Mechanics and Vibrations of Carbon Nanotube Atomic Force Microscopy Probes

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Single and multi-walled carbon nanotubes (CNT) have been described as ideal tips for atomic force microscope (AFM) microcantilevers. They offer high spatial resolution, excellent wear resistance, the ability to image high aspect ratio semiconductor trenches, and possess a low bending stiffness which allows imaging of soft biomolecules with reduced contact forces. The objective of the current research is to understand how the mechanics and vibrations of an AFM cantilever probe with a CNT tip affect the ease and accuracy of attractive-mode imaging. Experimental results will highlight some of the challenges of stable imaging with CNT probes, namely (a) the difficulty in setting up the cantilever purely in attractive mode, and (b) the possibility of nanotube vibrations and stiction causing unwanted artifacts on surfaces with large topography gradients.

The key to obtaining attractive mode non-contact images is to maintain sufficient attractive van der Waals force between tip and sample, and to ensure simultaneously that the tip is not tapping the sample. This becomes particularly challenging for CNT tips because their diameters are very small and therefore the van der Waals forces between the CNT tips and the samples is very small when compared with the blunter conventional silicon tips [1]. Because both attractive forces in NC operation and repulsive forces due to tapping cause a reduction in amplitude, the phase must be examined when dealing with an amplitude feedback system.

Figure 1 shows the amplitude and phase of a conventional AFM probe as the distance between tip and a silicon grating sample is decreased. As is well known in theory of dynamic force microscopy, the cantilever phase increases initially as the tip approaches the sample then sharply jumps and begins to decrease when the tip starts tapping the sample [2]. Thus the phase can be monitored to insure that the tip is operating in the attractive regime. Figure 1 also shows the amplitude and phase for an AFM probe with a 250nm CNT attached to its tip. Notice the amplitude does not monotonically decrease, but flattens and even increases slightly as the tip approaches the sample. The phase increases and then decreases as it did for the conventional AFM probe, but the sharp transition between attractive and repulsive regions is no longer as apparent, making it more difficult to guarantee that the tip is imaging in attractive-mode. The flattened amplitude signature is clearly problematic for amplitude feedback controllers because the vibration amplitude does not change significantly over a range of tip-sample separations. The problem is further complicated by evidence that shows that the attractive region is not easily optimized by adjusting the free vibration amplitude as it can be for a conventional tip.

CNT tips may create undesirable image artifacts while operating in attractive-mode, particularly when imaging objects with large topography gradients such as the sidewall of a silicon trench. Figure 2 shows 100nm sidewall images obtained with a conventional tip and the same CNT probe mentioned previously, both operated in attractive-mode. Notice the improvement in the resolution of the left edge in the image obtained with the CNT probe. More importantly notice CNT probe image of the right grating edge shows a large edge distortion. It is likely that this artifact arises from the stiction of the nanotube to this sidewall during imaging, creating a large decrease in amplitude which the controller momentarily interprets as an increase in topography.

The explanations of these attractive-mode instabilities will be presented with additional experiments and possible design guidelines to optimize the ease and accuracy of attractive mode imaging with CNT probes.

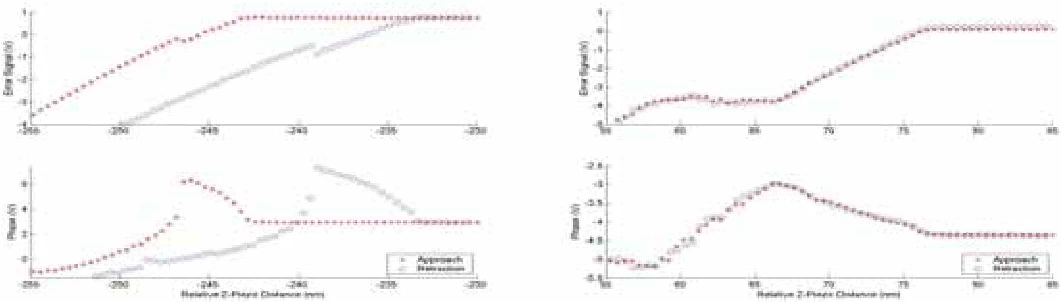

Figure 1: Amplitude and Phase versus tip-sample distance for conventional AFM probe (left) and CNT probe (right).

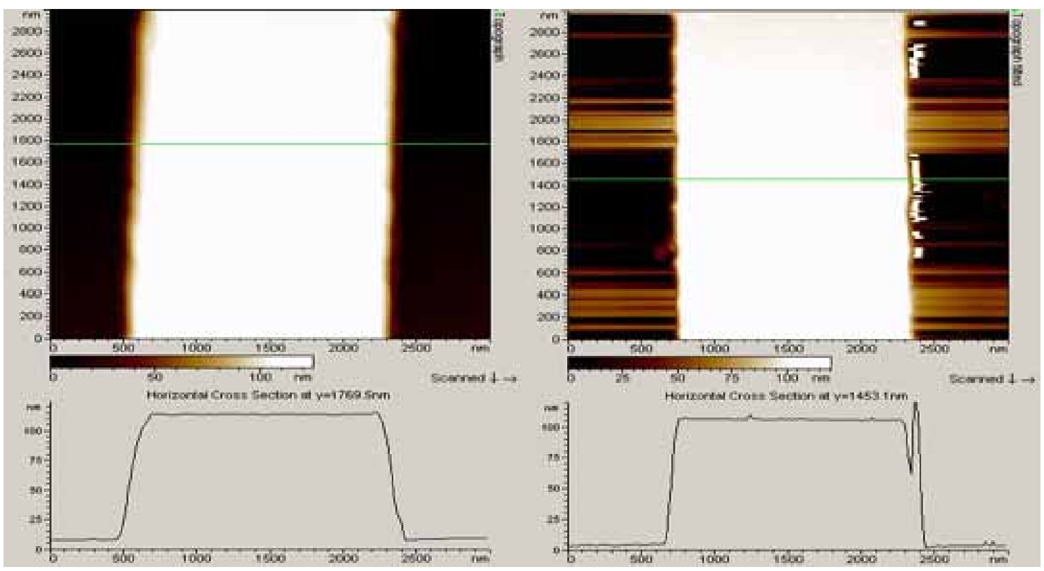

Figure 2: Scan of 100nm silicon grating with conventional AFM probe (left) and CNT probe (right).

References

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[2] S. I. Lee, S. W. Howell, A. Raman, R. Reifenberger, C. V. Nguyen, and M. Meyyappan, "Complex Dynamics of Carbon Nanotube Probe Tips," *Ultramicroscopy*, 2003.

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