

ME 487

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Chapter 1

ME 487

The lab safety training is already up and I have to do that before the first lab.

You'll make a pressure sensor, and then a microfluidic mixer (because mixing small fluids is hard).

THERE WILL BE POP QUIZZES IN LECTURE

1.1 LAB POLICY

- **NO SHORTS, CONTACTS, OPEN TOED SHOES**
- Don't touch anything unless told so
- If you do anything stupid you get kicked out.

1.2 Importance

MEMS are important because they take advantage of forces that scale dramatically at small scales

- Surface tension scales with l
- Fluid/electrostatic forces scale with l^2
- weight/inertia forces scale with l^3
- electromagnetic forces scale with l^4

So at very small scales, these forces act very differently than in macro-scale systems. You can almost completely ignore gravity.

1.2.1 Cantilever

Deflection under self weight goes down dramatically with l^2 .

Resonant frequency **increases** with l^{-1} .

1.2.2 Fabrication Scaling

- Devices are on a single substrate, and you can make thousands of devices on a single substrate.
- We can take infrastructure/technology from the semiconductor industry.

1.2.3 Function Integration

Both electrical and mechanical functions can be obtained with the same materials and processes.

Projectors use a MEM that has a mirror, tilting mechanism, and electronic controller all on 1 substrate.

1.2.4 Material Saving

Because MEMS are on the atomic scale, you use close to nothing on material saving. There is functionally 0 material cost.

1.3 Difficulties

- Really small (10^6)
- Only very very specific materials actually work in lithography
- All tools are only planar- we can only edit from the top/bottom of the wafer.
- You need very specific/expensive facilities and materials.

1.4 Typical Process

1. Deposition

You put a target material onto a substrate

2. Lithography

You put a photoresisting material onto that target, and you use lasers to get rid of material to leave a pattern.

3. Etching

You get rid of the target material with lasers, and all the target material under the photoresist is untouched.

You then remove the photoresist material and then you're left with just the target material in just the pattern you wish.

1.4.1 MUMPs (Multi-User MEMS Processes) Sequence

This is a 7 layer process of depositing, adding a photoresist, and etching.

This essentially allows a company to make multiple different MEMS blueprints on a single wafer.

Often used by fab-less companies. They buy a small bit of a wafer from a fab company and have that company etch a specific blueprint onto that small portion of wafer.

1.4.2 Finish Fabrication

- Singulation: Cut the large wafer into little dies such that each individual die has 1 MEM.

- Packaging:

Bond the functional pieces of the MEM with a wire so that it can work in a larger system.

- Encapsulation

seal the MEM so it becomes a functional black box with wires for input/output.

Chapter 2

Cleanroom Procedure

Something something something review.

We're usually going to be working in the $\sim 5\mu m$ range for our MEMS building.

2.1 Wafer Contamination

If you leave your wafer in the cleanroom uncovered, it will eventually get contaminated with dust particles. The amount of time it takes for your device to get contaminated is probabilistic. A more clean cleanroom will mean the chances your device gets contaminated in a certain amount of time decreases.

As we consider smaller and smaller dust particles, they move more and more randomly due to the random motion of air particles (Cunningham Correction Factor). Particles move at a speed dependent on some large convoluted equation.

Possible contaminants include dust particles, organic films, and atoms/ions.

2.1.1 Humidity

Fluid condensation is bad.

Water can contaminate your device, and as the water evaporates, the surface tension will warp your device (cantilever).

You can calculate the forces caused by the surface tension of water stuck in your cantilever.

2.2 Cleanroom Itself

You have to wear a whole bunch of silly clothes

The yellow room is for photolithography.

The white room is for deposition and etching.

2.2.1 Chase

A part of the cleanroom only available to staff.

New device will be brought in through the chase.

Chapter 3

Chemicals

All sorts of chemicals and they're all flammable and carcinogenic so don't touch anything or you'll die.

- Solvents
- Photoresists (Carcinogen)
- Developers (Weak base)
- Strippers (acetone)
- Etching (Acids)

3.1 Materials Safety Data Sheet (MSDS)

It gives you a bunch of information about certain chemicals

- Chemical breakdown
- Methods of exposure
- Effects/risks of exposure
- other
- other

16 different important bits of information on every MSDS.

There is a physical binder and a search engine that gives you the MSDS to every chemical in the cleanroom.

3.2 NFPA Diamond

It's the square with 4 parts that tells you everything about a certain chemical in a container.

Yellow is for reactivity, red is for flammability, blue is for health hazards, white is for miscellaneous.

White: OXY, ACID, ALK, COR, W-, RAD

3.3 PPE

You need certain equipment BEYOND THE CLEANROOM GOWN to work with certain chemicals.

HF spills have to be treated with special care.

3.3.1 Do's and Dont's

Do

- change gloves whenever dirty/broken
- Use fresh gloves
- use cleanroom paper
- remove rings and bracelets

Chapter 4

Lithography

Writing stuff on stone by using an insoluble material on top.

You can then put an acid on top and the resist on top will not be dissolved, but the rock will be dissolved.

4.0.1 Process (Etch)

1. Prepare surface and apply photoresist
2. Pre-bake oven
3. aligner exposure (with mask)
4. develop, rinse, and dry
5. Post-bake oven
6. Inspect and measure
7. Etch and Deposit
8. Strip the photoresist and clean
9. Deposit or grow new layer
10. repeat

Etching is putting down deposition material and then putting the photoresist on top and in a certain pattern and then removing all material **not** under the photoresist.

4.0.2 Lift-off

You put the photoresist on and get rid of the unwanted resist, **then** you put on the deposition material, and then the material that is on top of the photoresist gets removed.

4.0.3 Issues

Photoresists etch at various rates, so you need a tall photoresist layer to make sure that the photoresist doesn't completely etch away before your unwanted material is fully gone.

4.1 Wafer Cleaning

Degrease the wafer with acetone, alcohol (IPA), de-ionized (DI) water, dry with N_2 gas.

4.1.1 Standard Clean 1 (SC1, RCA1)

DI water, ammonium hydroxide, hydrogen peroxide
Removes light organic material.

4.1.2 Standard Clean 2 (SC2, RCA2)

DI water, HCl, hydrogen peroxide.
Good for removing metal ions.

Pirhana solution = sulfuric acid + hydrogen peroxide. very very harsh etch. Must be done in a fume hood!!!! Reactive mixture must be allowed to deactivate. Only really used if you're trying to salvage a wafer.

Surface tension determines how far into a crevasse a solvent will go.

4.1.3 Other Cleaning

Ultrasonic Cleaning - use sound in the 20-400 kHz range to dislodge large particles ($> 2\mu m$)

Megasonic cleaners use even faster waves (800-2000 kHz) to dislodge smaller particles ($< 0.5\mu m$).

Cryogenic Cleaning - immerse your substrate into liquid nitrogen to make your wafer (and debris) very brittle, which should break apart debris.

Supercritical cleaning/drying - Immerse in ethanol or methanol. Supercritical CO₂ dissolves the solvent. When pressure is lowered the gas changes.

4.2 Wafer Priming

You want a very hydrophobic surface for best adhesion. You also want to minimize humidity.

You can use a number of methods for priming

- Oxygen plasma descum
- Adhesion Promoter AP8000 (chemical)
- Increase soft bake
- Sputter the surface to induce micro-roughness.

4.3 Details Of Photolithography

1. Surface preparation
2. Spin coating
3. Alignment and Exposure
4. Post-exposure bake
5. Develop, clean, and dry
6. Inspection
7. Descum and Hard Bake
8. Resist Stripping (Removing the PR)

4.3.1 Photoresist

PR's consist of 3 main materials

- Polymer (resin)
- sensitizer
- Solvent

You want your PR to be as flat as possible so that you are at minimal risk of under-exposure or over-exposure.

4.3.2 Spin Coating

You just use centrifugal forces.

edge beading is what happens at the edge of your wafer that comes from excess PR at the edge of the wafer coming back into the wafer once it is done spinning.

The equation for spin coating is given by

$$T = \frac{KC^\beta\eta^\gamma}{\omega^\alpha}$$

- T = thickness
- K = calibration constant
- C = polymer concentration
- η = intrinsic viscosity
- ω = angular speed (rpm)
- α, β, γ = empirically determined parameters

Features on the wafer should be no more than 20% of the resist thickness, otherwise the resist may not have good coverage.

To estimate the dispense volume, you just do basic geometry

$$V = \pi r^2 T$$

4.3.3 Other Methods of PR Deposition

- Spray coating
- Electrostatic Spraying
- Meniscus Coating
- Electrodeposition
- Roller Coating
- Silkscreen Pirnting
- Dip Coating
- Curtain Coating
- Extrusion Coating

4.4 Soft Baking

Depends on the type and the thickness of the PR. It is also called pre-bake or pre-exposure bake. Hotplates are used in the 60C to 110C range.

Pre-baking is important because it

- Relieves stresses in the film
- Removes solvents
- Promotes adhesion

Too much heat can degrade photosensitivity!!

PR must be soft-baked so that it does not stick to your mask during alignment.

4.5 Exposure

Optical transfer of the pattern on the mask to the PR.

The light wavelength of our exposure is mainly in the UV range because we need visible light to see.

Lasers are monochromatic and coherent.

PR's have a required "dose" of light to successfully be removed from the wafer.

4.6 Mask

It's the device that blocks light at certain locations so that the PR is untouched underneath it. There are multiple types of masks

Masks are made of optically flat glass coated with a patterned absorber layer which blocks the light.

- lightfield mask
exposed almost everywhere
- darkfield mask
exposed only in features.
- Binary Mask
either completely exposed or completely blocked
- Greyscale mask
transparency varies so you can deposit material of varying heights with only a single layer of PR.
- Phase Shift Mask
Work like holograms and modulate the phase-shift of the light beam to create interference patterns in the PR. Requires a coherent light-source for exposure.

4.6.1 Mask Materials

- Chrome is opaque to both visible and UV light
- iron oxide is clear to visible light but opaque to UV
- emulsion based materials are transparent
Soda Lime glass, BK-7, Quartz, CaF_2

The emulsion based materials have various cutoff wavelengths, and you would use different mask materials depending on both your PR and your exposure wavelength.

Mask production is another lithography step.

4.6.2 Exposure Tools

- Contact mask: put the mask on the wafer directly
Fast, cheap, and simple, but the wafer has to be specifically made to withstand contact, there's no magnification, and the mask is the same size as the wafer.
- Proximity: put the mask as close as you can without touching
Fast, and no-contact, but slightly more complex, the separation leads to diffraction blur, and the mask needs to be the same size as the wafer (expensive).
- Projection: use lenses to be able to accurately place the light without proximity.

Masks are easier, laser is more expensive.

Projection is useful because the mask does not have to be the same size as the pattern because the lens will de-magnify the light.

The modulation transfer function is the function that determines the type of feature sizes that can be put into a system.

4.6.3 Projection Lithography

You have to worry about both resolution and depth of focus.

Chapter 5

SKIPPED OPTICS LECTURE

Chapter 6

Polymers

6.1 Crosslinking

This is what happens when a polymer changes into an insoluble product due to light exposure.

This is for negative photoresists

6.2 Scission

Polymers separate under light exposure and actually become soluble.

This is for positive photoresists

6.2.1 Examples of Positive PR

- PMMA
sensitive at 220nm and useful with DUV but not mercury
- DNQ resists
Have a DNQ ester and a resin
useful with mercury lamp lines

6.3 Pros and Cons

Positive PR's are better for resolving isolated holes and trenches

Negative PR's are better for resolving isolated lines.

Positive PR leaves PR everywhere except the illuminated parts

Negative PR leaves PR only on the illuminated parts and not anywhere else.

In order to use PR, you put your material **where there is no photoresist** and then the PR removes all the deposited material on top of it.

6.3.1 Permanent Resists

These are PR's that become permanent components of the device. Thicker layers are achievable. They use strong adhesion, which makes removal difficult.

6.3.2 Dry Resists

A film is directly laminated onto a surface. No liquids are used. Available thickness from $25\mu m$ to $100\mu m$. It conforms to surfaces of different topologies, and is developed in sodium carbonate solutions.

6.3.3 Image Reversal Resists

You can use both heat and UV to make the PR act as both a positive PR and a negative PR.

6.4 Overexposure

You use too much light and part of the PR that was meant to be not touched is touched.

6.4.1 Positive

Too much PR has been removed

6.4.2 Negative

Too much PR is solidified on the wafer.

6.4.3 Liftoff

Positive photoresists are better for liftoff when overexposed because the PR forms a concave structure that makes sure the deposition material is definitely disconnected.

6.5 Underexposure

The opposite of overexposure.

Negative PR is better when you underexpose.

6.6 PR Resolution and Contrast

Certain resists only change a certain amount depending on the dosage of light.

The sensitivity = resist contrast = the slope of resist removed over dosage

$$\gamma_p = \frac{1}{\log(D_p) - \log(D_p^0)} = \left(\log\left(\frac{D_p}{D_p^0}\right) \right)^{-1}$$

Having a PR with less contrast is useful if you have 2 masks.

6.7 Developers

- MIF (Metal Ion Free) Developer
- Inorganic (metal ion based) Developer

Do not mix these two developers

6.8 Choosing a PR

Dependent on wavelength, feature size, thickness, positive/negative, lift-off, chemical/plasma resistance, removal, developer, stripper.

6.8.1 Multi-layer Resists

These are used when you have resolution issues but still need a very thick layer.

A multi-layer resist could also be used if there are features already in the wafer. You use 1 layer to cover all your features and then use a second layer for your actual pattern.

The resist thickness should be $5\times$ as big as the largest feature.

6.8.2 LIGA

It's some German word.

Essentially you use a very thick PR to make a mold, and then you plate the PR mold with metal electroplating.

6.8.3 Lift-Off Resist

Basically you put a resist on top of an overexposed resist so you can get the nice concavity while still having a straight line for the deposition process. It's some German word.

6.8.4 Post-Exposure Treatment

Heavily Dependent on Resist. baking, radiation, reactive gas, vacuum, time.

6.8.5 Stripping

There's all sorts of ways to get PR's off of your wafer.

6.9 MONDAY LITHOGRAPHY QUIZ (it should only take 5 minutes)

Resist's have 3 components Sensitizer, resin, solvent.

Ferrera likes darkfield masks more than lightfield masks because he has more control.

6.9.1 Step and Repeat Process

Used for high-volume fabrication. I wasnt paying attention

Chapter 7

Alignment

You need both in-plane and out-of-plane alignment.

7.0.1 Out of Plane

Wedge error compensation. Necessary for good image transfer

7.0.2 In-Plane

Overlay Registration. This is important for when we need to add new features to features already on the plane.

7.0.3 Top-Down

Aligning features on the two faces of the wafer.

There are multiple ways to do this of varying quality

- Hole through the wafer
- IR Microscopy
- visible light with 2 masks
- back-side mask and top-side mask
- Wafer flats can also be used at reference points.

7.1 Errors

There are all sorts of errors that can occur due to misalignment in projection lithography.

7.1.1 Misalignment Examples

Thermal run-in and run-out is when your features move due to a change in temperature during lithography

$$R = r (\Delta T_{mask} \alpha_{mask} - \Delta T_{Si} \alpha_{Si})$$

7.2 Alignment Markers

7.2.1 Fiducial Marks

Little marks on the wafer that you can align your mask towards. They are usually on the sides of the wafer where you are not putting devices.

7.2.2 Contact Aligner

It's just a mark with depth such that you can align the wafer with a physical process instead of just visual.

7.2.3 Special Marks

Vernier scales and Moire-style marks are used for very quick alignment.

7.2.4 Vernier Scale

Vernier scales use slightly misaligned steps such that you can see very small measurements more easily. Each misalignment is 1 step, and you can see the total misalignment by seeing which step is aligned with the wafer itself.

LC = least count, MSP = main scale pitch.

$$O = ZL * MSP + (LC \times MB)$$

If the vernier scale aligns with the number 10, and the spacing difference is 0.2 microns, then the alignment is $10 * 0.2 = 2$ micron misalignment.

7.2.5 Moire Scale

Uses constructive and destructive interference to essentially show a large wave pattern with a very small misalignment.

7.3 Projection Lithography

If your wafer is at an angle to the mask, the diffraction will cause blurry portions, and the dimensions will also be off because you are no longer in the focal plane.

7.4 Resolution Enhancement Technology

How do you improve resolution?

You can use shadow printing

$$R = B_{min} = k \sqrt{\lambda \left(s + \frac{z}{2} \right)}$$

- Resists

You can use better resists or multi-layer resists. You can use an anti-reflection coating.

- New Masks

Phase shifting, optical proximity correction

- Exposure system

buy a new system

resists are the cheapest option of any of these. Masks are pretty expensive. Aligners are crazy expensive.

7.5 Chemically Amplified Resists

$$\text{Quantum Efficiency} = \frac{\text{Number of photons induced}}{\text{number of photon absorbed}}$$

They have improved efficiency compared to regular resists.

They do have some issues

- Poor stability
- dependent on process parameters
- Oxygen causes surface inhibition

Single layer photoresists also cause issues

7.5.1 Anti-Reflective Coatings

A coating is applied to the wafer before the PR is put on.

- reduce reflected light
- reduces standing waves
- planarized surface

We don't worry about non-standing waves in our cleanroom because we use a mercury lamp that release non-coherent light.

7.5.2 Thin Film Imaging

You use multiple layers of resists. Use a very thin top resist and only etch the top resist. Then the bottom resist acts to get rid of standing waves and interference, increasing resolution.

7.5.3 Wavelength

Decreased wavelength means less diffraction and greater resolution.

7.6 Mask/Wavefront Engineering

7.6.1 Phase Shifting Mask

A phase shifting mask improves both resolution and DOF. To use a phase shifting masks, you need **coherent light** (lasers), so that the phase is consistent.

Controls light diffraction using interference.

This can be done with features etched into glass, known as a **hard shifter mask**.

Soft shifter masks use a non-chrome material that allows only phase-shifted light to come through.

7.6.2 Levenson-type Mask

Masks can have additional material patterned onto the surface that shifts the phase by 180 degrees to create interference

7.6.3 Mask Geometry Engineering

When light goes through a pattern, some will diffract and there will be noise in the design.

optical proximity correction is encoding noise into the mask such that the light that goes through the mask will etch the pattern **and** account for the noise created by the light. Add light where the pattern isn't fully etched and remove light where the pattern is over-etched.

Mask is no longer WYS / WYG (what you see is what you get) (lmao).

7.6.4 Improved Exposure Systems

These improved systems only work with projective lithography.

Off-Axis Illumination changes the diffraction pattern by angling the light

Kohler Illumination focusing light at the entrance of the aperture. This minimizes glares, shadows, and contrast. The field is evenly illuminated.

7.6.5 Resolution Example

$$B_{min} = \frac{k_1 \lambda}{NA} \quad DOF = \pm \frac{k_2 \lambda}{(NA)^2} \quad NA = n \sin(\theta)$$

The maximum that NA can be is 1 (index of refraction of air), so even with the absolute maximum, with $\lambda = 193nm$ and $k_1 = 0.25$, we get

$$R = B_{min} = \frac{0.25(193)}{1} = 48.25nm$$

However, with this resolution, we were able to get 22nm features. The way that they increased their resolution was by increasing the refractive index n with a liquid medium. You need a liquid that does not absorb UV radiation, has a high refractive index, and is compatible with all of the materials on your wafer.

This is called immersion lithography (or immersion imaging for microscopes).

7.7 Summary

Wavefront engineering improves certain types of mask imaging. We have 3 major improvements

- phase shifting masks
- optical proximity correction
- off-axis illumination

Chapter 8

Optical Lithography

What's new? Limit shapes and keep it simple. Advances beyond PSM, OPC, and OAI. New light sources (F_2 lasers at 157nm, possibly lasers at 126nm).

Mask materials? Quartz cuts out at 190nm and CaF_2 at 150nm. Now what?

Throughput is impressive at 200WPH (wafers per hour). What is this number when new technology has to be introduced?

At some point, photolithography reaches its limit, so we have to switch to UV or even x-ray lithography. The newest 3nm ASML machines use EUV lithography or soft x-ray lithography. We also have e-beam lithography and ion-beam lithography and nano-imprint lithography.

8.1 Extreme UV Lithography

Wavelength range from 10nm to 14nm. These are also called soft x-rays or vacuum UV. They developed from laser produced plasmas (LPP) and synchrotrons. They are only surface resist and vacuum compatible.

8.1.1 Pros

Capable of printing sub-100nm features. All optics also must be reflective (no lenses)

8.1.2 Cons

EUV is strongly absorbed in all materials, so it must be done in a vacuum. All optics must be reflective (no lenses). Masks must be 100% defect free. New resists are needed for this very low wavelength beam.

8.2 X-ray Lithography

wavelength range from $0.4nm \rightarrow 5nm$. Also called deep x-ray lithography. Sources include electron impact tubes, laser based plasmas, and synchrotrons. PMMA can be used as a resist.

8.2.1 Pro

- Large DOF
- Capable of printing sub-200nm
- Diffraction is not an issue
- Dust is transparent
- no optics involved

8.2.2 Cons

- masks need to be opaque and transparent to x-ray
- Mask reduction is not possible
- Masks can only be written with e-beams

We can theoretically get smaller features, but the biggest issue is the masks (tubes instead of mirrors/lenses). The masks also are all shadowless.

8.3 E-Beam Lithography

Energy range from $10 \rightarrow 50keV$. Can be both narrow beam or flood exposure. PMMA and PGMA can both be used as a resist.

8.3.1 Pros

- Micron and sub-micron resist geometries
- Can be automated and precisely controlled
- Greater DOF
- Direct write without mask (narrow beam)

8.3.2 cons

- slow, low throughput (scanning a 4in wafer takes over an hour)
- must be done in a vacuum to avoid absorption
- Sample and resist must be able to handle electrons

8.4 Ion Beam Lithography

Energy range $> 100keV$. Uses positive ions (Gallium, Indium, Gold). Various methods for producing ion beams (both narrow and flood exposure). PMMA and PGMA both can be used as a resist.

8.4.1 Pros

- Smallest beam size of anything ($< 8nm$)
- Higher resist sensitivity than e-beam
- negligible ion scanning

8.4.2 Cons

- Slow, low throughput
- Must be done in a vacuum
- Ion contamination (Gallium can implant in your substrate)
- can break your wafer

8.5 Nanoimprint Lithography

Hot embossing applied to nanofabrication. A force presses a master against a polymer, so that it imprints with the desired patterns via UV, heat, or pressure. Essentially, you squish a polymer (liquid) onto your substrate with the mask in between. We're pressing a liquid through a very small channel at a very high pressure.

8.5.1 Pros

- Simple and relatively cheap
- Single layers are economical
- Small features are easier than large features (less stamping)

8.5.2 Cons

- Low throughput
- Alignment can be costly
- Mask can degrade
- Release can be challenging

8.6 Maskless Lithography

There is a machine called a Heidelberg that is a Spatial Light Modulator that produces patterns on the photoresist directly.

8.6.1 Pros

- good for R&D (no mask development)

8.6.2 Cons

- Write speeds depend on the model and can take minutes to hours

8.7 3D Nanoprinting

1. A negative PR is polymerized using 2 photon absorption
2. The polymer itself is used to pattern the surface
3. A master can be made with molding

The PR itself is not the material being used. Nanoprinting allows you to make 3D PR patterns, and then you get etch/deposit a 3d pattern based on that PR.

8.7.1 Pros

- Simple and Low cost
- Simple layers are cheap
- Small features are easier than large features (less printing)

8.7.2 Cons

- Stitching errors
- Limited size of patterns
- Limited polymer materials (must be a negative PR)

8.8 Soft Lithography

You use a stamp with a soft polymer and wack it into the thing.

Chapter 9

Physical Vapor Deposition (PVD)

Source/target to wafer/substrate.

The 2 things to do after you have a pattern on your wafer are deposition (adding stuff to the wafer), and etching (removing stuff from the wafer). There are 2 types of main deposition processes, PVD and CVD.

PVD is physical vapor deposition, where you use plasma or boiling or any sort of non-chemical process to atomize a material and place it onto a substrate.

CVD could involve 2 gasses being mixed such that the precipitate is formed on your wafer.

Epitaxial processes involve depositing only a single layer film onto a wafer. The way that this is done is with beams of molecules being placed (epitaxy).

Atomic layer deposition involves a self-terminating reaction. 2 materials react on the substrate, but they are self-terminating, so they stop very quickly. You condition your surface with 1 chemical and add a 2nd. They react and only create a single layer of reactant, and then you can purge your gasses to get only a very thin film.

Implantation and diffusion are types of doping (material modification)

9.0.1 Types of PVD

- Evaporation
- Sputtering
- Laser

- Molecular beam epitaxy

No matter what, film growth is achieved via **condensation** of a vapor onto your substrate. This can be done with evaporation, or bombardment/sputtering.

The deposition rate is proportional to the rate of mass transfer to the surface. PVD is usually done in a vacuum to increase your mean free path. Also, a very high vacuum keeps contamination to a bare minimum (ignore oxidation). Lastly, a high vacuum also depressed the boiling point of materials.

We usually work in a high vacuum of $10^{-5} \rightarrow 10^{-7}$ torr.

9.0.2 Evaporation

Heat up your substance with an electron beam, heating coil, laser, RF induction, resistive heating, etc.

9.0.3 Sputtering

Ion bombardment and laser ablation are used to wack atoms off of your target. We usually use Argon or Nitrogen ions for sputtering because they are unreactive.

9.1 Mean Free Path

Defined as the average distance a molecule travels before colliding with another molecule. The mean free path statistics result in the equation

p = pressure, T = temperature, d = diameter.

$$L = \frac{k_B T}{\sqrt{2} \pi d^2 p} \quad \frac{k_B T}{p} = \frac{V}{N}$$

We want to increase mean free path, so we decrease pressure. The math is in the lecture, but at a high vacuum, the mean free path is $L \approx 4m$.

9.1.1 Types of Pumps

Roughing pumps (rotary, etc.) can get you to a low/medium vacuum. Cryopumps, ion pumps, turbo pumps, etc. are able to get you to high vacuums.

9.1.2 Vacuum System Operation

Mechanical pump \rightarrow Hi-vacuum pump, with lots of valves in between. If a Hi-vacuum pump reaches atmospheric pressure, it breaks.

9.1.3 Pressure Gauges

At regular pressures, we use a gauge that measures that resistance of a heated wire (less pressure means less heat loss from convection)

9.1.4 Ion Gauge

Operates by measuring thermionic current. We boil a material to make ions and then accelerate them with a coil. The amount of ions collected is proportional to the pressure. Less pressure means less ions and less current.

9.1.5 Outgassing

gasses emanate from surfaces inside the chamber. This is a limiting factor for vacuums below 10^{-7} . There are a few potential solutions:

- Eliminate materials that absorb gases
- bake the entire vacuum system at 150C to evaporate them.

9.2 Evaporation

Use a heat source to turn a material to a gas. There are many types of heat sources for evaporation.

- Resistance heat (no radiation, but might contaminate)

- E-Beam (no contamination, but emits radiation)
- RF-induction (no radiation, but contamination)
- Laser (no radiation, but expensive)

The three steps of this type of PVD are evaporation, transport, condensation.

Very Long Tangent About Evaporation (Equilibrium Vapor Pressure and Stuff)

If you pull a vacuum, things evaporate easier.

9.2.1 Clausius-Calpeyron Equation

Boiling point and vapor pressure

$$\ln(P_v) = \frac{-\Delta H_{vap}}{R} \frac{1}{T} + C$$

9.2.2 Hertz-Knudsen Equation

$$N_e = (2\pi M k T)^{-1/2} P_v$$

N_e is the number of molecules evaporating per unit area per time. M is the molecular mass, P_v is the vapor pressure.

9.2.3 Thermal Evaporation

Pass current through a tungsten boat to generate heat.

9.3 Deposition

The deposition rate is more important than the evaporation rate, even if they are related. It depends on the evaporation rate, distance of the substrate, and the angle of deposition. The evaporated mass expands and spreads out from the source. We use Lambert's Cosine Law and

Knudsen's equation as well as a factor n that is related to the energy that an atom has when it leaves the surface. ϕ is between the normal and the line of sight, and θ is between the observer's line of sight and the normal of the surface.

$$\frac{dM_s}{dA_s} = \frac{M_e(n+1) \cos^n(\phi) \cos(\theta)}{2\pi r^2}$$

When $n = 0$, we get

$$\frac{dM_s}{dA_s} = \frac{M_e \cos(\theta)}{2\pi r^2}$$

The angles aren't completely intuitive, but there is a picture in the lab slides.

9.3.1 Film Thickness Variation

You get less deposition materials on the sides of the materials compared to the center depending on the angle of deposition and the distance difference. For a point source ($n=0$), we get a thickness of

$$t = \frac{M_e h}{4\pi(h^2 + l^2)^{3/2} \rho_{density}} \quad \frac{t_{max}}{t_{min}} = \frac{1}{\left(1 + \left(\frac{l}{h}\right)^2\right)^{3/2}}$$

This is found with the slightest amount of algebra. For a surface source ($n=1$), we get a different equation

$$t = \frac{M_e h}{4\pi(h^2 + l^2)^2 \rho_{density}} \quad \frac{t_{max}}{t_{min}} = \frac{1}{\left(1 + \left(\frac{l}{h}\right)^2\right)^2}$$

We want a thickness ratio as close to 1 as possible, so the point source is the most ideal source for deposition (maximizes min/max). We want to keep our point source as far as possible to decrease variation, but that also dramatically decreases your deposition rate.

9.3.2 Planetary Substrate Holder

Making a point source material radiator is impossible, but my move our wafers around mid-deposition so that the thickness anywhere on the wafer is approximately constant.

9.3.3 Directionality and Local Step Coverage

If you have features on your wafer, you have to worry about the fact that space under/behind a feature will not have material deposited on it.

9.4 Sources

Regular sources just have like a chamber that gets hot

9.4.1 E-Beam

Very locally heat material using E-Beams and a magnetic field that focuses and aligns it. The magnetic field can also raster scan the beam across the source material. The main benefit is you have evaporate high-melting-point materials without too much difficulty. 85% of the electron energy goes into heating, with the resting going into x-rays and electron generation. x-ray damage can be an issue (secondary radiation). E-beams result is higher quality films and deposition rates than thermal deposition.

9.5 Quartz Crystal Monitor (QCM)

Use a crystal to measure the thickness of thin films. You put a crystal in your sputterer, and the deposited thin film changes the resonant frequency of the crystal (because of the increased mass). The resonant frequency can be measured, and that can be use to calculate the thickness of the film.

9.5.1 Math

It's just a simple harmonic oscillator.

$$f_1 = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \Rightarrow f_1^2 = \frac{1}{4\pi^2} \frac{k}{m}$$

$$f_2 = \frac{1}{2\pi} \sqrt{\frac{k}{m + \Delta m}} \Rightarrow f_2^2 = \frac{1}{4\pi^2} \frac{k}{m + \Delta m}$$

$$\Delta m = \frac{k}{4\pi^2} \left[\frac{1}{f_1^2} - \frac{1}{f_2^2} \right]$$

9.6 Summary

- Evaporation is most suitable for metallic thin films
- Compounds and alloys don't deposit well
- Deposition is directional, so it does not do well with steps
- E-Beam deposition usually produces better films because of higher temperatures and less contamination
- High vacuum is required

Know a number of things about PVD. equilibrium vapor pressure. its relation to temperature (Clausius Clapeyron). Relation to evaporation rate (hertz-knudsen). Flux distribution. thickness variation.

Dramatically raising the temperature will cause bigger thickness variation and your boat will start melting (Lambert's Cosine Law).

What if you want to deposit something like tungsten with a high melting point? Don't use thermal evaporation. Use sputtering instead.

Chapter 10

Sputtering

Whack a material real hard so it gets kicked off the boat. You can use ion bombardment (plasma) or laser ablation.

10.1 Process

- The source and substrate are placed in a vacuum
- Bombard the surface with high energy ions
- Enough energy is added to a particle for it to escape the surface
- The ejected atoms deposit on the substrate

After the vacuum is made, a sputtering gas (argon) is used to strike a plasma.

10.2 Generating Plasma

Cathode (negative voltage) to Anode (grounded)

Apply a voltage to accelerate free electrons that collide with atoms to make ions.

10.2.1 Why Low Pressure?

At STP, the electrons would have a very small Mean Free Path, so they wouldn't have the energy to create Argon ions.

With low pressure, the electron has time to accelerate, so it gains enough energy to be able to ionize the Argon.

The reason that we're in a medium vacuum and not a high vacuum is because we need a decent amount of ion flux to be able to actually bombard our target.

10.2.2 Electron Origin?

Field Emitted Electrons. The cathode emits electrons because of the electric field created from the high voltage. It reduces the Work Function of the metal electrons, so they are released. You also get free electrons from the generated ions (Townsend Avalanche).

The plasma acts as a weakly charged gas in a quasi-neutral medium with some amount of influencing fields. The particles all influence each other because of their electric fields.

10.2.3 Glow Discharge

The electrons can be absorbed by ions, and when they're absorbed, they release light of a certain wavelength.

The plasma is slightly positively charged because the ions have a higher mass, so they need more time to accelerate and thus collect in that conductive region (slightly).

The cathode at the target. The anode is at the substrate holder.

10.2.4 THE IONS ARE POSITIVE

10.2.5 Magnetron Sputterer

Use an M field instead of an E field to accelerate electrons in circles. This increases their mean free path and thus makes a denser plasma. This is caused by the **Lorentz Force**

10.3 Ion Bombardment

Multiple things can happen with an ion hits a surface

- Reflection

- Absorption
- Sputtering
- Ion Implantation
- Chemical Reactions
- Electron and Photon Emission

10.3.1 Levels of Ion Bombardment

- Very low energy = $< 5\text{eV}$
Reflection or physisorption
- Low energy = $5 - 10\text{eV}$
Surface damage and surface migration
- Medium = $10 - 10000\text{eV}$
Lattice damage, atomic ejection, and heat - Sputtering
- high = $> 10\text{eV}$
Ion implantation into lattice (doping)

10.4 Sputtering Regimes

10.4.1 Single Knock-on Regime

Seen in the 10-30eV range. Mostly just recoil, but there are sometimes collisions.

10.4.2 Linear Collision Cascade Regime

Recoil is minimal. Cascading collisions produce sputtering, Binary collisions (independent atom-atom collisions)

10.4.3 Heat Spike Regime

- Everything is happening all at the same time
- Collisions cannot be considered independent
- Energetic ion and dense material
- feels like localized heating

10.5 Sputtering Yield

Defined as atoms ejected per incident ion.

Dependent on a million things (incident angle, incident ion energy, bombarding species, target materials). Varies from 0.1 - 10.

10.5.1 Sputtered Atoms

Tend to have small energies between 1-10 eV (evaporation would have just 0.1eV). Sputtering results in better film adhesion and density. There is a very wide distribution in sputtered atom energies because the process is roughly stochastic.

10.6 Contamination

Contamination causes all sorts of issues and comes from a million different sources

10.6.1 Sources

- Insufficient vacuum
- Outgassing
- Oxygen Impingement rate

Resistivity of film can increase tremendously from implanted oxygen.

10.6.2 Solution

- Pump down to lower pressures
- fill chamber with argon and pump down again to dilute remaining gas

10.7 Reactive vs Non-Reactive Sputtering

10.7.1 Non-Reactive

- Sputtering gas is not incorporated into film
- Common choices are noble gases (mainly Argon)

10.7.2 Reactive Sputtering

- Sputtering gas will be incorporated into film
- This allows for certain alloys to be made (Al_2O_3 , SiO_2 , ...)
- Common choices are O_2 , N_2 , NH_3 .

10.8 Laser Ablation Deposition

Instead of using a plasma to excite your target, you use a laser. Useful for complex compounds.

10.9 Molecular Beam Epitaxy (MBE)

You try to deposit a single crystal film onto a substrate by matching lattice constants.

Chapter 11

Chemical Vapor Deposition (CVD)

Instead of providing mechanical or thermal energy, you provide chemical potential energy of atoms in a gas.

11.1 Mechanism

1. Mass transport of reactant gases
2. Gas-phase reaction leading to film precursors (homogeneous)
3. Mass transport of film precursors
4. Adsorption of film precursors
5. Surface migration of film forming materials to the growth site
6. surface reaction (heterogeneous products)
7. Desorption of byproducts
8. Mass transport of byproducts

11.2 CVD Process Family

- CVD can occur in a million different ways.
- Can deposit metals, semiconductors, insulators, barriers, silicides, etc.

- Energy for CVD can be derived from thermal, plasma, and photon energy.
- There's a whole table in the slides

11.3 CVD Reaction Types

Thermal Decomposition (not common in semiconductors), Redox Reactions, Exchange Reactions, Coupled Reactions.

11.3.1 Precursor

- Chemicals must be volatile/gaseous.
- Film formation must be thermodynamically predicted (decrease Gibbs Free Energy).
- Byproducts must also be volatile.

11.3.2 Atmospheric Pressure CVD

Very fast reaction rate because there's a whole lot of gas. Main issue is contamination.

11.4 Modeling CVD Processes

Reactions occur at the surface. The concentration of species in gas (N_g) drops to the concentration of species at the surface (N_s) across the boundary (or stagnant) layer of thickness (δ).

Flux to surface (J_g) and flux consumed in film (J_s) are controlled by the reaction-rate constant (k_s) and the mass transport constant (h_g).

$$J_g = \frac{D_g}{\delta}(N_g - N_s) = h_g(N_g - N_s) \quad \text{Flux to Surface}$$

$$J_s = k_s \times N_s \quad \text{Flux consumed in grown film}$$

At steady state, fluxes must be equal

$$J_g = J_s = \frac{N_g}{\frac{1}{h_g} + \frac{1}{k_s}} = \frac{h_g k_s N_g}{h_g + k_s}$$

The film growth rate is given by

$$v \propto J_s = \frac{h_g k_s N_g}{h_g + k_s}$$

If the film growth rate is mainly limited by mass transport, then you have a diffusion limited regime $h_g \ll k_s$.

If it's limited by reaction rate, then $h_g \gg k_s$.

Those last 2 limitations are the important things to remember about CVD deposition rates.

The velocity is

$$v \propto h_g N_g \quad \text{limited by mass transport}$$

$$v \propto k_s N_g \quad \text{limited by reaction rate}$$

11.4.1 Flux to Surface

When we are difficult (mass transport) limited, the film growth rate depends on the flux to the surface (J_s).

If we have a low vacuum to atmospheric pressure, then a stationary boundary layer will develop, and the precursor gas must diffuse through it (caused by laminar flow, not an issue if high vacuum because there are minimal gas interactions).

If $\delta(x)$ is the boundary layer thickness and is a function of distance along the substrate x , then

$$\delta(x) = \left(\frac{\eta x}{\rho V} \right)^{1/2}$$

Where η is the gas viscosity, ρ is the gas density, and V is the gas stream velocity.

The average thickness of the boundary layer is

$$\delta = \frac{1}{L} \int_0^L \delta(x) dx = \frac{1}{L} \left(\frac{\eta}{\rho V} \right)^{1/2} \int_0^L x^{1/2} dx = \frac{2}{3} L \left(\frac{\eta}{\rho V L} \right)^{1/2} = \frac{2L}{3\sqrt{Re}}$$

Where Re is Reynold number which is the ratio of inertial forces to viscous forces (< 2000 is laminar and over is turbulent, CVD should be laminar).

Use Fick's first law of diffusion across the boundary layer

$$J_g = -D \frac{d\phi}{dx} \approx -D \frac{N_s - N_g}{\delta}$$

Where D is the diffusivity or diffusion constant. Further, at steady state, then $J_g = J_s$.

For a diffusion limited process, the molecules on the surface will be consumed as fast as they arrive, therefore the concentration at the surface

$$N_s = 0 \rightarrow J_s = J_g = D \frac{3N_g \sqrt{Re}}{2L}$$

11.4.2 Gas Flow Rate Dependence

At low flow rates, the film growth rate shows a square root dependence. At high flow rates, the growth rate reaches a maximum and becomes independent of flow. At this point, the reaction rate controls the deposition.

The rate limiting phenomenon can dictate the design of the reactor.

A vertical design is good for reaction-rate limited deposition, while a horizontal design that maximizes gas flow is best for a mass transport limited deposition.

11.5 Surface Adsorption and Reaction

It is worthwhile to study what occurs after a precursor molecule/atom reaches the surface.

The must find a site to adsorb to the surface long enough for the decomposition/ reduction/exchange reaction to take place. This will depend on

- Precursor arrival rate
- Density of sites available for adsorption of precursor molecules

- substrate temperature (that determines the residence time required for the reaction)

(sites consist of defects/discontinuities on the surface).

The elemental adatoms that result are not stationary but move in the surface until they encounter high-energy binding sites (vacancies, edges, kinks)

Trapped adatoms nucleate growth of islands by trapping other migrating adatoms, eventually developing a continuous film.

Nucleation \rightarrow Growth of Nuclei \rightarrow Coalescence \rightarrow Film Growth \rightarrow
Continuous Film.

An adatom is a single atom on a crystal

11.5.1 Material Bonding

Chemical bonds vs adhesive via coordinate bonds (Van der Waals, hydrogen, ionic) which determines if layer can exist and not delaminate.

11.5.2 Film Growth Rate vs Temperature

At high temperatures, the reaction rate is sufficiently, we get a mass shortage.

$$g = Ce^{\frac{-\Delta E}{k_b T}} \Rightarrow \log(g) = \frac{-\Delta E}{k_b} \frac{1}{T}$$

Log and $1/T$ are linearly proportional to each other (If reaction rate limited regime). As T increases you get back to a mass transport limited regime.

While higher temperatures produce higher growth rates, they also promote gas phase reactions that are generally undesirable in CVD because they produce particulates that fall onto the substrate and create film defects. To overcome this, we can

- Use a different precursor
- Reduce pressure (LPCVD) - increases diffusivity and reduces heat transfer.

11.6 Film Growth Mechanisms

What happens once the reactant reach the surface where the film needs to grow?

11.6.1 Nucleation of Growth

Generally, a stochastic process that strongly depends on the precursor arrival flux, adsorption site density, surface migration temperature, etc.

11.6.2 Type of Growth

Island vs layer determines the grain size and boundaries while step vs cluster determines the roughness and grain orientation. These can be thought of as a thermodynamic competition between surface / inter-surface energies.

- Frank-van der Merve mode (2 dimensional growth mode)

$$\gamma_{\text{substrate}} \geq \gamma_{\text{film}} + \gamma_{\text{interface}}$$

- Volmer-Weber mode (Island growth mode)

$$\gamma_{\text{substrate}} < \gamma_{\text{film}} + \gamma_{\text{interface}}$$

- Stranski-Krastanov mode

Initially, we have $\gamma_{\text{substrate}} \leq \gamma_{\text{film}} + \gamma_{\text{interface}}$

but then it turns to $\gamma_{\text{substrate}} < \gamma_{\text{film}} + \gamma_{\text{interface}}$ due to strain effect

γ is the surface energy or interface energy.

11.6.3 Step Coverage

This is dependent on several factors

- Flux arriving at the surface: local visibility angle nad precursor flux
 $\theta = \int J_g d\theta$.

As the visibility angle is reduced, we see a thickness $\theta = \tan^{-1}(\frac{w}{h})$.

Another thing that might affect this thickness given a hole/feature-y area is the fact that complex surfaces have far more surface area for the same amount of deposited material. SO basically, the two key factors are

- Mean Free Path
- Surface Diffusivity

The outside corners have an angle of $\theta = 270$ deg, which is the largest anywhere, the thus those corners have the most material deposited on them, and they might actually completely cover the hole with material.

11.6.4 Reactive Stiction (Sticking) S_c

That is the sticking coefficient

$$S_c = \frac{\Gamma_{incident} - \Gamma_{re-emission}}{\Gamma_{incident}} = \frac{\Gamma_{reaction}}{\Gamma_{Incident}}$$

Direct diffusion is $S_c = 1$, and bouncing means that $S_c < 1$.

Low S_c means that the film is conformal (it fills features evenly).

11.7 Thing to Keep In Mind

Uniformity of the film: Thickness, composition, structure, and properties are all affected by all sorts of factors.

- Throughput esired
- Intra-wafer and inter-wafer uniformity
- Film composition/purity
- Conformity on wafer topography

11.7.1 Stresses

If there is a lattice mismatch or thermal expansion mismatch, there might be residual stresses in the film.

Tensile stresses bring the sides up, and compressive stresses bring the center up. Both are bad.

Types of material structures of deposited films include

Polycrystalline, amorphous, epitaxial (single crystalline), columnar.

The type of resulting films affects basically everything.

11.7.2 LPCVD

LPCVD is usually reaction rate limited, so the amount of material just into the material is less important as much as the temperature of the substrate.

11.7.3 PECVD

PECVD is plasma-enhanced CVD. You use high energy ions to activate the precursor so that it is more reactive (increasing reaction rate), and the electrons also bombard the substrate to make it more reactive.

A common application is a low temperature insulator over metals.
typical process conditions include:

- 0.5 to 5 torr
- 200-400C
- Surface reaction rate limited
- Most common hot wall furnace

PECVD results in a low sticking coefficient. This results in low stress films, but because of the extra reactions, there might be contamination.

pros include uniformity, good step coverage, and low temperatures

cons include particle contamination, chemical contamination (high H content), and pinhole errors in the deposition.

11.7.4 MOCVD

This is known as metal-organic CVD (or metal-organic vapor phase epitaxy).

Gases included arsine, phosphine, ammonia, disilane, and silane, and liquid sources are trimethylgallium, trimethyl indium, trimethyl aluminum that react to form films including GaAs.

This is mainly used in solar cells and VCSELs and other things. It creates single layer growth.

11.7.5 ALD

Atomic Layer Deposition. CVD is broken down into 2 half-reactions.

- Precursors are kept separate and introduced sequentially to complete the reaction.
- One cycle lays down one monolayer for the film in a well controlled manner
- self-terminating reaction.

pros include uniformity, monolayer control, step coverage, and no gas phase reaction.

The main con is that it is very very slow.

11.8 Summary

- Seen all the steps of the CVD mechanism.
- We classified different types of reactions with examples of their use.
- Developed a simple intuitive model to identify different process regimes (mass transport limited and reaction rate limited regimes)
- film growth characteristics
- conformal coverages
- Different variants and types of CVD

11.9 MIDTERM 1 PREP

What's on the exam: Everything in Deposition (up to the end of Deposition). CVD will be on the exam, dry etching will not be on the exam.

Exam is on monday during class, should take about 1 hour, but we'll have the room for a full 2 hours. NO formulas need to be memorized, we will be given a sheet. Just know how to use them. Not heavy calculation- if you set up the equation correctly, you can make estimates. **YOU CAN BRING A CALCULATOR.** The best way to prepare is go through the notes, read texts, go through the homeworks (best way).

Know how cleanrooms are classified and clean room safety processes. Stokes settling and number of particles per hour that settle on a substrate .

Sources and types of contamination. Problems caused by contamination and humidity. Purpose of bunny suit and rules.

Know an MSDS.

NFPA and HMIS labels, how to read them, what they're meant for.

11.9.1 Lithography 1

- Process flow in microfabrication
- Typical patterning process flows (liftoff vs masking)
- Lithography process flows
- Cleaning processes (RCA1 vs RCA2, piranha solution, O₂ plasmas) and their purposes
- supercritical drying, ultrasonic cleaning, promoting surface adhesion for lithography
- Different methods of applying PR to a substrate with an emphasis on spinning. Know what happens during spinning and what are edge beads and why they form, why they're a problem, and how to alleviate the problem
- purpose of soft baking before exposure

- (me added) all baking processes and their purposes

11.9.2 Lithography 2

- Radiation for exposures, mercury lines, types of masks, transparency of mask materials at different wavelengths
- Exposure systems, contact, proximity, projection, their resolution, advantages nad disadvantages
- Resolution, diffraction and its impact resolution, diffraction limit, point spread function, numerical aperture, modulation transfer function.

11.9.3 Lithography 3

- Components of a PR_i resist tone nad what light does to PR's of different tones, different yypes of resists (single component, two-component, image reversal)
- What remains and what's gone with different tone resists and light-field/darkfield masks
- effects of over and under-exposure for different tones of resists (Fresnel Zone, **other zone (google)**)
- Resist sinsitivty and contrast; side-wall profiles
- Development and post-development processing; resist stripping (acetone bath).

11.9.4 Lithography 4

- Alignment errors and how they einfluence exposure
- Vernier and Moire fringes for allignment
- Sequence of things to do if you want to enhance resolution
- Resists: anti-reflection coatings, multi-layer resists, lift-off resists
- Masks: phase shift masks, mask geometry engineering

- Exposure: concept of different illumination systems, immersion lithography concepts
- Advanced lithography systems, particle-beams, maskless, soft.

11.9.5 Deposition 1

- Vacuum concepts, mean-free path and its relation to pressure, what does high vacuum do for deposition processes, technology ; pumps and gauges
- Evaporation, vapor pressure and oiling; Clausius Clapeyron Equation and how it is used to get the temperature from a given vapor pressure; Hertz-Knudsen equation and how it is used to calculate the mass evaporation rate
- Lamberts Cosine law and its use in determining evaporative flux density; point sources and plane sources; film thickness variation
- Evaporation technology, e.g., e-beam evaporation, virtual point sources; directionality and coverage, film thickness measurement with quartz crystal monitors - concept and calculations.

11.9.6 Deposition 2

- Sputtering concept, how and why plasmas are used, why is the pressure in sputtering higher than that for evaporation
- Rudimentary idea of plasmas, basic zones, voltage drops across a plasma
- Particle energy and sputtering regimes; sputtering yield and factors affecting sputtering yield; Directionality, and sub-cosine flux distributing
- Comparisons between sputtering and evaporation, reactive sputtering and laser ablation

Deposition is more conformal with sputtering because there are more collisions.

Know why the glow region is slightly positive (gas moves slower than electrons)

11.9.7 Deposition 3

- CVD mechanisms and reaction types. Conditions for use of a reaction in CVD, Diffusion across the boundary layer and surface reaction rates and how they determine CVD process regime
- Diffusion vs reaction rate limited regimes, growth rate behavior in these regimes
- Surface reaction and film growth mechanism and how these determine the type of film obtained
- Different CVD processes, the premises behind the variation and their advantages and disadvantages and applications; ALD and the use of sequenced coupled reactions to get atomic layers.
- Coverage, Reactive Sticking coefficient and how its effects conformal coverage.

Why use LPCVD vs just regular atmospheric CVD (if its reaction rate limited, you don't need much gas in the chamber. Also, the vacuum keeps the substrate hot)

Chapter 12

Removal - Dry Etching

How to get crap off of your substrate.

12.1 Subtractive Processes

Dry Etching is generally more used than dry etching

There are many many different etching techniques

- Wet and dry etching
- Focused ion beam (FIB) milling
- Laser Machining
- Ultrasonic drilling
- Electrical discharge machining (EDM)
- Tradition precision machining

12.1.1 Dry Etching

A solid surface is etched by the gas or vapor phase. Recall ashing (dry stripping of resists).

In general, ry etching has fewer disposal problems, less corrosion of metal features in the structure, less undercutting and broadening of PR features, and cleaner surfaces.

types of dry etching include

- Physically via ion bombardment

- Chemically by a reaction through a reactive species at the surface
- Combination of physical and chemical reactions

Source (CF_4) \rightarrow Plasma \rightarrow Reactant (F_0) \rightarrow Substrate (Si) \rightarrow product (SiF_4)

Dry etching, CVD, and evaporation all use vapor phase reactants. in CVD, the surface reaction gives rise to at least one solid product, but in etching one hopes that all the reaction products are vapors (having high vapor pressures). Dry Etching, sputtering, and version of CVD (PECVD) use plasmas, though sputtering uses a plasma for different purposes.

Source (SiH_4) \rightarrow Substrate (Si) \rightarrow gas byproduct (2H_2)

Dry etching is very similar to regular lithography because you put on the PR, and then dry etch, and then perform lift-off with the PR.

Anisotropic etching is vertical etching with no horizontal etching. Isotropic etching will etch underneath the mask, and that's bad.

dry etching is **highly directional** because the atoms hitting the substrate are charged, so they move along the path of the electric field.

12.1.2 SPUTTERING IS LESS DIRECTIONAL