

Nanotubes

The carbon nanotube sample represents the group of materials with macromolecules that are used for molecular nanotechnology. Other well-known examples are self-assembled particles, DNA, and nanotubes made of other materials.

AFMs can be used to characterize and manipulate such molecules. The well-defined structure of nanotubes makes them ideal for demonstrating the influence the structure of the end of the AFM tip has on the measured image. While manipulation is not demonstrated here, that does not mean it is impossible to do.

Measurement

The carbon nanotube sample consists of a piece of silicon wafer on which carbon nanotubes are deposited. Nanotubes are less than 10 nm in diameter and can reach lengths of several 100 micrometers.

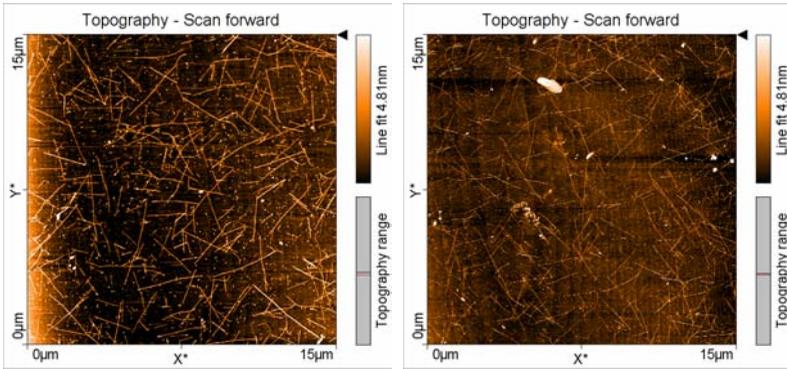
Image Acquisition

With this sample, the tip is likely to be damaged, if the scan parameters are not well optimised. Therefore, if you start with a relatively large range ($\sim 15 \mu\text{m}$) and successively zoom in on an area of interest, it may not be possible to measure the nanotubes at high resolution. Figure *Nanotube Images* shows images of nanotubes taken at optimal and less than optimal settings.

- Set a small scan range ($2 \mu\text{m}$ or less).
- Take a scan.
- Optimize scanning parameters
- Zoom out by taking a scan at a relatively large scan range ($\sim 15 \mu\text{m}$).
- Identify an area of interest.
- Zoom back in.

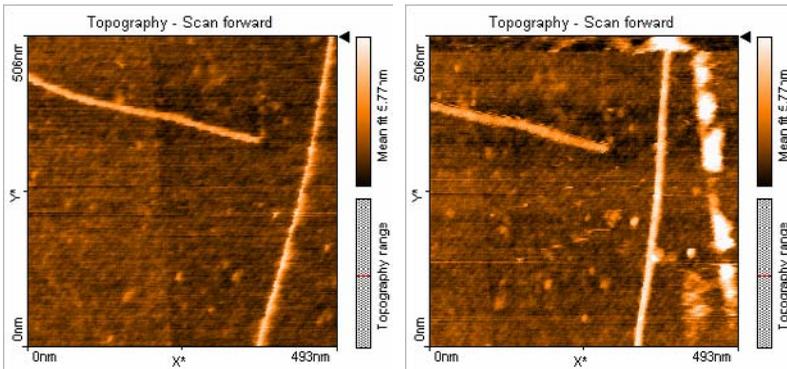
Figure *Optimising the Set Point* illustrates an optimization sequence. At first, the set point is too high (10nN), so the nanotube gets pushed around. This

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Nanotube Images: Left: blunt tip and set point too high (19 nN). Right: sharp tip and better set point (2nN).

makes it appear streaky and not as wide as it should be. With the Set Point lowered, the nanotube is imaged more stably. Note that the dirt that was pushed to the side in the first scan is visible on the side of the second scan.



Optimising the Set Point: Left: force set point (10 nN) is too high, right: lower force set point (2 nN), note dirt moved around by the previous measurement with too high force set point.

Image Analysis

Length

Use the length tool to measure the length of various nanotubes. For best results, measure the straighter nanotubes, as the curved or bent ones may be difficult to measure. Compare the lengths of the longer nanotubes to the shortest ones, and note the wide variations.

Height and Width

Use the section tool to measure the height and the width of a nanotube. First, use the line section tool to draw a line perpendicular to the axis of the nanotube to be measured. Then measure the nanotube height using the distance tool, and measure the width using the length tool. Figure [Nanotube Cross Section Measurements](#) shows how tip sharpness affects the measurements.

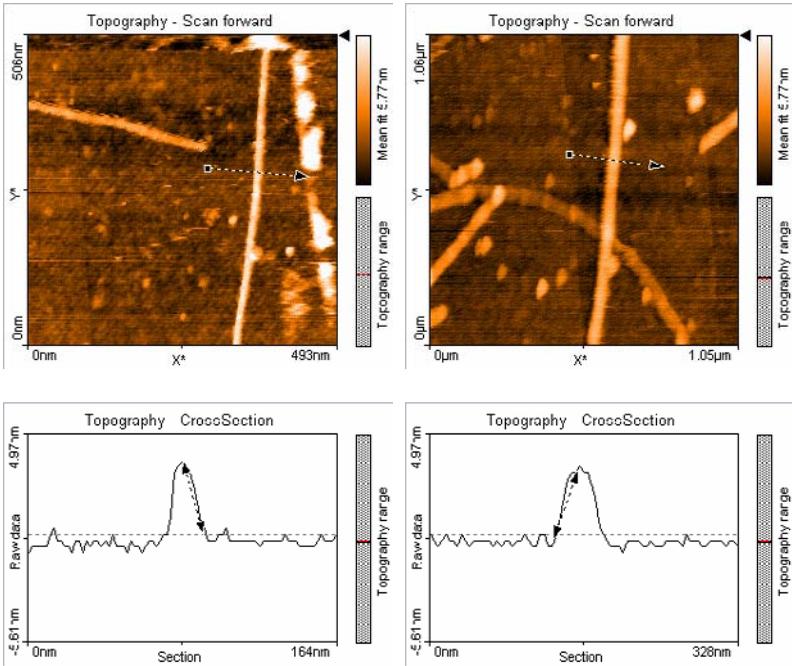
Tip Geometry

In theory, nanotubes are cylindrical. The above measurements indicate that the vertical distance between the top of one nanotube and the silicon substrate is around 3.6 nm, which is the nominal diameter. The width measurements, however, clearly do not represent a cylinder with this diameter.

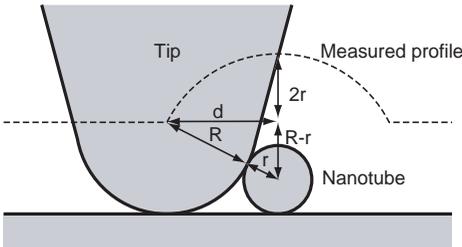
The reason for this discrepancy is that the horizontal measurements are limited by the shape of the end of the tip. A simple model of the end of the tip is a sphere. When a sphere scans over a cylinder that is smaller than the sphere radius, the measured topography will be a cut-off cylinder with a radius equal to the sum of the radii of the tip and the cylinder. The top of the cut-off cylinder will have the same height as the actual cylinder (i.e. the nanotube.), as illustrated in figure [Nanotube-tip Geometry](#).

Notice that the shape of the tip does not permit it to touch the silicon surface at the edge of the nanotube. Since the tip is approximately spherical, there is a significant area of the silicon surface on either side of the nanotube that it cannot touch. At the point where it does touch the silicon surface, a right triangle can be constructed to approximate the actual tip radius, as shown in figure [Nanotube-tip Geometry](#).

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Nanotube Cross Section Measurements: Left: with sharp tip, height is 3.7 nm, width is 20 nm; right: with blunt tip, height is 3.6 nm, width is 47 nm.



Nanotube-tip Geometry: The larger circle represents the end of the tip, where it is approximately spherical. The smaller circle is the cross sectional view of a nanotube. By setting up a right triangle whose hypotenuse is the line joining the centers of the two circles, it is possible to calculate the tip radius.

One leg of the triangle has length d , which is the horizontal distance measured from the highest point on the nanotube to the point where the tip touches the silicon. The other leg is $R-r$, which is the radius of the tip minus the radius of the nanotube. The hypotenuse is the sum of the two radii. Using the Pythagorean relationship, we find that:

$$(R - r)^2 + d^2 = (R + r)^2$$

$$R^2 - 2rR + r^2 + d^2 = R^2 + 2rR + r^2$$

$$d^2 = 4rR$$

$$R = \frac{d^2}{4r}$$

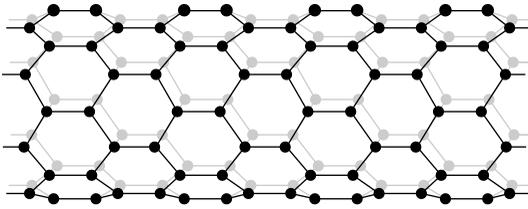
Entering the values determined from the analysis in figure *Nanotube Cross Section Measurements* (p.44) ($d=10$ nm and 23.5 nm and $r=1.8$ nm) gives a tip radius R of approximately 14 nm for the sharp tip. This is reasonable, considering that the nominal tip radius given by the manufacturer is 10 nm. For the blunt tip ($d=10$ nm and 23.5 nm and $r=1.8$ nm), the tip radius becomes 77 nm.

Carbon Nanotubes

A carbon nanotube is, as the name suggests, a tiny cylinder composed of carbon atoms. More specifically, it is a lattice of graphitic carbon rolled into a tube. Figure *Nanotube Molecular Structure* (p.46) shows an example of the molecular structure of a carbon nanotube. The ends of the tube in figure *Nanotube Molecular Structure* (p.46) are not capped, but it is possible to seal a nanotube at both ends with a fullerene. A fullerene is similar to a nanotube in molecular structure, but it is spherical rather than cylindrical.

The bonds that hold nanotubes together are entirely sp^2 bonds, as in graphite. These bonds are stronger than the chemical bonds of diamonds, making nanotubes very durable. Nanotubes naturally align themselves into bundles held together by Van der Waals forces.

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Nanotube Molecular Structure

Japanese physicist Sumio Iijima discovered the hollow, cylindrical nanotubes while studying fullerene synthesis in 1991. Today, nanotubes are used in a range of applications that is remarkable considering their short history.

A nanotube may or may not conduct electricity, depending on its structure. This opens the possibility of very tiny electrical circuit elements, particularly transistors (see the description in the Chip Structure chapter). Nanotubes have also been shown to conduct heat very effectively, a property that could be applied to the cooling of tiny mechanical elements. It has also been shown that by removing the cap at one end of a nanotube, it can be used as a nano-test-tube.

Under the proper conditions, nanotubes can be made sufficiently long to serve as carbon fibres. Researchers have found that newly synthesized nanotubes exhibit strong absorption of outside molecules, and this may have direct applications in medicine. A company called Babolat uses nanotubes in their tennis rackets to keep them stiffer, and controlled electron emission from nanotubes have been used in television-like displays. Building nanotubes will become simpler and more cost efficient as research into their production continues, likely leading to an even greater prevalence in their use and a further expansion in the variety their applications.