MSE 4803/8803A Nanomaterials and Nanotechnology

Introduces the concept of nanotechnology. Describe various types of nanomaterials that have been synthesized for applications in nanotechnology (mechanics, electronics, optoelectroics, energy and biomedical sciences). Describe the novel synthesis methods of various nanomaterials.

Instructors: Prof. Z.L. Wang (leader), Prof. C.J. Summers, Prof. R. Tannenbaum

e-mails: Prof. Z.L. Wang <zhong.wang@mse.gatech.edu>
Prof. Chris Summers <chris.summers@mse.gatech.edu>
Prof. Rina Tannenbaum <rina.tannenbaum@mse.gatech.edu>

Reference books:

"Handbook of Nanophase and Nanostructured Materials", eds. Z.L. Wang, Z. Zhang and Y. Liu, Kluwer Academic Publisher (2002).
"*Self-assembled Nanostructures*," by J.Z. Zhang, Z.L. Wang**,** J. Liu, S.W. Chen and G.Y. Liu, Kluwer Academic Publisher (New York, 2002).
"*Electron Microscopy of nanotubes*," ed. Z.L. Wang and C. Hui,, Kluwer Academic Publisher (New York, 2003).

Outline:

I. Introductioin to nanotechnology

In the history of industrial engineering, technology is characterized by length only occurred in microelectronics. The semiconductor industry in the last few decades follows the Moore's law. The projections extend to the year 2012, at which time the smallest component of a device would have a linear dimension of 50 nm. However, for years beyond 2006 and device features 100 nanometer (nm) or smaller, the roadmap is filled with the notation "No known solution." The semiconductor roadmap ends just short of true nanostructure devices because the principles, fabrication methods, and way of integrating devices into systems are unknown. The transition from microelectronics to nanoelectronics results in changes in fundamental physics.

Nanotechnology is the second time that technology is characterized by length. How small is one nanometer? A typical width of a human hair is 50 micrometer; one nanometer is 50,000th of a hair width.

Nanotechnology is the construction and utilization of functional structures designed from atomic/molecular scale and with at least one characteristic dimension measured in nanometers. Such materials and systems can be rationally designed to exhibit novel and significantly improved physical, chemical, and biological properties, phenomena, and processes because of their size. When characteristic structural features are intermediate in extent between isolated atoms and bulk materials, in the range of about 1 to 100 nm, the objects often display physical attributes substantially different from those displayed by either atoms or bulk materials.

As a start of this course, an introduction will be given about the history of nanotechnology, why it is becoming so important in the last few years? What is the industrial bases of nanotechnology? what are the main research directions in nanotechnology? what are the most important applications and impacts of nanotechnology. The lecture will answer the following questions:

1. What is nanotechnology?
2. Nanotechnology, why now?
3. Nanomaterials and nanotechnology
4. Nano vs miniturization

II. Introduction to quantum mechanics

An introduction to the fundamental concepts of quantum mechanics is presented as a background to describing the optical and electronic properties of nano materials and nano systems. The description of the electron as a wave is introduced and the consequence of reduced dimensionality on electron properties are discussed. The consequence of quantized states, and the new devices resulting: the quantum well laser, the resonant tunneling diode and transistor, and quantum cascade laser are then described.

The behavior of electrons in two- and three-dimensional quantum confined systems is then presented – starting with a description of the hydrogen atom. From this the size dependence of band structure is developed and the Brus model for clusters of atoms leading to the physical description of "quantum dots" developed. This is followed by a description of the physical, electronic and optical properties (and chemical synthesis and applications) of quantum dots and superlattices. The lectures will focus on following subtopics:

5. Wave
6. Energy quantization
7. Wave function for hydrogen atoms
8. Quantum phenomena

III. Phenomena at nano-scale

Phenomena at the nanometer scale are likely to be a completely new world. Properties of matter at the nanoscale may not be predictable from those observed at larger scales. Important changes in behavior are caused not only by continuous modification of characteristics with diminishing size, but also by the emergence of totally new phenomena such as quantum confinement, a typical example of which is that the color of light emitting from semiconductor nanoparticles depends on their sizes. Designed and controlled fabrication and integration of nanomaterials and nanodevices is likely to be a revolutionary for science and technology. Nanotechnology can provide unprecedented understanding about materials and devices, and is likely to impact many fields. By using structure at the nanoscale as a tunable physical variable, it is possible to greatly expand the range of performance of existing chemicals and materials. Alignment of linear molecules in an ordered array on a substrate surface, which is the self-assembled monolayers, can function as a new generation of chemical and biological sensors. Switching devices and functional units at nanoscale can improve computer storage and operation capacity by a factor of a million. The entirely new biological sensors are for early diagnostics and disease prevention of cancers. Nanostructured ceramics and metals have greatly improved mechanical properties, both in ductility and strength.

From the fundamental units of materials, all natural materials and systems establish their foundation at the nanoscale; control of matter at atomic/molecular levels means tailoring the fundamental properties, phenomena, and processes exactly at the scale where the basic properties are initiated. Nanotechnology could impact the production of virtually every human-made object—everything from automobiles, electronics, advanced diagnostics and surgery, to advanced medicines and tissue/bone replacements. If we like to build electronic devices using the atom-by-atom engineering, for example, we have to understand the interaction among atoms/molecules, how to manupilate them, how to keep them stable, how to communicate signals among them, and how to face them with the real world. This goal requires new knowledge, new tools and new approaches. The lecture will focus on following specific topics:

9. Electrical transport at nano-scale
10. Nano-dimension magnetics
11. Nanomechanics and nanotribology

12. Nano-scale thermal transport and nanofluidics
13. Chemisty at nano-scale
14. Nano-scale biology and medical science

IV. Nanomaterials systems

A key part of nanotechnology is nanomaterials. This section will introduce fundamental approaches and description of general synthesis and processing strategies and requirements: CVD, MOCVD, soft lithography, dip-pen lithography and self-assembly. Several examples from literature will be utilized: quantum dots, carbon nanotubes, hierarchical assemblies and chemical pattern (block co-polymers). The topics to be coveres are:

Synthesis – high vacuum techniques (CVD, MOCVD, apparatus, etc.), "wet" chemistry techniques (reduction of metal salts, sol-gel, decomposition of organometallic precursors, emulsion synthesis, etc).

Particle stabilization methods – surfactants, viscous media, polymers. Surface reactivity, adsorption, Langmuir-Blodgett films, self-assembled monolayers, assembly of multilayers, hierarchical assembly. Mechanism of stabilization – minimization of surface energy, entropy considerations, polymer conformations at surfaces, anchoring point calculations. The structure of the interfacial layer – implications to mechanical properties.

Particle size control (other than stabilization) – molecular cages (resorcarenes), zeolites, "soft" molecular capsules (micelles, reverse micelles, vesicles, latex), dendrimers.

Processing – self-assembly and chemical patterning – block co-polymer microstructure development, block reactivity as patterning driving force, molecule corrals, polymer nanopore arrays. Formation of periodic nanostructures and implications to opto-electronic applications (waveguides, grating couplers, sensors, etc).

Lithographic techniques – "soft" lithography, "soft" nanoscale lithography, dip-pen lithography (DPN), multi-DPN patterning, SAMs as inks in DPN patterning, 3-D patterning with combination DPN and self-assembly approaches, applications to molecular recognition.

The lectures will focus on following materials systems:

15. Metallic nanostructures
16. Polymer nanostructure
17. Nanocomposites
18. Ceramic nanostructures

V. Nanostructures

Recent investigations of the properties of nano-crystals and quantum superlattices (arrays of quantum dots) are then presented and potential nanoparticle quantum devices that depend on these phenomena, such as single electron effects, described. A three-class section on photonic crystals (properties, characterization and devices) concludes this module.

Carbon nanotubes, an important material for nanotechnology, will be introduced. We will cover its synthesis, novel physical properties and potential applications. The most recent development in one-dimensional nanowires and nanobetls of semiconductors and oxides will be covered. Details of the topics to be covered are

19. Quantum dots and quantum superlattices
20. Photonic crystals
21. Carbon based nanostructures
22. Nanobelts and nanowires
23. Self-assembled nanostructures

Teaching method: in-class lectures, and presentations given by invited speakers (prominent professors and graduate students).

Home work: there will be 4 homework assignments. The homework will be collected but will not be graded. A completion of the homework contributes 10% towards the final grade.

Exams: There will be 3 exams scheduled during the semester. Each exam contributes 20% towards the final grade.

Final term paper for undergraduate students: each student will write a review report for a scientific paper assigned by the instructors.

Final term paper for graduate students: the graduate students registered to this course will be divided into 5 groups. Each group will write one full term paper on a specific topic in the format specified by the instructors, and a group leader will be elected who will represent the group to give 20 min presentation in the class.

Final grades:

Homework	10%
Exam 1	20%
Exam 2	20%
Exam 3	20%
Term paper	30%
Total	100%