AC 2012-4270: VISUALIZATION OF NANOSCALE COMPONENTS USING ATOMIC FORCE MICROSCOPY

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Visualization of Nanoscale Components Using Atomic Force Microscopy

1.0 Introduction

As nanotechnology moves toward the development of new products, it is important that visualization coupled with interfacial interactions, and measurement at the nanoscale should be integrated into design strategies. It is predicted that the general need for measurement tools for the emerging field of nanotechnology applications is expected to create a multibillion-dollar market within the next decade[1]. One such tool is scanning electron microscopy (SEM) which has been widely used to image microscopic features on sample surfaces since its inception in the mid -1900s. However these measurements require the use of electron beams at high vacuum environment and cannot be used for biological non conductive samples and samples under liquid. Unlike scanning electron microscopy, Atomic Force Microscopy (AFM) uses sharp probe scanning over the sample while maintaining a very close spacing to the surface. It was developed by Binnig, Gerber and Quate (1985) at IBM-Zurich/ Stanford Research and followed the invention of scanning tunneling microscope (STM) in 1981 by Rohrer and Binnig [2,3]. AFM is high-resolution microscopy capable of measuring nanometer scale images of surfaces with little or no sample preparation as well as measuring three dimensional images of surfaces and studying the topography. Atomic force microscopy is a nondestructive technique and can also be used as a manipulation tool to move and arrange nano-particles and to build nanostructures.

Measurements of interfacial interactions along with visualization of nanoscale components is an important technique which can enhance the undergraduate students' understanding of the properties of matter at the nanometer level and how they change at the interface between the domains of macroscopic and nanoscale world. It helps integrate areas of science, technology, engineering and mathematics required to train work force needed in the development of new products and applications in the emerging field of nanotechnology. In order to provide such an understanding to the students at the undergraduate level the authors submitted a proposal to NSF's TUES/CCLI program[4] for a collaborative project to develop an instructional lab featuring low cost AFM for engineering technology students at the SUNYIT [5] (State University of New York Institute of Technology) and MVCC [6] (Mohawk Valley Community College). The objectives included development of instructional material for visualization and manipulation of nanoscale components using low cost atomic force microscopes for two year and four year college students. The objectives also included professional development of authors, training of faculty and students and dissemination of instructional material through publications, and presentations at the conferences and through a project website. The purpose of the paper is to review the results of the project. An introduction in section is followed by the applications of AFM in Section 2. Section 3 discusses the four phases of the project implementation. The first phase deals with the identification of the AFM; the second phase is the professional development; the third phase is development of instructional material and the fourth phase is training the students and faculty. Section 4 discusses the students' learning and teaching

effectiveness and section 5 gives the evaluation. Section 6 discusses the result and section 7 is the conclusion.

To further disseminate the results, a website (www.sunyit.edu/afm) was developed for the project. This website includes instructional material, lab exercises, powerpoint presentation of the workshop, samples of student work and a glossary of AFM with useful links.

2.0 Applications of AFMs

The capability of AFMs to investigate surfaces at the nanoscale with atomic resolution in 3D introduces new techniques using probes with local interactions in various environments such as air, liquid, vacuum, magnetic field and low and high temperatures. The capabilities of AFM beyond imaging non-conductive surfaces using force spectroscopy or force displacement analysis has opened a number of new applications. The AFM uses a nanometer-sized sharp scanning force tip that is moved relative to the sample surface to explore the strength of interfacial interactions such as ionic, covalent metallic or dipole origin atomic forces between molecules and solids. The short range dipole interactions are further classified in to strong hydrogen bonds and weak Van der Waals forces arising from dipole-dipole interactions. Both of these interactions can be responsible for structuring in fluidic systems but are also strong enough to build up condensed phases [7]. The use of atomic force microscopy for visualization of nanoscale components is currently applied to metals, semiconductors, thin films, soft biological samples, and live cells, conductive and nonconductive materials as illustrated in some of the examples given below.

Due to of high resolution and the ability to work under physiological conditions, AFM has been widely used to image live and fixed cells to observe cell surfaces, to study cellular mechanics, to localize cell surface receptors, and to measure the forces involved in cellular interactions in various environments. AFM images of cells show a surface details as well as nanomechanical information compared to information from the cell body obtained from optical images. The AFM technique of imaging is well-suited to the study of the surface of membrances and cytoskeleton because the images obtained are truly 3-D, and can be produced in buffer or cell culture medium without the need of labeling, fixing or staining. The nanoscale analysis of living cells using AFM is used in the monitoring of the effects of drugs and chemicals on the fine cell surface architecture in real-time to study the events such as cell growth and division. AFM is also capable of measuring the tiny forces experienced and exerted by cells and the molecules therein and to probe their attachment to substrates or to other cells, to measure their mechanical properties, and to assess the forces in single-molecule interactions. This ability of AFM is better than any optical microscopy technique for investigating these physical processes at the level of molecules and cells. Specific interactions can also be simulated by modifying the tip of the cantilever used in the AFM by functionalizing it with antibodies or peptides or allowing researchers to measure interaction forces and to resolve nanoscale chemical heterogeneities on cells. This makes AFM, an instrument capable of manipulating or stimulating a cell [8,9] .

In the last few years, the study of thin films has received a great deal of attention due to its importance in a range of applications such as optoelectronic devices, lasers, photovoltaic cells,

microscopes and others. The quality of these components is determined by the surface microstructure or surface morphology of the thin film made of semiconductor or optical coating and can be measured by use of an AFM. A new method to characterize the nanostructures of thin film magnetic recording media using AFM in phase imaging mode has been developed and compared to the images obtained by transmission electron microscopes. The result of nanoscale images and analysis of statistical distribution of grain size used in the development of computer, video and audio devices showed that AFM in the phases imaging is cheaper and faster than transmission electron microscope (TEM) characterization. In the case of optical components, scattering of light is greatly affected by the microstructure of the thin film coating which requires low scatter optics due the shift in optical lithography toward shorter wavelength [10,11,12]. For organic photovoltaic cells, scanning probe microscopy is used to characterize materials used in the cell to understand the bulk performance. Organic cells have the potential of producing inexpensive plastic devices whose performance depends upon nanoscale film morphology and optoelectronic properties. The most efficient of organic cells are the blends of poly (3-hexylthiophene) (P3HT) and [6, 6] phenyl C61 butyric acid methyl ester derivatives which power efficiencies of around 6-8%. These cells, however suffer from morphological instability and poorly controlled donor/acceptor domain size distribution. In order to improve the performance, it is necessary to appropriately control the nanoscale morphology for efficient exciton disassociation and optimal charge transport.AFM is used to investigate the morphologies of pi-conjugated systems in order to improve their performance[13,14] .

3.0 Project Implementation

The project objective of establishing an instructional lab consisted of development of instructional material using low cost AFMs, professional development of the authors, and training faculty and students. The project was implemented essentially in four phases as described below. It started with identification of low cost AFMs and purchase of low cost educational AFMs. It was followed by professional development of the authors in order to develop instructional material to be introduced in different courses at both the institutions. Having developed the instructional material the students and faculty was trained to use AFM in various courses. The project activities also included dissemination by presenting results of the project at various conferences, workshops and developing a project website.

3.1 Identification and Selection of AFMs

The first phase involved the identification and review of the capabilities of low cost AFMs at both the institutions. Bids were prepared by listing the specifications of AFMs required for educational purposes and sent to different manufactures of AFMs. After reviewing the capabilities of various AFMs, it was decided to purchase the first AFM for MVCC which is portable, rugged and easy to use for educational purposes. Based on our investigation and from the bids received, we selected the first AFM to be NanoSurf [15] EasyScan 2 which was adequate for usage at both the institutions for demonstrations as well as for outreach activities. After using the first AFM, it was decided to purchase the second AFM for SUNYIT to be a desktop and capable of performing advanced analysis including magnetic force microscopy, single point microscopy, and nano lithography. We selected Veeco caliber from Bruker/Veeco Inc [16].

3.2 Professional Development

The second phase of project implementation involved the commissioning of AFMs and professional development of the authors needed to operate and develop instructional material for various application of AFM. Training sessions on the operation of AFMs were arranged to become familiar with the workings of AFM and its applications. This involved learning about visualization and image analysis of various samples supplied by the manufacturers using different AFM modes. For further understanding of visualization and curriculum and instructional material development, the authors participated in various workshop/conferences and webinars organized by NSF-ATE centers as well as manufacturer of the AFMs. Among the NSF supported workshops/conferences include "Hands-On Nanofabrication for Educators" and "Train the Trainer Workshop for Educators" was organized by NACK[17] (Nanotechnology Applications & Career Knowledge Center) Penn. State University, University Park, PA. Other NSF supported workshop included a workshop on "MEMS and Nanotechnology" organized by SCME[18] (Southwest Center for Microsystems Education) and "Nano Manufacturing Curriculum for Advanced Technological Education (NaMCATE) [19] for Instructors" organized by SUNY Buffalo, NY. The authors also consulted the services of Nano-Link [20] for curriculum development.

3.3 Development of Instructional Material

The third phase in the project implementation involved the development of instructional material to be incorporated into existing or planned courses at both the institutions. These courses included the Introduction to Nanotechnology and MEMS Based Nanotechnology courses at SUNYIT, and the Introduction to Semiconductor Manufacturing course at MVCC. However, the team also anticipated interest in AFM on the part of the instructors in related disciplines such as Material Science and Physics 3 courses at MVCC. As such, a strategy was pursued to provide the instructors of said courses with deployable modules. The model developed included a multipage narrative for faculty members who may not be familiar with the specifics of AFM but acquainted with the general topics of visualization. This narrative detailed the history, theory, operation of AFM, modes of operation, and other related topics. Two interactive presentations on the basic theory and need for visualization as well as the main modes of operation (contact mode and intermittent contact mode) of AFM with references to the extended modes were created. Portions of each of these presentations were pilot tested in lectures at SUNYIT as part of the Introduction to Nanotechnology course. Portions of each presentation were also combined to create material for faculty presentations at MVCC and SUNYIT. In addition, these presentations were augmented, modified, or otherwise customized for delivery at a number of professional development activities for K-12 teachers, administrators and students. A sample of the instructional material is given on the project's website: www.sunyit.edu/afm.

The laboratory activities developed for this project included a short description of the main idea, some background, a procedure with data gathering entry, and review questions. Among these exercises was a detailed introductory activity that utilizes the AFM calibration grid as an analysis sample. The main purpose of this exercise was to acquaint the student with the on-screen menus for the AFM, steps necessary to prepare the AFM for usage including

replacement of a cantilever/tip, and the sample approach and visualization process. Given the expense of AFM tips and the need to develop familiarity with the tool, it was a critical, though time consuming first step. Later exercises developed for intermittent contact mode and feature measurement assumed that the user was more familiar with the AFM and built on this foundation to begin inquiry into sample properties and improvement of the captured image. As part of the faculty workshop development, excerpted versions of these activities were created for demonstration and participant use. A sample of the instructional material for lab exercises is given on the project's website: www.sunyit.edu/afm

3.4 Training of Students and Faculty

The fourth phase involved training the students and faculty by way of classroom instruction, demonstration and workshops on the use of AFMs at SUNYIT and MVCC. This was achieved by offering workshops to faculty and students, introducing the use of AFM in various courses and making presentations at various conferences and workshops as given below:

- Organized a workshop for training the faculty and administrators at MVCC Summer Institute soon after purchasing the first AFM. The workshop focused on describing the principles of visualization of nanoscale components and operation of AFM, its capabilities and applications. The participants included faculty from chemistry, biology and engineering technology departments.
- Introduced the operation and applications of AFM in a course on "Introduction to Nanotechnolgy" at SUNYIT. This involved classroom demonstration and powerpoint presentations of the working of NanoSurf easyScan 2 AFM using prepared samples.
- Introduced AFM in the course on "Materials Science" at MVCC. This instruction involved demonstration of AFM, imaging and analysis of prepared samples of Nanoscience advanced sample kit, PS/PMMA thin film samples, samples prepared at MVCC, and samples received from other NSF-ATE Centers at Penn State and at the University of New Mexico. The students were introduced to material properties and the development of sample preparation capabilities to broaden the use of the AFM.
- Introduced AFM in the course on "MEMS Based Nanotechnology" at SUNYIT. The students used the manufacturer's manual to become familiar with the Veeco Caliber AFM and made some basic measurements using tapping and contact modes with the prepared samples.
- Offered an independent study course on AFM for the students to work on projects relating to visualization of nanoscale components at SUNYIT. The students worked independently on their projects and prepared their own samples in the field of semiconductor and biology. Veeco Caliber AFM was used for imaging in various modes.
- Organized a second six hour workshop on "Visualization of Nanoscale Components Using Low Cost AFMs" at SUNYIT. The participants in this workshop included faculty from two and four year colleges, undergraduate students and personnel from industry. The participating faculty came from Engineering Technology, Physics, Chemistry, Life Sciences and vocational studies disciplines. The workshop consisted of three hours of lectures and three hours of hands-on laboratory. The material covered in the first part of the lecture included introductory concepts on Atomic Force Microscopy and its applications. The second part of the lecture included material on visualization by phase imaging,

visualization by magnetic force microscopy, and visualization by scanning tunnel microscopy, visualization in liquid, single point spectroscopy, description of AFM used and samples of students work.

The laboratory portion of the workshop included multiple workstations through use of the previously purchased NanoSurf EasyScan 2 AFM as well as the Veeco Caliber. The remote access AFM from the NACK Center was also demonstrated for the group during the workshop. Hands-on material was provided to the participants for using it in their classes. The powerpoint presentations developed for Part 1 and part 2 are given on the project's website: www.sunyit.edu/afm.

- Conducted an interactive lecture in Engineering Physics 3 course at MVCC using NanoSurf easyScan 2 AFM. The lecture included theory, operation of AFM, and a demonstration of AFM using prepared samples. Students were required to complete a written assessment including Internet research on AFM and prepare questions for the presentation as part of this activity.
- Made a presentation on the "Use of Atomic Force Microscopes in Visualization and Manipulation of Nanoscale Components in Engineering Technology Programs" at the annual HI-TEC conference, San Francisco. The presentation discussed visualization of nanoscale components which can help students understand the smallest levels of matter in ways that intuition and textbook examples alone cannot. It also discussed the use of low-cost AFMs for instructional use and materials developed for laboratory activities.
- Made two presentations at the workshop on "Visualization of Nanoscale Components Using Atomic Force Microscopy" for K-12 teachers from the Utica City School District as a part of three-day STEM Institute at SUNYIT. The presentation included an introduction to visualization of nanoscale components, use of AFM by remote access and a list of useful links which can be used to teach AFM in their classes. A glossary on AFM with useful website links was also provided.
- Offered a project course for Master of Science program in Advanced Technology which incorporated both AFMs to conduct a study on visualization of nanoscale components.
- Made two presentations on "Visualization of Nanoscale components Using Atomic Force Microscopy," to K-12 teachers and Community College faculty at the NEATE (Northeast Advanced Technological Education Center) Conference & Workshop, Hudson Valley Community College Troy, New York.

4.0 Students' Learning and Teaching Effectiveness

Matter appearing in the form of solids, liquids and gases can exhibit unusual physical, chemical and biological properties at the nanoscale, differing in important ways from the properties of bulk materials. For example bulk gold appears yellow in color but 12 nm (nanosized) gold particles appear red. Similarly large ZnO (zinc oxide) particles (traditional sunscreen) scatter visible light and appear white but nanosized ZnO particles of 30 nm do not scatter light and appear transparent. The boundaries between traditional disciplines of science such as biology, chemistry and physics disappear when characterizing or describing the behavior of matter at the nanoscale. There are essentially four different ways in which nanoscale materials differ from macroscale materials [21].

1. In nanoscale materials, a quantum mechanical model is used to describe motion and energy instead of a classical model. The quantum mechanical model describes phenomena at the nanoscale better than the classical mechanical models which break down for nanoparticles moving near the speed of light.
2. The random molecular motion (Brownian) in nanoscale materials becomes more important than for bulk material and the nanoparticles move wildly, hitting each other.
3. The gravitational forces in nanoscale materials become negligible and electromagnetic forces become strong and dominant. This is caused because the gravitational force is a function of mass and distance, while electromagnetic force is a function of charge and distance.
4. The surface area to volume ratio in nanoscale materials is greater than bulk material which brings a greater proportion of a substance in contact with surrounding material. This makes nanoscale material better catalysts, since a greater proportion of the material is exposed for potential reaction.

The concepts at the nanoscale are abstract, difficult to describe, and their relationships to the observable world can be counterintuitive. Students' understanding of nanoscale phenomena has been addressed through undergraduate-level preparation which introduces hands–on visualization of nanoscale materials through the use of low cost AFMs. This form of study enhances the students' understanding of the material world down to smallest levels of matter where intuition and textbook examples alone are not enough. It also allows the instructor to improve teaching effectiveness by relating to the difficult and abstract concepts of nanoscale phenomena with real time visualization.

To achieve this, instructional material consisting of lab assignments, PowerPoint presentations and narratives on "Visualization of Nanoscale components Using Low Cost AFMs" was developed for engineering technology students and faculty. This instructional material was used in different courses and workshops as mentioned in section 3.4. The result of the formal evaluations and informal feedback from the students and faculty (given in the next section 5.0) showed a positive response, increased interest in studying physics, chemistry and biology and better understanding of nanoscale phenomena.

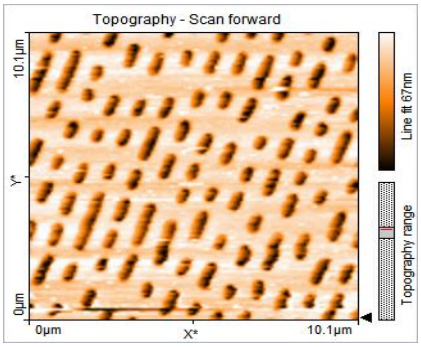
A brief summary of students' lab assignments are given below:

1. Measurement of Nanoscale Features by Imaging DVD and BlueRay Disc Samples

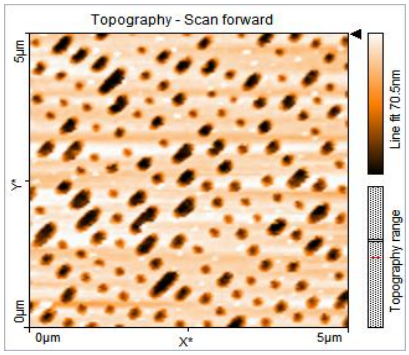
This assignment involved the visualization of digital video discs (DVDs), and BluRay DVDs to study the nanoscale features and determine density of information by direct measurement of the patterns and tracks. To measure nanoscale features an Atomic Force Microscope with a sharpened tip with a typical radius of approximately 10 nm is used. NanoSurf EasyScan 2 AFM was used to image the discs using an Intermittent contact (tapping mode) to avoid damage to the samples.

Video data requires significantly more storage density and in order to accommodate the data, the pit and land sizes must be shrunk to smaller values. The spacing between tracks, width of tracks, their depth and reflectance vary according to the type of disc. Measuring the physical characteristics

of the disc can help calculate the storage capacity of the disc. The smallest features of the DVDs are pits about 400 nm long, 320 nm wide, 120 nm deep, with a track pitch of 740 nm. BluRay DVD players provide high definition video for HDTV, requiring more data density. On Blu-ray the pits are written on about 300 nanometer wide tracks, which is less than half the width of a DVD as shown in the images of two types of DVDs given in the following figures.



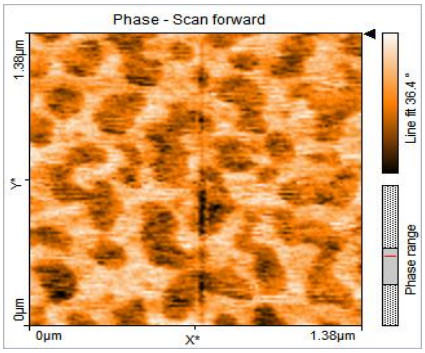
Topographic image of DVD



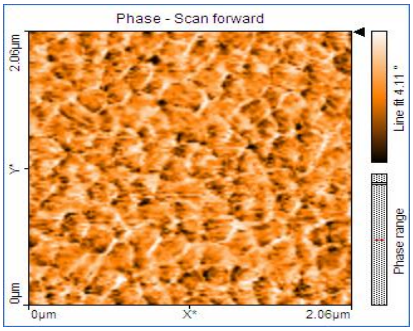
Topographic image of BlueRay DVD

2. Surface Morphology of PS/PMAA (polystyrene/ polymethylmethacrylate)

The PS/PMMA sample is a thin layer of a blend of two polymer solutions spread onto a piece of silicon wafer. PS (polystyrene), and PMMA (polymethyl methacrylate), when mixed together, separate into well-defined phases on the silicon. This thin film of self-organizing diblock copolymers have semiconductor applications because it allows high resolution patterning of ordered domains to be made in nanoscale dimensions over wafer-scale areas. AFM topographic imaging was used to monitor the surface roughness of PMMA/PS blends versus PMMA/PS copolymers. Phase imaging is used to detect the differences in surface morphology for the blend. It uses an intermittent mode and is a power technique for producing contrasts on heterogeneous samples.



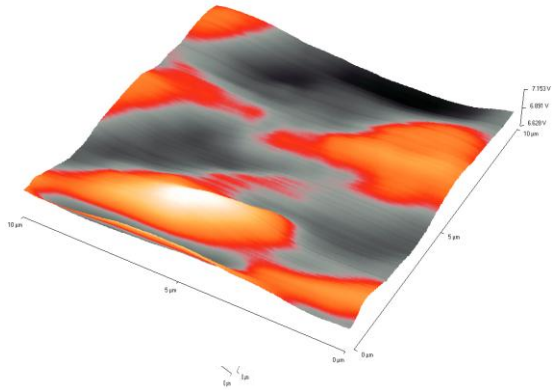
Topographic image of PS/PMAA film



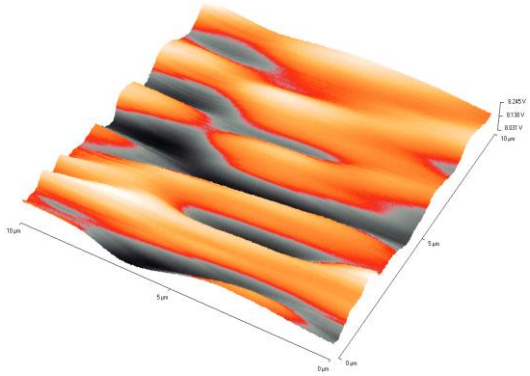
Phase image of PS/PMAA film

3. Nanolithography of CD Using Veeco Caliber AFM

Atomic force microscopy, in addition to obtaining morphological image of a surface can also be used in the lithographical techniques to create nanoscale patterns on metals, semiconductors, and monolayer functionalized surfaces. This is obtained by applying force or voltage between the AFM probe and the surface or substrate. The typical radius of probe is 20-60 nm and the probe-substrate separation in close contact condition is less than 1 nm. Dip-pen lithography uses AFM tip to write chemical onto surfaces similar to a conventional fountain pen, with AFM tip as the pen and the substrate being the paper. AFM nanolithography is less expensive, faster and relatively simpler than traditional methods of achieving features of similar dimension like electron beam lithography or focused ion beam milling lithography [22]. Nanolithography is both a fabrication and imaging tool, as the patterened areas can be imaged with clean or –link coated tips. AFM mages of pre and post nanolithography on a simple CD in the lab using Veeco/Bruker Caliber AFM are given below:



Pre lithography attempt of CD



Post lithography attempt of CD

5.0 Evaluation

Formal evaluations were conducted by external evaluators to assess the teaching effectiveness and students learning after the end of each workshop organized to train the students, faculty and administrators. The external evaluator participated in the workshop and sought informal feedback by interviewing the students and faculty. The results are given below:

Result of first Evaluation: A formal survey was conducted in May 2009 at the end of the workshop on the "Use of the Atomic Force Microscopes to Visualize objects down to Nanoscale Dimensions." This workshop was held at the Mohawk Valley community college after buying the first AFM and developing the instructional material. The participants included faculty from 2 year and 4 year engineering technology programs and live science programs as well as the college administrators.

- The participants were asked to rate "The materials were presented in an organized and interesting way" on a 4-point scale: 1-strongly disagree, 2 disagree, 3 –agree 4- strongly agree. On average the respondent rated the material as 4.00.

- The Participants were asked to rate "The presentation increased my understanding of atomic force microscopy." On average the respondent rated material as 4.00.
- The survey also helped us to improve based on the suggestions. All the participants expressed to repeat such a workshop.

Result of Second Evaluation: The next evaluation was conducted at the end of the workshop on Visualization of Nanoscale components Using Atomic Force Microscopes, held at SUNYIT, in November 2010. This workshop was organized after buying the second AFM and developing the material for various advanced modes of visualization. The participants included students, college faculty from 2 year and four colleges and administrators.

- The Participants were asked to rate the "materials provided were helpful and will be worthwhile" on a 5-point scale: 1-strongly disagree, 2 disagree, 3- neutral, 4 –agree 5-strongly agree. On average the respondents rated the material as strongly agree (4.64).
- The survey also asked to rate the " level at which the instructors presented the materials was appropriate materials provided were helpful and will be worthwhile" on a 5-point scale: 1-strongly disagree , 2 disagree, 3 neutral , 4 –agree, 5- strongly agree . On average the respondents rated the material as strongly agree (4.27).
- On the laboratory experience, the participants in the workshop were asked to rate the "The level at which the instructors presented the laboratory materials was appropriate" on a 4-point scale: 1-strongly disagree, 2 disagree, 3 neutral, 4 –agree 5- strongly agree. On average the respondents rated the material as strongly agree (4.45).
- On the laboratory experience, the participants in the workshop were asked to rate the "The laboratory experience portion of the workshop met or exceeded my expectations" on a 4-point scale: 1-strongly disagree, 2 disagree, 3 neutral, 4 –agree 5- strongly agree. On average the respondents rated the material as strongly agree (4.36).

Result of Third Evaluation: The third evaluation was conducted at the end of two workshops on "Visualization and Manipulation of Nanoscale components Using Atomic Force Microscopes" held at the SUNYIT on August 1, 2011. This workshop was attended by K-12 school teachers as a part of STEM Institute. This evaluation was conducted by Research Works, Practical Solutions- Positive Outcomes of Albany, New York (http://www.researchworks.org/). A summary of survey data on the qualitative comments about workshop experience is given below:

What worked well?

- I enjoyed seeing the detail of minute items
- I can use the information to aid my microscopy discussed with my students. It's something new and interesting.

What did not work well?

- Seemed dry and a little too technical, even though I have a strong science research background.

How might you use the content from the workshop in your classroom/teaching situation?

- To explain to the children how important detail is.

- I can discuss the nanotech microscopy with my students and have them use the provided websites in a lesson.

6.0 Results

The outcomes of the project included development of instructional material on visualization and manipulation of nanoscale components using AFMs for training faculty and students. This was achieved through the purchase of two atomic force microscopes followed by the completion of training from the manufacturers on their use and subsequent practice and research by the authors. The authors participated in 21 different professional development events which included manufacturer supported training workshops, NSF supported workshops, conferences and webinars. Visualization of nanoscale components using AFM was introduced in 5 different engineering technology courses at SUNYIT and MVCC. During the course of the project, the authors made a total of 32 presentations for educators, students, parents, administrators and industry personnel which also included 5 workshops for training and development. Our accomplishments also included publications of two papers in the proceedings of the Annual ASEE Conference & Exposition [23,24] and one article in the "Nanoadvisor" that was published by NanoScience Inc[25]. The detailed abstract for the poster presentation was published in the proceedings of "Seeing at the Nanoscale 2011[26] " Conference held at the University of California, Santa Barbara, CA. The power point presentations given by the authors was also published in the proceedings of the 2011 HI-TEC [27] (High Impact Technology Exchange) Conference, held at San Francisco, CA. A website (www.sunyit.edu/afm) consisting of instructional material, lab exercises, powerpoint presentation of the workshop, samples of student work and a glossary of AFM with useful links is also developed.

7.0 Conclusion

Visualization of nanoscale components coupled with the measurement of interfacial interaction forces at the nanoscale has many applications ranging from imaging of living cells for cancer treatment to the morphology of thin film for the design of high efficiency photovoltaic cells. Introduction of visualization of nanoscale components using AFM at both the institutions helped improve our engineering technology curriculums. It also helped to enhance students' understanding of nanoscale phenomena and teaching effectiveness of the instructors. The author's participation in various conferences/workshops organized by NSF-ATE centers helped in the professional development and development of instructional material. The use of remote access of AFM by the students was an important resource in helping them understand the concept of scanning probe microscopy as applied to visualization of nanoscale components. The authors' participation in manufacturer's webinars, and workshops was instrumental in selecting the AFMs at both the institutions.

In our investigation it was found that there are a number of lower cost AFM instruments for educational purposes available from different manufacturers. The basic instruments however have limitations in their applications beyond basic visualization. The portable AFM purchased early in this project was not initially equipped for extended mode imaging but was upgradeable to add these modes. The imaging quality improved considerably when a vibration isolation system was incorporated. This was found to be especially true when the portable AFM was

taken to outreach activities where the mounting platform and room qualities varied. The Veeco Caliber system at SUNYIT included such a system as ordered but the Nanosurf portable system did not. There were variations in imaging quality based on the tip/cantilever used. Lower cost cantilevers provided reduced quality images, but also provided a more economical solution for laboratory use by new operators. Lower cost and mid-priced cantilever/tip sets were purchased to facilitate exercises at both the introductory and intermediate level.

This collaborative project between SUNYIT and MVCC helped train the students in the visualization of nanoscale components by providing better understanding of phenomena taking place at the nanoscale level. It is expected that such training will enable the students to join a rapidly growing workforce in the field of nanotechnology applications. The project could not have been implemented without the support of NSF under the TUES/CCLI program.

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