before manipulation. This could also be seen from the fact that the force required to “break” the oxide and move the wire for the first time was higher than the force required to move the wire subsequently.

Figure 4.9. Illustration of the orientation of the nanowires on the substrate. a) NW before manipulation, b) After manipulation, c) Black and white version of b) in which the greyscale has been adjusted so that the two traces of oxide can be seen.

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Further, conclusive, evidence for the hexagonal cross-section of the NWs and for the positioning of the NWs on the substrate is shown in fig. 4.10. This is an SEM micrograph showing a thick wire close to a thinner one lying on a Si$_3$N$_4$ substrate. It can clearly be seen that the larger diameter wire has a hexagonal cross-section and is lying with one flat against the substrate. The shape of the smaller wire is just below the spatial resolution of the SEM, here degraded by the wire’s proximity with the insulating silicon nitride substrate.

![Figure 4.10. SEM micrograph of two InAs nanowires lying on a Si$_3$N$_4$ substrate. (Image made by Aline Ribayrol)](image)

From a number of bent wires with the diameter around 40 nm, the friction force per unit length has been calculated and a value of the order of a few tens of piconewtons per nanometer was found [40]. This is equivalent to saying that in order to bend a 1 µm length of nanowire a force of the order of a few tens of nanonewtons is required. The shear stress derived for this set of nanowires had a value of $\sigma = (0.99 \pm 0.25)$ MPa.

Software has been developed in our group to measure more precisely the radius of curvature at the maximum bending point, so as to check the precision of our analysis done “by-eye” and eliminate bias and human errors when drawing circles at the point where the wire appears to have its maximum curvature. The program finds the backbone of the wire using a differentiation filter to identify those pixels where the local gradient is zero. It then draws a smooth curve through those points at sub-pixel resolution, using the Polygonal Line Algorithm to estimate the principal curve of the set of pixels forming the backbone [42]. This procedure eliminates errors caused by tip-sample convolution, which is important because in many of our images the apparent width of the wires in the AFM topograph is many
times larger than their actual size, which leads to an infilling of the curved wire.

We have performed an initial analysis of our data using the method of drawing circles and afterwards the same data has been processed using the software. In the “by eye” version the curvature and thus the bending is underestimated and so the friction force appears slightly smaller than in the computerized version. We did not observe large differences in patterns and trends in the data processed with the two methods, and it was reassuring to see that we could trust a method that might appear in the first instance to be less “scientific”. As a further check, a calibration of the AFM scanner has been performed and the horizontal distances as well as the nanowire heights have been corrected.

4.4 Measuring friction

4.4.1 Static friction

The analysis presented in section 4.3 has been used to investigate in detail the behaviour of the nanowires on three different substrates: silicon dioxide, silanized silicon dioxide and silicon nitride. By performing experiments in two different ways we have also been able to measure static and sliding friction separately. In this section static friction experiments are described in detail.

In the quantitative experiments described in the previous section we were in fact measuring static friction. Because one end of the wire is fixed in these experiments, and because stresses in the wire wish to move it against the direction of forced motion, the wire must pass through a period of zero velocity when released by the tip. Once the tip has started to push the wire there are two possible ways it can release it again. In the first, a random vibration makes the tip jump over the wire and leave it behind. This is more likely with small diameter wires, and they can often be seen to move in a series of small steps during the manipulation procedure as each trace-retrace scan pushes them a little further before letting them go. In the second sort of release, the wire bends enough that the AFM tip can simply slide past. This second sort of release might be expected to produce more reliable results for static friction, by ensuring that the wire is either still or moving sufficiently slowly that the mechanism for creating static friction has time to operate. However, as is shown below, collating our results for nanowires of different diameters shows that both sorts of release give values for friction that are consistent with each other. In fact, it is possible that the wire can actually be bent beyond the position at which it is found when imaged after the
manipulation step. In this case, after the tip has passed it will relax back into an equilibrium position in which the friction force balances the elastic restoring force within the wire. Even in cases where we suspect this has occurred, the value for static friction agrees with other forms of release, i.e. the relaxation of the wire is slow enough for static friction to establish itself. This seems reasonable as relaxation is likely to be overdamped since inertia is negligible at these length scales.

Experimentally, the wire of interest is pushed close to its ends, at a typical distance one fourth up to one eighth of the whole length of the wire. The manipulation force is increased by increasing the negative lift in small steps until a significant change in position of the wire is observed, if this is not achieved upon the first movement of the NW. Then the wire is imaged and another place is chosen to apply the manipulation force and the procedure is repeated.

Figure 4.5 shows a typical static friction experiment. The static friction force per unit length was calculated from the step just before the wire was broken, fig. 4.5. e), which we take to be the most bent state of the wire. For a majority of the wires that have been manipulated we have tried to bend them into or as close as possible to the most bent state. Another example is shown in fig 4.11 where a thin NW, 25 nm in diameter is pushed on a silanized silicon dioxide substrate. The first attempts to coax it into a most-bent state break it, but after it has been broken (d) one fragment is then pushed in order to obtain an “U” shape, which is taken to be the most bent state. Figure 4.11 f) has been used to determine the maximum static friction force per unit length. Obviously there is an element of judgement in deciding where and how to manipulate a given wire, and in deciding whether a wire is as bent as it can be without breaking or moving it as a whole. Experience gained from performing many such experiments - often without contributing a useful friction value - is of great assistance when making this judgement.
4.4.2 Sliding friction

In a sliding friction experiment the nanowires of interest are pushed at their centre in consecutive steps until significant movement of the wire is seen. An image is then taken to see the result of manipulation. In most cases after applying enough force to displace the nanowire the sliding process occurs in small steps which are seen as a series of shifts in the trace signal while keeping the force constant. In contrast, in most static friction experiments the wires bend in single, large shifts, and the force usually needs to be increased in order to bend the wire further. We take this as a sign that in a sliding experiment the release mechanism is the first one discussed above, where the tip jumps up over the wire; while in a static experiment, the release mechanism tends to be of the second type.

An example of a sliding experiment is shown in fig. 4.4 c)-e) where it can be seen how the wire keeps an almost constant shape as it moves, and so all parts of the wire are moving with an uniform speed and direction on the surface. As we don’t see kinks and the curves are smooth, the friction is distributed uniformly over the whole length of the wire. The resulting curvature is therefore set by the coefficient of dynamic, sliding friction. Figure 4.12 shows another NW, 45 nm in diameter, on a silanized substrate, which has been manipulated in a sliding friction experiment in steps c)-e).
The curvature typically remains the same in these kinds of sequences of manipulations, and the calculated sliding friction keeps a constant value.

The value for the friction force is calculated in the same way as the static friction. The only problem is that it is important to ensure that the wire is translating smoothly with a constant shape, and that it has translated far enough to adopt its final, stable configuration. The first two jumps of the wire in fig. 4.12 are examples of movement that cannot be used to derive values for static or sliding friction. The whole wire moves, and the release mechanism is uncertain, so it is not possible to assign a value for static friction as it is not known which parts of the wire are stationary and at what point during the motion. On the other hand, the movement is a combination of translation and rotation, so different parts of the wire will experience sliding friction acting in different, unknown directions, which makes it impossible to apply the analysis based on curvature to extract a value for sliding friction. Typically, analysis of the curvature after manipulation steps like this gives a value that lies between those for pure sliding or static friction.

Finally, it should be mentioned that it is important to perform sliding experiments on a wire that is not too long. With long wires, the total friction integrated along the wire away from the push point is sufficient to cause more bending than local friction alone. That is, the curvature at the centre of the wire becomes an elastic response to a torque transmitted from the ends of the wire.

Figure 4.12. Manipulation experiment on a 45 nm diameter NW on silanized silicon dioxide substrate. Steps c)-e) show a sliding friction experiment.
4.4.3 Static and sliding friction on the same nanowire

To compare sliding and static friction it is extremely useful to perform both types of experiments on the same wire. This eliminates complications caused by unknown aspects of the wire’s structure, and ensures that the sliding and static values are obtained on the same area of the substrate, which avoids differences caused by inhomogeneities in the surface structure or its chemical composition. Figure 4.13 shows a typical experiment performed on a 35 nm diameter NW on a silanized substrate. The manipulation sequence was longer and several intermediate steps have been omitted for clarity. After the wire has been found in a position shown in a) it was first opened up to give b), this being followed by steps c)-e) in which the wire is translated across the surface while keeping a constant shape determined by sliding friction. The wire was moved typically up to the edge of the initial image and so to keep the size of the image constant, the newer images are shifted with an offset with respect to the initial one. After sliding, the wire was bent at one end the result being shown in 4.13 f) and the curvature is determined in this case by the static friction. We can see how with static friction the radius of curvature of the wires is noticeably smaller than the radius of curvature of the same wire when sliding. As the wires adopt a tighter curve in static friction experiments than in sliding friction experiments this means that the static friction is higher than the sliding friction according to equation 4.5.

![Figure 4.13. Manipulation experiment on a 35 nm diameter NW on a silanized silicon dioxide substrate. The first 6 steps in the series have been omitted. After the wire has been opened up, steps b)-d) show a sliding friction experiment while the steps e)-f) show the static friction.](image)
4.4.4 Quantitative friction measurements on InAs nanowires on Si₃N₄

The method developed in ref. [40] to calculate the friction force per unit length of InAs NWs lying on a Si/SiO₂ substrate was applied to study in detail the friction between InAs NWs and a Si₃N₄ substrate. We chose silicon nitride because from macroscopic studies it was known that it has lower friction than silicon dioxide. A wide range of NW diameters was investigated (20-80 nm) and the friction force per unit length was determined for both static and sliding friction using the experimental methods described above.

Figure 4.14 shows the measured sliding and static friction force per unit length as a function of the wire diameter. The friction is shown in logarithmic scale. For large diameter wires there is a clear difference between sliding and static friction of two or even three orders of magnitude. For wires below around 40 nm diameter the sliding friction values jump upwards to mix with those for static friction. We interpret this as a transition from pure sliding to stick-slip motion where although the wire is moving as a whole, its shape is determined by the static friction which dominates between the jumps of the slip phase when the wire “sticks” to the substrate.

There is an upward trend in the static friction data, i.e. the friction increases with the nanowire diameter. We have assumed a constant value for the Young’s modulus, and the observed trend could be due to a rise in the Young’s modulus for smaller diameter wires, which would lead to a less-bent wire and hence a lower derived value for the friction. However, the change in the apparent Young’s modulus of the wires would have to be one order of magnitude over the size range investigated, which is too large to be explained by a likely models such as a surface reconstruction, or a stiff oxide shell surrounding the nanowire core. Either a more exotic process is changing the Young’s modulus or, which seems more likely, the friction coefficient is changing due to a variation in the contact pressure from small to large nanowire diameter.
It is worth noting that the relatively large spread in the data that can be observed, particularly at small nanowire diameters, is an ensemble variation. For any single wire, repeated measurements of friction will give in the worst case a factor of two variation, but usually much smaller. The fact that the variability in the data is increasing for small diameter nanowires suggests a transition from a distributed model of friction to one where a few point contacts dominate, and so the details of individual micro-asperities influence the whole rather than being averaged away.

Compared with the results on silicon dioxide sample, the silicon nitride had a higher friction. This was surprising as it is known that silicon nitride has low macroscopic coefficient of friction with many materials and is widely used in nanotechnology whenever a hard, inert, non-conductive, stable material is required.

Is hard to place our case of investigation in one of the two extreme cases of macroscopic or atomic-scale regime because characteristics of both are present. For example, in the absence of adhesion and chemical bonding a change in the friction with normal load is a macroscopic phenomenon. In point-contact studies the friction is only dependent on the true contact area, which for our hexagonal wires should only vary linearly with the nanowire
diameter. On the other hand, in the macroscopic regime such a large difference between sliding and static friction has not been previously observed, but such differences have been seen in atomic-scale friction.

### 4.4.5 Friction measurements on InAs nanowires on three different substrates – a comparison

We have investigated friction for a wide range of nanowire diameters on three different substrates, SiO$_2$, silanized SiO$_2$ and Si$_3$N$_4$. The results are shown in fig. 4.15. We observed the same general features as were seen for nanowires deposited on the nitride substrate, discussed in the previous section and shown in fig. 4.14. The upward trend in the data, and the spread in the data which reduces at larger diameters are observed once more, but most surprising is that the transition to stick-slip motion occurs at the same nanowire diameter for all three substrates. Such transitions have been observed but as a function of applied load [27], scan speed or scan direction with respect to crystallographic directions [2], but in our case the transition seems to be a spatial effect related to the size of the contact area. It is particularly intriguing that the transition occurs at about 40 nm diameter even on the silanized SiO$_2$, where the absence of a water film might be expected to shift a threshold determined by, saying, the contact pressure. It is intriguing that this transition occurs at a size where the zero-bias conductivity is seen to drop substantially in transport measurements [43], which suggests that it may be related to the wires’ electronic structure.

The ensemble spread in the data was observed again but is not so pronounced as with the nitride. We must point out however that on silicon nitride we have investigated a much larger number of cases.

We observed also some differences for the silanized substrate compared to the others. One difference is that the sliding friction on the silanized substrate is lower than for the other substrates once we are out of the stick-slip regime. Technologically, this makes silanized surfaces the most promising for our original goal of self-assembly. Another interesting behaviour not seen on other substrates is that if we exceed the maximum friction in a static experiment the wires can open up. This also may be a consequence of the very low values for sliding friction. For wires with diameters larger than 40 nm, we can’t perform static friction experiments at all because with the lengths of wire available to us we always move the whole wire: we cannot get out of the rigid stick or semi-rigid stick regime. Finally, it is a surprise to us that the static friction is of the same order on the silanized substrate as for the other ones, as we thought beforehand that the
reduction of sliding friction would be accompanied by a similar reduction in static friction.

![Figure 4.15](image)

Figure 4.15. Friction force per unit length vs. NW diameter for InAs NWs deposited on Si/SiO₂, silanized SiO₂ and Si₃N₄ substrates.

From these intensive measurements of friction between nanowires on different substrates we have gained some important knowledge which will be useful when designing self-assembly environments. If we want the nanowires to move easily across the surface while seeking a trap or positioner and not to be pinned by friction, it is best to use silanised substrates and larger diameter nanowires as they show the lowest friction. We plan to use this in some controlled vibrational experiments, in order to achieve self-assembly.

4.5 Conclusions

A detailed theoretical interpretation of our data is complicated by a range of unknowns, but the geometry invites analysis in terms of a set of point-contacts distributed over the length of the wire. Independent measurement of, for example, the Young’s modulus for these wires would be of great
assistance in eliminating some possible explanations for the trends in our data.

The transition from pure sliding to stick-slip motion at what appears to be a critical nanowire diameter is the most intriguing aspect of our data. This might be related to a spatial characteristic of contact between the nanowire and the substrate. Or it might be a signature of an electronic component to the friction, where the change in the wire’s electronic structure is reflected in the dissipation of energy as it moves. Finally, it may reflect a critical dimension at which the contact points spread out along the length of the nanowire start to act as individuals and not as part of an average.

We have achieved an experimental test bench for studying friction on the mesoscopic scale. We can observe and measure friction for extended contacts between nanowires and their substrates. The technique allows us to study both static and sliding friction in a quantitative manner, and can easily be extended to a wide range of materials and environments. For the InAs wires we have studied on our three substrates there has been both confirmation of our expectations, and few surprises. There are clear trends and thresholds in the variation of friction with nanowire diameter which beg for further clarification.
References


