ME 487

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Contents

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 esseentially 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 crevass 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 CO_2 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 odulate 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 you 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

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

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

6.7 Developers

- MIF (Metal Ion Free) Developesr

- 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

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

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 interferencec 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

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 with defract 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

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

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 vacumm 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 need 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 ot 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 Spacial 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 you 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 sinlge 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 bombardent/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.

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

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 absord 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 Evaportation (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

$$N_e = (2\pi MkT)^{-1/2}P_v$$

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 nad

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 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

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

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

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

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 direction, so it does not do well will 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 $= < 5ev$

  Reflection or physisorption

- Low energy $= 5 - 10ev$

  Surface damage and surface migration

- Medium $= 10 - 10000eV$

  Lattice damage, atomic ejection, nad heat - Sputtering

- high $= > 10eV$

  Ion implanatation 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 ($Al_2O_3, SiO_2, \ldots$)

- 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 contration of species at the surface (N_s) across the boundary (or tagnant) 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 trnasport constant (h_g).

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

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

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 $h_g << k_s$.

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

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

The velocity is

$$v \propto h_g N_g \qquad \text{limited by mass transport}$$
$$v \propto k_s N_g \qquad \text{limited by reaction rate}$$

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

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

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 sconsumed 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 reachesa 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 uintil 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.

$$\text{Nucleation} \rightarrow \text{Growth of Nuclei} \rightarrow \text{Coalescence} \rightarrow \text{Film Growth} \rightarrow \text{Continuous Film.}$$

An adatom is a single atom on a crystal

11.5.1 Material Bonding

Chemical bonds vs adhesive via coordinate bonds (Van der Vaals, 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 sreach 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)

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

- Volmer-Weber mode (Island growth mode)

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

- Stranski-Krastanov mode
  Initially, we have $\gamma_{substrate} \leq \gamma_{film} + \gamma_{interface}$
  but then it turns to $\gamma_{substrate} < \gamma_{film} + \gamma_{interface}$ 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 trmethylgallium, trymethyl indium, trymethyl 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 squentially to complete the reaction.

- One cycle lays down one monolayer for the film in a well controlled manner

- self-terminating reaction.

pros include uniformity, monolyaer 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 adn 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, pihrana 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¡ 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; Clasusium Clapeyron Equation and how it is used to get the temperature fro 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 desnity; point sources and plane sources; film thickness variation

- Evapoeation technology, e.g., e-beam evaporation, virtual point sources; direactionality 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 pressrue 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 cputtering nad 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 adn how these determine the type of film obtained

- Different CVD processes, the presmises behind the variation nad their advantages and disadvantages nad 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 - 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 throuhg a reactive species at the surface

- Combination of physical and chemical reactions

Source (CF4) → Plasma → Reactant (F0) → Substrate (Si) → product (SiF4)
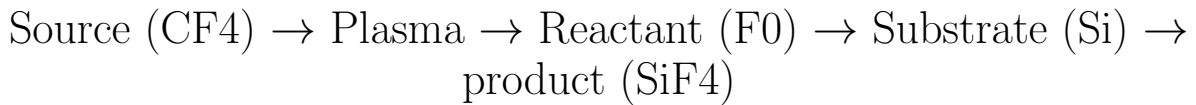
Dry etching, CVD, and evaporation all use vapor phase reactants. in CVD, the surface reaction gies rise to at least one solid product, but in etching one hopes that all the reaction products are vapors (having high vapor pressures). Dry Etching, sputtering, adn version of CVD (PECVD) use plasmas, though suttering uses a plasma for different purposes.

Source (SiH4) → Substrate (Si) → gas byproduct (2H2)
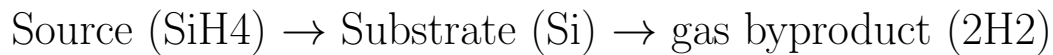
Dry etching is very similar to regular lithography because you put on the PR, and then dry etch, and the perform lift-off with the PR.

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 (UNRELATED) SPUTTERING IS LESS DIRECTIONAL

12.2 Etching (Repeat)

Subtractive Process. There are many types of etching

- Wet and Dry Etching

- focused ion beam (FIB) milling

  Used to make specimens for tunneling electron microscopy

- laser machining

  Use femto-second lasers such that no heat is transferred into the substrate, but the wanted material is blasted off. It is also used in opto-electronics to melt and change the refractive index of glass for things like waveguides.

- Ultrasonic drilling

  Used especially for hard brittle materials. Used a while ago before deep RIE became popular. You have an oscillating tool and a slurry with granular hard particles in it. The particles couple with the oscillator and wack the surface hard enough to remove the surface. Cavitation also happens during utrasonic drilling which aides in etching.

- Electrical discharge machining (EDM)

  Generate a spark to cause ablation. Not a very used process because it causes melting and oxidation.

- Tradition precision machining

Dry etching is when a surface is etched by the gas or vapor phase. Recall ashing (dry stripping of resist). In general ,dry etching has fewer disposal problems, less corrosion of metal features in the structure, less undercutting and broadening of photoresist features, and cleaner surfaces.

Types of dry etching include:

- Physically by ion bombardment

- Chemically by a reaction through a reactive species at teh surface

- Combination of physical and chemical reactions

In CVD, the surface reaction gives rise to at least one solid product, but in etching one hopes that all the reaction projects are vapors (have high vapor pressures) so that nothing can condense/precipitate on the wafer.

Dry Etching, sputtering, and versions of CVD (PECVD) use plasmas, though sputtering uses a plasma for different purposes.

Wet etching must be used to etch silver because many dry etching processes use

12.2.1   Damascene Process

Used for making interconnects on devices

- Deposit copper onto your substrate (photolithography)

- perform CMP (chemical mechanical polishing) to remove the top layers of excess copper and keep the copper inside your trenches

- Repeat until you have thick enough copper for your interconnects.

Interconnects used to be made with Aluminum because you could use dry etching without salts staying on your wafer.

12.2.2 Plasma

In sputtering, you essentially dry etch you target to then deposit the waste on your wafer.

In PECVD, you create a very reactive species with the energy from the plasma, and that reactive species attaches to the wafer. The plasma also moves unwanted species from the substrate.

Dry etching with plasma can make a very reactive species that removes material. The plasma is also just cause high energy particles to remove material (physical etching).

12.3 Dry Etching in Fabrication

1. Lithographic Patterning

2. Dry Etching

3. Stripping

4. Repeat until happy

The mask has to be made of anything that isnt etched by your etchant (usually PR).

Edge profile is important.

12.3.1 Anisotropic

Vertical etching with no horizontal etching (directional).

12.3.2   Isotropic

Veritcla etching wit hequal horizontal etching. This usually leads to etching under your PR.

Anisotropic etching is usually preferred. Many etching processes are very close to antisotropic (good enough). The way to do this is by tuning the amount of physical and chemical etching within a single process.

12.4   Etch Selectivity

$$\text{Etch Selectivity} = \frac{\text{Etch rate of material to be removed}}{\text{Etch rate of material to stay}}$$

If the Etch selectivity is 1, then the etch will evently remove your substrate and your thin film, so you can produce a trench the height of the thin film before the mask is entirely gone.

Etching selectivity defines the amount that you can etch given a certain layer of PR. If you etch selectivity is low, then you need a thicker mask.

We want etch selectivity to be high with respect to both the mask (PR) and substrate (so it acts as an etch stop).

There exist a number of papers that take notes of etch rates for micromachining processes.

12.5   Why Use Plasmas

Basically all dry etching uses a plasma.

Plasmas contain Ions, atoms, excited ,neutrals, and radicals. All species play a role in etching.

The soruce gas is the most abundant species followed by the etch reaction products, then neutrals, then ions.

$$e - + O_2 \Rightarrow 2O^0 + e'$$
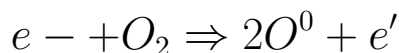
12.5.1   Radical

$\hat{}0$ denotes a free radical. It is a neutral or ion with unpaired electrons (very reactive).

12.5.2   Role of Ions

Ions are very useful

- Bombard the surface

- Clean (remove contaminating films)

- Activate the surface (reaction sites) by causing defects/broken bonds on the surface.

- Ion energy $\rightarrow$ directional etching

12.5.3   Etching Si with Cl

We ram the dichloride gas with an electron to form 2 radicals, and then those react with the silicon to form $SiCl_2$ to $SiCl_4$, which is a gas that is easily removed from the wafer.

There are many types of etching

12.6   Dry Etching

Gas phase etching - all reaction byproducts are volatile or gas phase

Use plasmas, offers lots of advantages over wet etching.

Typically, low pressures, 1mT to 10T, are used.

12.6.1   Plasma Advantages

- Tune etching from isotropic to directional to anisotropic

- Increase rates by radical generation

- Ion bombardment to surface cleans and activates it

- y providing high energy partcile interaction, they produce new reaction pathways, thus enabling "high temperature chemistry" at low temperatures

Typically, Cl_2, CF_4, O_2, H_2, and SiH_4 are flowed through the plasma to generate radicals Cl, F, O, H radicals to etch

12.6.2 Function

Negative cathode to positive anode negative glow plasma is next to negative cathode. A potential of from 1.5kV across 15 cm is used for plasma etching. The change in potential accelerates and ionizes the argon atoms.

(-) Cathode → Cathode dark space → glow plasma (+) → anode dark space → anode(+)

The potential is 0 in the glow plasma, so the atoms are not accelerated there.

12.7 Paschen Curve

Paschen's Law: The breakkdown voltage, V, is a function of the product of gas pressure, P, vs electrode gap distance d.

The right side of the graph has too many collisions, or the gap is to large to allow for sufficient acceleration for ionization.

$$V_{\text{breakdown}} = f(P \times d)$$

The graph starts by going sharply downward from $V = \infty$ and then curves back up to an oblique asymptote (diagonal).

If pressure is 0 or gap distance is 0, it makes sense for the breakdown voltage to be ∞ because there are no atoms to breakdown in between the cathode and anode if there's no pressure or no space for gases to exist.

If $P \to \infty$ or $d \to \infty$, it also makes sense for $V \to \infty$ because if $P \to \infty$, there's so many particles that absorb so much energy that you need a crazy potential to break down all of them. If $d \to \infty$, then the anode and cathode are so far away that nothing fun happens without a crazy potential because nothing accelerates quickly. The change in potential over distance is going to be close to nothing because there is so much distance to cover.

There exists some nice ratio of P and d that minimizes $V_{\text{breakdown}}$, which is the ratio that we experimentally want.

- On the left side, the gap is too small for the ionization avalanche to occur.

- On the right side, there's too many collisions, or the gap is too large for sufficient acceleration

- Argon is mainly used because it has a low minimum breakdown voltage.

12.8 Spacial Zones

and species in a glow discharge

1. Cathode

2. Aston dark space

3. Cathode glow

4. Crookes (Hittorf) dark space

5. Negative Glow (brightest region)

6. Faraday dark space

7. Positive column (provides most of the light from the plasma)

8. Anode glow

9. Anode dark space

10. Anode

At 20mT, the plasma contains $10^{15}cm^{-3}$ Neutrals, $0.01-0.5$ radicals to neutrals ratio. Ions to neutrals raio of $10^{-6} - 10^{-3}$.

Plasma density is just the number of ions plus the number of electrons.

Ion temperature is $\frac{1}{2}m_i v_i^2 = k_B T_i$ can be used to calculate velocity.

The brightness is important because it tells you about your ion density.

12.8.1 Sheath Voltage Drop

Tells you how much your ions will accelerate before hitting the substrate.

12.9   RF Plasmas

DC plasma will note work if we place an insulating substrate on one of the electrodes.

We go to a RF plasma with a frequency in $1 - 20MHz$ Range. f $= 13.56MHz$ is common because it is permitted by the FCC.

Often times the anode is a grounded electrode and the cathode is a power electrode.

Now there's
cathode, sheath, plasma , sheath, anode.
The plasma has an extra positive charge.

$$2V_p \sim \frac{V_{rf_{pp}}}{2} - |V_{dc}| \qquad V_{dc} = \frac{kT_e}{2e} \ln\left(\frac{T_e M_i}{T_i M_e}\right)$$

Where M_e is electron mass, ion mass, T_e is electron temperature, ion temperature. $T_e = 2 * 10^4$ $T_i = T_{gas} = 500K$, and $M_e/M_i = 10^?$

12.9.1   Power Electrode

The power electrode gets a DC bias and becomes negative.

The plasma itself has a potential, but the DC current has a much higher amplitude than the plasma potential, so it much be centered around $V < 0$ so that the peak of the DC is at the voltage of the plasma.

12.10   Configurations of RF Plasma Etching

12.10.1   Capacitively Coupled Plasma (CCP) (Parallel Plate Configuration)

You make a plasma because some stuff in between 2 charged things.

The sheaths behave like capacitors

The plasma behaves like a diode because none of the electrode can become positive with respect to the plasma. As soon as any electrode

tends to become positive W.R.T. the plasma, the current increases dramatically to raise the plasma potential

The dark spaces in the plasma are areas of limited conductiivty

$$C \sim A/d \qquad \frac{V_T}{V_p} = \frac{C_p}{C_T} = \left(\frac{A_p}{d_p}\right)\left(\frac{d_T}{A_T}\right)$$

From the Child-Langmuir Law, we get

$$\frac{V_T^{3/2}}{d_T^2} = \frac{V_p^{3/2}}{d_p^2} \Rightarrow \frac{V_T}{V_p} = \left(\frac{A_T}{A_p}\right)$$

A is electrode area and d is sheath length. V_T is cathode potential and V_p is plasma potential.

12.10.2   Capacitance

The capacitance is what connects the plasma charge to the sheath charge.

The capacitor works because the plasma itself is very conductive, but the sheaths are insulators, so current does not flow.

12.10.3   CCP RIE configuration

Use a smaller cathode which holds the substrate. This will mean that more energetic ions bombard the substrate.

The system operates at $\sim 20mT$, so there are very few collisions in the sheath.

RIE is more directional than plasma etching. Bombardment leads to more dislocations and dangling bonds resulting in a more reactive surface for initialting etching reactions.

Etch rates in the vertical direction are much much more than etch rates in the horizontal direction because bombardment is usually vertical.

Etch rates in RIE ar emuch higher than just ion etching.

12.10.4   CCP Cons

- Low plasma densities - Ions/Neutrals ratio ($10^{-6} \sim 10^{-3}$)

- RF power simultaneously influences plasma nad sheath powers.

12.10.5   Inductively Coupled Plasma (ICP)

Fixes the issues with CCP

- Inductive coupling produces a high density plasma with higher Ions/Neutrals ratio ($10^{-3} - 10^{-1}$).

  This is the case because of something with Lorentz forces and the magnetic fields also accelerating the ions in the plasma, leading to a higher plasma density.

- ICP plasmas have virtually no sheath voltages. A separate RF circuit is used to capacitively couple the plasma ot the electrode holding the substrate.

  With 1 circuit, you can tune the plasma density, and with the other, you tune the rate that ions bombard the surface.
  There is a picture in the slides.
  We use a mix of chemical and physical etching/sputtering to get high etching rates and directionality.
  We have 1 RF source driving an induction coil.

12.10.6   ICP Results

Very high etching rates (5-10 microns/min)
  And can etch with very high aspect ratio (9 times deeper than wide). Can go up to 100x. This can be compared to other feature size aspect ratios of 2-3 or even just isotropic 1.

12.10.7   Downstream/Remote Plasma

Plasma is generated with ICP, CCP, or microwave. Only reactive radicals make it to the substrate. Ions themselves are blocked (no ion bombardment).

The plasma is in a chamber separate from the substrate. Used for pure chemical etching because there is not acceleration. Used to cleaning, activation, or stripping PR.

12.10.8 Sidetrack About Plasmas

ALL PLASMAS ARE POSITIVE. It's called the negative glow because it's near the negative side of the capacitor.

12.11 Dry Etching Mechanisms

We talked about how plasmas can make radicals and also be used for just ion bombardment. We mix chemical and physical based etching processes to get useful tools.

12.11.1 Physical Sputtering

- Atomic sand blasting.

- Sheath voltage determined ion energy.

- Most tools use Argon ions.

- It tends to be anisotropic (directional).

- Low selectivity, redeposition issues, surface damage issues.

- Etch rates depend on ion current, energy, and substrate material (higher etch rates means you should use an inductively coupled pasma to tune parameters).

- Etch rates are low (10-50nm / min).

- Used when chemistry is not available to produce volatile products to etch.

$< 3eV$ leads to physical adsorption. 4-10eV is some surface sputtering. 10-5000 is sputtering. > 5000 leads to implantation instead of sputtering.

12.11.2 Sputter Etching or Ion Beam Milling

Similar to sputtering, but the plasma source is decoupled from the substrate. Pure ion bombardment with 0 chemistry.

Typical features include rounded corners. Sidewalls reflect ions to form trenches near edges. Side profiling in directional.

1. Low energy ions are extracted from liquid source

2. Made into a beam and accelerated through a column

3. Focused at a point on the substrate/specimen to cause local sputtering

4. Deflector plates/Scanner allows the beam to be directed to different points on the substrate/specimen

Lenses are usually electrostatic instead of electromagnetic. Ion beams are very very slow, slow applications are mainly research or metrology related.

12.11.3 Pure Chemical Dry Etching

Silicon can be etched by XeF_2

- No plasma is required

- XeF_2 is a white powder with a low vapor pressure

- Vapor reacts with Si

- Etch rate is dependent on feature size (100-200nm/minute), but can be as high as $10\mu m$/minute in a plasma

- High selectivity with silica and nitride masks

- Highly reactive with water (bad)

We can also use CF_4 to produce radicals for etching.

Etching rates will depend strongly on temperature. Higher temperature means higher etch rate, and increased loading (exposed area) will decrease etch rate.

Etching is isotropic. Being chemical, it is highly selective and faster than sputtering.

May use various reactor configurations: Downstream/Remote Plasma, Parallel Plate Plasmas, etc.

Etching may be inhibited by surface deposition and production of non-volatile products.

Depending on the voltage bias of the substrate, negative ions (F- in CF4) will be repelled by the substrate, and will not help in the etching process.

The neutral radicals diffuse towards the surface and are the **primary etch species**.

The plasma is important because it creates not only the reactive species, but also the species that aid with desorption.

12.12 Loading Effects

- A macroscopic loading effect occurs when the amount of etchant is being depleted by the amount of reactant.

- The etch rate is inversely proportional to the exposed silicon.

- The more chemical etching, the bigger the loading effect

- At lower pressures, the effect becomes smaller

- Uniformity is compromised by an etch rate dependent on loading

- Gas flow and residence time (the average length of time a molecule of gas spends in the chamber) are now much more important in the overall uniformity of the etching process.

12.13 Mixed Physical and Chemical Etching

A combination of bot ha physical and a chemical plasma etching process leads ot the combined benefits of both (i.e. Ar^+ kinetically exciting Cl gas). Sidewalls are etched back, bottom curved, some undercutting can occur, and etch profiles are more vertical.

Generally, this involves high energy ions that

1. Sputter (ion mill) the surface

2. Drive the etching reaction on the surface

3. drive desorption of products from the surface

4. Create reactive products

Less dependence on temperature, loading, and surface contamination. Good selectivity and anisotropic etching (This is not only because of the 2 reaction mechanisms, but become reaction products that are hard to etch end up on the side-wall, decreasing the etch rate in those directions).

12.14 Etching Rules

Bulk etching of Si is done by CF_4 which etches Si isotropically and produces high vapor pressure SiF_4. In RIE (mixed phys. + chem.) etching, chlorofluorocarbons and oxidizing additives are also added. In general, Cl and Br do not spontaneously react with Si (need ion bombardment) and CFC's produced polymerization. In this context it is good to hae some guidelines.

12.14.1 Fluorine to Carbon (F/C) Ratio

- When Fl and C are both present, etching and polymerization occur.

- Etching is caused by Fl

- Polymerization occurs due to hydrocarbon formation and deposition

- the lower the F/C ratio, the lower the etching

- Adding H forms HF and lowers the F/C ratio and etch rate and increases polymerization

- Adding oxygen forms CO products and increases the F/C ratio and etch rate.

- O also aggressively attacks the resist, redicing selectivity with respect to the PR.

12.14.2   Selectivity

- The desirable etch process with etch the sample and not the mask

- The polymerization point is when the polymer removal rate equals the polymerization rate

- A better selectivity is achieved closer to the polymerization point

- Factors that increase the polymerization rate (and selectivity) include:

  - lower temperature
  - high H concentration
  - low plasma power
  - high chamber pressure
  - high monomer concentration

- Unselective etches for Si include CF_4 and SF_6

- Selective etches for Si include Cl_2, CCl_2, Cl_2-C_2F_6

by-products from chemical etching can decrease the selectivity of the etch because the by-products can attack your photoresist.

12.14.3   Substrate Bias

Increased substrate bias means increased sheet voltage drop which means more electric field change and acceleration and thus physical etching

- If all other factors are kept constant, a negative bias on the surface exposed to the plasma increases the etching behavior over polymerizaiton

- This is a physical process where the ions are bombarding the surface and sputtering the polymer

12.14.4   Metal Etching

- Chlorocarbons and fluorocarbons are typically used to etch metal films

- Native metal oxides are removed chemically, some metal halides are removed with physical sputtering.

- O and water vapor must be removed from the etching processing chamber so additional metal oxides are not formed

- Ion bombardment is essential due to the strong metal oxide bond

12.14.5   Etching Mixtures

Flourinated Carbons are very common because the products are very volatile

12.14.6   Ion-enhanced Inhibitor Etching

Simulaneously deposit a material onto the substrate while also etching it. Certain gases can be added to the system to promote deposition, which slows down or blocks etching.

Ion bombardment removes the deposited film from horizontal surfaces, but not vertical surfaces. This increases anisotropy which keep it selective.

Ion bombardment, when well tuned, can lead to high aspect rations of 9:1.

12.15   Dry Etching

Diagram in the slides.

Physical processes have low pressure and low selectivity, but high energy and anisotropy, while chemical processes have the opposite.

Ion enhanced chemical etching and inhibitor etching are mixed forms, which sputtering is purely physical and chemical etching is purely chemical.

Physical etching results in slightly rounded corners or mostly straight (ion enhanced), while chemical etching can be either completely round (isotropic) or completely straight (inhibition)

12.16 Si Etching

In the 90's there were many issues with dry etching

- etch rates were stupid slow (1 μm/min)

- 300 μm wafers took 5 hours to thru-etch, which resists won't survive

- Something about aspect ratios

- Something about something else

12.16.1 Fixes

High density plasma (ICP) with density $> 10^{11}/\text{cm}^3$ and low pressures of 1-100mT with good Ion uniformity.

This leads to higher, more consistent, higher aspect ratio etching rates.

12.17 Bosch Process (Deep RIE)

crazy high aspect ratios (100:1) and etch speeds (20 microns/min). Super flat wall angles. Very selective to both PR and oxide films (250:1).

Process switches between etching and deposition. Polymer is deposited on the walls and the bottom is etched. The gas is Octafluorocyclobutane (C_4F_8 lmao), and the ring breaks and they the broken polymers combine to form a long chain polymer that can't be etched away easily. The etch gas is SF_6 which decomposes and etches silicon.

It is important to put in these two gases separately because they react together to prevent long polymer formation.

12.17.1 Challenges

- Side wall profile control is difficult

- Silicon grass, scalloping, microloading, mask undercutting, and uniformity

- ARDE: Aspect Ratio Dependent Etch rate

Even with these challenges, selectivity, etch rate, aspect ratio, and uniformity are still better than other plasma methods on Si.

12.17.2 Sidewall Quality

Should be vertical. It can be controlled by power, pulse duration, gas flow, and pressure.

Some profiles can be corrected. The types of profiles are positive taper, retrograde taper, barrelling/undercutting, and facetic (bottom bulges) and trenching (bottom sinks down).

Scalloping happens due to the switching of gases, and it leads to little ribs in the trench.

Silicon Grass is towers caused by dust blocking a vertical etching process.

Some other one I wasn't paying attention.

Bad resist profiles (undercut, overcut) will also cause the etching to be poor because it will inhibit correct etching.

12.18 SOI Notching

Dry etching on SOI wafers can have challenges

- Ions can build up on the oxide layer

- Over-etching can cause ions to be deflected and etch into the sidewalls of the bottom of the feature

Using pulsed power can allow the charge to dissipate. End point detection methods can also be used to determine when you reach the oxide layer.

Chapter 13

Single Crystal Silicon

It's an element with a bandgap lmao. It's cheap as shit so we've gotten very good at purifying it for chips.

It's also very tunable so we can mess around with it. We can make it piezo-resistive, it has an indirect bandgap, it has high thermal conductivity and low thermal expansion.

13.1 Crystal

Repeating structures of atoms. The Unit cell is the smallest repeating structure in a lattice.

Simple Cubic is SC. Body Centered Cubic (BCC) has 1 atom in the center. Face-Centered Cubic has a center at each face.

The number of atoms in a unit cell is wacky. SC has 1, BCC has 2, and FCC at 4 based on some magic.

13.2 Miller Indices (h, k, l) - Planes

Planes and directions are described with numbers. You take the intercept, take the reciprocal of the intercept, and reduce it to the lowest set of integers for a ratio.

$1, \infty, \infty \Rightarrow \frac{1}{1}, \frac{1}{\infty}, \frac{1}{\infty} \Rightarrow 1, 0, 0$

$2, 1, 4 \Rightarrow \frac{1}{2}, \frac{1}{1}, \frac{1}{4} \Rightarrow 2, 4, 1$

Direction can also be described with Miller Indices. [100] is the type of plane that describes all possible flat straight planes perpendicular planes, no matter their orientations $(010, \bar{1}00, etc)$

13.3   Elemental Si

It's got 4 electrons. It's got a diamond cubic structure. The atom density is $4/\sqrt{2} \cdot a$ where a is the side length. During anisotropic etching, the 111 plane is etched less because it has the lowest danging bond density.

13.3.1   Electrical Properties

Both electrons and holes can be treated as charged particles that contribute to the overall conductivity of the of the material.

The reason that our chromium resistivity was so messed up because of boundary scattering.

13.3.2   Czochralski method for Si Wafer Making

You put a seed of actually crystal Si in a bunch of molten Si and then spin it until you get a flat wafer.

All the wafers we use in this class are [100] wafers. 111 wafers aren't particularly common because that plane does not etch well. You can use the flat sides of the wafer to figure out the orientation.

13.4   Doping

You put stuff in things to change the band gap.

N-type doping is arsenic, phosphorus, etc. electron donors.

P-type doping is Boron, gallium etc. electron acceptors.

Why does the float zone method produce high resistivity silicon? Because there are less impurities with this method (no crucible).

13.5   Wafer Spec

Some wafers are more flat than others (flatness, planarity). Wafers deflect/warp some amount over the entire surface.

There are all sorts of defects. Pits, scratches, etc.

- Prime wafers: highest possible

- epi wafers: thin Si layer

- Test wafer: cheap

- etc

You can polish the back of the wafer if you want.

Chapter 14

Anisotropic Etching

Dry etching is physical or chemical while wet etching is chemical. Dry etching is very expensive and very slow because it uses big fancy plasma machines. Wet etching is cheaper because it just uses acid. Wet etching is very good with selectivity because it uses chemistry magic vs just brute force wacking the material in dry etching.

14.1   Wet Etching

For wet etching, you can use a bunch of different chemicals (HF etches SiO2). Etch selectivity is high, but can be sensitive to impurities.

Etch rate is a function of concentration, mixing rate, etc. Arrhenius relationship.

$$\text{rate} \propto e^{-E_a/k_B T}$$

Etch selectivity should ideally be infinity (etch rate of substrate vs mask).

Etching occurs in equal rates in all directions which is bad because because your walls are not flat. However, it removes rust and damaged surfaces.

Amorphous nad Polycrystalline films can be etched anisotropically due to material "randomness".

single crystal materials have varying etch rates dependent on planes.

14.1.1   Etching Process

1. Etching species generation

2. Diffuse to surface

3. Adsorption

4. Reaction

5. Desorption

6. Diffusion away/ byproduct removal

Etching is diffusion limited in trenches because it is hard to get material to the bottom of a trench.

Reaction rate limited etching is dependent on temperature and that's basically it.

Diffusion limited etching can be increased with stirring.

14.2 Sidewall slope

You can actually get near straight walls if you allow alot of undercutting because its basically the surface of a sphere, and bigger spheres have flatter surfaces.

Reaction rate limited etching is useful because it means that parts of the wafer aren't going to be etched faster than others due to geometry.

14.3 Device "releasing"

You can add "etch holes" to increase etch speed of material underneath a feature.

This is important because something something cantilevers and van der waal forces.

14.4 Loading

If there are too many features in a local area, it will take a long time to etch relative to a different part of the wafer.

14.5 Challenges

- Findind a suitable mask for high precision

- Etch rate is agitation sensitive

- Etch rate is temperature sensitive

14.5.1 Agitation

With agitation, etching happens everywhere equally, so larger mask holes means faster etching rates. Without agitation, the depth etch rate is the same no matter the mask hole, so etched features are not spherical.

If the regime isn't reaction rate limited, agitation will not change etching. In this case, you change temperature.

14.6 Isotropic Etchants

Usually acids (HF, HNA, nitric acid, etc.). Produces rounded features, used at lower temperatures ($< 50C$). Tend to be diffusion limited and not rate limited. Selective etching can be used to vary etch rates. Often used for polishing.

Wet etching is almost never used to high aspect ratio etching.

14.6.1 WetER2 Table

It's just a table with a bunch of etchances and what they do.

14.7 HF

- Etches SiO2 and not Si. Also attacks aluminum and silicon nitride.

- Etch rate from 0.1-1 microns/min

- It's considered a weak acid but will like immediately kill you. Goes into your skin and eats your bones. Health Hazard 4.

- Completely isotropic etching

HF is usually used in a buffered solution of NH_4F so that it's less evil. HF can diffuse through polymers, so no mask will survive all that long or be all that effective.

You can use a nitride mask for a long HF etch.

14.8 Phosphoric Acid

etches nitride. 50nm/min etch (pretty slow). Need a tough Oxide mask because PR will not work at 50C. Etches completely isotropically.

14.9 HNA (HF:Nitric:Acetic)

Put everything together to make a new etchant. Nitric acid oxidizes Si. HF reacts with silica. Acetic acid prevents the dissociation of Nitric acid.

14.9.1 Doping

P type silicon will etch very fast because you need holes in the chemical reaction. N type inhibits etching because there are no holes.

You can change the ratio of each acid in the solution to change the etching properties of it. You get different types of etching and polishing and all sorts of stuff depending on the ratio. The ratio also determines how the etchant is reaction limited.

5:2:3 is the regular ratio.

14.10 Masks

SiO2 can be used for shallow etching. Nitride or Gold are good for long etches. PR and Al are bad. Doping affects etching pretty significantly.

14.10.1 Summary

- Iso etching is primarily done with acids.

- Acid mixtures are pretty important.

- The etching mechanism is mainly oxidation, which makes it independent of the crystal properties in the material.

- This kind of etching is used for shallow etches due to undercutting. Not used for deep structures

- very good for release etching.

Chapter 15

Anisotropic Etching (Bases)

Etch the silicon planes at different rates. It was developed in Bell Labs in the 60's. You can use anisotropic etching to produce certain shapes, and the patterns are bound by the slowest etching plane. You get more control than isotropic wet etching, and you get more reproducability and accuracy ($0.5\mu m$).

Base etching is slower than isotropic etching, usually $1\mu m$/min. You need higher temperatures to encourage etching, and anisotropic etching is less sensitive to agitation. Anisotropic etching is mainly used for single crystal materials (Si, Quartz, Germanium, etc.). The 111 plane in Si resists etching the most.

The orientation and type of wafer used if important to how it gets etched. Corners will etch in weird ways.

You want the number of danging bonds to be high to increase etch rates in certain planes.

Etch rate goes down with bond density and back-plane bond density. Etch rate goes up with dangling bond density. Etch rate is slower with increased atom density. Etch rate is faster with greater surface bond density. More surface oxidation means less etching.

15.1   Etchants

Alkaline aqueous based etchants include KOH, NaOH, LiOH, etc. There are also alkaline organic etchants like hydrazine. No external voltage is needed. Etching is dopant insensitive (doesn't matter). Alcohols slow down the etching process.

Etch rate is reaction rate controlled.

Pros are KOH etching are:

- fastest

- selective

- makes vertical sidewalls

Cons include

- not CMOS compatible (etches matal)

- ion contamination

EDP is a very common organic alkali etchant. CMOS compatible, lots of masks, and lowest Boron doping etch stop. However, it'l corosive and optically dense (hard to see). It also ages quickly, has a low aspect ratio, and precipitates.

TMAH is another etchant, it is CMOS compatible and smooth, but has a slow etch rate and bad selectivity.

15.2 Reactions

Electrons are injected into the conduction band to cause Si atoms to bond with other things. Basically silicon hydrolyses water, but OH isnt really consumed in the process.

15.3 Etch Rates

Arrhenius relationship with 1/T. Very temperature dependent.

15.4 Surface Roughness

Anisoptropic etching leaves behind a rough surface compared to acid etching. You can do a small amount of isotropic etching to just smooth the surface.

Macroscopic roughness (notching or pillowing) increase with depths.

Average roughness is dependent on agitation.

15.4.1 Terracing

Stair case of etching based on the crystal planes.

15.5 Masks

Difficult because anisotropic takes a long time, and it has to not eat through the entire mask

15.6 Doping

Doping affects the etch rate of silicon dramatically (boron). Ion implanted dopants can be used as etch stops. EDP is more sensitive than KOH against dopants.

KOH, EDP, and TMAH are the main anisotropic etchants, but choose which of the three requires many considerations.

15.6.1 Thermal Diffusion

Use heat

15.6.2 Ion Implantation

Use electron beams

15.6.3 Spin On Products

SOG (spin on glass) is a dielectric applied to a wafer in liquid form.

15.7 Alignment

A "Wagon-wheel" etch mask produces a flower pattern that visually depicts the etch ratio along different planes. Etching will occur under your mask :(. Concave and convex corners are etched very different my isotropic etching (concave corners become rounded).

15.8   Silicon Oxidation

There's like a million slides on this and I'm not paying attention. Wet oxidation is usually faster than dry oxidation.

MEMS usually uses wet oxide because everything we make is big and not very detailed, so we like being faster.

There's a deel drog equation or fuckin whatever.

Chapter 16

Bonding and Packaging

It's kind of an additive process. Put 2 MEMs devices or thin films together to get a bigger thing.

16.1 Need for Wafer Bonding

It is good for creating single crystal structures. Membranes and embedded channels/cavities. You can also make thick or multi-level systems.

These can be combined with anisotropic etching to make unique shapes.

16.2 Fusion Bonding Process

Take two pristine surfaces and stick them together. This adheres them with van der waals forces. Then you use high forces and temperatures to get chemical reformation and turn the 2 wafers into 1 wafer.

16.2.1 Poly-silicon Bonding

Use something for surface hydration or plasma. Needs very high temperatures (450 C)

16.2.2 Hydrogen Bond Bridging

When H is connected to a very electronegative atom, the H atom gets polarized, so it can attract to other things at high temperatures. This usually occurs at 200 C.

There's a thing called thermal gradient bonding(?). Si-Si bonding also requires a hydration process.

Make OH groups- put them together so you get attraction/bond bridging- increase temperature to encourage chemical bonding.

16.3 Voids

Voids are what happens when there is an imperfect bond. Voids have very high stress.

16.4 Application

You can make cool pumps and stuff

16.5 Anoding Bonding

High voltage generates high electrostatic forces at gaps, which squishes em together.

You must use a glass with a mobile cation, and then you use voltage to migrate that cation, which enables bond reformation.

16.5.1 CTE Mismatch

I have no idea what CTE is but bad things happen if you ignore it.

16.6 Eutectic Bonding

You need only 2 materials. Bring 2 metals to the transition between solid and liquid.

You find a specific perfect composition such that the melting point of each individual material are the same.

Gold is very common for eutectic bonding.

16.6.1 Melting Alloys

When you do that, the first melt that comes out is the eutectic concentration.

16.7 Polymer Bonding

adhesives and stuff. Simple and cheap, but not as permanent as the fancy wafer bonding methods.

16.8 Packaging

Put your tiny fragile device in a thing that will stop it from exploding. It also provides connections do you can actually use the MEMS device without being microscale yourself.

MEMS packaging is generally harder than semiconductor packaging because you need to maintain a vacuum and allow throughput of physical acceleration while still making sure the device cant break.

Packaging is generally done on the full wafer-scale instead of the chip-scale.

We know which chips are gonna be good depending on their location on the wafer.

16.8.1 Flip Chip Substrate

Flip the chip onto a laminate such that bumps make contact with the die pads and carry signal. This is the superior method and has much higher contact density.

16.8.2 Wire Bonded Substrate

You just have a very thin wire connecting the die to the outside.

Ball Bonding, Wedge bonding, ribbon bonding, etc. all used in wire bonding.

16.8.3   Leadframe

Metal structure that moves signals from the die to the outside.

16.9   Sensors

Biological and Chemical sensors are very hard because they need direct contact with the environment. Most packaging needs to be done in a vacuum.

Chapter 17

Recipes and Approaches to Fabricating Devices

1. Novel idea

2. Standardized CAD tools

3. Design layout with standard cells

4. fabricate with standard processes (foundry)

5. success

This is generally easy and cheap, but limited in terms of available tools and materials and whatnot.

17.1 MUMPS

Multi User MEMS Processes.

I think it's a bajillion people all making difference devices on the same wafer so it looks like one big mess.

You call someone and give them a cad file and they produce it on their own machines.

17.2 SOI MEMS

Silicon on insulator

You can buy an SOI wafer and specify the thickness of the handle layer, oxide layer, and device layer.

Does not scale well, but is good for industry research.

17.2.1   SUMMIT V

Sandia ultra-planar, multi-level MEMS Technology 5

5-layer polycilicon and IoO2 with planarization. Can be used to generate even more complex MEMS.

Chapter 18

FINAL

Exam is monday 7pm-10pm at this classroom. It should only be a 2 hour exam. 80% of the exam will be material NOT covered on the 1st exam. 20% will be review.

18.1 KNOW MUMPS ON THE FINAL

There might be a question discussing the MUMPS process.

$$SNR = 10 \log_{10} \left(\frac{P_{target}}{P_{noise}} \right)$$