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AFM-based manipulation of InAs nanowires

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Abstract. A controlled method of manipulation of nanowires was found using the tip of an Atomic Force Microscope (AFM). Manipulation is done in the 'Retrace Lift' mode, where feedback is turned off for the reverse scan and the tip follows a nominal path. The effective manipulation force during the reverse scan can be changed by varying an offset in the height of the tip over the surface. Using this method, we have studied InAs nanowires on different substrates. We have also investigated interactions between wires and with gold features patterned onto the substrates.

1. Introduction
Nanowires (NWs) have for the past years attracted considerable attention due to their interesting fundamental properties and the exciting prospects for using these materials in future electronic and photonic applications [1]. For example, nanoscale field-effect transistors [2-4], inverters [5] and more complex logic gates [4] have been demonstrated using well-defined NW building blocks. Furthermore, it has recently been shown that it is possible to form heterostructures in NWs [6] facilitating 1-D electronics, e.g. resonant tunneling diodes [7] and single-electron transistors [8]. For photonic applications, LEDs [3], lasers [9] and infrared photodetectors [10-11] have also been assembled using NWs.

Devices based on NWs can be of two types: vertical or lateral. Although vertical device designs may be the obvious choice for NWs which grow vertically from the surface, interesting lateral devices such as cross-linked electronics, can be made by depositing the NWs horizontally on a substrate using a dry technique or from a dispersion. Placing NWs at pre-determined positions in a controlled manner requires an understanding of the adhesion and friction forces between the NWs and the surface. In this paper we present a procedure for manipulating NWs using the tip of an Atomic Force Microscope (AFM). We also show different types of behaviour observed during manipulation of InAs nanowires on three different substrates, silicon dioxide, silanized silicon dioxide and silicon nitride.

2. Materials
The InAs NWs were fabricated by chemical beam epitaxy (CBE) at 430°C using gold particles synthetized using aerosol method and deposited on InAs (111)B substrates. Further details are described in [6, 12]. The nanowires have diameters in the range 20-60 nm.

3. Methods

The silicon dioxide and silicon nitride substrates were patterned using Electron Beam Lithography (EBL) and Nanoimprint Lithography (NIL) followed by metal evaporation of Au and lift-off. To prepare silanized silicon/silicon dioxide substrates F_{13}-TCS (tridecafluoro-tetrahydrooctyl trichlorosilane) was deposited from vapour phase using a method described in [13].

In order to remove the InAs NWs from the substrate on which they were grown a dry deposition method was employed, consisting of wiping them off from the substrate with a piece of cleanroom wipe and subsequently wiping them off from the paper onto the patterned substrates.

4. Manipulation procedure

In the AFM-manipulation experiments it was used a Nanoscope IIIa Dimension 3100 from Veeco and rectangular cantilevers with a nominal spring constant of about 40 N/m. We found a method to bend NWs in a gentle controlled manner. After finding a nanowire of interest and acquiring an image in tapping mode, the point where we want to apply the manipulation force vector was determined. For the manipulation, was invoked a repetitive mode involving a ‘Retrace Lift’ mode with a negative lift of the tip combined with setting the oscillation of the cantilever to zero. In this way the cantilever is scanned above the surface at a certain height in tapping mode (‘trace’ scan), while in the ‘retrace’ scan the oscillation is stopped and a manipulation force is applied by introducing a negative lift of the tip (i.e. the tip-surface distance is decreased). In the ‘retrace’ scan the tip follows the same profile as in the ‘trace’ scan but with a gradually increased manipulation force. This ‘trace’ – ‘retrace’ scan sequence is repeated until a movement of the NW is observed in the ‘trace’ scan.

5. Results

In figures 1, 2 and 3 are shown different types of behaviour seen during manipulation on all three substrates that have been used in the experiments. Figure 1 shows a rigid body behaviour with negligible bending resulting from a relatively weak sticking force in combination with a comparatively stiff NW. The images are the initial and the final one from a sequence of manipulations of a short NW of 26 nm diameter on a silicon dioxide surface.

Figure 2 shows a behaviour, denoted static bending mode, in which the NW can be bent substantially without moving and where the sticking force is large. The images a)-f) show how both ends of the nanowire can be bent round to form a curve. In the final step the wire is broken. The arrows show how the wire was pushed in order to move to the next picture in the series.

In figure 3 it can be seen that the NWs are both flexible and strongly held on the surface. Only parts of the NW can move, this being a local bending behaviour and this was denoted a ‘wet spaghetti’ behaviour. The NW had a diameter of 29-44 nm (tapered NW) and was deposited on silicon nitride.

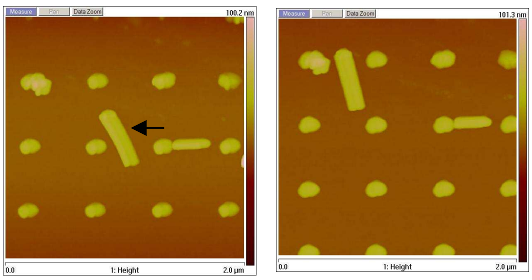

Figure 1. Rigid stick-like behaviour of an InAs nanowire during AFM manipulation.

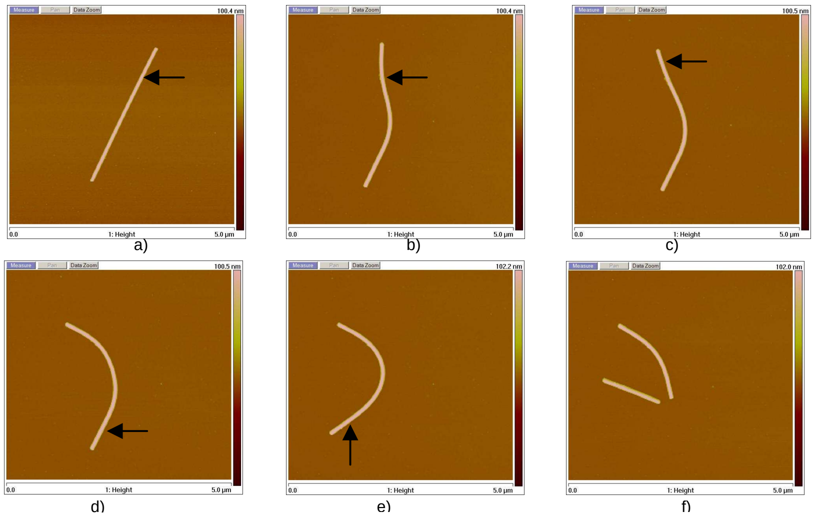

Figure 2. AFM manipulation of an InAs nanowire on silicon nitride, 54 nm diameter, 4 microns long.

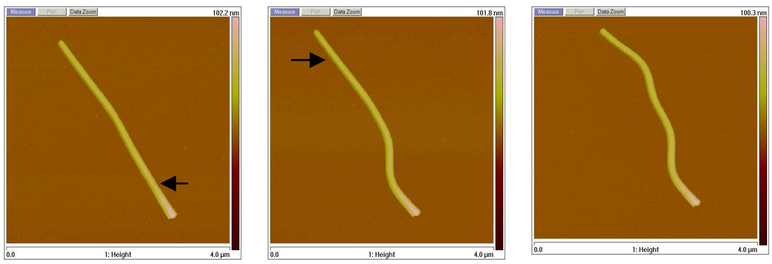

Figure 3. The final stage on the behaviour spectrum. The interaction with the substrate is sufficiently strong, that only small sections of the wire can be moved by a tip push.

From the qualitative investigations on different substrates it could be seen that relatively small diameter NWs seem to have lower surface friction on silanized silicon dioxide than on non-silanized ones (more pronounced rigid stick behaviour on silanized silicon dioxide). However, the surface friction seems to be similar for the two substrates for very thin NWs, an interesting behaviour that has to be investigated further. On silicon nitride it was generally observed more of the ‘spaghetti behaviour’ than on silicon dioxide, silanized or non-silanized, from which we conclude that the friction between NWs and the surface is higher for silicon nitride than for silicon dioxide.

6. Discussion

The different types of behaviour that were observed on our substrates are due to an interplay between friction with the substrate and aspect ratio of the nanowire (length over diameter). For a small aspect ratio, i.e. short and thick wires, the NWs are more rigid and tend to move as inflexible units and the behaviour is that of a ‘rigid stick’ as it could be seen from figure 1. For a larger aspect ratio a type of behaviour shown in figure 2 i.e. static bending was observed. For a very high aspect ratio, i.e. for very long and thin wires, the NWs can only be bent locally (figure 3).

From the experiments on different substrates we can conclude that a NW of a medium diameter and length lying on a silicon dioxide substrate will exhibit a static bending. If we put the same NW on a

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silanized silicon dioxide substrate it will bend slightly and move, showing a behaviour closer to the 'rigid stick' and on silicon nitride substrates it will be subject of local bending, i.e. it will behave like 'wet spaghetti'.

7. Conclusions and outlook

The experiments were performed in ambient environment so the water film always present could modify the 'sticking force' between the nanowire and the substrate. In a future study we intend to make investigations in liquid environment so that the capillary forces will be eliminated.

In order to study other types of interactions between NWs, and between NWs and gold dots our experiments show that we have to drastically reduce the sticking force to the surface by employing e.g. fluoro silane.

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