University of California, Berkeley
Department of Mechanical Engineering

ME 203: Nanoscale Processing of Materials (3 units)

Graduate Course

Syllabus

CATALOG DESCRIPTION

This course surveys sub-micrometer pattern-transfer techniques and methods for handling materials with one or more sub-micrometer dimensions. The optical and mechanical principles underlying a spectrum of candidate lithography techniques are introduced, and extensive examples of industrial applications are discussed. Class material also covers techniques for assembling structures from zero-, one- and two-dimensional materials including nanoparticles, nanotubes, nanowires, and single- and few-atomic-layer sheets of van der Waals solids such as graphene and molybdenite. Applications in semiconductor manufacturing, photonics, data storage, and surface engineering are considered. Assignments may include the numerical simulation of processes, the writing of a literature review on a current topic in nanoscale material processing, and the design and prototyping of a piece of apparatus for manipulating or characterizing material at the micrometer scale or below.

COURSE PREREQUISITES

An understanding of solid mechanics and statics, or permission of instructor. Experience programming in Matlab is desirable for simulation assignments.

TEXTBOOK(S) AND/OR OTHER REQUIRED MATERIAL

Notes are provided; there is no required textbook. Readings are drawn from journals and from the proceedings of conferences in the field.

COURSE OBJECTIVES

The objectives of the course are to:

- Make students aware of current capabilities and innovations in sub-micrometer lithography and in the handling of nanoscale materials;
- Equip students to select an appropriate lithography or processing technique for a given application from among multiple alternatives;
- Provide students with an understanding of the transformations of material that occur in sub-micrometer lithography techniques, such that they can understand why certain processing routes might be preferable to others for particular applications.

DESIRED COURSE OUTCOMES

At the end of this course, students will be able to:

- Articulate the key requirements (*i.e.* resolution, maximum defect density, and multi-layer alignment precision) of micro- and nano-patterning processes to be used in a range of applications, such as semiconductors, hard disk-drives, large-area photovoltaics, and biomedical microdevices.

- Identify which of a set of available micro-/nano-patterning processes (*e.g.* extreme-UV lithography, directed self-assembly, multiple e-beam lithography, and imprint lithography) are suitable for a given patterning application.
- Accurately explain and distinguish between the physical transformations of material that occur in a number of sub-micrometer patterning processes, including imprint lithography, micro-contact printing, micro-embossing, and micro-gravure.
- Identify a number of currently open research questions relating to nanoscale processing of materials and suggest possible creative solutions to them.
- Use numerical simulation techniques to model the behavior of one or more lithographic techniques, including nanoimprint, photolithography, or electron-beam lithography. Use insights from modeling to optimize key process parameters and to make trade-offs in the geometrical design of a pattern that is to be fabricated.

TOPICS COVERED

1. *Overview of nanoscale materials processing techniques*. Criteria for evaluating the capabilities of a lithographic technique.
2. *Nanoimprint lithography*: mechanics of material deformation; rheological properties of imprintable materials; modeling the compliance of multilayered solid bodies to transmit loads to imprintable materials; applications.
3. *Microcontact printing*: analysis of deformation models for a printing stamp; sources of pattern-transfer defects.
4. *Optical patterning*: photolithography; two-photon sterolithography; holographic lithography; extreme ultraviolet lithography. Techniques for enhancing resolution: multiple patterning, phase-shift masks, optical proximity correction. Alignment and registration principles.
5. *Additive processes in micro- and nano-fabrication*. Application to, *e.g.*, microfluidics manufacturing and the printing of ceramic nanostructures.
6. *Injection molding with nanoscale features*. Polymer flow at the nanoscale; mold fabrication coatings and patterning techniques; applications.
7. *Scanning-beam methods*. Electron-, proton-, and ion-beam patterning: techniques and limitations.
8. *Handling of van der Waals solids (2D materials)*. Mechanical exfoliation (dry and liquid-phase); superlubricity; adhesion and wrinkling. Examples of electronic and optoelectronic devices fabricated with 2D materials.
9. *Production of zero- and one-dimensional materials and heterogeneous particles.* Precipitation; chemical vapor deposition; flame synthesis; stop-flow lithography.
10. *Emerging techniques, e.g.*, zone plate array lithography, sacrificial colloids, micro-gravure printing, and directed self-assembly.

CLASS/LABORATORY SCHEDULE

Three hours of lecture per week.

CONTRIBUTION OF THE COURSE TO MEETING THE PROFESSIONAL COMPONENT

The class project will involve the design and prototyping of a piece of apparatus for manipulating or characterizing material at the micrometer scale or below. During the project, students will need to make design decisions and compromises that are representative of those they may encounter professionally. The projects will typically be done in teams, which will enable students to develop their collaborative and communication skills. Projects will involve presentation of progress to class staff and industry professionals in periodic design reviews, which will sharpen students’ oral communication skills. The simulation assignments and possibly the project will require numerical modeling, generally using Matlab, which is prevalent in industry. The literature review will involve analyzing publications from current technical literature, which will require students to read critically and will prepare them for professional situations in which they may need to evaluate the potential of a technology or the validity of technical arguments. The literature review will also require students to practice technical writing.

ASSESSMENT OF STUDENT PROGRESS TOWARD COURSE OBJECTIVES

Approximately three simulation assignments: 36%
A focused literature review: 14%
Design and prototyping project: 50%

PERSON(S) WHO PREPARED THIS DESCRIPTION

Professor Hayden Taylor
10/1/2017

ABBREVIATED TRANSCRIPT TITLE (19 SPACES MAXIMUM): NANO PROC MAT
TIE CODE: LECT
GRADING: Letter
SEMESTER OFFERED: Fall
COURSES THAT WILL RESTRICT CREDIT: None
INSTRUCTORS: Hayden Taylor
DURATION OF COURSE: 15 Weeks
EST. TOTAL NUMBER OF REQUIRED HRS OF STUDENT WORK PER WEEK: 9 hours
IS COURSE REPEATABLE FOR CREDIT? No
CROSSLIST: None

Course schedule

Class #	Date	Class topic	**Assignments due** (unless otherwise noted, due by 11:59pm on the date of the class, with work to be uploaded on bCourses)
1	Wed Aug 23	**Introduction.** Overview of current and emerging lithography technologies and challenges. Future lithography requirements (with reference to the International Roadmap for Devices and Systems). Requirements for integration of lithography with other process steps. Scope of design and simulation projects. Start-of-term logistics. **Performance metrics for lithography techniques** (ways to evaluate a lithography process). Resolution; line edge roughness; overlay capability; throughput; cost of ownership; capital cost; energy consumption and environmental impact (*e.g*. solvent usage; material wastage); pattern dependences.	Start-of-term survey due by 11:59pm *on Fri Aug 25*
2	Mon Aug 28	**Nanoimprint lithography (NIL), part 1: process mechanics.** Spun-on *vs* droplet-dispensed resist. Die-scale, wafer-scale and roll-to-roll formats. Contact mechanics of stamp-wafer interactions. Resist deformation models. Sources of defects.	
3	Wed Aug 30	**Nanoimprint lithography, part 2: imprintable materials.** Thermal *vs* UV-curing resist materials. Temperature-viscosity relationships of thermoplastic resists. Shear thinning. Photocrosslinking and thermal crosslinking reactions. Oxygen inhibition. Use of surfactants and release layers.	General Workshop Safety training completed
	Mon Sep 4	Labor Day – no class	

Class #	Date	Class topic	Assignments due
4	Wed Sep 6	**Nanoimprint lithography, part 3: stamp/template fabrication technologies.** Materials (quartz, silicon, metallic, polymeric). Intermediate stamp replication strategies. Pattern-writing processes (e-beam, directed self-assembly). Segmented, layered, and monolithic stamps. Seamless rollers for roller-based patterning. Defect inspection approaches. **Introduction to Simulation Project 1.**	Topic for literature review selected
5	Mon Sep 11	**Nanoimprint lithography, part 4: machine design.** Step-and-flash *vs* whole-wafer patterning. Roll-to-roll and roll-to-plate configurations. Resist dispensing methods: droplet, spin-on, doctor blade. Load application: flexure; stamp-bowing mechanism; air cushion press. "Self-Aligned Imprint Lithography". Managing defect sources.	
6	Wed Sep 13	**Nanoimprint lithography, part 5: applications.** Photonic crystal LEDs. Dual damascene dielectric imprinting. Bit-patterned data storage. Flash memory. Novel memory structures (*e.g.* by "topolithography"). Surface nanoengineering (*e.g*. superhydrophobicity; "printing color" using plasmonics).	
7	Mon Sep 18	**Discussion of expectations and ideas for Design and Prototyping Project, and introduction to Jacobs Hall facilities**	
8	Wed Sep 20	**Design and Prototyping Project pitches**	Pitch slides (required only if pitching) due on bCourses by 11:59pm on Sep 19
9	Mon Sep 25	**Microcontact printing.** Ink transfer processes. Design of stamps and sources of defects – collapse, buckling, *etc*. Metal film peel-off patterning via rate-dependent adhesion. Application example, *e.g*. printing transparent conductive patterns.	Design project teams created in bCourses
10	Wed Sep 27	**Handling of van der Waals solids.** Definition and properties of van der Waals materials and potential applications. Handling requirements. Mechanical exfoliation. Open research questions.	Simulation Project 1 (NIL)
11	Mon Oct 2	**Photolithography.** Factors determining resolution (numerical aperture, *k*, wavelength). Illumination technology. Alignment methods (fiducial, moiré). Resist technology (positive, negative, image reversal, contrast concepts). *Resolution-enhancing innovations.* Multiple-patterning. Coloring algorithms. Line cutting. Immersion lithography. Source-mask optimization. Phase masks. Computational lithography (optical proximity correction). **Introduction to Simulation Project 2.**	Initial concept sketches for Design and Prototyping Project
12	Wed Oct 4	**Extreme ultraviolet lithography.** Technical considerations: source power, mask infrastructure, economics.	Literature Review
13	Mon Oct 9	**Design reviews 1**	Preliminary design calculations and renderings to be shown at the design review and due on bCourses by 11:59pm on Fri Oct 13.
14	Wed Oct 11		

Class #	Date	Class topic	Assignments due
15	Mon Oct 16	**Additive manufacturing in micro- and nano-fabrication**. Resolution capabilities of current commercial printers, including stereolithography and inkjet systems. Multiple-photon stereolithography. Stimulated emission depletion lithography. Multiple-wavelength photopatterning.	
16	Wed Oct 18	**Additive manufacturing in micro- and nano-fabrication continued.**	
17	Mon Oct 23	**Scanning-beam lithographic methods.** Electron-beam lithography: resolution-limiting factors. Grayscale and reflow techniques. Proximity correction. Ion and proton beam techniques. **Introduction to Simulation Project 3.**	Simulation project 2 (photopatterning)
18	Wed Oct 25	**Emerging X-ray and optically-based lithographic techniques.** Zone-plate array lithography; near-field methods; interference lithography; 3D holographic photopatterning.	
19	Mon Oct 30	**Injection molding of nanoscale geometries.** Polymer flow considerations. Mold coatings: materials and patterning processes. Applications.	Literature Review peer critique
20	Wed Nov 1	**Lithography for MEMS and microfluidics.** LIGA (very high-aspect-ratio patterning); hot embossing; soft lithography. Examples in microfluidics manufacturing.	
21	Mon Nov 6	**Design reviews 2**	Initial physical prototype and preliminary data due at review in class
22	Wed Nov 8		
23	Mon Nov 13	**Production of zero- and one-dimensional materials and heterogeneous particles.** Precipitation methods. Stop flow lithography. Flame/plasma synthesis. Nanotube and nanowire growth. Examples of electronic devices composed of these materials.	
24	Wed Nov 15	**Bottom-up patterning with top-down guidance.** Directed self-assembly of block copolymers. Selective deposition.	Simulation project 3 (scanning-beam patterning)
25	Mon Nov 20	**Emerging mechanical lithography techniques.** NIL variants. “Nanoskiving”. Edge-based lithography. Shrink-induced nanostructures. Sacrificial colloids. Scanning probe methods.	
	Wed Nov 22	No class – Happy Thanksgiving	
26	Mon Nov 27	**Open workshop time for project assembly/testing and faculty consultation**	Literature review revisions and responses (optional)
27	Wed Nov 29		
	Wed/Thu Dec 6/7	**Jacobs Design Showcase**	Final physical prototypes due at the Showcase; final presentation slides due on bCourses and web presence of design due by 11:59pm on Fri Dec 8.