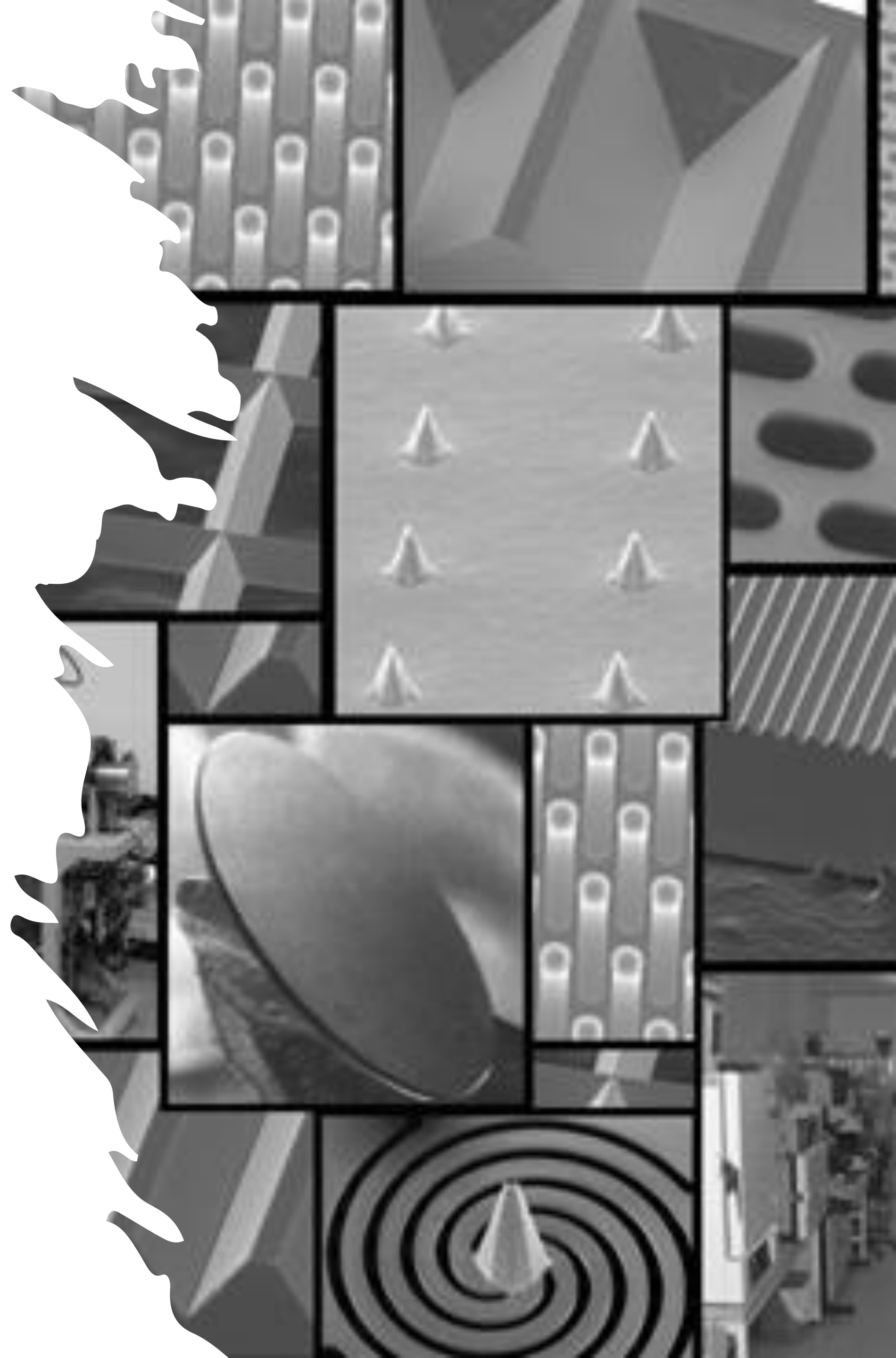
Introduction to Micro Fabrication



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Introduction

- Recent innovations in the area of *micro fabrication* have created a unique opportunity for manufacturing structures in the nanometer–millimeter range. We can fabricate novel electronic, optical, magnetic, mechanical, and chemical/biological devices with applications ranging from sensors to computation and control.

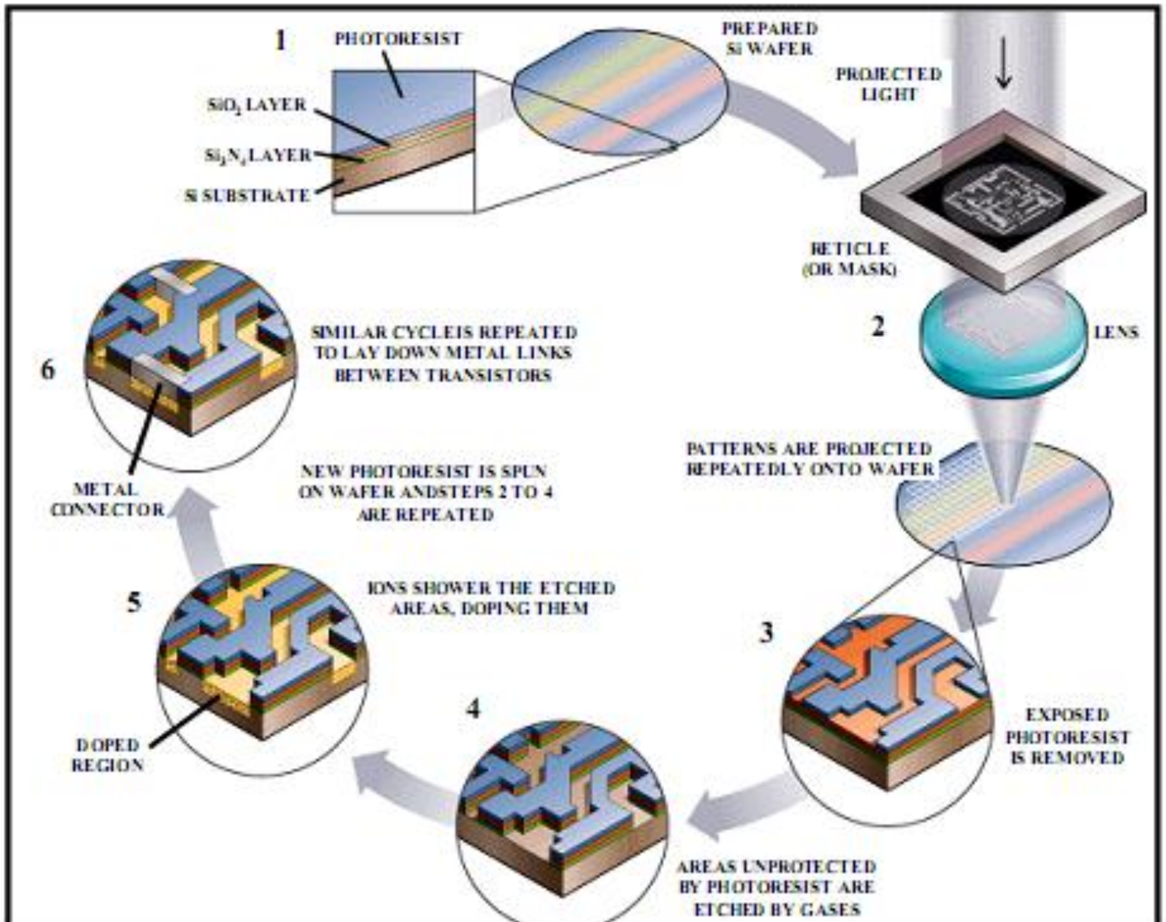
Nano Fabrication

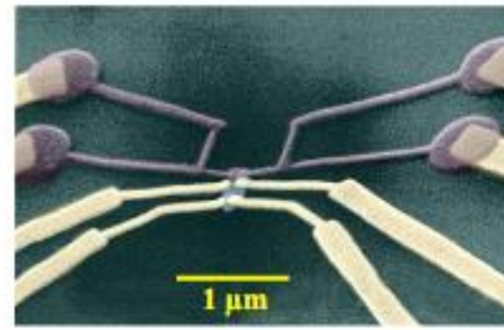
- **Basic Microfabrication Techniques**
  - Lithography
  - Thin Film Deposition and Doping
  - Etching and Substrate Removal
  - Substrate Bonding

Fabrication

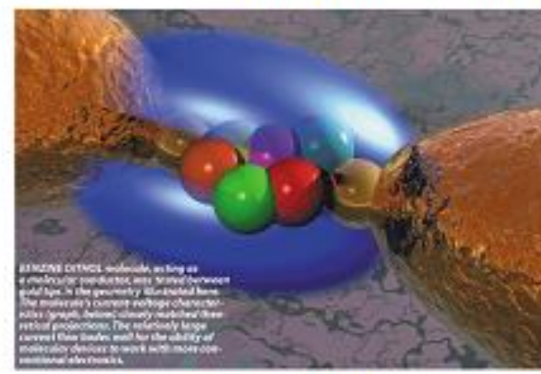
- Top-down: Chisel away material to make nanoscale objects
- Bottom-up: Assemble nanoscale objects out of even smaller units (e.g., atoms and molecules)
- Ultimate Goal: Dial in the properties that you want by designing and building at the scale of nature (i.e., the nanoscale)

Top-Down: Photolithography





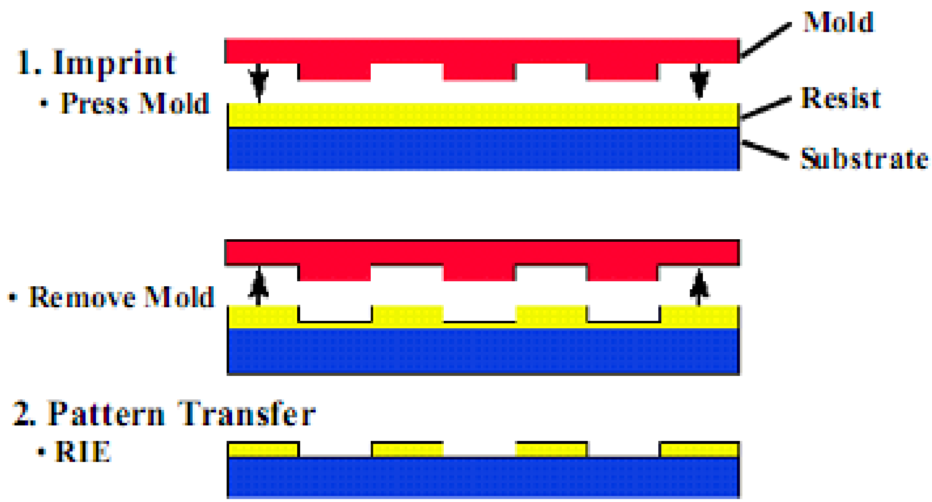
Ferromagnetic/superconducting devices (e-beam lithography)

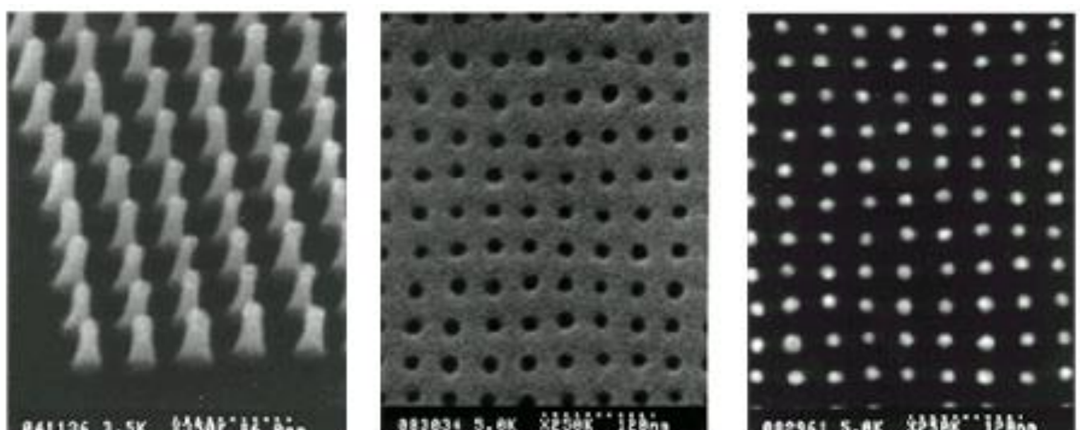


Molecular electronics (e-beam lithography)

Mark C. Hersam: Northwestern University

Top-Down: Nanoimprint Lithography





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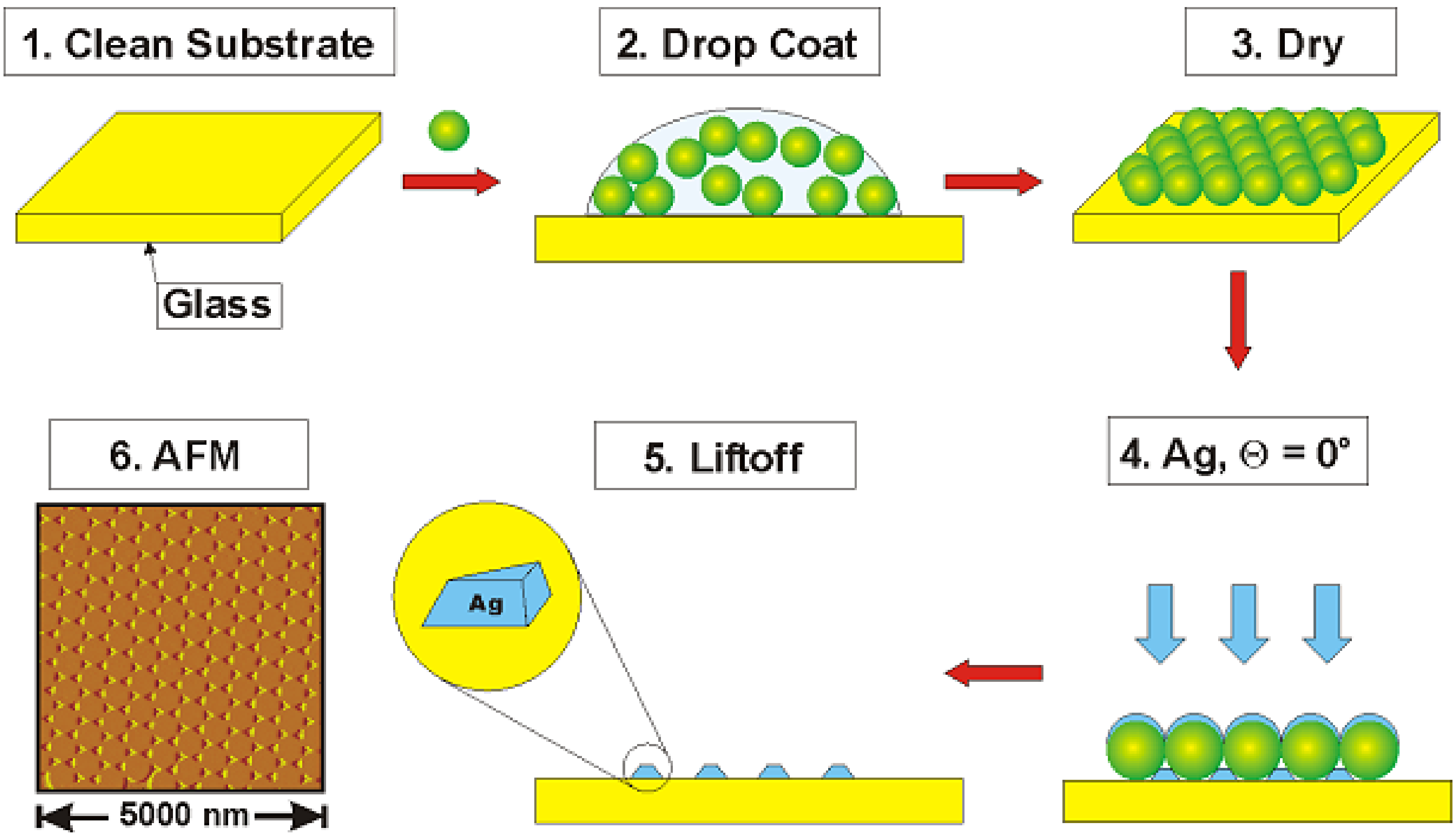
Top-Down: Nanosphere Lithography



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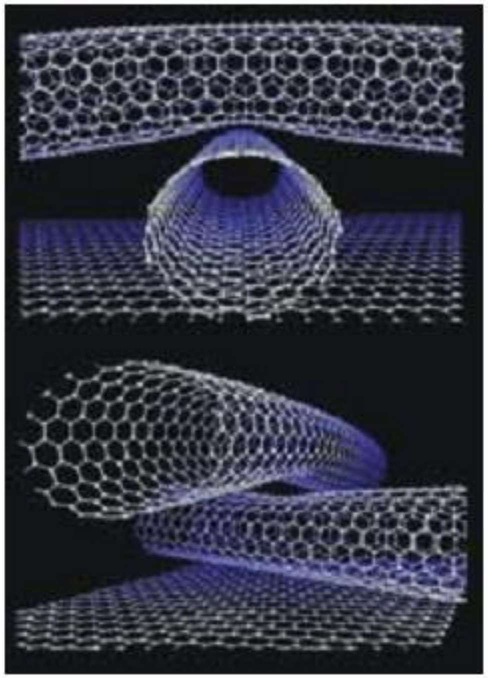
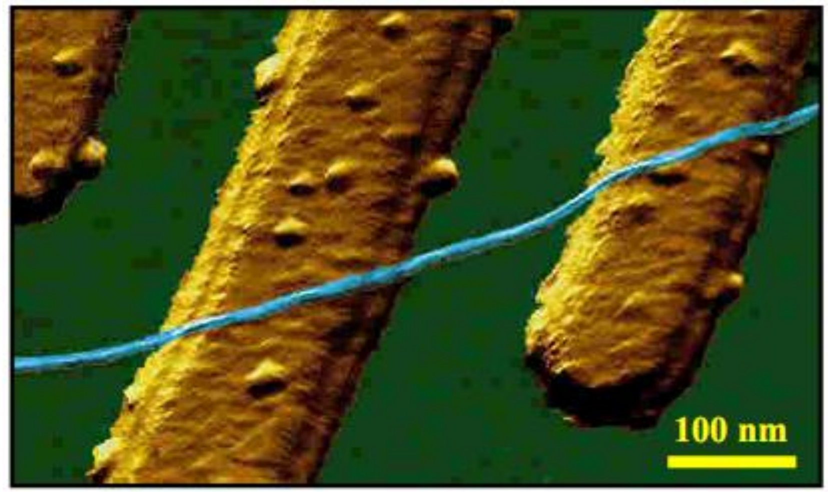
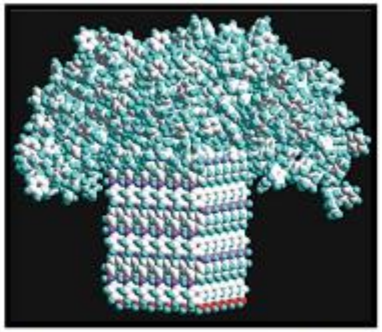
Bottom-Up: Carbon Nanotube Synthesis



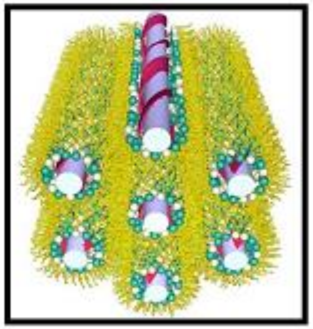


Bottom-Up: Molecular Self-Assembly

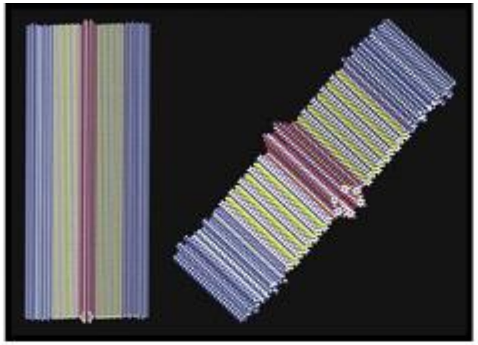
- Spontaneous organization of molecules into stable, structurally
- well-defined aggregates (nanometer length scale).
- Molecules can be transported to surfaces through liquids to form self-assembled monolayers (SAMs).



Supramolecular rodcoil "mushrooms"



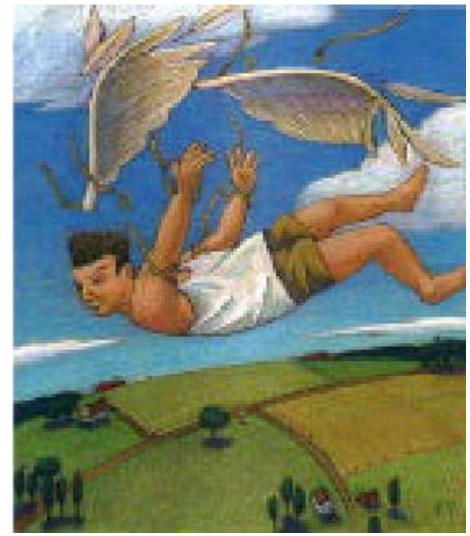
Polythiophene wires

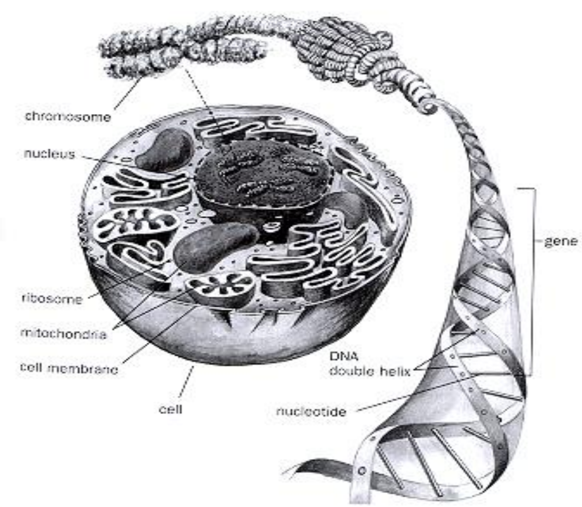


Supramolecular rodcoil nanoribbons

Merging of two approaches: Top-down and bottom-up machining methodologies

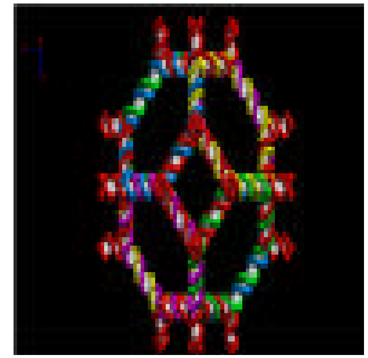
- Most human manufacturing methods of small devices involve top-down approaches. Starting from larger blocks of material we make smaller and smaller things. Nature works the other way, i.e., from the bottom-up.
- All living things are made atom by atom , molecule by molecule; from the small to the large. As manufacturing of very small things with top-down techniques (NEMS or nano mechanical devices) become too expensive or hit other barriers we are looking at nature for guidance (biomimetics).
- Further miniaturization might be inspired by biology but will most likely be different again from nature -- the drivers for human and natural manufacturing techniques are very different.



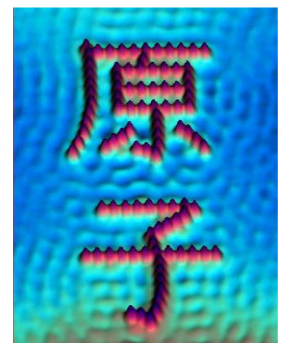


Merging of two approaches: Top-down and bottom-up machining methodologies --NEMS

- MEMS’ little brother is NEMS, the top-down approach to nano devices. This biomimetic approach to nano devices I like to call nanochemistry. To succeed in the latter we will need :
  - self-assembly and directed assembly (e.,g, using electrical fields -see next viewgraph)
  - massive parallelism
  - understanding of molecular mechanisms--chemomechanics
  - engineers/scientists who understand ‘wet’ and ‘dry’ disciplines
- Example nano chemistry approaches:
  - Natural polymers: e.g., NAs and proteins not only as sensors but also as actuators and building blocks (Genetic engineer NA’s and proteins-rely on extremophiles for guidance)
  - Mechanosynthesis
  - NEMS/biology hybrids --to learn only



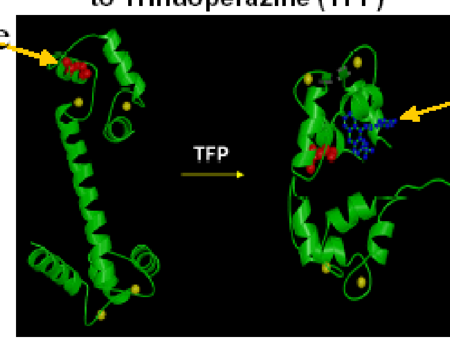
Seeman



Eigler

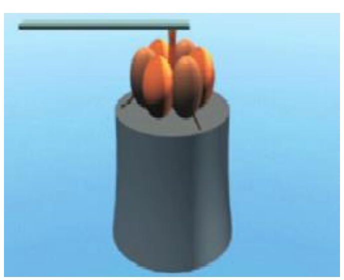
Crystal Structure of Calmodulin Bound to Trifluoperazine (TFP)

Fluorophore



TFP

Daunert - Madou



Montemagno

Lithography

- Lithography is the technique used to transfer a computer generated pattern onto a substrate (silicon, glass, GaAs, etc.). This pattern is subsequently used to etch an underlying thin film (oxide, nitride, etc.) for various purposes (doping, etching, etc.). Although photolithography, i. e., the lithography using a UV light source, is by far the most widely used lithography technique in microelectronic fabrication, electron-beam (e-beam) and X-ray lithography are two other alternatives that have attracted considerable attention in theMEMSand nanofabrication areas.

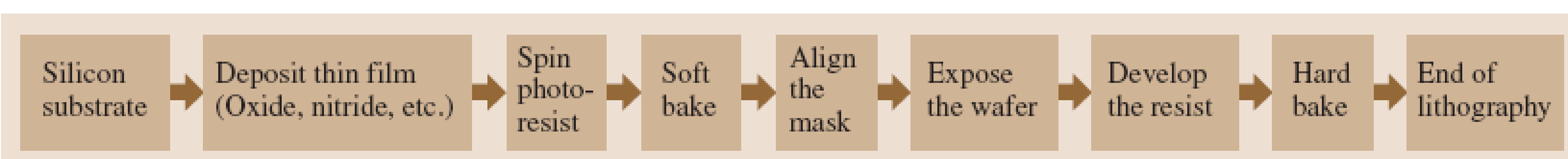


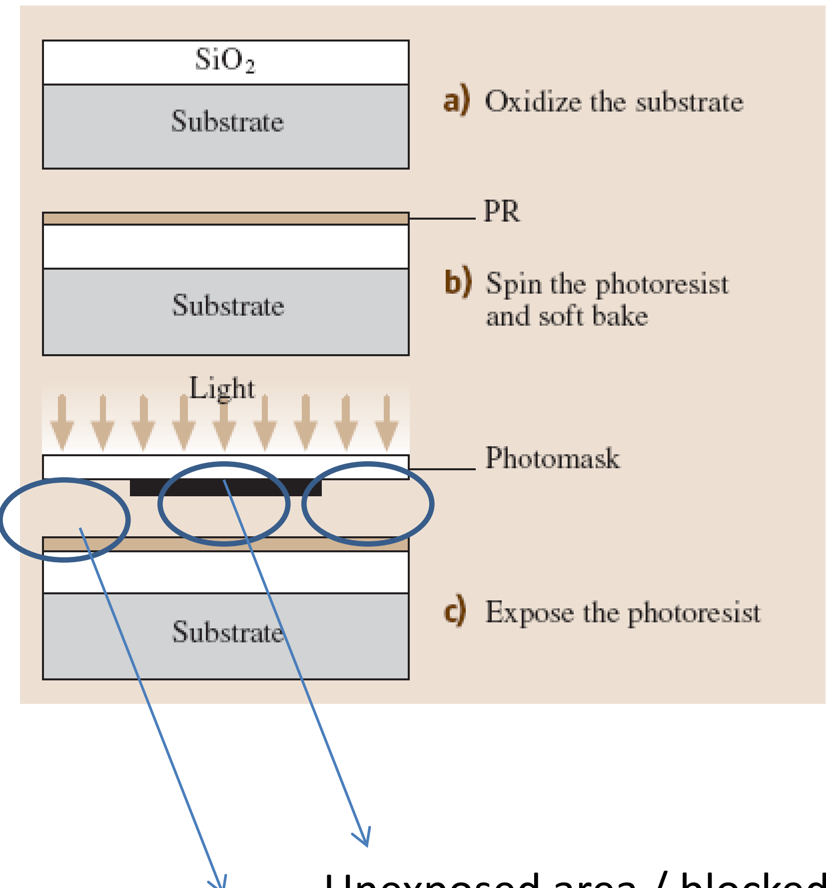
Fig. 5.1 Lithography process flow

exposure systems

- Depending on the separation between the mask and the wafer, three different exposure systems are available:

1. Contact : gives better resolution than proximity.
2. Proximity
3. Projection
   - uses a dual lens optical system to project the mask image onto the wafer.
   - Widely used system in microfabrication and can yield superior resolutions compared to contact and proximity methods

Thin Film Deposition and Doping



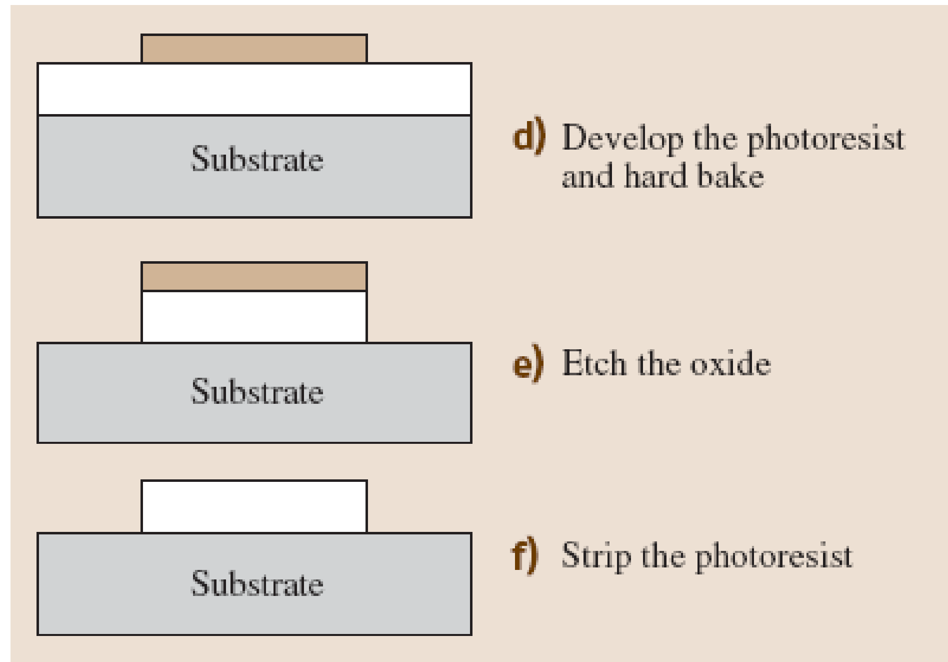


Fig. 5.2 Schematic drawing of the photolithographic steps with a positive photoresist (PR)

Unexposed area / blocked area

Exposed area

Step coverage and conformality

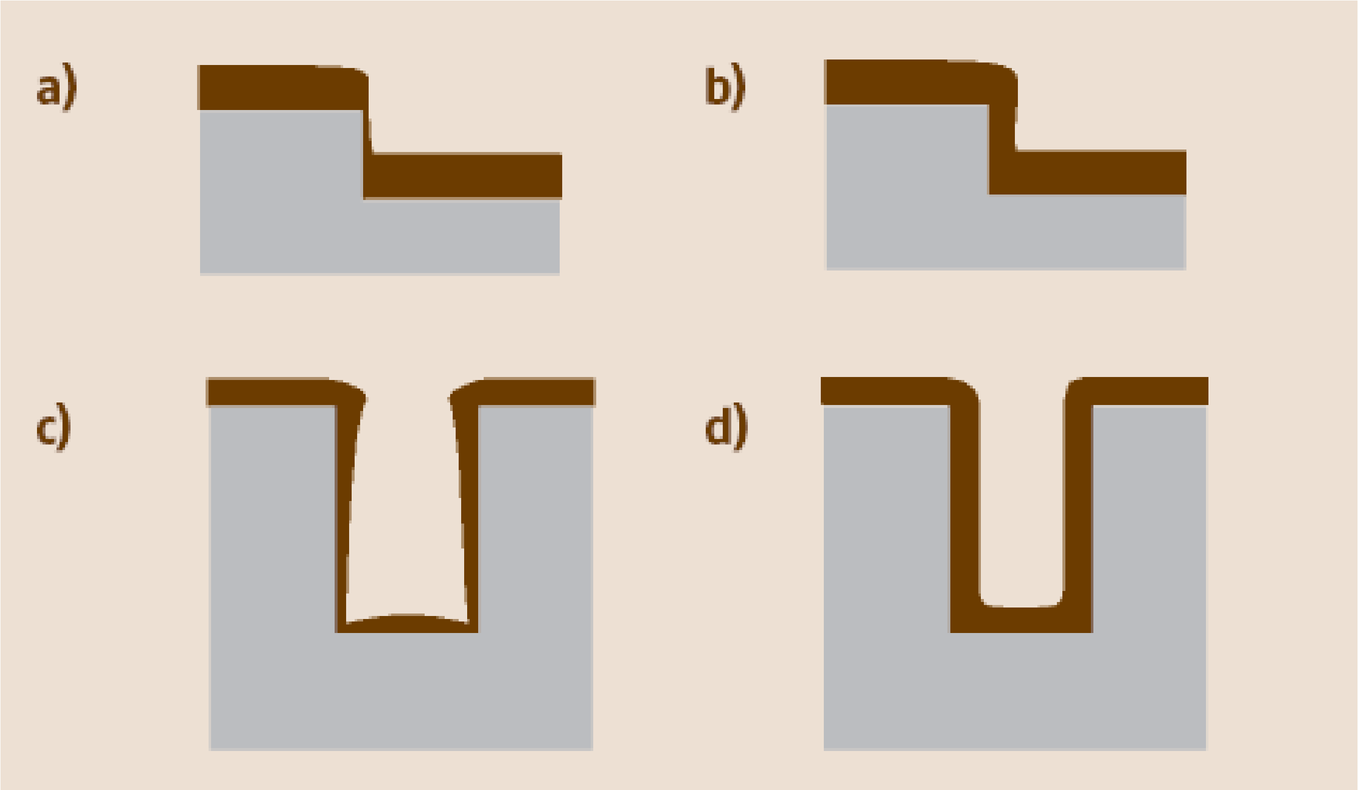


Fig. 5.3a–d Step coverage and conformality: **(a)** poor step coverage, **(b)** good step coverage, **(c)** nonconformal layer, and **(d)** conformal layer

Oxidation

- Oxidation of silicon is a process used to obtain a thin film of SiO2 of excellent quality (very low density of defects) and thickness homogeneity.

$$Si_{(solid)} + O_{2(gas)} \Rightarrow SiO_{2(solid)}$$

and

$$Si_{(solid)} + 2H_2O_{(steam)} \Rightarrow SiO_{2(solid)} + 2H_{2(gas)}$$

The oxidation of silicon also occurs at room temperature, however, a layer of about 20Å (native oxide) is enough to passivate the surface and prevent further oxidation.

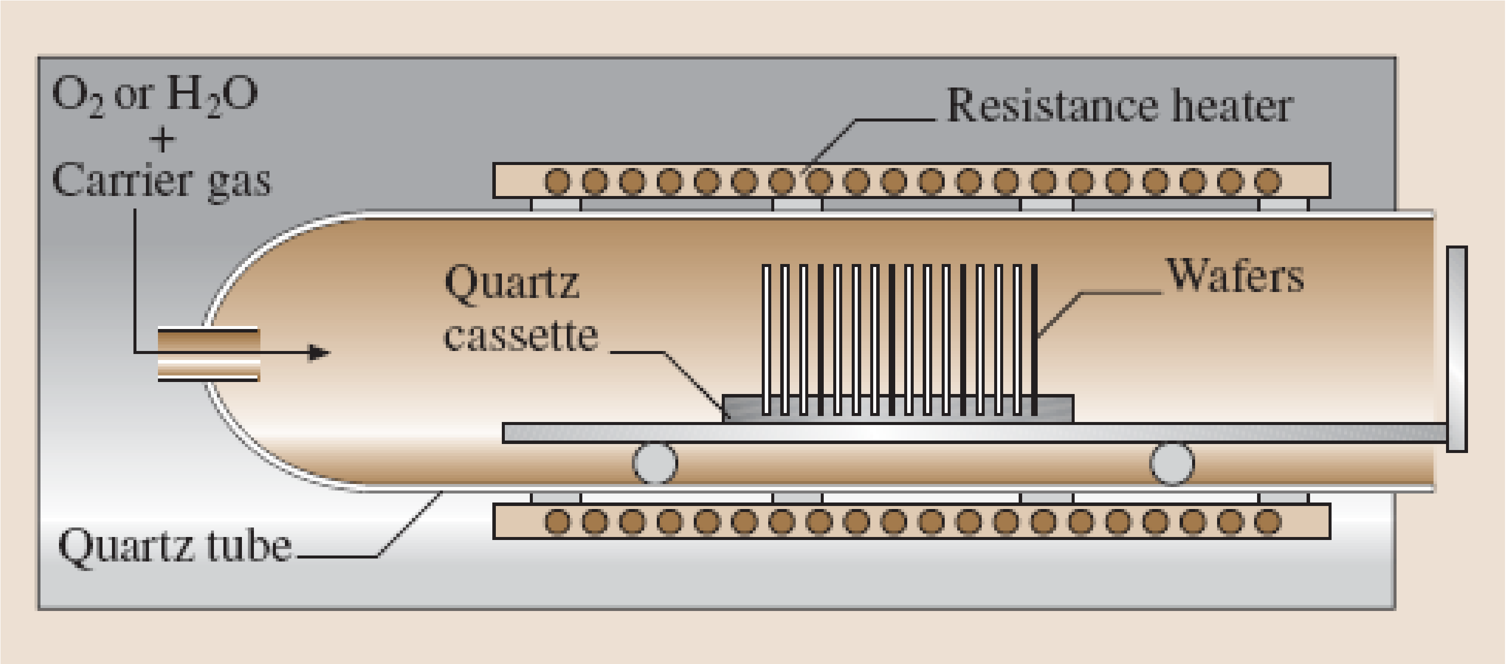


Fig. 5.4 Schematic representation of a typical oxidation furnace

Doping

- The introduction of certain impurities in a semiconductor can change its electrical, chemical, and even mechanical properties.
- Typical impurities, or *dopants,* used in silicon include boron (to form p-type regions) and phosphorous or arsenic (to form n-type regions).
- Doping is the main process used in the microelectronic industry to fabricate major components such as diodes and transistors.

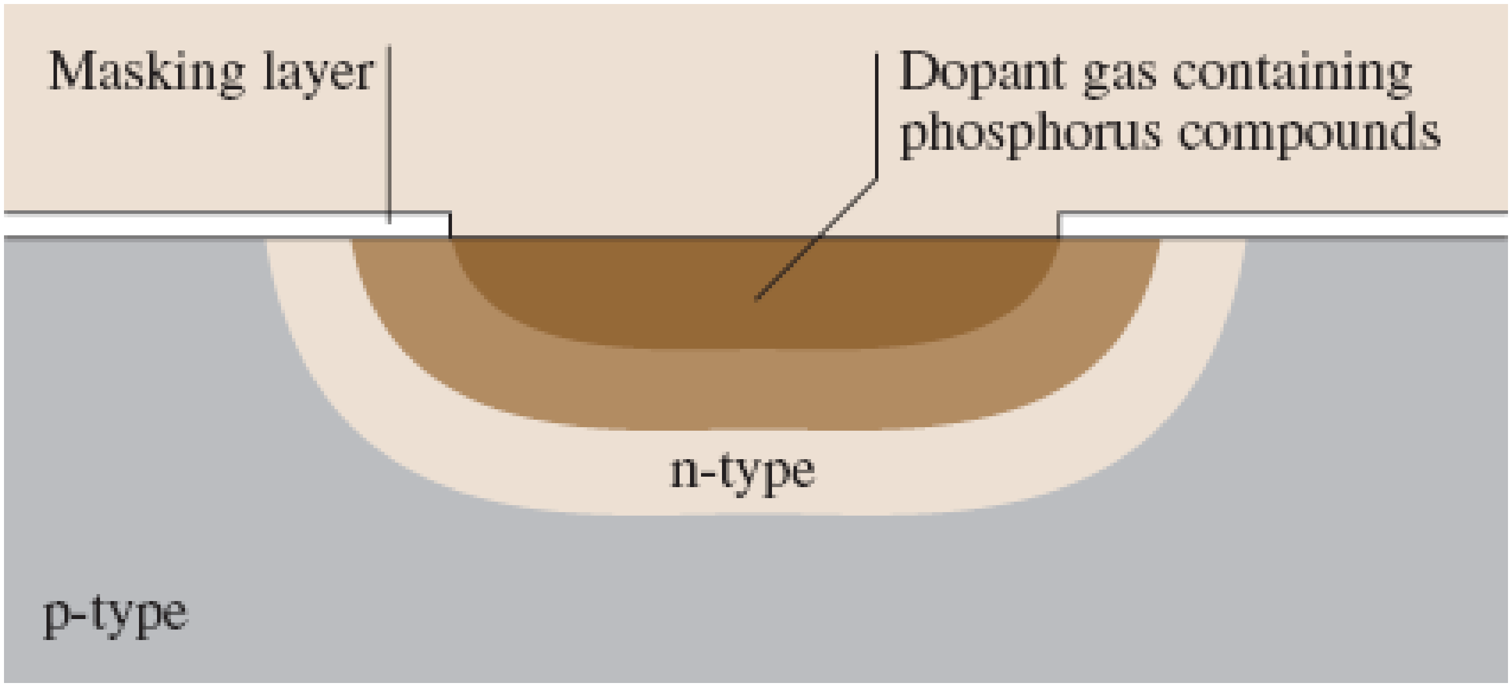


Fig. 5.5 Formation of an n-type region on a p-type silicon substrate by diffusion of phosphorous

Chemical Vapor Deposition and Epitaxy

- Reaction of chemicals in a gas phase to form the deposited thin film
  - LPCVD (lowpressureCVD)
  - PECVD (plasma enhanced CVD).

LPCVD

- LPCVD process is typically carried out in electrically heated tubes, similar to the oxidation tubes, equipped with pumping capabilities to achieve the needed low pressures (0*.1 to 1.0 torr). A large number* of wafers can be processed simultaneously, and the material is deposited in both sides of the wafers.
- The process temperatures depend on the material to be deposited, but generally are in the range of 550 to 900 ◦C.
- As in the oxidation, high temperatures and contamination issues can restrict the type of processes used prior to the LPCVD. Typical materials deposited by LPCVD include silicon oxide (e.g., SiCl2H2 + 2N2O⇒SiO2+2N2+2HCl at 900 ◦C)

PECVD

- The PECVD process is performed in plasma systems such as the one represented in Fig. The use of RF energy to create highly reactive species in the plasma allows for the use of lower temperatures at the substrates (150 to 350 ◦C). Parallel-plate plasma reactors normally used in microfabrication can only process a limited number of wafers per batch.
- The wafers are positioned horizontally on top of the lower electrode, so only one side gets deposited. Typical materials deposited with PECVD include silicon oxide, nitride, and amorphous silicon. Conformality is good for low-aspect-ratio structures, but becomes very poor for deep trenches (20% of the surface thickness inside through-wafer holes with aspect ratio of ten).

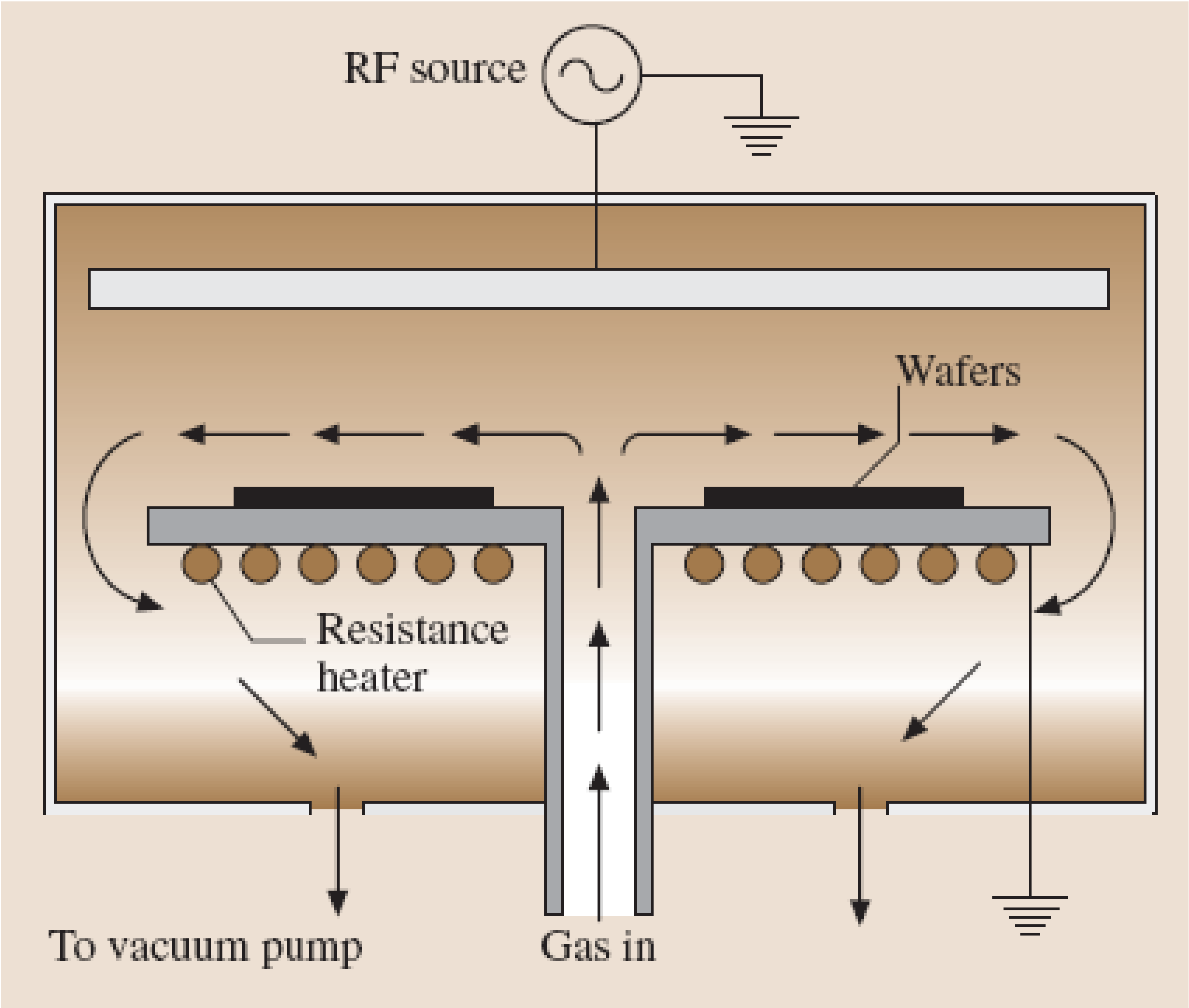


Fig. 5.6 Schematic representation of a typical PECVD system

Epitaxial growth

- In this process, a single crystalline material is grown as an extension of the crystal structure of the substrate.
- It is possible to grow dissimilar materials if the crystal structures are somehow similar (lattice-matched).
- Silicon-on-sapphire (SOS) substrates and some heterostructures are fabricated in this way.

Physical Vapor Deposition

- In physical deposition systems the material to be deposited is transported from a source to the wafers, both being in the same chamber. Two physical principles are used to do so:
  - Evaporation
  - sputtering

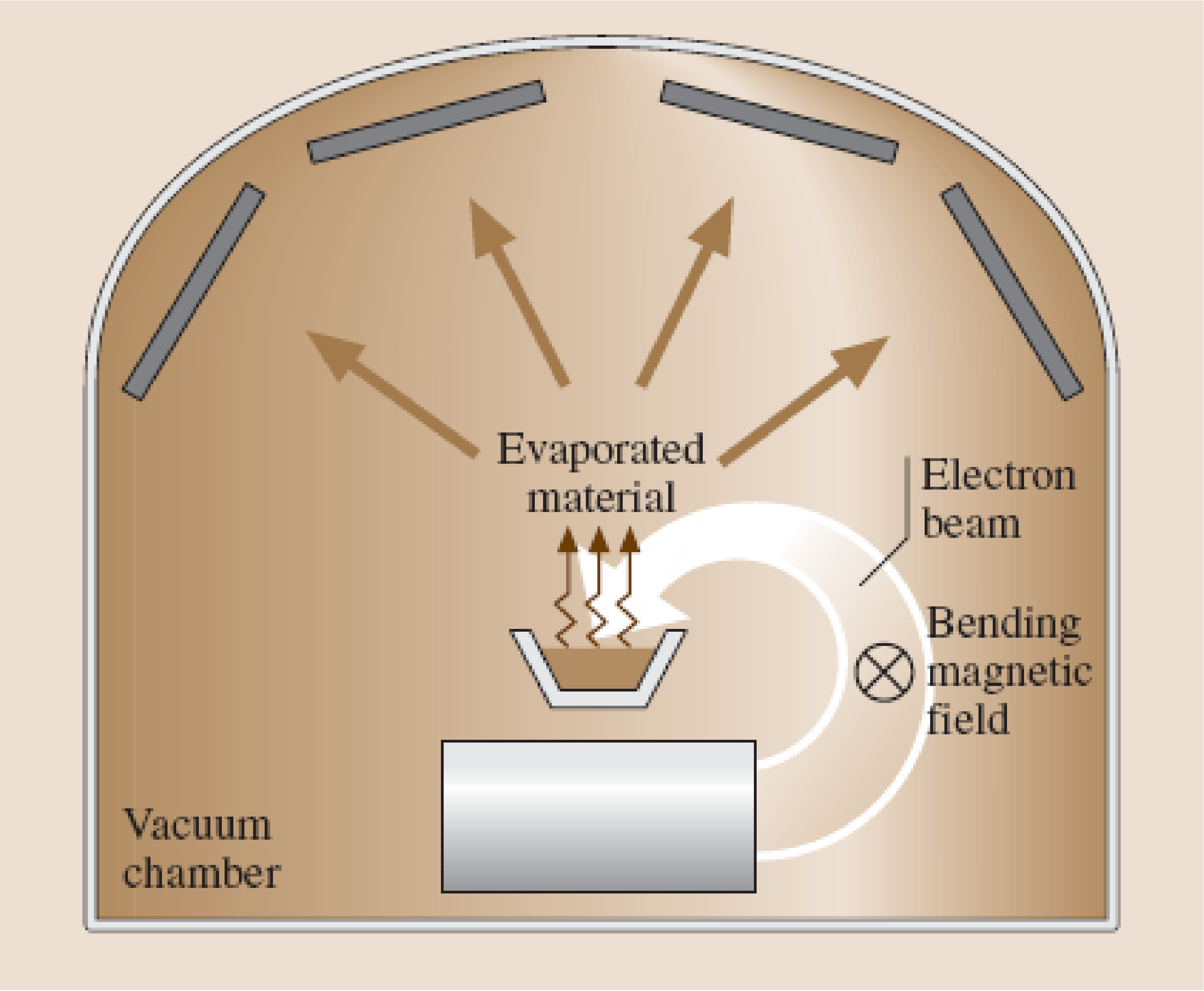


Fig. 5.7 Schematic representation of an electron-beam deposition system

Sputtering

- In sputtering, a target of the material to be deposited is bombarded with high-energy inert ions (usually argon).
- The outcome of the bombardment is that individual atoms or clusters are removed from the surface and ejected toward the wafer.
- The physical nature of this process allows its use with virtually any existing material: metals, dielectrics, alloys, and all kinds of compounds (for example, piezoelectric PZT).
- The inert ions bombarding the target are produced in DC or RF plasma.

Etching and Substrate Removal

- very often the substrate (silicon, glass, GaAs, etc.) also needs to be removed in order to create various mechanical micro-/nanostructures (beams, plates, etc.). Two important figures of merit for any etching process are selectivity and directionality.
  - Wet Etching
  - Dry Etching

Wet Etching

- due to the lateral undercut, the minimum feature achievable with wet etchants is limited to *> 3μm.*
- *Silicon dioxide is commonly etched in a dilute* (6:1, 10:1, or 20:1 by volume) or buffered HF (BHF, HF+NH4F) solutions (etch rate of ~ 1*,000Å/min in* BHF).
- Photoresist and silicon nitride are the two most common masking materials for the wet oxide etch.

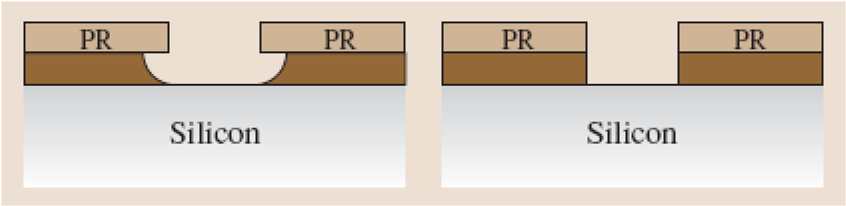


Fig. 5.11a,b Profile for isotropic **(a)** and anisotropic **(b)** etch through a photoresist (PR) mask

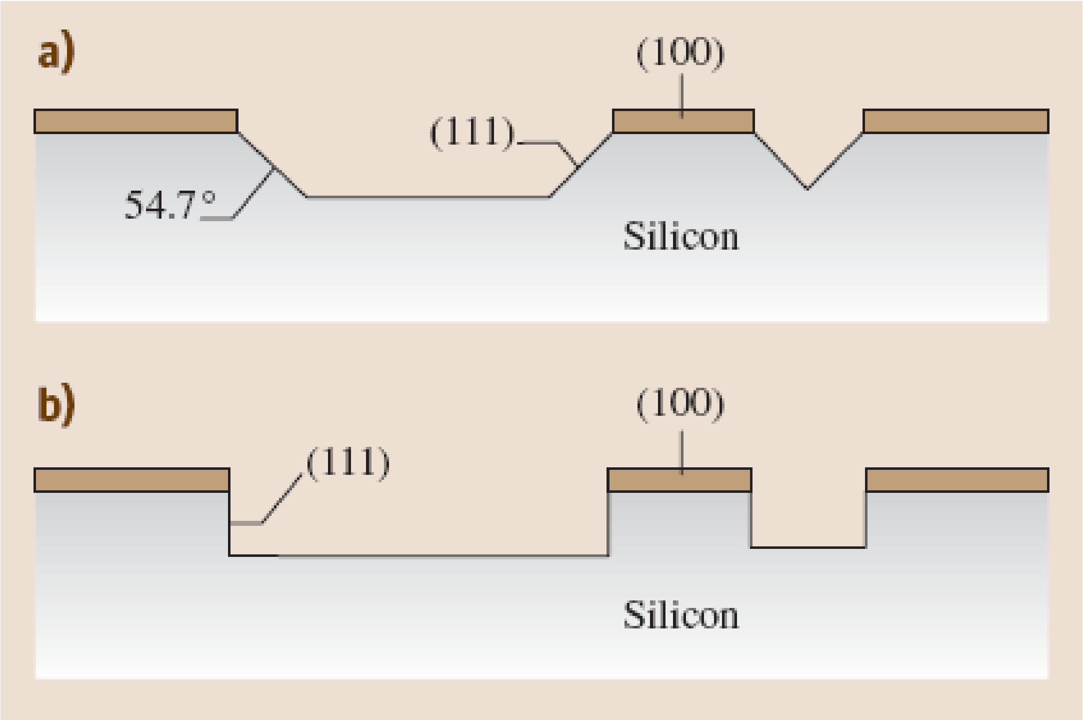


Fig. 5.12a,b Anisotropic etch profiles for: **(a)** (100) and **(b)** (110) silicon wafers

Isotropic etching

- Isotropic etching of silicon using HF/HNO3/CH3COOH.
- Silicon anisotropic wet etch constitutes an important technique in bulk micromachining. The three most important silicon etchants in this category are potassium hydroxide (KOH), ethylene diamine pyrochatechol (EDP), and tetramethyl ammonium hydroxide (TMAH).

Dry Etching

- Most dry etching techniques are plasma-based. They have several advantages compared with wet etching.
- These include smaller undercut (allowing smaller lines to be patterned) and higher anisotropicity (allowing high-aspect-ratio vertical structures).
- The three basic dry etching techniques:
  - high-pressure plasma etching
  - Reactive ion etching (RIE)
  - ion milling