Proceedings of the ASME 2010 3rd Joint US-European Fluids Engineering Summer Meeting and 8th International Conference on Nanochannels, Microchannels, and Minichannels
FEDSM-ICNMM2010
August 1-5, 2010, Montreal, Canada

FEDSM-ICNMM2010-30600

SEQUENCE OF COURSES ON PARTICLE TRANSPORT, DEPOSITION AND REMOVAL AND ENGINEERING OF NANO/MICRO-SCALE SYSTEMS

Goodarz Ahmadi
Department of Mechanical and Aeronautical Engineering, Clarkson University
Potsdam, NY, 13699-5725, USA
ahmadi@clarkson.edu

Cetin Cetinkaya
Department of Mechanical and Aeronautical Engineering, Clarkson University
Potsdam, NY, 13699-5725, USA
cetin@clarkson.edu

ABSTRACT

Small (nano-/micro-scale) particle transport, deposition and removal are of critical importance in many industries including semiconductor manufacturing, imaging, pharmaceutical and food processing. In addition, numerous environmental processes involve particle transport, deposition and removal. In the last decade, significant research progress in the areas of nano- and micro-particle transport, deposition and removal has been made. In this project, a series of courses was developed to make these class of new important research findings available to seniors and graduate students in engineering through developing and offering of specialized curricula at Clarkson University. The project involved integration of particle transport, deposition and removal numerical simulations and experiments in the developed courses. The course materials are mostly made available on the web and some courses have been taught at Clarkson University and Syracuse University campuses simultaneously. Based on the course materials, a series of short courses was also offered at several countries. The first two courses on particle transport, deposition and removal are composed of four modules: (i) fundamental of particle transport, dispersion, deposition and removal, (ii) computational modeling of particle transport, deposition and removal, (iii) experimental study of particle transport, deposition and removal, and (iv) industrial applications of particle transport, deposition and removal.

Based on this course development experience, more recently, a new undergraduate course (*Nano/Micro-scale Systems Engineering*) was developed. The course development and implementation was supported a grant from NSF under the Nanotechnology Undergraduate Education program following an initial grant from Clarkson University. The chief instructional objective of the new course is to familiarize the students to the design, analysis, simulation and implementation/fabrication of nano/micro-scale engineering systems. This nanotechnology course consists of three main components to address a set of its well-defined educational objectives: (i) lectures developed and delivered by a multidisciplinary team at Clarkson University, (ii) instructions on computational design/analysis and simulation tools, and (iii) a hands-on workshop for gaining experience with cleanroom procedures and fabrication facilities. The second component has been developed with help of a software company. The third component is being realized through collaboration with the NNIN supported CNF facility at Cornell University as a hands-on workshop for the Clarkson students. An outline of this ongoing course development activity has been given and main features of the course has been discussed.

INTRODUCTION

Understanding particle transport, deposition and removal is of crucial importance to many technologies that are critical for the competitiveness of semiconductor manufacturing, imaging and pharmaceutical industries. In addition, understanding and solving a number of environmental problems requires a detailed understanding of particle transport and deposition processes. In the last decade, significant research progress in the areas of particle transport, deposition and removal has been made. The primary objective of this combined research and curriculum development project is to make the fruits of these new important research findings available to seniors and first year graduate students in engineering through developing and offering of a sequence of specialized courses. In these courses the process of particle transport, deposition and removal and re-entrainment was described. An extensive web site for the

course materials was developed and the courses were taught simultaneously at Clarkson University and Syracuse University.

Following the small-particle courses, a new nanotechnology course for Clarkson undergraduates has been developed. The main instructional objective of the course *Nano/Micro-scale Systems Engineering* is for undergraduate students to become competent in solving problems faced in the design, analysis, simulation and implementation/fabrication of nano/micro-scale systems. The specific *instructional and intellectual objectives* of this nano/microengineering course are determined as follows: Students will (i) be able to link meso-scale engineering to micro/nano-scale engineering, (ii) compare/contrast/evaluate nano/micro-scale engineering applications, (iii) use the computational/design tools available for nano/micro-scale engineering and will know their limitations, and (iv) use fabrication facilities to implement micro-scale structures. This course development activity is ongoing and additional data on its effectiveness will be reported shortly.

MODULES OF PARTICLE TRANSPORT COURSE

These combined research and curriculum development (CRCD) courses are composed of four modules. The models include: (i) fundamental of particle transport, dispersion, deposition and removal, (ii) computational modeling of particle transport, deposition and removal, (iii) experimental study of particle transport, deposition and removal, and (iv) industrial applications of particle transport, deposition and removal.

The front page of the course webpage is shown in Figure 1. The lecture notes and the calculations models are uploaded into the course web and are available in both pdf format as well as html format.

Figure 1. Front webpage of CRCD and the related courses.

MODULE I: FUNDAMENTAL CONCEPTS

In Module I the descriptions of fundamental concepts of aerosols including hydrodynamic forces (e.g. drag and lift), and adhesion forces were provided. The nature and mechanics of particle adhesion and removal was also discussed. This module contains the descriptions of particle interactions with laminar flow, Brownian motion process, and particle deposition by diffusion, interception and impaction.

The sections on interactions of particles with turbulence and turbulent deposition that are normally taught in the second course. Computational modeling of turbulent flows was also discussed, and classical models of turbulent deposition were described in Module 1. In addition the process of aerosol charging and transport under the action of electrical forces and turbulence were discussed.

We have added a number of computational modules to make the course presentations of the materials more interactive. The plan is to include a sufficient number of calculation modules for the student to experiment with and explore various scenarios. As a result of this exposure, the student will develop a physical understanding of some of the more advanced concepts of particle transport.

MODULE II: COMPUTER SIMULATIONS

We refined and developed several computer modules that were incorporated into the course sequence. One class of examples was concerned with exploring the flow and particle transport in a variety obstructed ducts. FORTRAN simulation programs that were developed in earlier research and education efforts were converted to JAVA. These programs were incorporated in the modules dealing with the motion of aerosol particles in the obstructed duct flows. The students are able to interactively use the programs to explore the effects of various forces (e.g. gravity, drag, lift, Brownian), materials properties (particle density), and the flow geometry on the motion and deposition of small-scale particles. For example, a software component was developed for illustrating Brownian particle motion in cross flows. The flow field in this module is a parabolic velocity profile between two parallel plates. The particle equation of motion includes Brownian motion, drag, lift, and gravity. Figure 2 depicts the user interface for this module. Here, particles are injected from a nozzle in the middle of the channel, and the dispersion of the Brownian particles can be seen. The module can also be used to illustrate the effects of the lift force on larger particles. In the simulations, the student can select values of the particle diameter and density, the number of particles, and the centerline fluid velocity.

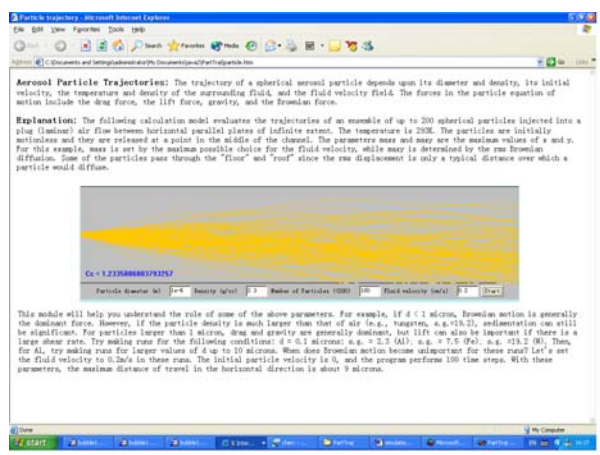


Figure 2. User interface for the module for Brownian particle motions in cross flows.

MODULE III: EXPERIMENTAL METHODS

The course sequence includes several experimental modules. One main experiment is the measurement in the aerosol wind tunnel with the use of Particle Image Velocimeter (PIV). The aerosol wind tunnel is located in the Turbulence and Multiphase Flow Laboratory at Clarkson University. The pulsed laser used in the experiments is a 120mJ Nd:YaG laser with a 20° adjustable width sheet generator. In this particular experiment, the sheet width was 0.5 mm. A digital camera integrated into the experimental set-up is a Kodak ES1.0 MegaPlus with a pixel range of 1008x1008 and the pixel size of 25 micrometers and the interframe delay of 12 microseconds. A photograph of the experimental setup is shown in Figure 3. A sample PIV measurement of the velocity field behind a step is depicted in Figure 4.

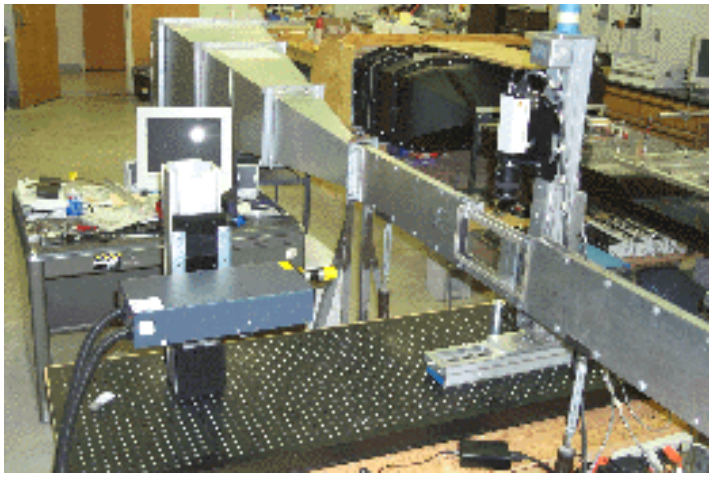


Figure 3. A picture of the aerosol wind tunnel.

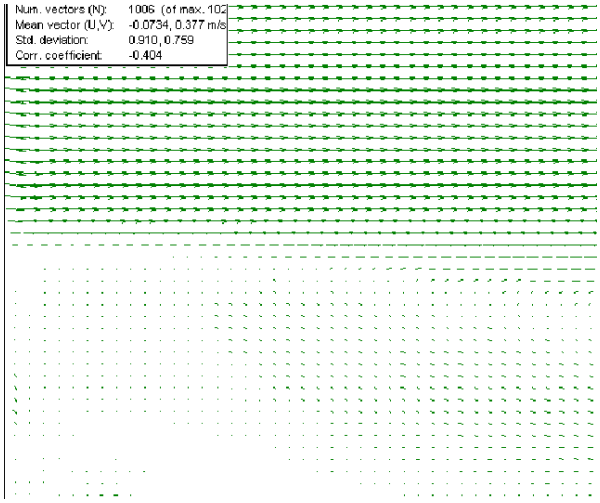


Figure 4. Sample PIV measurement behind a step in the aerosol wind tunnel.

MODULE IV: SPECIFIC APPLICATIONS

The applications module concerns with a number of particle motion and deposition examples from air pollution dispersion to Xerography. In Figure 5 the satellite photograph of the Peace Bridge area in the south west Buffalo, NY. Figure 6 shows a sample computational result for the dispersion of particulate emission form the traffic on the Bridge.

COURSE WEB EFFECTIVENESS

The effectiveness of the course website was assessed in two ways:

1. Usability tests were first conducted on an early version of the site and the same test was later conducted on a revised version of the website. In both tests, participants were given tasks to find course material and use the calculation model available on the site. The main purpose of these tests was to determine how efficiently the participants could complete each task.

2. A multi-question survey questionnaire was administered to students enrolled in the courses designed to assess the students' satisfaction with the website.

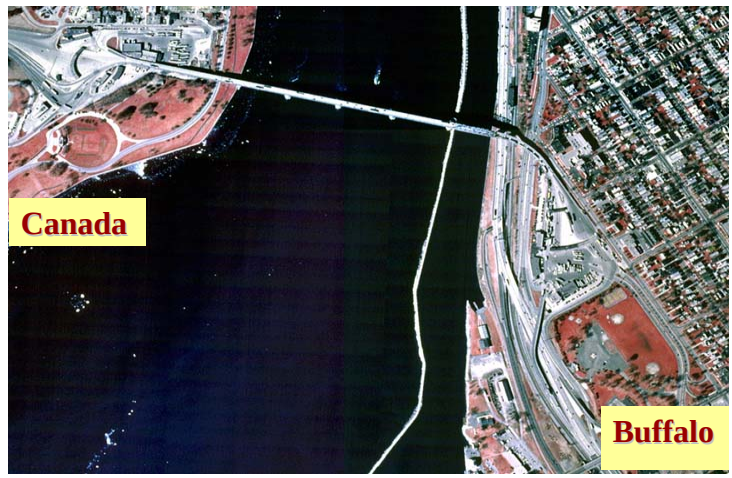


Figure 5. A picture of Peace Bridge area and city of Buffalo.

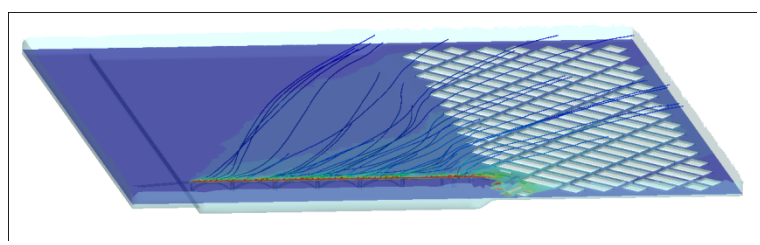


Figure 6. Sample computational result for pollutant dispersion form Peace Bridge traffics.

USABILITY TESTS

The Usability Testing Lab at the Eastman Kodak Center for Excellence in Communication at Clarkson University was set up to record users testing out the effectiveness of the website developed under this program. Participating in the first test on the early version of the website were twelve student

volunteers: six Mechanical Engineering majors and six Information Technology majors. The results of the test and the lessons from these tests was communicated to the website designers. A year later after the website had been redesigned a second usability test was conducted with two Mechanical Engineering majors and three Information Technology majors

For both test sessions a list of twelve tasks was devised that would cover a variety of possible uses of the website. All tasks required the students to search the site for course-related information. One task asked the students to do a calculation using the calculation model currently embedded into the site. As reported below, the results indicate that the participants using the revised site completed the tasks more efficiently.

Original Site
Average number of clicks, searches, scrolls to complete each task per user: **3.70**
Revised Site
Average number of clicks, searches, scrolls to complete each task per user: **2.56**

Original Site
Average number of failed or incomplete completions of the task per user: **1.41**
Revised Site
Average number of failed or incomplete completions of the task per user: **0.60**

SURVEY QUESTIONNAIRE

Twenty-two students completed a questionnaire upon completing the course in which the students could use the website to assess their education and instructional experience. Overall, the participating students found the website useful for their needs:

1. The website was used to access information and employ calculation models:

- 77% used the website to read the course syllabus
- 86% used the website to read homework assignments
- 77% used the website to download course notes
- 54% used one or more of the calculation models

2. Students found the availability of course notes to be useful:

- 86% found the course notes to be easy to moderately easy to find.
- 96% found the course notes helpful to moderately helpful to their coursework.
- 86% found the course notes to be easy to moderately easy to understand.

3. Students found the calculation models to be useful:

- 81% found the calculation models to be helpful to moderately helpful.
- 81% found the calculation models to be easy to moderately easy to use.

4. Overall, 86% found the website to be very to moderately helpful to their coursework.

NANO/MICRO-SCALE SYSTEMS ENGINEERING COURSE[8]

The course *Nano/Micro-scale Systems Engineering* consists of three main components to address its well-defined educational objectives, as discussed below in detail, (i) lectures developed and delivered by a multidisciplinary team at Clarkson University, (ii) instructions on computational design/analysis and simulation tools and (iii) a hands-on workshop for experience with cleanroom and fabrication facilities. The third component is realized through collaboration with the Cornell Nanoscale Facilities (CNF) at Cornell University in Ithaca, New York, as a hands-on workshop for Clarkson students (named the CNF Workshop) (Figure 7). A video clip reporting the activities of the CNF Workshop and the class visit is available at the CNF website.[5] CNF is an NSF (the National Science Foundation) NNIN (the National Nanotechnology Infrastructure Network) supported facility.[6] This course development project is currently ongoing and various changes to the course contents are under consideration.

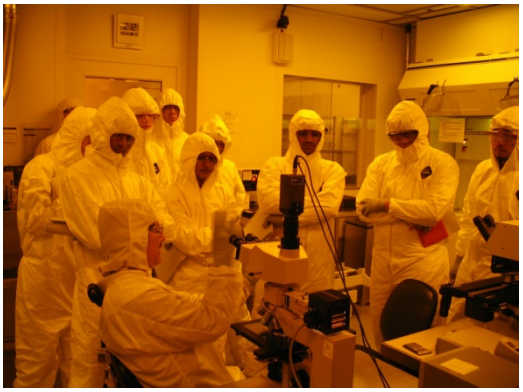


Figure 7. A group of Clarkson students at the cleanroom of CNF during their micro/nanofabrication workshop.

In the following, various activities and topics covered in a 16-week semester on a weekly basis are outlined:

Weeks 1-4: Introduction to nano/micro-scale engineering: Students submit their weekly homework assignments based on lectures and reading assignments.
Topics:
Engineering process in the nanoscale
Scaling laws for length and time and its effect on modeling
Nano-scale materials and systems (Man-made systems vs. biological systems)
Nanoparticles, Nanotubes, Nanowires, Quantum Dots
Fabrication and testing fundamentals; Fabrication of Semiconductor/IC circuits (chips, switches)
MEMS Devices: Design/Analysis Principles, Sensors, Switches, and Mirrors
Sensing and actuation in nano/micro-scale
Analysis and design tools for nano/micro-scale systems
MEMS: MEMS vs. NEMS

Overviews: CNF project and trips, and computational project

Week 5: CNF Nanocourses Videos - Basics (Part 1). These videos are watched in class. Before starting the videos, brief discussions are made to answer/address questions/concerns from previous video sessions. If needed, teleconferences are scheduled with the CNF staff. The CNF workshop schedule and trip planning:

Topics:

Fabrication of cantilever beam arrays

Cleanroom and Fab Procedures

Photolithography: Processes, Design, E-Beam lithography

Week 6: Basic Training: (CNF Workshop 1 at Ithaca, New York)

Topics :

Safety training

Cleanroom operation and training

Basic tools operation and training

Metrology training

Week 7-8: Software workshop/instructions [with support from Nanorex]

Topics:

Principles of molecular mechanics with Nanorex/NanoEngineer-1

Overview of Molecular dynamics methods and simulations

Brief Overview of FE (finite element methods) and DEM (Discreet element method)

Project: Goal/Objective/Function: Develop a nano-mechanism to transfer rotational motion from a motor driven nanogear to a free-spinning nanogear through the use of a middle component.Requirements: The gear assembly must be stable for a simulation of 25,000 total frames, 10 steps/frame, at 300K. Restrictions: No jig or anchor can be connected directly for covalent bonding of the middle component.

Week 9: Module 1 (Ian Suni): Principles and Applications of Nanobiosensors

Topics:

Principles and operation of nanobiosensors (including practical aspects)

Effects of mass transport on nano-sensor performance

Lab: Development of multilayers of alternating nanoscale films for sensing elements

Week 10: Module 2 (W. Ding): Micro/nano-scale Mechanics in Sensor Development

Topics:

Mechanics of micro/nano-scale structure

Structure of cantilever beam-based sensors

Lab: Experimental mechanics of cantilevered beams in sensor application: Force-deflection curves

Week 11: Module 3 (F. Hua): Engineering of Sensor Nanomaterials

Topics:

Methods of engineered nanomaterials

Electronic, thermal, optical and mechanical properties of materials in micro/nano-scales

Lab: Nanoprinting with particles and films

Week 12: CNF Nanocourses Videos – Fabrication (Part 2)

Topics:

Vacuum: Vacuum systems, pumps and gauges

Thin Film Processes: Evaporation, dry and wet etching, sputter deposition, chemical mechanical planarization (CMP), bonding and embossing

Characterization: Optical techniques and microscopy, SEM, optical and electrical properties, Auger and thin film analysis, atomic force microscopy (AFM)

Week 13: Fabrication Training: (CNF Workshop 2 at Ithaca, New York)

Topics:

Development of fabrication steps

Fabrication of sensor elements (beams and disks with nano- and micro-scales

Characterization and imaging of sensor elements

Week 14: Testing and Characterization of Sensor Elements (University 1)

Topics:

Mechanical modeling and characterization of sensor elements fabricated at CNF

Instructions on the use of the air-coupled/interferometer set-up for micro-structure testing

Lab: Hands-on testing and characterization experiments with the cantilever beams and rotational oscillators.

Week 15: Computational project reports (oral and written reports); preparation and corrective feedback for the final report. (University 1)

Activities:

Oral report presentation

Final written reports

Week 16: Final exams week: final project report and presentations due finals week.

Module 1 Principles and Applications of Nanobiosensors (Prof. Ian Suni): Creation of nanoscale protein films on cantilever for sensor applications

Lecture 1: Self-assembly techniques for attachment of biomolecules to cantilever surfaces

For many sensor applications, biosensors offer the promise of superior selectivity due to their biological specificity. For example, through the use of enzymes or receptor proteins that interact specifically with glucose, the concentration of glucose can be measured independently of the presence of other sugars that are quite chemically similar. As for industrial catalysis, practical sensor applications require that enzymes and receptor proteins be immobilized onto a solid surface. The chemical scheme most commonly employed on the laboratory scale involves the use of Au-S self-assembly chemistry. This allows both direct immobilization of proteins that contain cysteine residues, and indirect attachment of proteins to surfaces through linker chemistries. As will also be discussed, protein immobilization can also be made directly onto Si for integration into MEMS devices. Protein films created in Prof. Suni's laboratory range from 5-15 nm in thickness.

Lecture 2: Effects of Mass Transport on Nano-Sensor Performance

For many sensor applications, rapid analysis is of critical importance. For glucose biosensors, patients with diabetes or hypoglycemia need real time information on blood glucose levels. However, many traditional biosensor methods are quite slow and incapable of providing real-time information. When the sensing element is arrayed as one monolayer onto a solid surface, or when the sensing element is confined to nanoscale geometries within a porous surface, rapid measurements are possible. On the other hand, distribution of the sensing element throughout longer length scales within a porous surface will increase the time constant of the sensor, and prevent real-time measurements. Students from all engineering disciplines can learn to do both back-of-the-envelope calculations of transport rates and solve simple transport models. Valuable lessons can include, for example, the large difference in effective diffusion coefficients between small molecules (glucose) and large molecules (proteins, including antibodies).

Experiment (two lectures, one week): Undergraduate students can easily construct multilayers of alternating nanoscale films of streptavidin and biotin. Streptavidin is a 60,000 dalton tetrameric protein purified from the bacterium *Streptomyces avidinii*. It finds wide use in molecular biology through its extraordinary affinity for the vitamin biotin, and streptavidin-biotin binding is often used as a model system for testing biosensor strategies. The dissociation constant (K_d) of the biotin-streptavidin complex is on the order of ~10^{-15} mol/L, one of the strongest known non-covalent interactions. Numerous methods have been developed to immobilize nanoscale films of streptavidin and biotin. In addition, electrochemical methods can easily measure the increased electrical isolation from the surface as the thickness of the streptavidin-biotin multilayer increases. Thus students can indirectly measure the thickness of the nanoscale protein film. Detailed characterization of the nanoscale protein films will be done at the CNF facility.

Module 2 Micro/nano-scale Mechanics in Sensor Development (Prof. Weiqiang Ding): Two lectures will be given on the mechanics aspect of micro/nanoscale sensing structure and system:

Lecture 1: Micro/nano-structure Mechanics

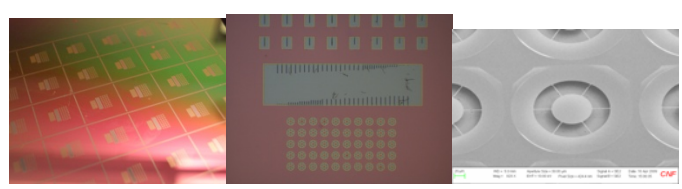
This lecture will cover experimental nanomechanics studies of micro/nano-scale structures. To provide essential nanomaterials background, several nanostructure synthesis techniques such as vapor-phase, vapor-liquid-solid, electro-spinning and template-directed methods will first be briefly reviewed. Then a number of micro/nano-scale mechanical characterization techniques, including atomic force microscopy, nanoindentation, tensile testing, bending and mechanical resonance methods, will be presented. The underlying principles of each technique will be addressed, and corresponding experimental studies from the recent literature will be presented. While a number of related testing instruments such as STM, AFM and FIB are not available at University 1, the students will get a chance to see demonstrations of these instruments at CNF. As a homework assignment, the students will be asked to compare the performance of different nanoscale mechanical characterization techniques based on the literature.

Lecture 2: Mechanics of Cantilever Beam-based Sensors

This lecture will be an in-depth discussion on microsize cantilever beam sensor mechanics studied by nanomanipulation inside an SEM. First the principle of SEM imaging will be briefly introduced. Then two techniques to characterize the cantilever beam mechanics, the bending method and the mechanical resonance method, will be presented. Mechanical characterization examples from Dr. Ding's previous and ongoing research projects will be presented, including tensile and resonance studies of carbon nanotubes, boron nanowires and carbon nanofibers. Several important issues in beam mechanics study such as the boundary condition and beam nonlinearity will be discussed. The student will get a homework assignment to analyze the resonance frequencies of silicon cantilever beams that they will fabricate at CNF.

Hands-on Lab Session on Beam Sensor Mechanics:

In addition to the two lectures, a hands-on lab session of microfabricated cantilever beam stiffness determination inside the SEM will be given (Figure 8). The experiments will be carried out with a custom-made SEM nanomanipulator from Dr. Ding's group inside the vacuum chamber of a JEOL 7400F SEM in the Center for Advanced Materials Processing at University 1. The nanomanipulator is composed of two positioning stages driven by piezoelectric actuators. AFM cantilever probes are mounted on top of the stages for nanostructure manipulation and mechanical testing. An AFM cantilever of known force constant will be used to determine the force constant of a microfabricated silicon cantilever beam with the bending method. Through nanomanipulation, the AFM cantilever will be pushed against the silicon cantilever beam. The deflection of both cantilevers will be monitored in the SEM, and the force constant of the silicon cantilever beam will be obtained from its bending response. As a comparison, the force constant of this microfabricated silicon beam will also be determined with the mechanical resonance method. The students will observe the entire testing process on the SEM monitor. They will also learn the data analysis process. Through the lectures and the lab demonstration, the students are expected to develop a general understanding of current techniques in characterizing the mechanical properties of micro/nano-scale structures.



(a) **(b)** **(c)**

Figure 8. Optical (a and b) and scanning electron images (b) of a set of micro-cantilever beams and free-standing rotational disks fabricated by ME 591 students at CNF.

Module 3 Engineering of Sensor Nanomaterials (Prof. Feng Hua)

Two more lectures will be given on the design, formation and function of micro/nano systems using nanostructured materials as the building block. Furthermore, the macroscopic properties

of the system will be correlated to those of the nanomaterials from which they are made. One lab session will be implemented at CNF's cleanroom to offer both the hands-on experience and practical link to the contents of the lectures.

Lecture 1: Sensor Surface Modification by Nanomaterials

This lecture will first briefly introduce the concept of surface tension, and its relation with the hydrophobic and hydrophilic properties of the surface. Then various nanomaterials that have been used to modify the surface property will be introduced, including self-assembled monolayers (SAMs) of hydrophobic and hydrophilic molecules and layer-by-layer self-assembled polyions and nanoparticles. The nanofabrication techniques that manipulate those nanomaterials will be reviewed. Eventually, different patterning techniques to generate surface wetting function will be covered. In an attempt to attract the student interest, many pictures of an alternate wetting/dewetting pattern on one surface will be shown in class. One homework assignment will be given asking students to design a simple approach to modify the wetting properties of a glass window.

Lecture 2: Strength Enhancement

This lecture will review a class of layer-by-layer self-assembled nanoparticle thin films and their unique properties. Then the nanostructure, property and self-assembly of the clay nanosheet will be introduced. The multilayer assembly of nanoparticles and clay will be demonstrated. The students will find that the mechanical strength of the self-assembled thin film is significantly improved with the integration of the clay nanosheet. The improved strength will be correlated to the properties and structure of the clay nanosheet. Relative pictures and videos will be shown in class. One homework assignment will be given, asking students to sketch a multilayer with clay and nanoparticles.

Hands-on Lab Session:

In order to solidify the class knowledge, one hands-on module is designed. The lab module will be implemented after the homework from the first lecture is due because it is the lab version of this homework assignment. The purpose is to demonstrate to students the modification of the surface wetting based on nanomaterials' properties. The module will be not only demonstrated by the lecturer, but also allow student participation. This includes (i) the self-assembly of a hydrophobic SAM over the surface, (ii) the fabrication of a silicon mold, (iii) the fabrication of a polydimethylsiloxane (PDMS) mold which is derived from the silicon mold, (iv) printing of the hydrophobic group onto the surface, and (v) observing the wetting/dewetting pattern on the surface. This lab will take advantage of the cleanroom and facilities at CNF for photomask fabrication, photolithography, etc.

Through the lectures and the lab, the students are expected to develop a general concept of nanomaterials, as well as the nanofabrication techniques that manipulate them. They should also gain the basic idea of the design and fabrication of micro/nano systems with appropriate nanomaterials for a specific application.

Methods of Evaluation

The final grade of the student is based on the following tasks and associated percentage weights:

Project: Computational Analysis/Design of a Nanosystem	20%
Project: Nanosystem Simulations	25%
Homework Assignments	20%
Final Written/Oral Report on Micro-oscillators (Team)	35%

The homework assignments will include (i) problems based on materials covered in lectures and (ii) open-ended research problems based on reading assignments.

Students were presented with post-course instrument items that asked them to answer questions about the instructional elements. Items were answered using a five-point scale in which one signified a strong negative response and five signified a strong positive response (e.g., 1 = strongly disagree and 5 = strongly agree). Overall mean ratings and percent distributions are provided in Table 1.

CONCLUSIONS

The development effort for a sequence of web-based courses on particle transport, deposition and removal was described, and its activities are discussed. A number of modules of the course are outlined and the integration of the simulation and experiment into the curriculum was described. The suitability of the course website in helping the student learning was assessed. The results showed that the availability of the course material and computational module on the website was very helpful to student learning. As a result of the course webpage, students at multiple campuses could take the course simultaneously.

Table 1. Summary of course evaluation data on the instructional elements

Instructional Elements	Strongly Disagree	2	Neutral	4	Strongly Agree	Mean	n
The reading assignments were relevant to the course objectives.	0%	0%	0%	0%	100%	5.0	7
The assigned readings were at an appropriate level for me.	0%	0%	0%	43%	57%	4.6	7
The reading assignments were interesting.	0%	0%	0%	71%	29%	4.3	7
I spent an appropriate amount of time completing reading assignments for this course.	0%	0%	0%	57%	43%	4.4	7
The instructor generally used computer-based instructional materials effectively.	0%	0%	14%	57%	29%	4.1	7
The computer-based instructional materials used in this course helped me learn.	0%	0%	29%	71%	0%	3.7	7
The use of the CNF Workshop enriched my learning experience in this class.	0%	0%	0%	14%	86%	4.9	7
The instructor clearly explained expectations for use of the CNF Workshop in this course.	0%	0%	0%	29%	71%	4.7	7
The instructor effectively used the CNF Workshop as a basis for group work in class.	0%	0%	0%	0%	100%	5.0	7
The CNF Workshop has been a valuable part of this course.	0%	0%	0%	0%	100%	5.0	7

An ongoing nanotechnology course development activity based on the CRCD experience is also outlined. One challenge in developing and implementing experimental aspects of the course *Nano/Micro-scale Systems Engineering* at CU, a small research-intensive university, has been the unavailability of

needed on-site cleanroom and fabrication facilities and required support staff. This is a common limitation for several small universities, and we have demonstrated that this limitation can be overcome by teaming up with a larger institution where nano/micro-scale fabrication facilities with trained staff are available. We believe that our experience will play a key role developing such a course in other similar small universities. As the reports from the independent assessor of the course indicate, the student satisfaction with the course and the instructors was high in the first year of the program (Spring 2009). This course development activity is ongoing and additional data on its effectiveness and lessons learned during the course of the development and teaching efforts will be reported in a separate article at the completion of the program.

ACKNOWLEDGMENTS

The support from the National Science Foundation under the grants EEC 0087873 (CRCD Engineering Education) and EEC 0836640 (Nanotechnology Undergraduate Education in Engineering Education) is gratefully acknowledged.

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