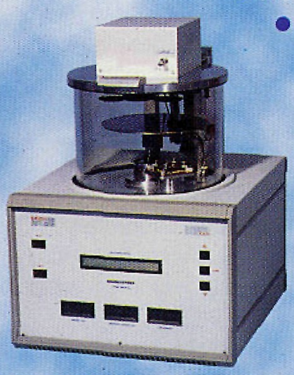

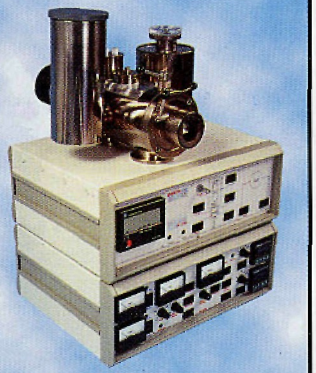

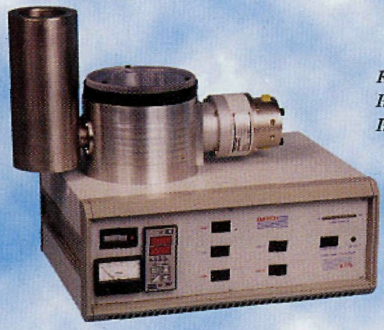

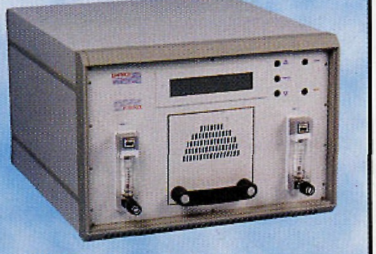

Anomalous Changes in Tip Height in Tapping AFM

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This effect can be understood by considering what happens to the cantilever and tip as the base of the vibrating cantilever is brought closer to the sample (like in a force curve). When the vibrating cantilever first approaches the surface, the tip senses attractive forces. In standard imaging conditions, these are usually due to meniscus forces between a layer of adsorbed liquid (often water) on the surface of the sample and the tip. However, even in clean conditions, other attractive forces like Van der Waals will generally be present. These attractive forces move the resonance of the cantilever downward in frequency. Since the cantilever is being driven at the original resonance frequency of the cantilever, this will cause the cantilever amplitude to decrease as the attractive forces pull the resonance peak out from under the drive frequency. This decrease is often quite linear with distance, but doesn't have to be. In this case the tip is actually turning around some distance (this could typically be a few nanometers) before it touches the surface. This regime is commonly called the "attractive" regime because attractive forces dominate the behavior of the cantilever.

As the base of the vibrating cantilever continues to get closer to the sample, a sort of contest occurs. The attractive forces grow larger as the tip gets closer, making the amplitude decrease further, but on the other hand, the tip has moved closer to the sample bringing it closer to repulsive contact forces. Depending on who wins the contest, two things can occur. If the attractive forces are effectively "large" (this can be due to a blunt tip, a low k cantilever, a high Q cantilever, or low drive amplitudes), the cantilever may never touch the sample; it remains in the attractive regime throughout the force curve. For example, the base of the cantilever might be moved 5 nm closer to the sample, but the attractive forces may cause the amplitude to decrease 5.2 nm. I think of this case as a protective force field protecting the sample. The cantilever can't be made to touch the sample because the amplitude decreases faster than the cantilever can reach for the sample.

The other case is that eventually the tip does begin to experience repulsive forces (the "repulsive" regime). Then things can occur quite quickly. Remember that at this point the resonance of the cantilever is well below the drive frequency because of the attractive forces. When the tip then experiences the beginning of repulsive forces, the resonance gets pushed up a little toward the drive frequency. This means the amplitude wants to grow a bit bigger, but it can't because the sample is now in the way. So instead it hits the sample a little harder which means more repulsive forces, etc. This positive feedback keeps going on until the resonance has been pushed back above the drive frequency, at which point things are stable again. After this point, the amplitude is generally very linear with distance on hard samples. It is this sudden transition that can be seen in force curves and images. The tip is turning around a few nanometers above the surface and then suddenly it senses enough repulsion, and this transition occurs to where the tip is touching the sample. So the turn-around point of the cantilever has suddenly moved a few nanometers and this is what looks like a "z height change" in the force curves or images.

When imaging, this transition from attractive to repulsive imaging can occur at different cantilever amplitudes over different regions of the sample. For instance, attractive forces may be bigger over hydrophilic parts of the sample because of the water meniscus. An easy way to diagnose whether this is occurring is to look at a phase image simultaneously with the height image. If the phase is bouncing back and forth around 90 degrees (defined to be zero in the Nanoscope software), the tip is moving back and forth between attractive and repulsive regimes, and the height data may be subject to this artifact.

The physics that actually govern all of this are a bit complicated, and the above "intuitive" explanation isn't meant to be complete. However, it does provide a simple framework for understanding things. There are several papers that study this phenomena. I don't have the literature references at hand, but literature searches for J. Colchero, B. Anczykowski, A. Kuhle, Ricardo Garcia, and J. Van Noort will turn up some of these. ■