Carbon Nanotubes as AFM Tips

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Introduction

As part of NIST support for semiconductor lithography metrology, we are working with SEMATECH to address traceability issues in semiconductor dimensional metrology.

In semiconductor manufacturing, many of the measurements made in the fab are not traceable to the SI unit of length.

This is because a greater emphasis is often placed on precision and tool matching than on accuracy. Furthermore, the fast pace of development in the industry makes it difficult to introduce suitable traceable standard artifacts in a timely manner.

To address this issue, NIST and SEMATECH implemented a critical-dimension atomic-force-microscope based reference measurement system RMS. The system is calibrated for height, pitch, and width, and has traceability to the SI definition of length in all three axes.

A Reference Measurement System

- *is well characterized using the best the science and technology dimensional metrology can offer: applied physics, sound statistics and proper handling of all measurement error contributions.*

- *must be sufficiently stable that other measurement systems can be related to it. An RMS can be used to track measurement discrepancies among the metrology instruments of a fab, and to control the performance and matching of production metrology instruments over time.*

--International Technology Roadmap for Semiconductors (ITRS) 2003 Edition (Metrology Chapter)

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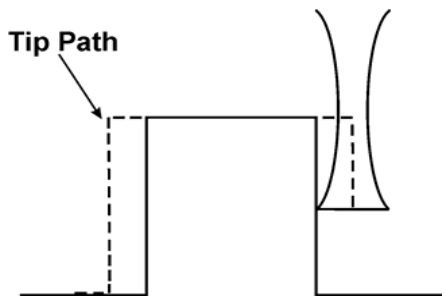
CD-AFM based- RMS

- **Key differences with 1D AFM**

- **Boot shaped or flared tips**

- **Scanning algorithm/sidewall access**



Some Capabilities

- **CD/Width**
- **Height**
- **Pitch**
- **Sidewall Roughness**
- **Sidewall Angle**

Other RMS under development

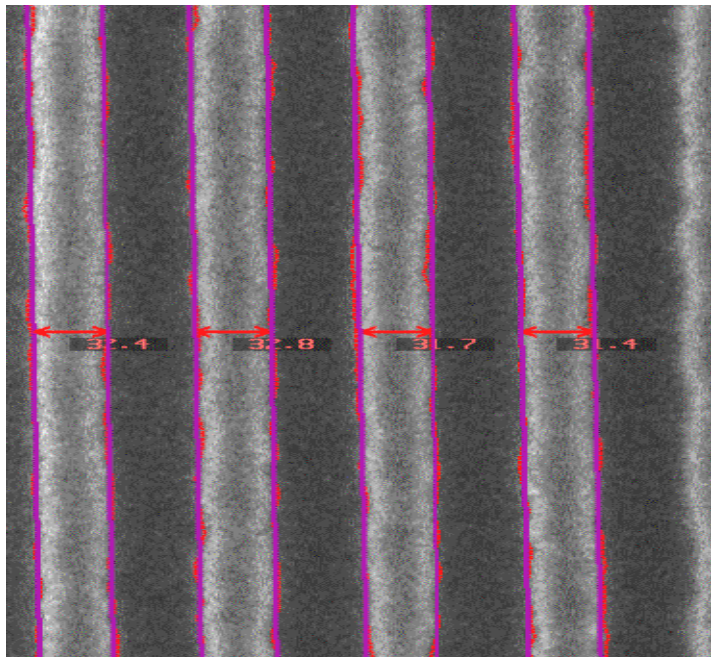
- Critical dimension SEM and Helium Ion Microscope

CD-AFM based- RMS

Key Limitation

Current CD-AFM tips will not be able to measure feature trenches less than 50 nm width, such as the image on the right. →

Smaller tips are required to extend CD-AFM RMS to 32 nm half pitch technology and below.



Resist features with 70 nm pitch.

CNT as AFM Tips

Carbon nanotube AFM tips offer key advantages for sub 50 nm CD measurements:

- Small size (7 nm to 30 nm)
- Can be grown or attached to the tips
- The orientation can be controlled

However, most of the dimensional measurements made with CNT tips are not accurate. This is because the interaction of the CNT tip and other nanostructures are not well understood.

The details of this interaction depend on accurately determining both the dimensions, and mechanical properties of the CNT probe.

This leads to a lack of fundamental understanding of the interpretation and uncertainty of these measurements.

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CNT as AFM Tips

To answer some of these questions

- We are developing a suite of characterization methods and physical standards for evaluating carbon nanotubes used in dimensional metrology.

- This involves investigating the tip-sample interaction for different geometries and the effect on dimensional measurements and accuracy.

-The physical standard would provide a quick and stable way to determine CNT probe parameters such as alignment angle, length, and diameter and relevant mechanical properties of the probe.

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CNT as AFM Tips

Before we can use CNT tips to measure critical dimensions, we need to do the following:

- Get a better understanding of the tip sample interaction.
- Determine the key sources of uncertainty.
- Determine the best practices for use in a semiconductor development environment.

Performance Evaluation

Key Questions

- Are values obtained from the evaluation samples correct?
- Can the tip track the differences?

Optimum engage setting and scanning parameters

Changes to settings and engage parameters include but are not limited to the

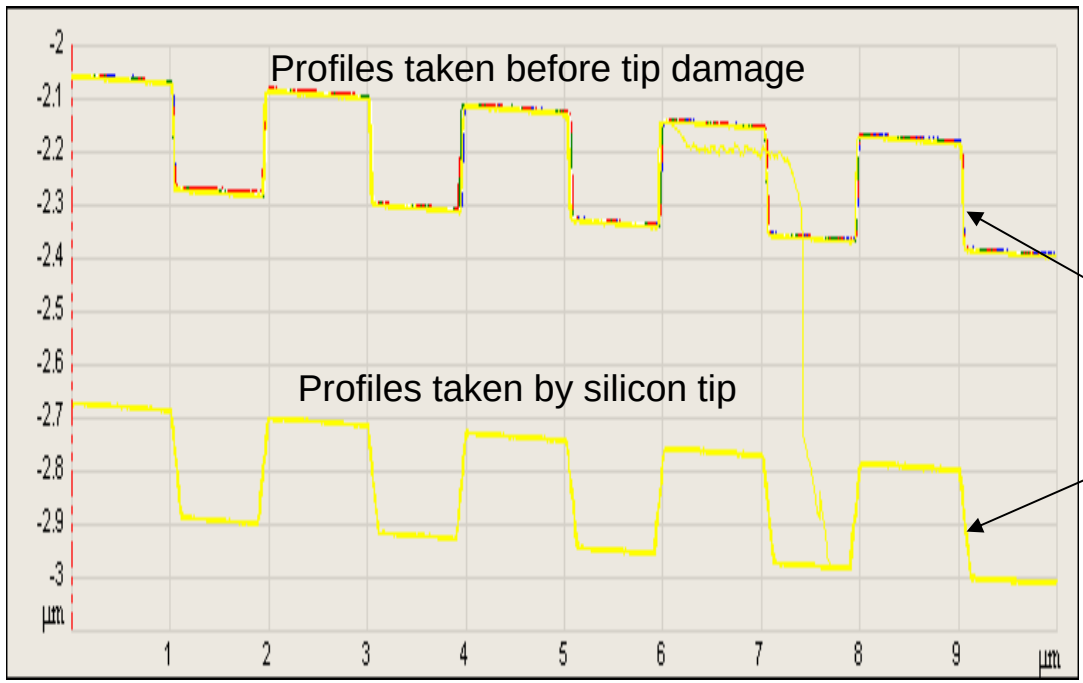
- Free amplitude
- Set-point
- Dither amplitude, ..etc

We are working closely with one of the instrument manufacturers to optimize some of the settings.

The settings that provides images with the minimum amount of scan to scan variation and relatively low noise are regarded as optimum.

CNT as AFM Tips

The image below shows one of the advantages of CNT tips over regular tips. A CNT tip was damaged during test, the profiles before and after damage clearly show the difference in sidewall angle. The fabrication process that produced this tip has since been optimized to improve durability.



Note the slope of the sidewalls

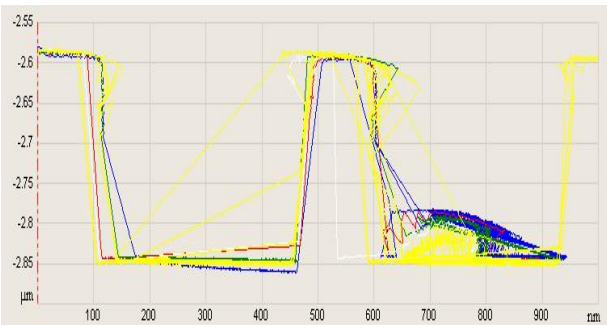
Scan to scan variation – Differences in the sidewall angle, height, pitch

Sample: 2 mm grating, SOCS

➢Methodology: The gratings is used for comparison of multiple images of the same location (static repeatability). Differences in sidewall angle and feature shape indicate that the tip may be flexing.

Sticking

➢Methodology : Examination of the individual scan line from the images.

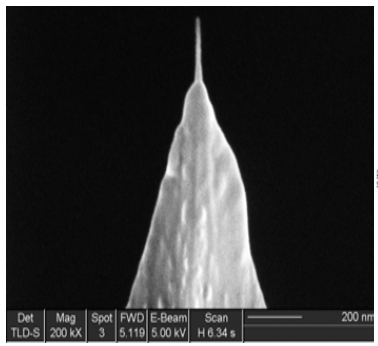


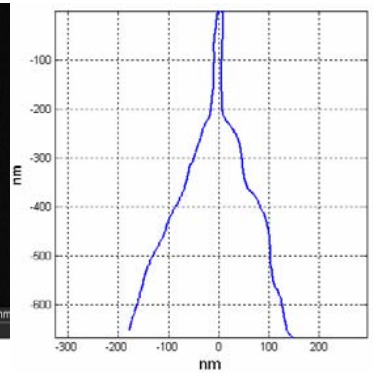
← An extreme example of sticking. The feature sidewalls are supposed to be vertical. Understanding CNT tip/sample interaction will help prevent this.

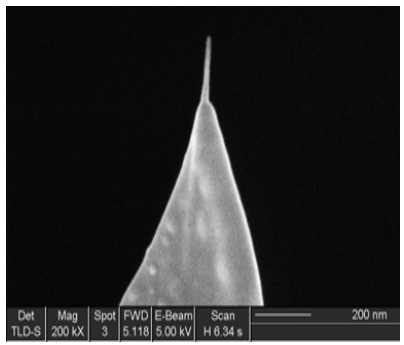
Shape Verification

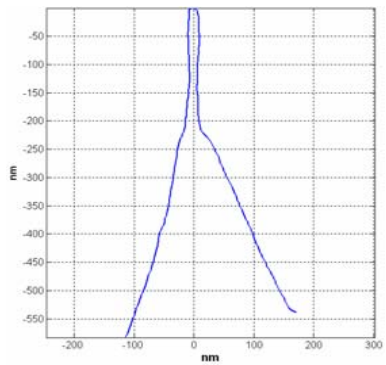
The overall shape and orientation of the CNT is determined using the silicon overhang sample (SOCS). This helps in interpreting the data. Scanning electron microscope images are also helpful, however, it is difficult to determine the specific orientation of the tip along the scanning direction.

The figures below show SEM images of CNTs grown on AFM tips and the corresponding reconstructed AFM profiles.





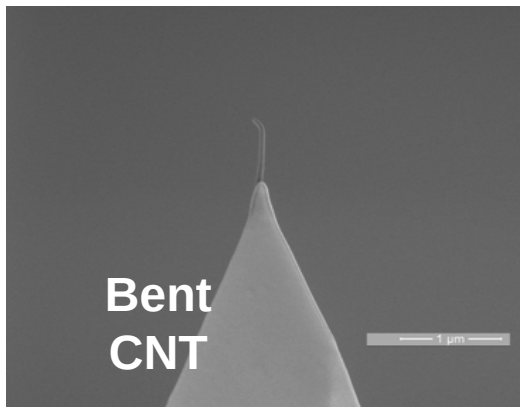




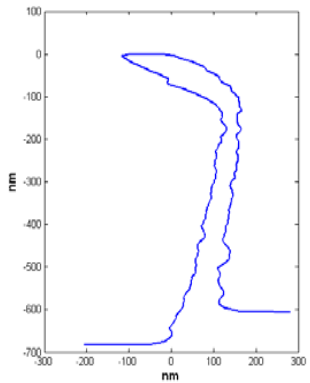
Specialized CNT Tips

Among the CNT tips we are evaluating are some whose shape has been modified to enable sidewall profiling. The aim is to produce CNT tips that resemble and function like boot shaped but with increased resolution because of the small size.

The figure below shows a prototype specialized tip.



SEM image



reconstructed profile from an AFM scan of a SOCS sample.

Preliminary Results -1

AFM CNT Tips Evaluation-- Summary

5 manufacturers (Commercial, university and government lab).

Only one manufacturer has grown tips.

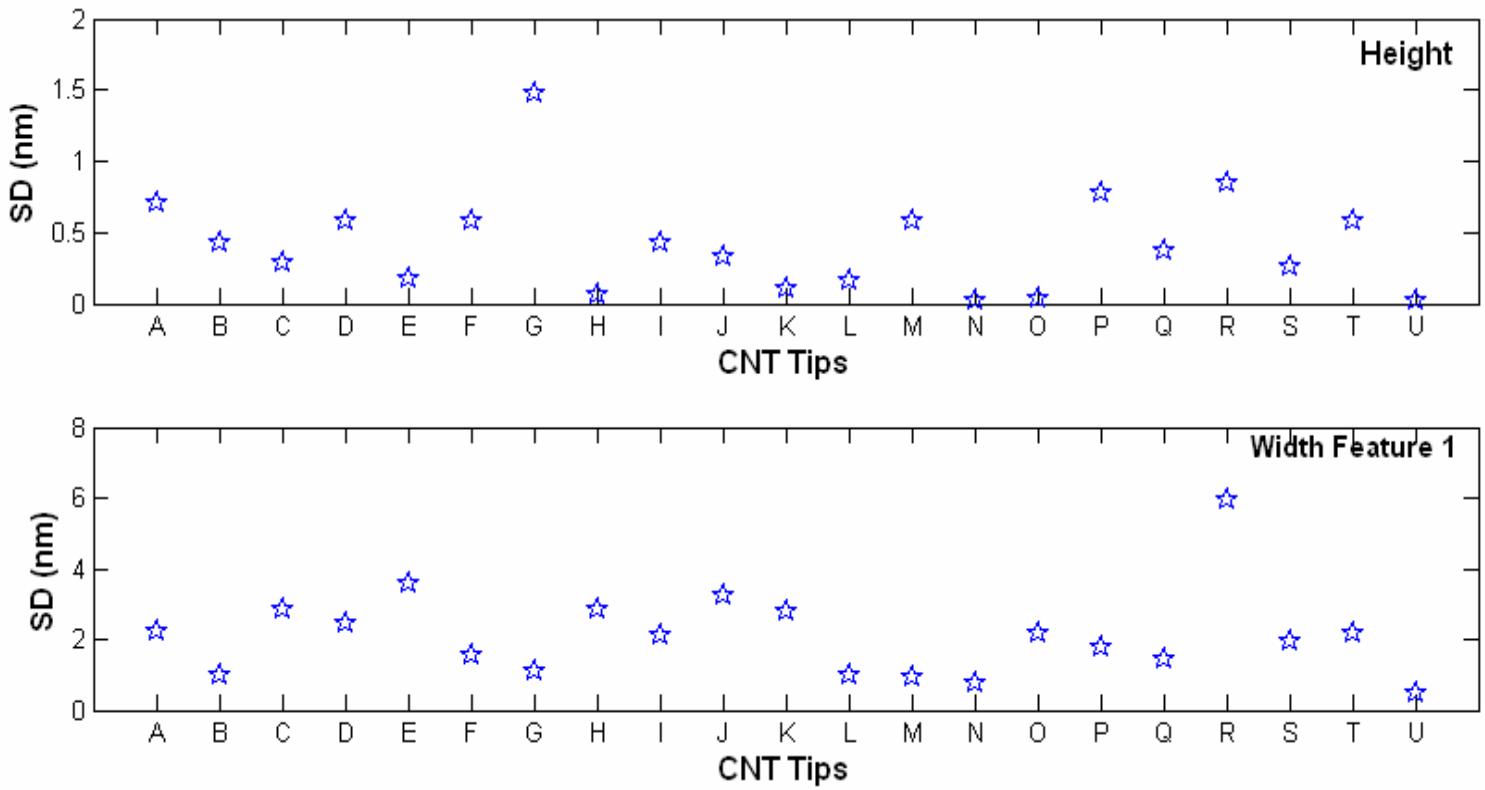
A total of 81 tips were evaluated.

Tip length ranged from 120 nm to 700 nm.

Diameters ranged from 10 nm to 50 nm.

Preliminary Results -2

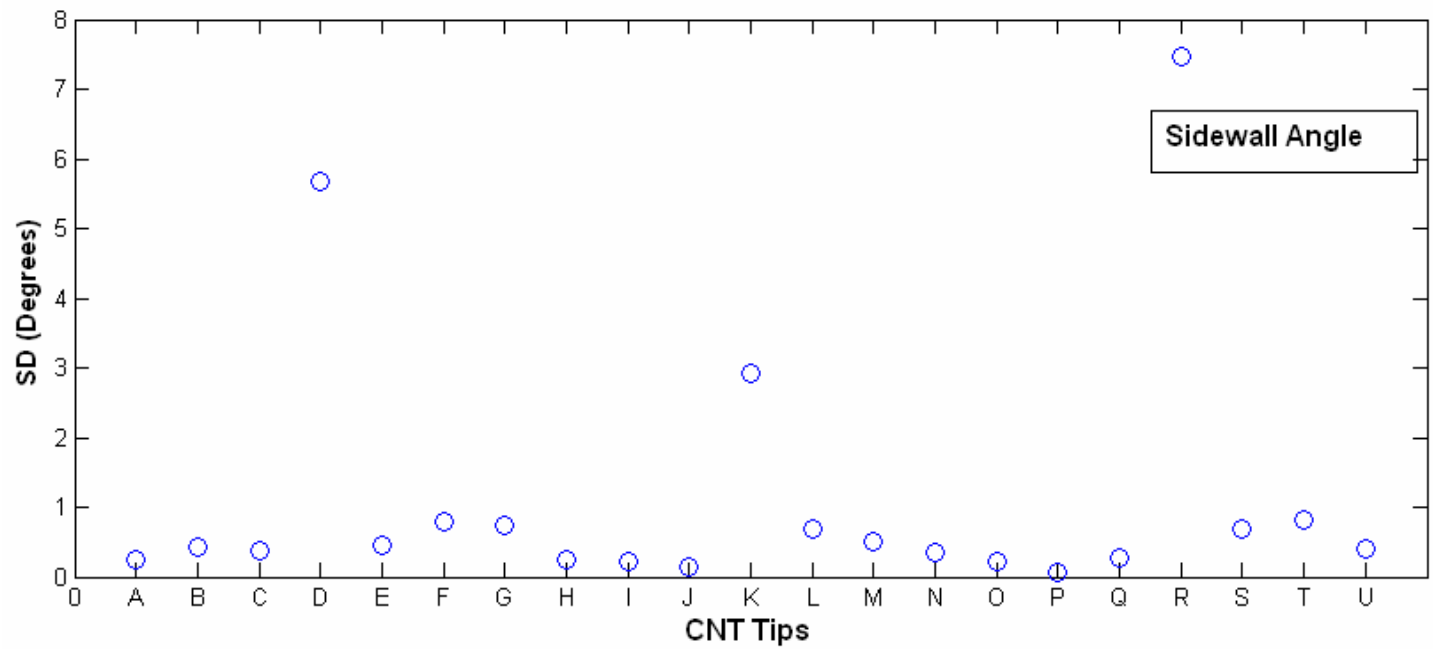
Scan to scan variation from 21 different CNT tips.



Each standard deviation is from 10 images

Preliminary Results -3

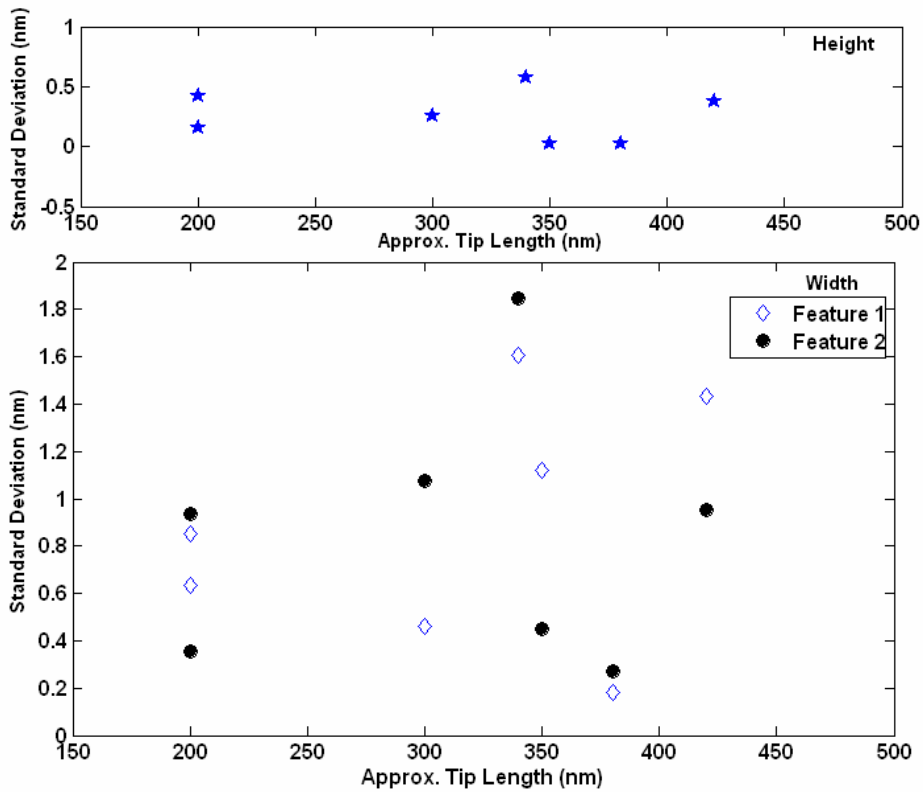
Scan to scan variation: Sidewall Angle



Each standard deviation is from 10 images

Preliminary Results -4

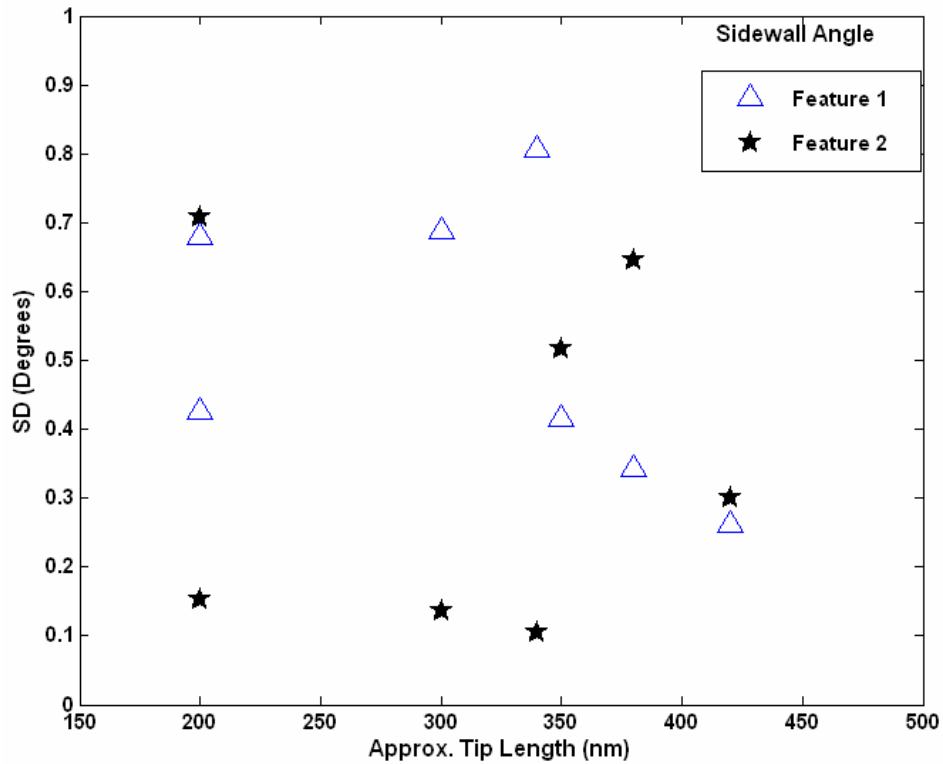
Results with less than 2 nm width standard deviation



Tips of less than 400 nm in length had the least variability.

Preliminary Results -5

Sidewall Angles Results with less than 2 nm width variation.



Tips of less than 400 nm in length had the least variability.

Some General Observations

For the types of tips we evaluated, the scanning parameter with the largest influence is the free amplitude.

In general, tips with a length of less than 400 nm produced the most stable images. Stable images are those with low standard deviations (SD). It is important to note that when compared with the SD produced by regular CD tips, those produced by the CNT probes are larger by a factor of two.

The test structures had heights of 100 nm and 200 nm. The most stable images were produced by tips with a height of 1.5X to 2X relative to the height of the feature. We intend to use structures with heights of 400 nm to 600 nm to see if this observation holds for taller features.

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Feedback to Tip Manufacturers

Based on the feedback from this work one of the tip suppliers was able to make changes to their tip manufacturing process. This addressed issues that were discovered during the evaluation. We have also delivered tips to several SEMATECH member companies.

We are evaluating more tips that will be delivered to member companies, and also working on applicability to different semiconductor measurement needs.

Future Work

Continue to evaluate different CNT tips, especially those that can be applied to specific applications such as line edge roughness and contact holes.

A quick and stable way to determine CNT probe parameters such as alignment angle, length, and diameter and relevant mechanical properties of the probe, different geometries and the effect on dimensional measurements and accuracy

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