University of California, Berkeley
Department of Mechanical Engineering

ME 203 — Nanoscale Processing of Materials
Fall 2019

Instructor: Prof. Hayden Taylor

Class meetings: T, Th 3.30–5pm in Davis 534
Office hours: Mondays 2–3.30pm in 6159 Etcheverry, or by arrangement

Last updated October 3, 2019

Welcome

Welcome to ME 203. This graduate elective surveys sub-micrometer pattern-transfer techniques and methods of handling nanoscale materials. We introduce the optical and mechanical principles underlying a spectrum of established and emerging lithographic techniques, and discuss examples of applications by reading recent papers. Class material also covers techniques for handling and assembling structures from zero-, one- and two-dimensional nanomaterials including nanoparticles, nanotubes, nanowires, and single- and few-atomic-layer sheets of van der Waals solids such as graphene and molybdenite. The course culminates in team projects, which provide the opportunity to propose a new lithography process or nanostructure analysis method, and either to analyze it theoretically/computationally or to build a prototype apparatus to carry out the method, with an emphasis on making the hardware extremely low-capital-cost and 'open-source' in nature.

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	Thu Aug 29	**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 projects. **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.	
2	Tue Sep 3		Start-of-semester survey
3	Thu Sep 5	**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.	
4	Tue Sep 10		Topic for literature review selected
5	Thu Sep 12		
6	Tue Sep 17	**Introduction to Simulation Assignment 1 (NIL).**	
7	Thu Sep 19	**Discussion of expectations and ideas for Nanofabrication process project, and introduction to Jacobs Hall facilities**	
8	Tue Sep 24	**Nanofabrication process project pitches**	Pitch slides (required only if pitching) due on bCourses by noon on Sep 24
9	Thu Sep 26	**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.	
10	Tue Oct 1		• Project teams created in bCourses
11	Thu Oct 3	**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.	• *Recommended for experimental project teams*: General Workshop Safety training completed
12	Tue Oct 8	**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.	• Literature Review (Oct 8^{th}) • Initial concepts for Project. (**Oct 9^{th}**)

Class #	Date	Class topic	Assignments due
13	Thu Oct 10	**(Power outage)**	
14	Tue Oct 15	No live lecture; remaining recorded material on NIL will be posted if schedule demands. **Remaining project reviews 1 to be scheduled at mutually convenient times**	
15	Thu Oct 17	**Project reviews 1**	
16	Tue Oct 22	**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). **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 Assignment 2 (photopatterning).**	• Simulation Assignment 1 (NIL)
17	Thu Oct 24	**Photolithography continued. Extreme ultraviolet lithography.** Technical considerations: source power, mask infrastructure, economics.	Preliminary project design/process feasibility calculations and illustrations to be presented at the project review and due on bCourses by 11:59pm on **Thu Oct 24**.
18	Tue Oct 29	**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.	
19	Thu Oct 31	**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. Other routes to 3D nanofabrication.	• Literature Review peer critique • Last day to receive training on Jacobs Hall tools
20	Tue Nov 5	**Scanning-beam lithographic methods.** Electron-beam lithography: resolution-limiting factors. Grayscale and reflow techniques. Proximity correction. Ion and proton beam techniques. **Introduction to Simulation Assignment 3 (scanning-beam patterning).**	

Class #	Date	Class topic	Assignments due
21	Thu Nov 7	**Emerging X-ray and optically-based lithographic techniques.** Zone-plate array lithography; near-field methods; interference lithography; 3D holographic photopatterning.	
22	Tue Nov 12	**Project reviews 2 (other reviews may be scheduled at other mutually convenient times outside of class)**	Initial physical prototype and preliminary data or preliminary modeling/simulation results due at review in class
23	Thu Nov 14	**Injection molding of nanoscale geometries.** Polymer flow considerations. Mold coatings: materials and patterning processes. Applications.	Simulation assignment 2 (photopatterning)
24	Tue Nov 19	**Lithography for MEMS and microfluidics.** LIGA (very high-aspect-ratio patterning); hot embossing; soft lithography. Examples in microfluidics manufacturing.	
25	Thu Nov 21	**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. **Bottom-up patterning with top-down guidance.** Directed self-assembly of block copolymers. Selective deposition.	
26	Tue Nov 26	**Emerging mechanical lithography techniques.** NIL variants. "Nanoskiving". Edge-based lithography. Shrink-induced nanostructures. Sacrificial colloids. Scanning probe methods.	Literature review revisions and responses (optional)
	Thu Nov 28	No class – Happy Thanksgiving	
27	Tue Dec 3	**Project presentations**	Simulation assignment 3 (scanning-beam patterning)
28	Thu Dec 5	**Project presentations**	Final presentation slides due on bCourses by 11:59pm on Fri Dec 6. For hardware projects, physical prototype due at the project presentation; for modeling/simulation projects, 6-page IEEE-style paper due on bCourses by 11:59pm on Fri Dec 6.

Activities and assessment

Credit for this course will be weighted in the following way:

Nanofabrication process project			**50%**
	Selection of an interesting and relevant problem in the micro- or nano-scale manipulation, imaging, or characterization of material (project teams to be formed by 10/1)	4%	
	A range of initial concepts generated and clearly communicated (due 10/3)	5%	
	Well-conceived design calculations or process modeling approaches assessing the feasibility of the working principle selected (to be presented in project review 1 and uploaded by 10/24)	10%	
	For hardware projects: clear renderings (CAD or hand-drawn) of the proposed embodiment of the selected concept. For modeling/simulation projects: clear figures communicating any modeling or preliminary simulations already done (due in project review 1 and uploaded by 10/24)	5%	
	Active participation in and thoughtful answers to questions at project reviews	4%	
	For hardware projects: ingenuity in mechanical, optical, or electronic design, and ease of production (initial prototype due in project review 2; final prototype due at final project presentations). For modeling/simulation projects: ingenuity in constructing a realistic, convincing, and, where appropriate, computationally affordable process model	12%	
	Sufficient technical documentation to enable a third party to reproduce the design or modeling/simulation results (due in final presentation slides and, in for modeling/simulation projects, in a 6-page paper)	5%	
	Hardware projects: extent and quality of experimental results obtained with the prototype. Modeling/simulation projects: quality, convincingness, and extent of results described. (Due in final presentation slides, and the 6-page paper in the case of modeling/simulation projects)	8%	
	Reflections and future recommendations (due in final presentation slides and, in for modeling/simulation projects, in 6-page paper)	2%	
Three simulation assignments (12% each) If you wish, you can elect to complete only two of the assignments and the score for those two would be scaled to be worth up to 18% of the class grade per assignment.			**36%**
A focused literature review			**14%**
	Identification and citation in IEEE format of a substantial number (likely 10–20) of archival publications relevant to the topic selected for the review	4%	
	Well-written, critical appraisal of the publications found, synthesizing the information uncovered, highlighting any contradictions and unresolved questions, and pointing out opportunities for future research	6%	
	A thoughtful, constructive, and well-structured peer review of an assigned literature review written by another class participant	4%	

I will also make available some homework problems to enable familiarization with the lecture material. I will release solutions for these problem sets, but will not collect or grade your work on them.

Class recordings

Lectures will be recorded and available afterwards on CalCentral. To view the recording, If you are registered for ME 203, the class will appear under "My Classes" and the videos under "Course Captures" on the right hand side of the ME 203 class page. In case of any technical issues in accessing the recordings, please contact Educational Technology Services via the web form at https://www.ets.berkeley.edu/request-support-or-give-feedback-calnet.

Simulation assignments

There will be three simulation assignments which will make use of the material introduced in class to model three different lithography processes, probe their capabilities and limitations, and make suggestions for process-aware pattern layout refinements. The handout for each project will be available about four weeks before it is due. Solutions will be turned in individually and while I do encourage collaboration I ask you to write your answers independently and to understand fully the solutions you are uploading.

Foundry tour

I am in the process of organizing a tour for the class of an industrial nanofabrication cleanroom — more details soon.

Literature review

The literature review assignment will be done individually and has two phases. In the first phase, you will select a focused topic related to the nanoscale manipulation of materials. I will provide a list of suggested topics, or you can propose your own topic and we will discuss and hone it. You will then search the archival literature, find 10–20 papers that represent the current state of knowledge in your topic, and write a concise review of it. The review should be no longer than four pages in two-column IEEE journal format. The four-page limit does not include references, which should be given at the end of the paper in IEEE format. A Word template is available on bCourses under Files > Literature review. The review needs not simply to summarize the papers you cite, but to *synthesize* information from the papers, highlight points of consensus and any apparent contradictions or unresolved questions, and look ahead to future opportunities.

The second phase of the assignment will be to take the literature review written by one of the other class participants (reviewers will be randomly assigned) and write a *peer review* of it, as if the literature review was being considered for publication. If you disagree with any of the interpretations made in the review, you need to explain why. The peer reviewer may need to read some of the papers cited in the literature review to complete this task fully. Credit will be given for a thoughtful and well-written review.

Whether the peer review is favorable or not to the literature review will *not* have an impact on the score received by the literature review author in the first phase of this assignment. However, the peer reviews will be passed to the original literature review authors and you will have an opportunity to revise your manuscript and respond to the peer review comments. If you choose to revise your article in this way, please upload a revised version by 11/26 for a possible increase in your phase-1 score. Please prepend to your revised version a list of changes made and responses to peer review comments.

Nanofabrication process project

Option 1: Design and prototype a piece of 'open-source' nanofabrication apparatus

The purpose of an Option 1 project is to design and prototype a piece of apparatus that can usefully *manipulate, image or characterize material at the micro- or nano-scale*. The focus is on using your ingenuity and readily available materials and components to devise a piece of apparatus that is particularly affordable, and could therefore be deployed more widely than existing, commercial apparatus with a similar function.

With the development of increasingly powerful image sensors in consumer electronics, inexpensive microcontrollers, actuators and sensors, and accessible prototyping techniques such as 3D printing, it is becoming increasingly possible to imagine 'open-source' benchtop laboratory hardware that can perform some of the functions previously only available from far more expensive, commercially developed apparatus.

One might imagine that the availability of open-source micro/nano-fabrication apparatus could have multiple benefits, including:

- Accelerating the pace of research by enabling individual labs to have equipment previously available only in overbooked, shared facilities, or not available at all in some institutions;
- Increasing the ability to provide hands-on learning of micro- and nano-fabrication in schools and at the undergraduate and graduate levels around the world, potentially attracting more talent into the field;
- Enabling micro- and nano-fabrication-focused startup companies to develop their processes and products without needing (as much) access to expensive fabrication facilities;
- Providing the ability to customize apparatus without fear of voiding a warranty.

This movement towards open-source lab hardware has begun to gather steam[1], with, for example, the Open Lab Tools project at Cambridge[2] and Tekla Labs[3] at Berkeley. Early efforts have focused

[1] https://blogs.scientificamerican.com/guest-blog/science-for-all-how-to-make-free-open-source-laboratory-hardware/
[2] http://openlabtools.eng.cam.ac.uk/index.php
[3] http://www.teklalabs.org/

on the simplest, most common pieces of apparatus, such as hotplates and stirrers. There has also been much work on open-source microscopy[4], a particularly ripe area because of the current explosion of the field of computational imaging.

The potential of the open-source approach, however, remains largely untapped, particularly for micro- and nano-scale material manipulation. The opportunity for participants in this class to gain access to the makerspace facilities of Jacobs Hall has prompted me to make the design of low-cost, ingenious hardware a possible focus of the ME 203 class project.

Option 2: Conceptualize and model/simulate a new nanofabrication or nanoscale characterization process

The emphasis of an Option 2 project is rather different – here, we are asking you to conceive a new or enhanced way of creating deterministic nanostructures or measuring the dimensions or other attributes of fabricated nanoscale structures in a superior way to the current state of the art (*e.g.* by being potentially more precise, faster, or more affordable). Here, we are not asking you to make a physical prototype but to test your idea through a combination of analytical modeling and/or numerical simulation. Practical resources are therefore not necessarily at issue; the idea is to explore quite new ideas for manipulating material and to evaluate their likelihood of being effective.

Idea generation and pitching

I will mention several ideas in class, but I have no doubt that many brilliant ideas will come up as you begin to discuss the project with others in the class. In class on Tue Sept 24 we will hear project pitches. These pitches can come from individuals or from partly or completely formed teams, but I would like every class participant to be involved in pitching at least one idea.

To pitch an idea, please prepare 1–2 slides highlighting why your idea is relevant and interesting, and, in the case of Option 1 projects, how you think it is feasible to build a prototype within the semester. Upload this to bCourses by noon on September 24. We will take the length of the class (80 minutes) and divide by the number of pitches uploaded, and that will be the amount of time available to present each pitch.

Team formation

After the pitches have taken place, you will have an opportunity to coalesce into teams to work on the most popular ideas. I suggest forming teams of 3–5 people and ideally finding members with a complementary mix of skills. Consider what expertise will be needed for the project: solid modeling, electronics, optics, software, the finite element method? However, individual projects with reasonable scope will be fine.

Under “People” in bCourses, one member of your group should create a group within the “Nanofabrication process project” Group Set, giving the group a descriptive name that captures the essence of your project. Add all your team members to this group. Teams need to be formed by Tuesday October 1.

---

[4] http://www.scidev.net/global/technology/multimedia/open-source-through-the-lens-of-a-microscope.html

Jacobs Hall Maker Pass: optional

Access to Jacobs Hall is available to ME 203 participants and may prove valuable if your project team elects to fabricate a physical prototype. To access the fabrication facilities in Jacobs Hall and the CITRIS Invention Lab you would need a Maker Pass, which can be obtained by following the instructions at: http://jacobsinstitute.berkeley.edu/our-space/makerpass/get-maker-pass/. The fee for the pass is $100 for the semester. Fee waivers are available to students with financial need and requestable via the above link. You may want to wait until you have formed a project team and decided whether your project will be theoretical/computational or fabrication-based before deciding whether to buy a Maker Pass. If your team needs fabrication access, you are free to decide how many of your team will obtain Passes. However, please bear in mind that the last day of training on any Jacobs Hall equipment is October 31st, so you may need to move quickly after your team is formed.

If you decide to obtain a Maker Pass and have not previously completed the General Workshop Safety (GWS) Training for Jacobs Hall, please do so online before starting work on your project: https://bcourses.berkeley.edu/enroll/TY4ETA (requires CalNet authorization). This link will enroll you in the Jacobs Hall Equipment and Safety Training bCourses site (which is separate from the ME203 bCourses site) and will provide you with access not only to the GWS Training but to training materials for all the tools in Jacobs and for some equipment elsewhere on campus.

If you embark on a hardware/fabrication-based project, you will very likely find that you need access to multiple tools for producing components of your apparatus. These needs may include, for example, the 3D printers, laser cutters and desktop CNC mills. While you may not be able to predict your exact equipment needs in advance of your design process, we encourage you to sign up for training on one or more of these tools as soon as you identify a need for them, and certainly before the October 31st training deadline. You can complete the online training materials and sign up for the subsequent hands-on training using the Jacobs Hall Equipment and Safety Training bCourses site.

Initial concepts

On Oct 9 is a deadline for 2–5 slides showing initial concepts for the project.

For hardware projects, these concepts should address all the required functions of the apparatus, and concept sketches may be hand sketches of preliminary CAD renderings. The emphasis here is on thinking divergently yet practically to think of as many possible ways of achieving micro- or nano-scale control over material structure, or imaging/characterization of that structure, potentially with a combination of off-the-shelf, readily affordable components and customized components that you fabricate in Jacobs. Think particularly of how commonly available pieces of equipment (cellphones being one example) could be used as part of the apparatus to reduce cost. I would like to see at least three alternative concepts at this stage.

For modeling/simulation projects, the initial idea generation stage should dig into the physical principle(s) that could be exploited, and if possible involve order-of-magnitude calculations to support feasibility.

Project review 1

I will schedule one review slot per team during the class times on Oct 10 and 15. By this stage I anticipate that you will be leaning towards one of your initial ideas and will have completed calculations that will show the feasibility of your approach. For hardware projects, I will also be looking for a fairly substantial fabrication plan, where the required components have been identified. Drawings could be hand sketches but are more likely at this stage to be preliminary CAD renderings.

You will also need to think about how you will validate the operation of your device or the accuracy of your modeling/simulations. For hardware projects, can you compare its results with those of an existing, standard piece of equipment (if you are making a tool to image or characterize material) or independently measure the geometries/patterns created by your apparatus (if you are making a tool to manipulate or pattern material)? For modeling/simulation projects, what sources of experimental data exist in the literature that could be used to validate the realism of your approach?

Please come to the review with the materials described above, and upload them in the form of a ~five-slide presentation by the end of Oct 24.

Project review 2

The goal by the second review is to be able to show either a preliminary functional physical prototype, or substantial modeling/simulation results of your new. This session will be used to try to troubleshoot any challenges you are facing.

Final presentations and deliverables

These presentations will take place during the final week of classes (Dec 3 and 5) Each team will be given a specific time slot during one of the sessions but we ask that everyone attends all presentations and engages by asking questions. Hardware teams will need to bring and be prepared to demonstrate their completed prototype apparatus. This presentation should cover:

- Why your apparatus or new conceptual process is needed;
- Summary of key design or modeling calculations: enough for the viewer to understand how you predicted the key performance characteristic(s) of your design (*e.g*. spatial resolution, repeatability, processing speed);
- Diagrams illustrating the operating principle of your prototype or concept. These might include exploded or cross-sectional views, and step-by-step cartoons of the operation;
- Any results/data obtained, and discussion of them;
- Conclusions: how effective is your prototype or modeled/simulated new process; what would you change in a revised version?

The final presentation slides can, if desired, be modified based on feedback at the presentations and needs to be uploaded to bCourses by the end of December 6. Additionally, for modeling/simulation teams, in lieu of a physical prototype we ask that you draft a ~6-page paper in the style of, *e.g*., the IEEE *Transactions on Nanotechnology*, explaining your results.

Reading

There is no required course text book; all the material you need to succeed in ME 203 will be included in the lecture slides and additional materials that will be posted on bCourses.

Books for possible supplementary reading include:

- *Silicon VLSI Technology: Fundamentals, Practice, and Modeling*, Plummer, Deal and Griffin, Prentice Hall, 2000. TK7874.75.P58 2000
- *Nanolithography*, ed. S Landis, Wiley, 2011. Available online on campus/via VPN: http://onlinelibrary.wiley.com/book/10.1002/9781118622582
- *Fundamental Principles of Optical Lithography: The Science of Microfabrication*, C. Mack, Wiley, 2007. TK7874 .M196 2007
- *Fundamentals of Microfabrication*, M.J. Madou, CRC Press, 2002. TK7836.M33 2002

A glossary of specialized lithography technical terms will be posted on bCourses (under Files > Other materials) and will be periodically updated as new terms are used in lectures.

Also: this podcast on the role of Berkeley in the early development of Silicon Valley is worth a listen, as it testifies to the enormous impact that student class projects can have on the development of technology (in this case, how the pre-eminent integrated circuit simulation software, SPICE, was written by students in a Berkeley graduate class and then disseminated freely): https://update.lib.berkeley.edu/2019/07/24/the-berkeley-remix-podcast-season-4-episode-2-berkeley-lightning-a-public-universitys-role-in-the-rise-of-silicon-valley/

Software

Matlab will be needed for the simulation assignments. A Matlab license can be obtained free of charge by following the instructions at https://software.berkeley.edu/MATLAB. Any other software that might be required will be free to download.

For the nanofabrication process project, your team might need to use a solid modeling software package to design mechanical components. All Berkeley students have free access to Solidworks and to all Autodesk products including AutoCAD and Fusion 360. Details for obtaining Solidworks are available on bCourses under Files > Other materials > Solidworks Access Jan 2019.pdf. Autodesk products can be obtained at https://www.autodesk.com/education/free-software/all.

Academic integrity

We will be adhering to the Berkeley Honor Code (http://asuc.org/honorcode/index.php). If anyone has any questions about the responsibilities they have as part of this Code, please contact Hayden Taylor.