NOTES

BRIEF contributions in any field of instrumentation or technique within the scope of the journal should be submitted for this section. Contributions should in general not exceed 500 words.

Cross talk between friction and height signals in atomic force microscopy

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Atomic force and lateral force microscopes use a four quadrant *p-i-n* detector to measure the motion of a laser beam reflected from the top of a cantilever. If the detector is rotated slightly in the plane of the *p-i-n* diode, this will cause frictional forces to be detected as a false height signal. In this article, we will show how this coupling between friction and height signals can adversely affect the measurement of topology at height scales below 10 nm. This will be demonstrated with contact mode images of single-walled carbon nanotubes. We will also show how to detect this effect and possible ways to correct for it. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1499539]

Most modern atomic force microscopes (AFMs) detect the position of the cantilever by means of a four quadrant spot detector. A laser beam is reflected from the top of the cantilever. As the cantilever bends up or down, the reflected beam will be deflected up or down. Likewise, frictional drag forces will cause the cantilever to twist. This in turn will deflect the laser beam left or right, depending on scan direction. A schematic of such a detector is shown in Fig. 1. A spot detector consists of a single *p-i-n* diode solid state detector that is divided into four quadrants. The vertical position of the laser spot is detected by adding the signals from UL+UR, and DL+DR, and these two sums are then subtracted. This difference is proportional to the vertical deflection of the laser beam. The lateral force is measured by adding the signals from the two left detectors and the two right detectors, and taking the difference, i.e., (UL+DL)−(UR+DR).

While this detection scheme is simple in practice, it has one weakness. If the detector is rotated as shown on the right side of Fig. 1, then lateral motion of the laser spot will cause the vertical signal to change. The rotation of the detector and the lateral motion of the laser spot have been exaggerated for clarity. In this way, frictional forces are sensed by the AFM as changes in height. In other words, lateral and vertical force signals are coupled. It should be noted that coupling of lateral force to height signals will even occur in older style AFMs with just a two segment detector, if that detector is rotated. Other researchers have noted the coupling of signals in passing.[1–3] However, these articles were concerned with the calibration of lateral force signals, and they correctly noted that the coupling had a small effect on topology. However, small is not zero. This effect was also noted in an article on etch pits in highly oriented pyrolytic graphite.[4]

Given the possibility of such coupling between lateral and vertical force signals if the detector rotates, the question arises: what effect does this have on typical AFM operation? A simple method to check the spot detector alignment is to scan a freshly cleaved mica substrate. We did this, with one of our instruments, Park Scientific, Model CP, in our lab. The instrument was set up to record images in topology and lateral force mode, and both left and right scans were recorded. The signals were set to be dc, not ac, coupled. Detector output is shown in Fig. 2. In the lateral force trace, the separation of trace and retrace was about 0.8 V, or 5% of total scale. The separation of the trace and retrace signal in the topology was about 2 nm. Since mica is atomically flat, the topology traces should be exactly equal, so the difference represents a false height signal. If the AFM had an adjustment for the rotation of the detector, this technique could be used to set correct orientation of the detector. *As far as we know, no commercially available AFMs allow the adjustment of the rotational position of the detector.*

If one is scanning samples with surface features greater than 10 nm, then this artifact will have little effect. However, if a sample has height features of 10 nm or less, then coupling of lateral and vertical signals can have a dramatic effect. One obvious example of this is AFM studies of self-assembled monolayers (SAMs) where height differences of 1 nm are routinely measured. If the SAM has any variation in friction, then this will be coupled into the topology image. Another example of this effect is seen in studies on adsorbed

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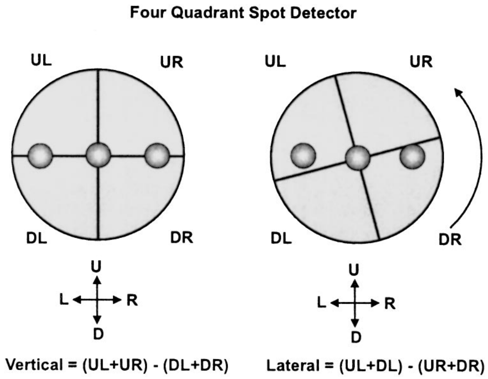

FIG. 1. Schematic representation of misaligned atomic force and lateral force (AFM/LFM) spot detector. Correctly aligned detector is shown on the left. When the laser spot moves left or right it must track the dividing line between upper and lower quadrants. On the right, as the spot moves, it crosses the line between upper and lower quadrants.

water layers.[5,6] Here, variation in friction due to water transport is reflected in the topology image as well.

Finally, we include an example from our current work on single-walled carbon nanotubes (SWCNTs). In Fig. 3, left and right scans of both topology and friction are shown. SWCNTs are generally believed to be hydrophobic and this may account for the contrast in the friction image. Alternatively, it may just be that SWCNTs exhibit the lower friction characteristic of graphite. In either case, the sharp reduction in friction shows up in the height image as a drop in height as the AFM tip crosses the nanotube. The diameter of SWCNTs is approximately 1 nm, and, of course, not −1 nm. One will note that in the right to left scan, the sense of the friction signal is reversed, and so the height of the tubes is increased rather than decreased by the coupling of the lateral force signal. The measured height on the tubes is approximately −1 nm in the first case, and +2 nm in the second. The nanotubes were from Tubes@Rice, grown by the laser ablation method, and their diameter is given as 1.2 nm. Thus it seems that the friction to topology coupling, in this case, subtracts or adds ≈1 nm in height depending on scan direction.

We offer suggestions to reduce this artifact in future AFM studies of samples with small variations in height. First would be a modification of the AFM detector design. It would be very useful if the detector could be rotated as well as translated as part of the alignment procedure. However, since AFM tube scanners bend in an arc to translate samples, it may not be possible to perfectly align the detector to eliminate this artifact. It might be possible and necessary to add a coupling factor correction to the normal suite of mathematical corrections included with most commercial AFM systems. This would take data from the lateral force image and use it as a correction factor for the topology image.

We report that coupling between lateral force and vertical signals can greatly affect the measurement of height on samples with height features <10 nm. This artifact is present in all AFMs using spot detectors in contact scanning mode. Future AFM studies need to take this effect into account and, where possible, compensate for it.

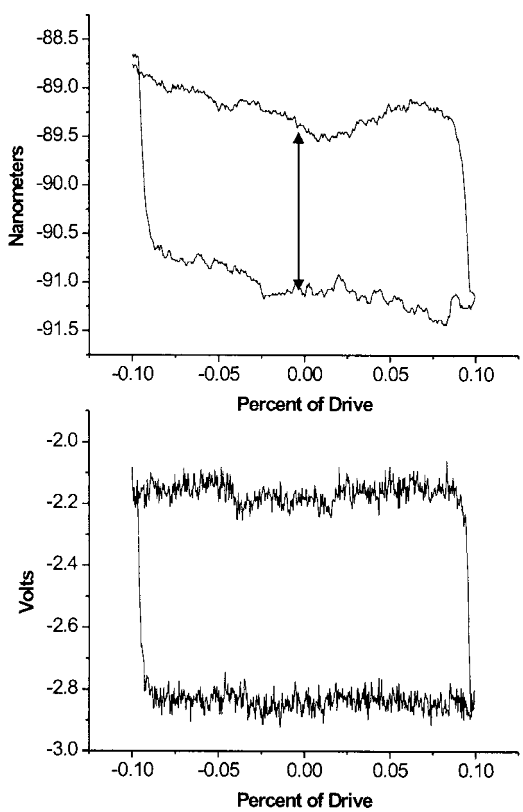

FIG. 2. Friction loop and topology loop. The lower plot is from the lateral force detector and is a traditional friction loop. The upper plot is the output from the topology detector. The separation of the left and right traces (marked with arrow) should be zero, but is about 2 nm.

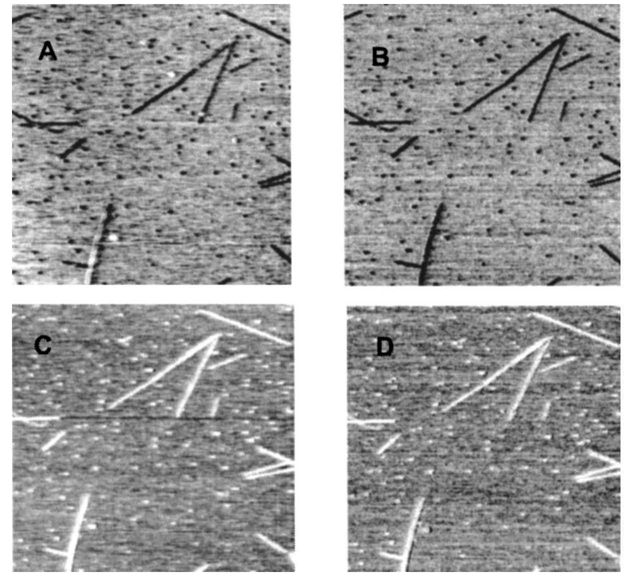

FIG. 3. Four simultaneous AFM images of SWCNTs, deposited on a mica surface. Scan size is 2 μm and total height scale is 10 nm. (A) Topology image, lighter color represents greater height. The scan direction is from left to right. (B) LFM image, lighter color represents higher friction. Scan direction is the same as (A). (C) Topology image recorded with a right to left scan. (D) LFM image scanned right to left.

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