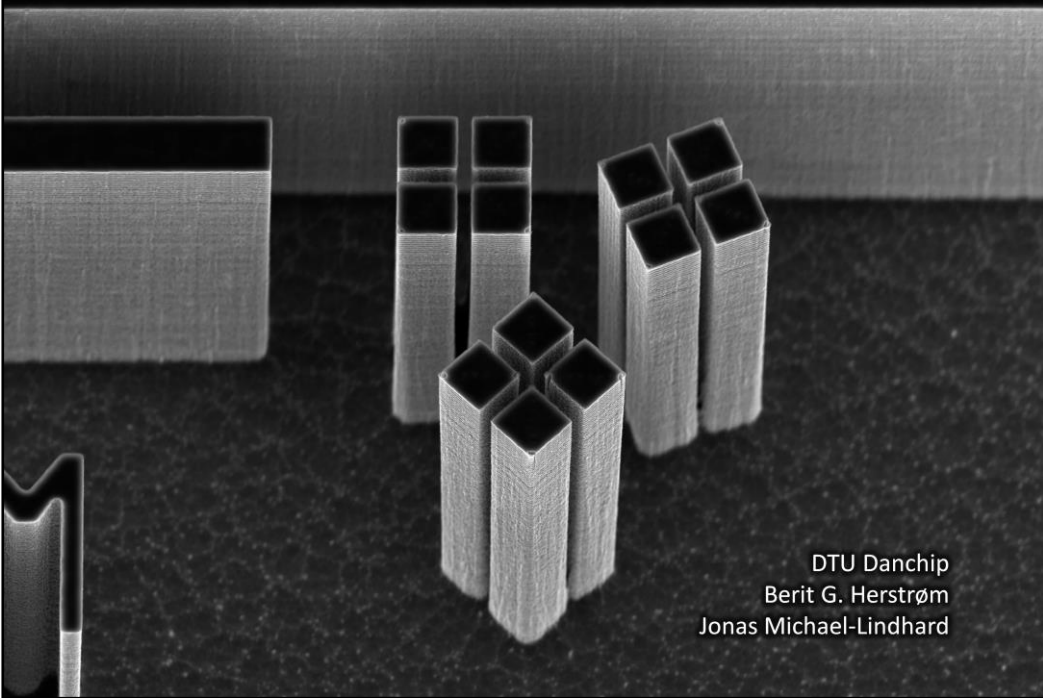


Dry Etch Tool Package Training Course



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 Si_3N_4 and metal etch*

Motivation: Why plasma etching?

The regular tools for structuring materials in the 'real' world do not work in the micro/nano world:

- Downscaling not possible
- Lack of precision/control
- Serial and not parallel



In the non nano/micro world we have a lot of ways to pattern a substrate:

- Tools that separate big things into smaller things:
 - Saws
 - Laser cutters
 - Pliers
 - Knives
- Tools that remove some selected parts of a material:
 - Drills (holes)
 - Chisels
 - Laser cutting
 - Chemicals (wet etching)
 - Mechanical cutting
 - Milling

These tools all fail when the dimensions of the structures become smaller and smaller. The reasons are:

- Lack of precision/control
- Downscaling not possible

Also, most processes are serial – it would be desirable to have a process that works on entire substrates at once rather than creating one feature at a time, i.e. a parallel process.

Motivation: Why plasma etching?

Important distinction:

Isotropy

versus

Anisotropy

or

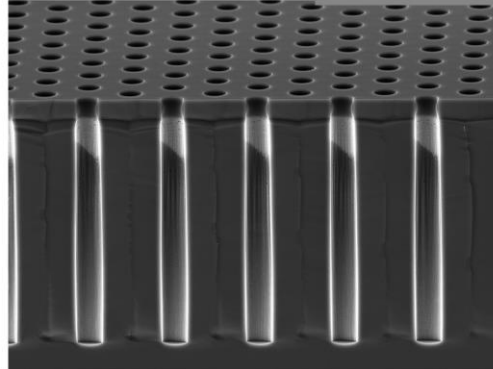
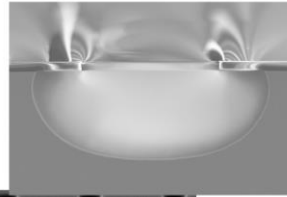
Etching in All directions

versus

Etching in One direction



ISOTROPIC:
A profile view of
a 25 μm wide
trench etched
isotropically into
silicon



ANISOTROPIC:
A profile view of
an array of 20
 μm diameter
holes etched into
silicon

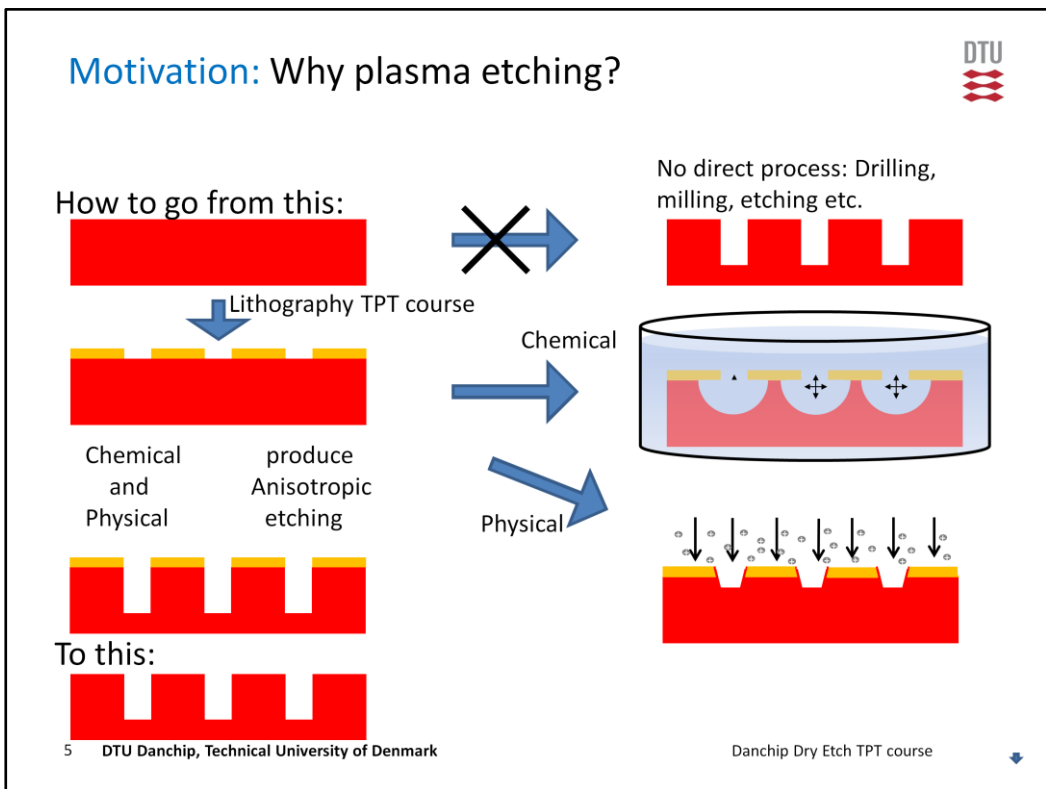


Before going further it is important to define some parameters: Isotropy and anisotropy.

When something is isotropic, it is uniform in all directions – there is no way one direction is different from the others or has any preference. In terms of etching, or removal/addition of material in general, this means that the etching will occur at equal rates in all directions.

If, on the other hand, one direction is preferred to the others, the etching is labelled *anisotropic*.

Some examples of isotropic and anisotropic profiles are shown.



To understand why we use plasmas for etching of micro and nanostructures, consider how we can come from a flat/blank substrate to one in which the structures that we have designed have been etched to some depth.

The direct path is not possible, there is no way creating this using:

- Drilling (not small or precise enough)
- Milling with a laser (problems with redeposition, not small enough)
- Chemical etching (no way of selecting where to etch and where not to etch)

We need a mask to protect areas that are not to be etched -> This is the subject for the Lithography TPT.

With a mask on the surface of our substrate we have defined:

- Open structures that are subject to some process in which the material is gradually removed, and
- Areas protected by the mask that are to remain protected throughout the process of removing material from the open areas.

Chemical etching: The chemical (both wet and gas phase) etching is typically isotropic with equal rates of the downward and lateral etching. With crystal orientation dependant etching, such as KOH etch of silicon, there are severe restrictions of alignment and on what type of features can be realized (only along crystal planes).

Physical etching: Suffers from redeposition and low selectivity (hence low achievable etch depths).

Combining the chemical and physical etchings will prove to be a good solution.

Motivation: Why plasma etching?



What do we need?

- **Chemical component:** A gas that reacts chemically with the substrate to form volatile reaction products.
- **Physical component:** A bombardment with particles/molecules/gas.

➔ **The answer is a low pressure plasma**

Benefits:

- It increases reactivity of reactants
- It is highly controllable/tunable
- The processing is done in parallel
- The etch products are pumped away

Disadvantages:

- Complex
- Expensive
- Requires toxic/hazardous gasses



Combining

- Chemical etching
- Physical etching

is best done in a low pressure plasma.

The advantages of this are:

- **Reactivity:** A plasma will dissociate the gas molecules into smaller and more reactive constituents and hence increase the achievable etch rates compared to etching with neutral gas molecules
- **Tunability:** Using electrodes or coils (more about this later) we can accelerate ions/electrons very precisely and with great control.
- **Parallel process:** The entire substrate is etched simultaneously
- **Well collimated beam:** The low pressure ensures that ions and radicals created in the plasma have a sufficiently long mean free path so that they arrive at the substrate without losing momentum in collisions with gas molecules.

The disadvantages are:

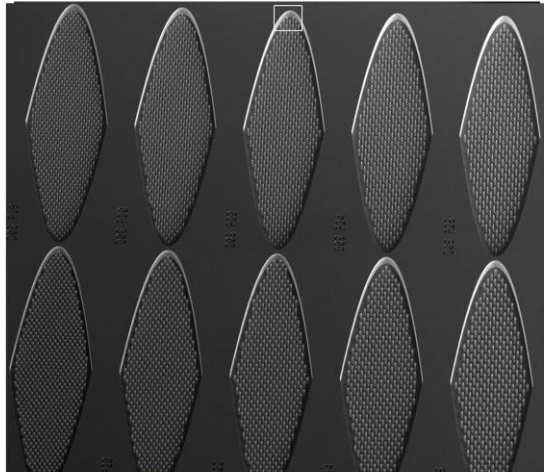
- The processes are quite complex and involves a lot of hardware as will be seen on the next slide.

Motivation: Why plasma etching?

Test structures for X-ray lenses: Silicon wafer with parabolically shaped cavities filled with pillars.

What characteristics are interesting?

- Etched depth
 - Substrate vs mask/stop layers
 - Speed
 - Features
- Sidewalls
 - Angle
 - Profile
- Surface roughness
 - Sidewalls
 - Top/Bottom
- Uniformity
 - Across wafer
 - Wafer to wafer
 - Process robustness



→ One recipe does not meet all requirements.
The Dry Etch TPT course will provide some tools.



So if we put our substrate into a plasma with some gaseous etchant it will come out ok, right? Well, not quite of course - as there are many things to consider.

Etched depth:

The process will etch into the substrate at some rate as well as into the mask. The ratio between the two rates, the selectivity, determines how deep one may etch before running out of mask material. The desired etch depths range from a few tens of nanometers to through wafer (a 150 mm wafer is typically 625 μm) making the etch rate an important parameter.

Sidewalls and surface roughness:

Depending on the application, the demands on the sidewalls produced by the etch process may vary a lot: From etching of alignment marks to 90.00 degrees sidewalls with zero roughness – and perfectly straight profile.

Uniformity:

Users typically assume that the uniformity across the wafer is flawless; all structures are etched identically regardless of their location on the substrate, center or wafer periphery does not matter. Also, all etch processes obviously produce the same results irregardless of chamber conditioning, location in a batch or design changes. Well, not quite!

Result:

It is clear you will need to know more about this – this is why we have made the Dry Etch Tool Package Training course

- After this TPT you should be able to:
 - Know why and when to use dry etching
 - Use the dry etchers without harming the machines
 - Select the right instrument to use for your dry etch processing
 - Select an appropriate etch recipe for your dry etch processing
 - Spot when the recipe needs to be tuned for your needs and
 - Suggest relevant tuning parameters



Learning Objectives



Above you see the learning objectives for this course.

Motivation: Contents of the Dry Etch Tool Package Training course



Today:

1. Motivation: Why bother about dry etching?
2. Etch Plasmas
3. Etch Mechanisms
4. Etch characteristics
5. Process Tuning
6. Equipment for dry etching at Danchip

Later:

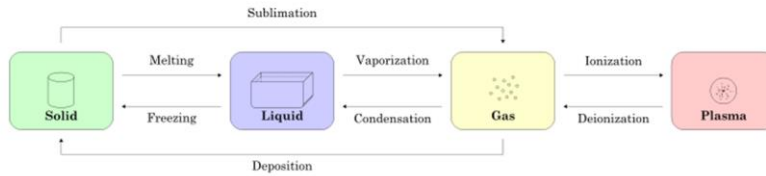
7. Hands-on training at Dry etch equipment.
 - This requires that you have watched some screen cast videos



1. In the introduction we tried to give some of the good reasons why it is a good idea to learn a little bit about dry etching and plasmas.
2. First we will introduce you to the basics of the plasma processes that take place inside a dry etcher.
3. Understanding what mechanisms that occur is also important. The physics of molecules and ions travelling to a surface, adsorbing, reacting and desorbing will be described.
4. "Etch characteristics" will introduce some of the requirements you will have for the performance of the etch .
5. Process Tuning or Optimizing the etch process is not always straight forward. In this section, we will go through some practical tuning issue with the hardware and also go though the process parameters to give you an understanding of how they affect the etch results.
6. At last a overview of our dry etch equipment is given to let you know what the instruments are best suited for.

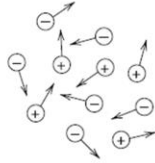
Etch Plasmas: What is a plasma?

The fourth state of matter:



By ElfQrin - Own work, GFDL, <https://commons.wikimedia.org/w/index.php?curid=15779425>

Plasma:
Freely moving charged particles
(positive ions and electrons)



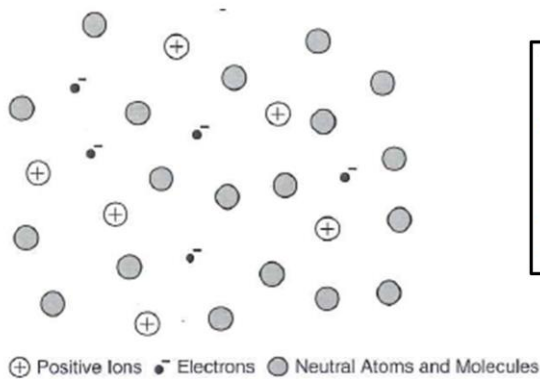
NASA/GSFC/SDO



Plasma is called the 4th state of matter.

If we have a solid and we heat it up – we get a liquid. If you heat up further we get a gas. If we keep heating up to somewhere between 4.000K and 20.000K depending on the gas, we get a fully ionized plasma. The plasma state consists of freely moving charged particles (positive ions and electrons). The sun is an example of a plasma. A fully ionized plasma is a very hot and that will not be suitable for processing. So this is not exactly what we are using in plasma etching.

A glow discharge plasma: A weakly ionized plasma



The ionization degrees for plasma etching is typically:
 10^{-6} to 10^{-4}

$\sim 10^{15} \text{ cm}^{-3}$ neutral species
 $\sim 10^{13} - 10^{14} \text{ cm}^{-3}$ free radicals
 $\sim 10^9 - 10^{11} \text{ cm}^{-3}$ ions/electrons

From Kazuo Nojiri, "Dry Etching Technology for Semiconductors", 2014

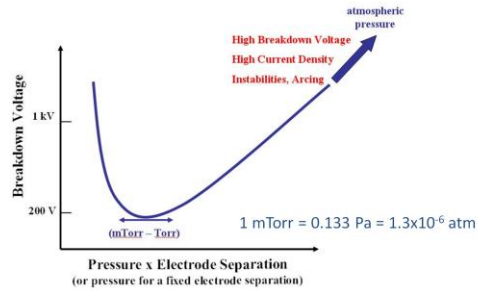
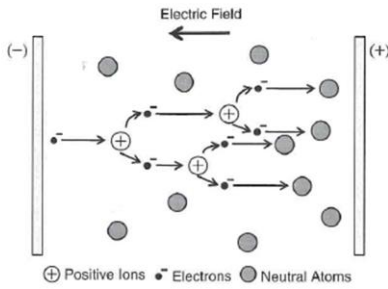


The plasma we use for etching is not generated by heat but is electrically driven. And is it only a weakly ionized plasmas with a ionization degree of between only 10^{-6} and 10^{-4} . So no more than 1 out of 10000 atoms has been ionized. At this state there is not thermal equilibrium. The average Plasma temperature is only about room temperature where as the electron temperature is about 10.000K and the ion temperature is about 300-1000K. Since the plasma temperature is so low this plasma can be used for etching. Another reason for using weakly ionized plasmas is that neutral atoms and molecules are formed in the plasma that are very reactive with the substrate.

Etch Plasmas: Generation of a weakly ionized plasma



The plasma is electrically driven



From Kazuo Nojiri, "Dry Etching Technology for Semiconductors", 2014

<http://www.wikiwand.com/en/Microplasma>

Collisions in the gas:

Ionization:



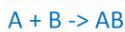
Excitation:



Dissociation:



Recombination:

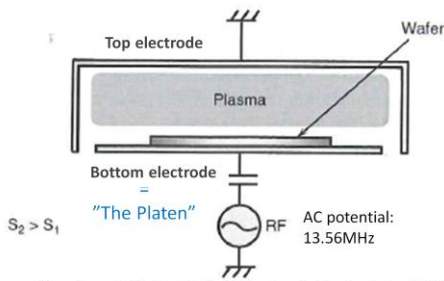


So how is the plasma generated? If we have a gas in an electric field an electron will be accelerated towards the +electrode. On its way to the electrode it will collide with the atoms/molecules in the gas. An ionization can take place and this will create an extra free electron that participate in the creation of other ions in the gas. In this way a plasma is generated that consists of ions, neutrals and electrons.

If we take a closer look at the collisions that takes place in the plasma we have:

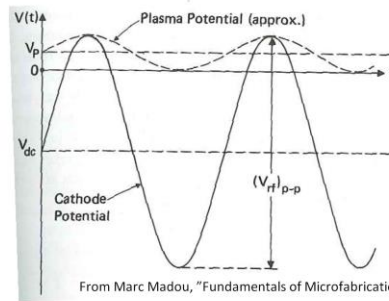
1. The Ionization – where an atom or molecule will loss and electron and become a positive ion - and the extra electron will participate in collision processes.
2. The Excitation – where an electron will be excited to and outer electron shell in the atom and after a while it will relax again by sending out light – this is what makes the plasma glow.
3. But we also have an dissociation when the electron energy is higher than the bond dissociation energy of the molecule. These free atoms are called radicals and they are very reactive. An example of this that is very used in plasma etching is the dissociation of CF_4
4. Also some recombination will take place.

Etch Plasmas: The Reactive Ion Etcher (RIE)

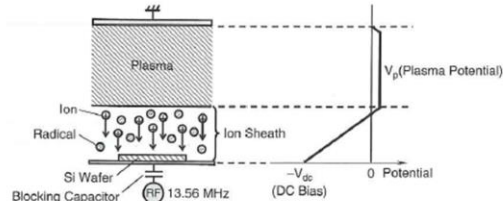


From Kazuo Najiri, "Dry Etching Technology for Semiconductors", 2014

- Electron build up on the platen=> negative potential.
- Ions are accelerated towards the electrode/platen.
- Neutrals diffuse around in the chamber.



From Marc Madou, "Fundamentals of Microfabrication, 1997



From Kazuo Najiri, "Dry Etching Technology for Semiconductors", 2014

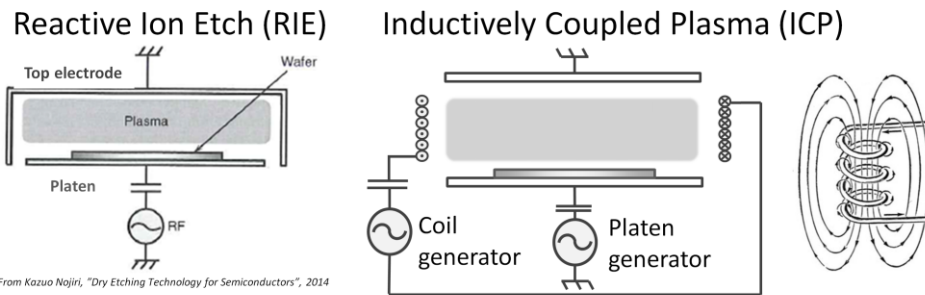
Let's take a look at the principle of one of our plasma etchers. The RIE is a parallel plate capacitive coupled plasma system. The top electrode is grounded and the bottom electrode is connected to an RF generator through a matching network that works as a blocking capacitor. With an RF alternating potential the polarity is changed on the bottom electrode. In principle the electrons will be attracted to the bottom electrode when the polarization is positive and the ions will be attracted when the electrode is of negative polarization. But when the frequency of the alternating potential is very high (radiofrequency level) the ions are too heavy to travel across the plasma in that time frame only the electrons will reach the electrode.

On the curve to the right you see the potential on the bottom electrode when it has reached the equilibrium.

At equilibrium: most of the time the bottom electrode will be negatively charged and the electrons will be pushed away from the bottom electrode and therefore almost no electrons exist in the nearest region of the electrode. This part is called the ion sheath. No collisions with electron will happen here including the excitations and therefore no light is coming out from this part. It is therefore also called the dark space. Only when the cathode potential is above zero electron will flow to the bottom electrode. Because of the average negative potential of the bottom electrode the ions in the Ion sheath are accelerated toward the bottom electrode and will bombard a sample laying on that electrode. The larger a V_{dc} the stronger the bombardment will be. This ion bombardment is involved in the etching process.

The last image down to the right is showing:

- The plasma is at a slightly positive potential
- The ion sheath: consisting of neutrals and of ions being accelerated by the average negative potential on the bottom electrode.



From Kazuo Najiri, "Dry Etching Technology for Semiconductors", 2014

Chamber	RIE	ICP
Type	Plasma between electrodes	Induced by B-field from coil
Coupling	Capacitive	Inductive
Generator(s)	One	Two decoupled (coil and platen)
Plasma density	10^{10} cm^{-3}	10^{11} cm^{-3}
Cooling/clamping	Water/No clamping	Oil and He/Electrostatic clamping

The RIE chamber:

In the RIE chamber the electrodes sit inside the chamber. The electric field that generates the plasma originates and terminates here. This means that increasing the RF power will increase the bombardment of the electrodes with electrons and charged particles. In fact, a large part of the supplied power is dissipated in the electrodes. This way of generating a plasma is referred to as capacitive coupling.

The more power is supplied and the more reactive gasses are used – the faster the electrodes will corrode. This effectively puts a limit to what power may be applied – and hence what plasma densities may be achieved in an RIE system.

The ICP chamber:

In the ICP chamber, a coil is wound around the upper part of the chamber which is made of a non-metallic material (here ceramic) so that the magnetic field easily penetrates into the chamber. If an RF generator is connected to the coil, it generates a cylindrically symmetric magnetic field that changes polarity with the RF generator. If a gas is introduced into the chamber, electrons will be ripped off* the atoms and start to oscillate back and forth while the atoms remain relatively immobile (they are much heavier than the electrons). The process is similar to one in the RIE chamber, but here there are no electrodes inside the chamber. This enables us to obtain high density plasmas without problems of corrosion and power lost through dissipation.

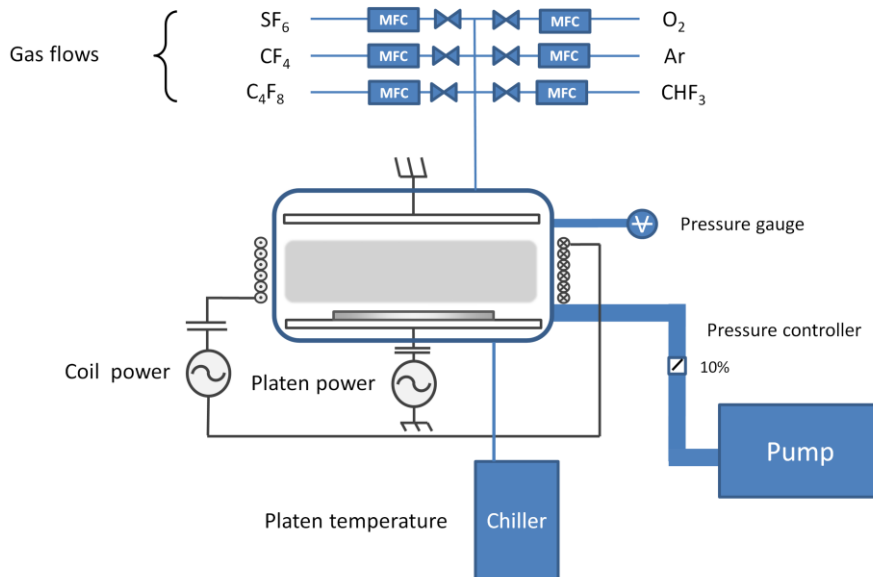
The plasma created by the coil does not have any preferred direction (the RIE plasma did have one because of the grounded upper electrode). An RF generator is therefore connected to the platen electrode so that ions from the plasma may be driven towards it in order to assist in the etching process.

The magnetic field induces an electrical current in the plasma that flows so as to oppose the RF magnetic field (in the same way as in any transformer etc.). This is why this plasma is referred to as an Inductively coupled plasma.

*When a time-varying electric current is passed through the coil, it creates a time-varying

magnetic field around it, which in turn induces [azimuthal](#) electric field in the [rarefied](#) gas, leading to the formation of electron trajectories providing a plasma generation (see [Hamilton-Jacobi equation](#) in electromagnetic fields). (Found on wikipedia: https://en.wikipedia.org/wiki/Inductively_coupled_plasma)

Process parameters: system overview



This is an overview of an ICP system.

Here you can see that the process gasses are lead into the chamber through Mass Flow Controllers (MFC) to control the flow rate.

The pressure in the chamber is measured with the pressure gauge and controlled by the pressure controller. The pressure controller is a valve in the pumping line that can be more or less open.

The platen is cooled by the chiller.

Coil power and platen power are connected to the coils around the chamber and to the platen electrode.

Contents of the Dry Etch Tool Package Training Lecture



1. Motivation: Why bother about dry etching?
2. Etch Plasmas
3. Etch Mechanisms
4. Etch characteristics
5. Process Tuning
6. Equipment for dry etching at Danchip



We will now continue with the etch mechanisms.

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 - The chemical etch mechanisms
 - The process gas
 - Fundamental etch reactions
 - The role of the ions
 - Passivation mechanisms
 - The Bosch process
4. Etch characteristics
5. Process Tuning
6. Equipment for dry etching at Danchip



In this part I will go through:

- The chemical etch mechanisms and what is required from the process etch gas.
- The fundamental etch reactions and the role of the ions
- Passivation mechanisms will be introduced.
- And you will learn about the Bosch process.

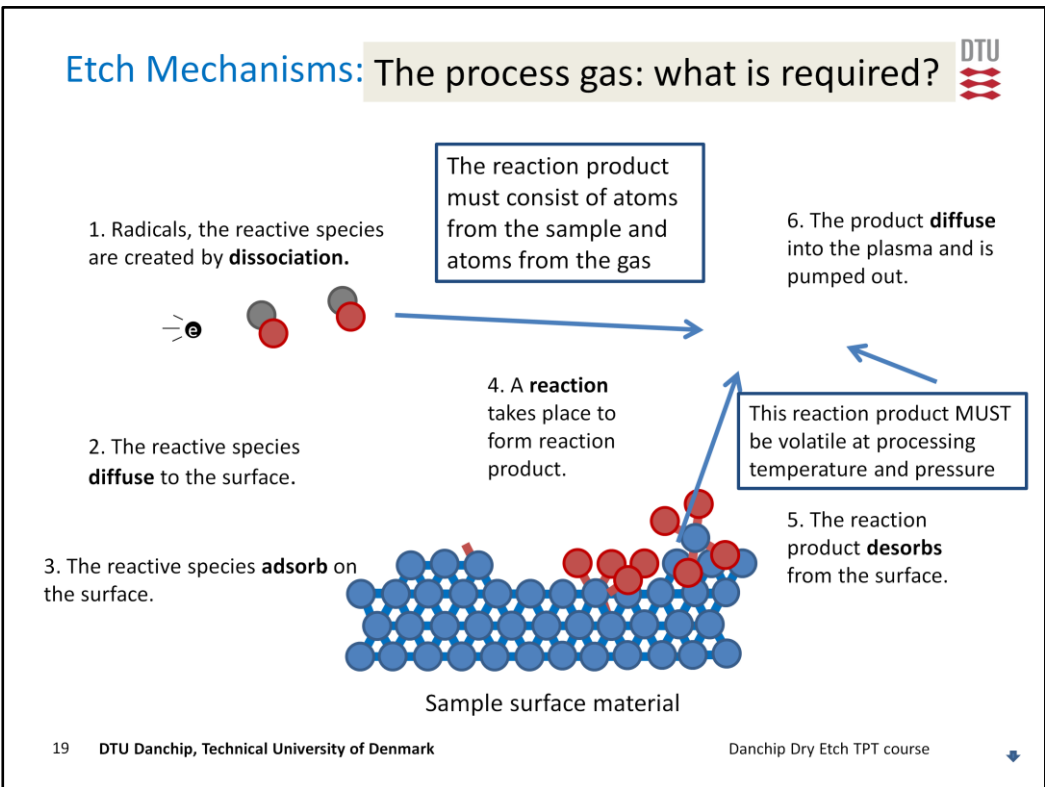
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We will now move on to understand the chemical etch mechanisms and how to choose the process gas.



Here we see the sample surface material which is illustrated with the blue atoms. The red dots are the radicals. The radicals are formed when the process gas is dissociated in the plasma.

The etching mechanisms are actually a very complicated matter and all details are still not fully understood, so we will present a simplified version that helps understanding what is going on and helps in choosing the right gasses and process parameters.

1. The radicals or the reactive species are created in the plasma by dissociation.
2. These radicals are not electrically charged and will therefore move around by diffusion.
3. Some will get close enough to the sample surface to be adsorbed on the surface.
4. A reaction may take place between the sample and the radical to form a reaction product.
5. The reaction product may desorb from the surface.
6. And the product may diffuse into the plasma to be pumped out.

This is the chemical assist mechanism that will take place under the right circumstances.

So what is required from the process gas for this to happen?

- The reaction product **MUST** be volatile at processing temperature and pressure
- The reaction product must consist of atoms from both the process gas and the substrate material.

Let us now take a look at some etch product and their volatility.

Etch Mechanisms: Etch product volatility – examples



Compound	Boiling Point [°C] @ 1 atm.	Temperature required to get a vapor pressure of 1 Torr [°C]	Compound	Boiling Point [°C] @ 1 atm.	Temperature required to get a vapor pressure of 1 Torr [°C]
SiF ₄	-86	-144	GaCl ₃	200	48
SiCl ₄	58	-63	GaF ₃	1000	-
SiBr ₄	154	-	AsF ₅	-53	-118
CO ₂	-78	-134	AsCl ₃	130	-11
AlCl ₃	181 ^α	100	CrF ₂	>1300	-
AlF ₃	1291 ^α	1238	CrCl ₃	1300 ^α	-
MoF ₆	35	-66	CrO ₂ Cl ₂	117	-18
TiCl ₄	136	-14	AgF	1160	-
WF ₆	17	-71	AgCl	1550	-
InCl	608	175 ^β	NiF ₂	1000 ^α	-
In(CH ₃) ₃	134	19	NiCl ₂	987	671

^α Sublimation. ^β at 5 mtorr.

20 DTU Danchip, Technical University of Denmark

Danchip Dry Etch TPT course

Here you see a list of boiling points at atmosphere for some relevant compounds containing silicon and other materials to be etched.

Notice that Si makes volatile compounds with both F, Cl and Br.

Aluminum forms a volatile compound with Cl but not with F.

If we take a look at InCl we see that at 175 degrees Celsius it has a vapor pressure of 5 mTorr. That means if the process is running at a pressure of 5mTorr the chamber has to be near 175 degrees for the InCl to be volatile.

A good guide line for the boiling point at atmosphere given in the table is that the boiling point should be below 600 degrees Celsius to be volatile. If it gets close to 600 degrees the chamber temperature has to be set to an elevated temperature. But as you can see in the table most of the compounds below 600 degrees are well below 600 degrees, so they will be volatile at room temperature.

Reference to more table values:

Melting and boiling points:

http://www.kayelaby.npl.co.uk/chemistry/3_2/3_2.html

Vapor pressure data:

Inorganic Compounds

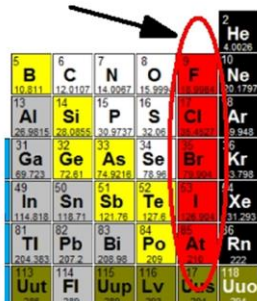
Daniel R. Stull

Ind. Eng. Chem., **1947**, *39* (4), pp 540–550

The Halogens are used for etching

- Very reactive radicals.
- Form volatile products with semiconductors and some metals

13 14 15 16 17 18



5	6	7	8	9	10				
B	C	N	O	F	Ne				
10.811	12.0107	14.0067	15.999	18.998	20.1797				
13	14	15	16	17	18				
Al	Si	P	S	Cl	Ar				
26.9815	28.0855	30.9737	32.06	35.453	39.948				
31	32	33	34	35	36				
Ga	Ge	As	Se	Br	Kr				
69.723	72.61	74.9216	78.96	79.904	83.798				
49	50	51	52	53	54				
In	Sn	Sb	Te	I	Xe				
114.818	118.71	121.76	127.6	126.905	131.29				
61	62	63	64	65	66				
Tl	Pb	Bi	Po	At	Rn				
204.383	207.2	208.98	209	210	222				
113	114	115	116	117	118				
Uut	Ff	Uup	Lv	Lus	Uuo				
288	289	289	291	294	294				

Gases forming reactive species:

SF₆ C₄F₈ CF₄ CHF₃ C₂F₆ C₃F₈ C₅F₈
C₄F₆ CH₃F CH₂F₂ NF₃

Cl₂ BCl₃ HBr CFCI₃ CF₂Cl₂ CCl₄

O₂

Assist gasses:

H₂ O₂ Ar CH₄ He N₂ CO₂



What gasses/radicals/neutrals are typically used:

Halogens from the 17th group of the periodic table of elements are normally used for etching. These form very reactive radicals and they form many volatile products with semiconductors and some metals. These are delivered to the plasma in the form of halogen containing gasses. The list of halogen containing gasses we have here at Danchip is showed to the right together with a few other relevant assist gasses.

Etch Mechanisms: Example/Quiz: Select gas(es) for Cr etching – Solution:



Gases:

SF₆
C₄F₈
CF₄
CHF₃
CH₄
Cl₂
BCl₃
HBr
H₂
O₂
Ar

Compound	Boiling Point [°C]	Temperature required to get a vapor pressure of 1 Torr [°C]
GaCl ₃	200	48
GaF ₃	1000	-
AsF ₅	-53	-118
AsCl ₃	130	-11
CrF ₂	>1300	-
CrCl ₃	1300 ^α	-
CrO ₂ Cl ₂	117	-18
AgF	1160	-
AgCl	1550	-

Gases needed: Cl₂ and O₂



Example of question: What gas or gasses would be good for chromium etching? Give them time to suggest and explain.

Solution:

First take a look at what compounds with Cr that will be volatile.

CrF₂ will not – CrCl₃ will not but CrO₂Cl₂ will be volatile.

Then what gasses do we need?

O₂ and Cl₂.

Question: What happens if you try to etch it with fluorine gas? – Answer: You will create CrF₂ on the surface.

Question: But what if you have a high ion bombardment – can't you etch it then? – Answer: You will sputter of the CrF₂ and that will end up on your sample and in the chamber. Is that good? – No

Why? – The next users will potentially have their sample contaminated with CrF₂

Could that harm their sample? – maybe!!!

So be aware of what you are doing. Although it is allowed to etch Cr in one of our chambers it not allowed to try and etch it with F-gasses.

Contents of the Dry Etch Tool Package Training Lecture

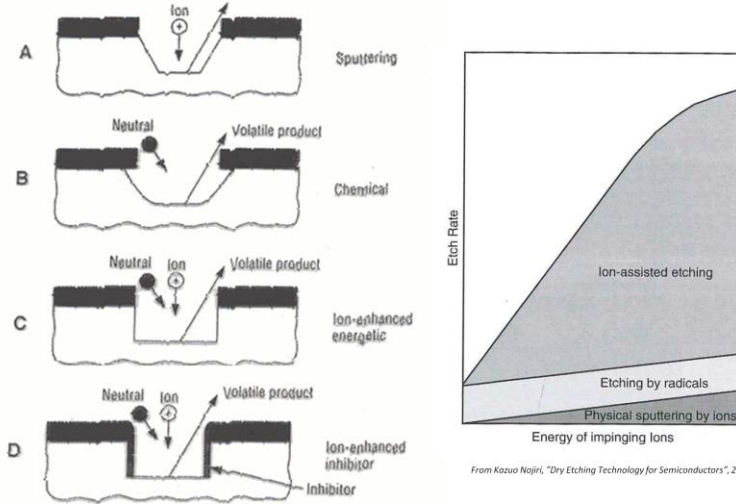


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 - Passivation mechanisms
 - The Bosch process
4. Etch characteristics
5. Process Tuning
6. Equipment for dry etching at Danchip



We will now take a look at the fundamental etch reactions and the role of the ions.

Etch Mechanisms: Fundamental etch reactions



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Now we take a look at the fundamental etch mechanisms taking place as they can be presented in a simplified way.

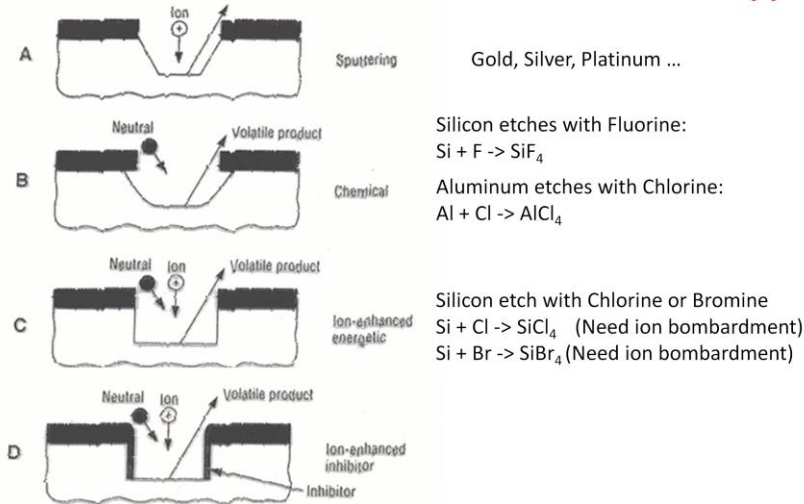
There are several etch mechanisms going on at the same time.

- In image A is shown a pure physical etch. Here the ions bombard the surface and sputter off material. Some material will re-deposit on the sidewalls giving a slightly angled sidewall (typically 70-85 degrees).
- In image B a pure isotropic chemical etch is shown. Reactive neutrals (radicals) that are created in the plasma reacts with the sample and creates a volatile reaction product that is pumped out of the chamber.
- Image C is showing an anisotropic etch that only takes place with a reaction between the neutrals and the substrate when assisted by impinging ions.
- The last image D shows an etch using a passivation gas together with the etch gas. The passivation gas deposited a thin layer all over the substrate. Then the role of the ions are to sputter away the layer in the horizontal plane leaving the passivation layer on the sidewalls. The neutrals then get access to etch the substrate only in the horizontal plane thereby giving an anisotropic etch profile.

The image to the right illustrates the etch rate as a function of the ion energy.

- The physical etching is zero when the ion energy is zero and then it increases with the energy of the ions. Even at high energies the etch rate from the physical sputter is low.
- The pure chemical etch is completely independent of the energy of the ions, so this give a constant and in many cases also small contribution to the etch rate, but it depends on the material to be etched and the etching gas chemistry. Etching Si with F-gasses can have a high contribution from the chemical etching mechanisms and so can the Al etched by Cl_2 .
- (and D) The ion-assisted etching is more complex and not fully understood yet. This is however the most important one in most plasma etching as it contributes significantly to the etch rate and also enables anisotropic etching. If the process is limited by the ion flux that etch rate will also be more uniform over the wafer and for different etch loads and dimensions on the wafers as the ion flux is very uniform over the wafer.

Etch Mechanisms: Examples



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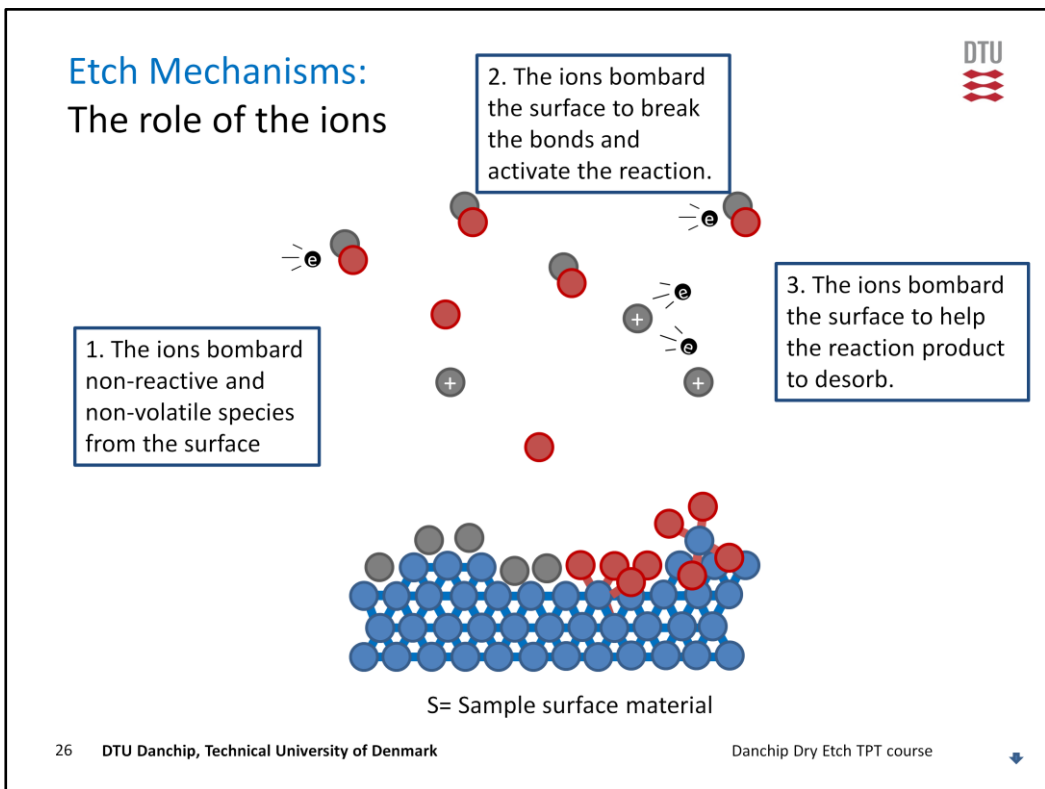
Let us look at some examples of when the different mechanisms are important:

Sputtering: Metals like Gold, Silver and Platinum cannot for volatile etch products with any materials therefor the sputter mechanism is the only one for this metals (and a lot of other materials). Do to cross contamination these materials are not allowed in any of our plasma etchers. Only our Ion Beam Etcher must be used for these.

Chemical plasma etching: Silicon etching in a fluorine containing plasma is a isotropic etch – not ions are need to get the etching going.
The same goes for Aluminum etching in a chlorine containing plasma.

Ion assist energetic etching: This means that the chemical etching will only occur when it is assist with en ion bombardment. This is the case for silicon etching in a chlorine plasma or in a bromine plasma.

We will come back to the passivation mechanism (Ion enhanced inhibitor mechanism).



Here we see the sample surface material which is illustrated with the blue atoms. The red dots are the reactive species. The gray dots are species that do not react or do not form volatile reaction products with the sample.

The roles of the ions are:

1. The ions bombard the surface to remove the non reactive species – this leaves room for the reactive species to diffuse onto the surface.
2. When the ions bombard the surface they help activating the reactions. Some reaction do not need it but others do.
3. The ion bombardment also has the role of helping the reaction products to desorb from the surface.

So when do we need high ion energy:

- When we have a lot of passivation on the surface (we will come back to that when we discuss the passivation mechanism).
- When the reaction to form the etch product needs activation energy (like silicon in the Chlorine plasma)
- When there are strong bonds in the substrate that needs to be broken.

Then we also need to look at the binding energies. These can be looked up in a table of binding energies or bond dissociation energies. There is a link to one here:

<https://labs.chem.ucsb.edu/zakarian/armen/11---bonddissociationenergy.pdf>

Etch Mechanisms: Bond dissociation energies - examples



Bond	Bond Energy [kJ/mol]	Bond	Bond Energy [kJ/mol]	Bond	Bond Energy [kJ/mol]
Si-Si	327	Al-Br	439	Ti-O	662
Si-F	540	Al-F	664	Ti-N	464
Si-Cl	456	Al-O	512	In-P	198
Si-Br	343	Al-N	297	In-Cl	439
Si-O	798	Cr-Cr	155	In-F	506
C-O	1076	Cr-Br	328	Ga-N	205
Si-N	439	Cr-Cl	366	Ga-F	577
Si-C	435	Cr-F	437	Ga-Cl	481
S-O	521	Cr-O	427	N-N	945
S-F	343	Ti-Ti	141	O-O	498
Al-Al	186	Ti-Cl	494	C-H	337
Al-Cl	494	Ti-F	569	C-F	536

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***The electron affinity of gallium nitride (GaN) and digallium nitride (GaNGa): The importance of the basis set superposition error in strongly bound systems**

Article (PDF Available) in [The Journal of Chemical Physics](#) 128(14):144103 · May 2008 with 44 ReadsDOI: 10.1063/1.2883997 · Source: [PubMed](#)

Ref all others: <https://labs.chem.ucsb.edu/zakarian/armen/11---bonddissociationenergy.pdf>

Here are some examples of bond dissociation energies. Here you can see that for example Si-Si bonds are weaker than Si-O bonds. That means that that SiO₂ needs more ion energy to get the etching going. In general oxides and many nitride have higher bonding energies that for example many metals. That also means that they do not sputter off so easily and therefor also works will as masking materials.

Etch Mechanisms:

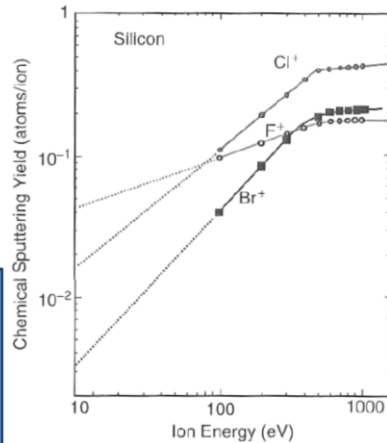
The role of the ions – an example: Silicon etching

Etching silicon with three different halogens: F, Cl, Br

1. SiF_4 forms and desorbs easily without ion bombardment.
2. SiCl_4 and SiBr_4 do NOT form and desorb easily without ion bombardment.

The role of the ion bombardment:

- Etching silicon with **F** chemistry:
 - the ion energy has a **minor effect** on the etch rate.
- Etching silicon with **Cl or Br** chemistry:
 - the ion energy has a **larger effect** on the etch rate.
- **How will that influence the anisotropy of the chlorine etch compared to the fluorine etch?**



S Tachi and S. Okudaira: J. Vac. Sci. & Technol. B 4, 459 (1986)

Let's take a closer look at the role of the ions when etching silicon.

Silicon forms volatile compounds with both fluorine, chlorine and bromine.

1. SiF_4 is formed easily and desorbs easily without ion bombardment.
2. SiCl_4 and SiBr_4 does NOT form and desorb easily without ion bombardment.

Let's take a look at how the ion bombardment affect these gas chemistries.

The graph to the right shows how the silicon etch is affected by the ion bombardment. It shows the chemical sputtering yield, that is how many atoms are etched off the surface pr. ion bombardment – as a function of the ion energy. (isotropic – directional/vertical etch?)

Here you see that bombarding with F-ions is lightly affected by the ion energy but not much compared to the bombardment with Cl-ions and Br-ions. So:

- Etching silicon with **F** chemistry:
 - the ion energy has a **minor effect** on the etch rate.
- Etching silicon with **Cl or Br** chemistry:
 - the ion energy has a **larger effect** on the etch rate.

Question: How do you think this will influence the anisotropy of the chlorine etch compared to the fluorine etch?

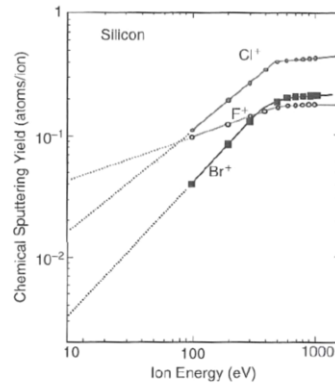
Etch Mechanisms: Example/Quiz: Etching Si with either Cl or F?

Example:

- Etching silicon with F chemistry, the ion energy has a minor effect on the etch rate.
- Etching silicon with Cl chemistry the ion energy has a larger effect on the etch rate.
- **How will that influence the anisotropy of the Cl etch compared to the fluorine etch?**

Answer:

- When the ion energy is low:
 - F-etch: will etch isotropically
 - Cl-etch: very slow etch
- When ion energy is high
 - F-etch: etch rate will not change much => the etch will still be almost isotropic
 - Cl-etch: etch rate will go up and the etch will be anisotropic because the ion energy is directional and the limiting factor.



S Tachi and S. Okudaira: *J. Vac. Sci. & Technol. B* 4, 459 (1986)



Question – read the answer on the slide.

Contents of the Dry Etch Tool Package Training Lecture

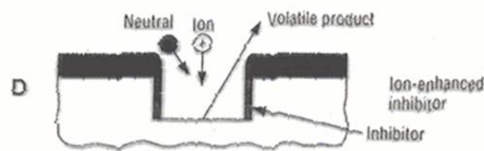


1. Motivation: Why bother about dry etching?
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 - The role of the ions
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You will now learn about some passivation mechanisms.

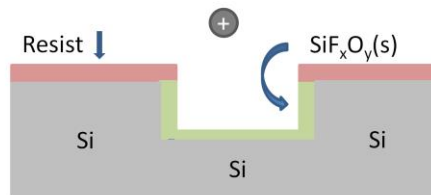
Etch Mechanisms: Passivation mechanisms – essential for etching Si with F chemistry.



Etching with SF_6 :



Etching with $\text{SF}_6 + \text{O}_2$:



So far we have only talked about the gases for etching – but we also mentioned one of the etch mechanisms for anisotropic etching is based on using a passivation gas together with the etch gas. The passivation gas deposits a thin layer all over the substrate or on the material to be etched. Then the role of the ions is to sputter away the layer in the horizontal plane leaving the passivation layer on the sidewalls. The neutrals then get access to etch the substrate only in the horizontal plane thereby producing an anisotropic etch profile. This is used for many materials but it is especially valuable when etching with a gas chemistry that is isotropic in nature. For example silicon etching with fluorine chemistry. As we have talked about, the etching of Si with fluorine will occur without ion bombardment and is only enhanced slightly with the ion energy. Therefore passivation is needed.

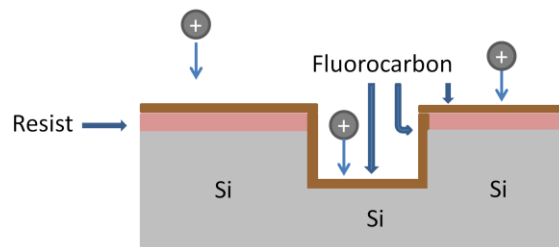
The passivation can either happen simultaneously with the etching or it can be done in a so called Bosch process where the etch step and passivation steps are alternating fast.

So for etching only with SF_6 , SiF_4 is formed in an isotropic etch. When adding O_2 to the gas a layer of siliconoxyfluoride will form on the silicon. To continue etching an ion bombardment is needed to sputter off the layer and open it up for the fluorine atoms to get access to the Si to form silicon fluoride. The ions only sputter off the horizontal layer of silicon oxyfluoride and not the sidewalls and therefore the etch becomes anisotropic.

Etch Mechanisms: Passivation mechanisms

– Passivating with fluorocarbons

- Fluorocarbons:
- $\text{CF}_4(\text{g})$
 - $\text{CHF}_3(\text{g})$
 - $\text{C}_4\text{F}_8(\text{g})$



Two mechanisms:

- Continuous process: Fluorocarbon + high ion bombardment
- Cycle process: **The Bosch process**
 - Fluorocarbon – deposition of polymer
 - Ion bombardment – removes polymer in horizontal plane
 - Etch with e.g. SF_6

Another way to passivate is to use fluorocarbons for etching, like CF_4 , CHF_3 and C_4F_8 . The fluorocarbons form polymers on the whole surface: On the mask, on the sidewalls and in the bottom of the etched structures. The ions are then needed to sputter of the polymer on the horizontal plane to leave open space for the reactive species.

The inhibitor process can be done in two different ways. Either in a continuous process where the fluorocarbon gas is the etching gas and the ion bombardment is high during the etching. Or in a cyclic process where

1. The fluorocarbon polymer is deposited
2. Followed by an ion bombardment
3. Followed by an etch step – e.g. using SF_6 as the etch gas.

This cycle will be repeated a number of times. This is called the Bosch process and this is a very important process for deep silicon etching.

Contents of the Dry Etch Tool Package Training Lecture



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This leads us to the last part of the etch mechanisms which is the Bosch process.

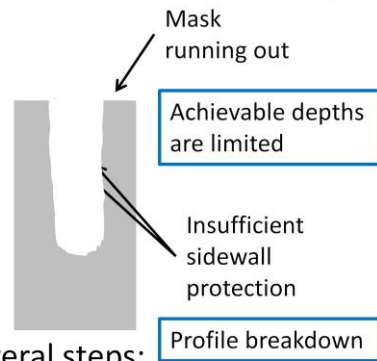
Etching of materials: Silicon

Dry etching of silicon is a special case :

- Si wafers serve as substrates
- Deeper etches
- Continuous processes are unfit

The solution: The Bosch process in which the etch process is split into several steps:

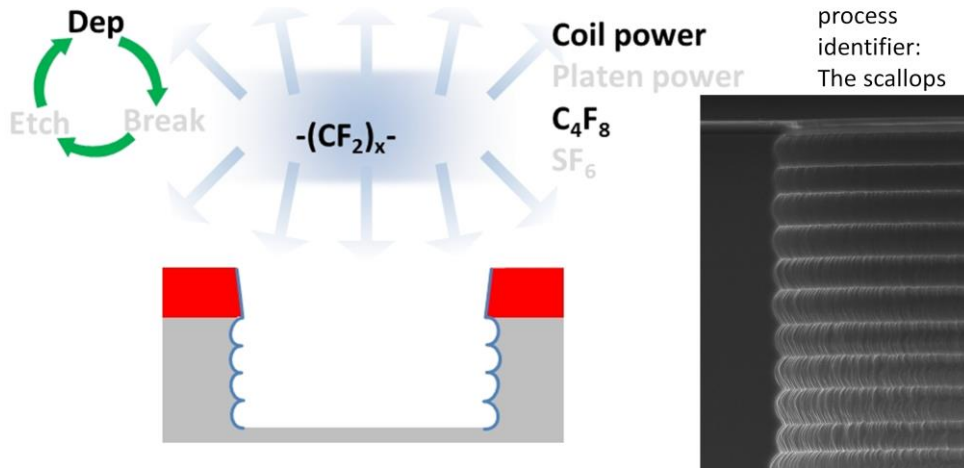
- **Dep:** Deposition of a sidewall protecting polymer
- **Break:** Removal of dep layer on horizontal faces with ion bombardment
- **Etch:** Etching of silicon at the bottom of open features



Dry etching of silicon is a special case compared to the remaining dry etch applications. The reasons are many:

- **Historical:** Silicon substrates have been used as the backbone in the semiconductor industry for decades and still is despite competition from other materials. As a result, dry etching of silicon has been thoroughly researched and the technique is therefore very sophisticated.
- **Deeper etches:** For most applications of dry etching except silicon, the target depths rarely exceed 5-10 μm because the layers to be etched are not deeper. It is obviously different with substrate materials that are typically some hundreds of microns thick
- **Faster, better selectivity, sidewalls:** Realizing deeper etches one immediately identifies the limits of the sidewall protection in a continuous etch process: As the trench deepens, maintaining sidewall passivation becomes increasingly more difficult and the profile suffers. Also, deeper etches require faster etch rates and finally better selectivity.

How does the Bosch process work?



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The principle of the Bosch process:

The term Bosch refers to the splitting of the process into (at least two: etch and dep) separate cycles. One typically divides the etch cycle into more steps:

Dep:

In the dep cycle, the plasma will dissociate C_4F_8 and form a $-(CF_2)_x-$ containing polymer on all surfaces. A certain flow of gas is necessary and some pressure but the requirements are not very strict.

Break:

The purpose of the break is to remove the polymer on horizontal surfaces while keeping it on vertical (the sidewalls) surfaces. To optimize this we need:

- **Pressure:** A low pressure to maximize the inelastic mean free path of the ions so that they can reach the bottoms of potentially deep trenches without being scattered.
- **SF_6 :** Some SF_6 to provide ions for the break. Oxygen is not used as it will spontaneously react with polymer on the sidewalls.
- **Platen power:** A high platen power to drive the ions down.

Etch:

As seen earlier in this course, fluorine readily etches silicon without any need of ion bombardment, therefore we need:

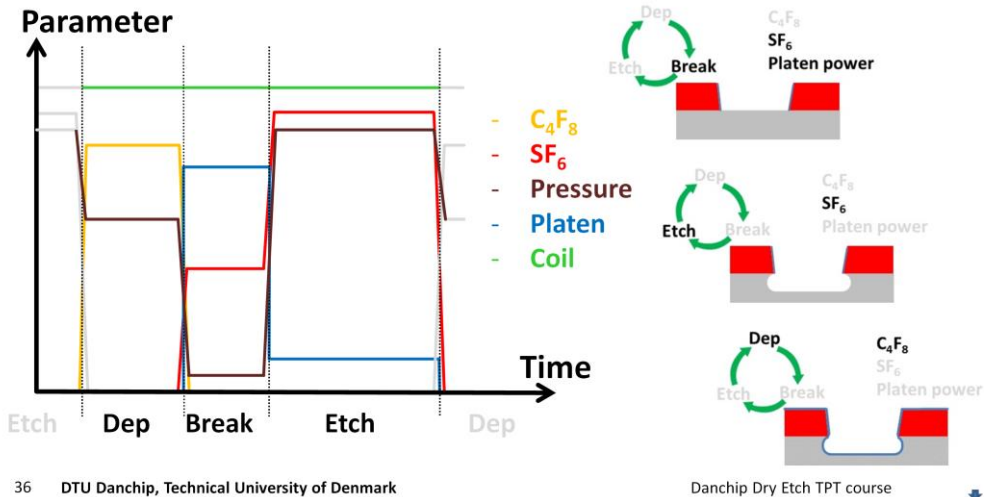
- **Platen power:** The platen power is lowered significantly
- **SF_6 and Pressure:** The higher values gives a high concentration of fluorine to increase etch rate.

The cyclic sequence of the Bosch process is illustrated by the figures.

Etching of materials: Silicon and the Bosch process



The parameters of the Bosch process:



The principle of the Bosch process:

The term Bosch refers to the splitting of the process into (at least two: etch and dep) separate cycles. One typically divides the etch cycle into more steps:

Dep:

In the dep cycle, the plasma will dissociate C_4F_8 and form a $-(CF_2)_x$ - containing polymer on all surfaces. A certain flow of gas is necessary and some pressure but the requirements are not very strict.

Break:

The purpose of the break is to remove the polymer on horizontal surfaces while keeping it on vertical (the sidewalls) surfaces. To optimize this we need:

- **Pressure:** A low pressure to maximize the inelastic mean free path of the ions so that they can reach the bottoms of potentially deep trenches without being scattered.
- **SF_6 :** Some SF_6 to provide ions for the break. Oxygen is not used as it will spontaneously react with polymer on the sidewalls.
- **Platen power:** A high platen power to drive the ions down.

Etch:

As seen earlier in this course, chlorine readily etches silicon without any need of ion bombardment, therefore we need:

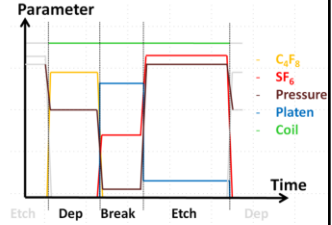
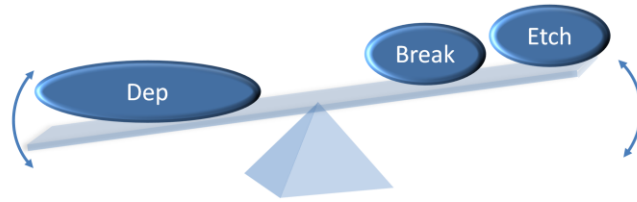
- **Platen power:** The pp is lowered significantly
- **SF_6 and Pressure:** The higher values gives a high concentration of fluorine to increase etch rate.

The cyclic sequence of the Bosch process is illustrated by the figures.

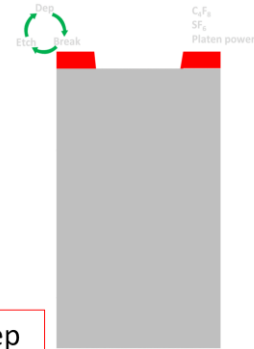
Etching of materials: Silicon and the Bosch process



The balance of the Bosch process:



Dependency	Deposition	Break	Etch
Highly	Temperature, C ₄ F ₈	Pressure, Platen	SF ₆ , Coil
Moderately	Coil	SF ₆	Pressure
Lightly	Pressure		Platen
Off	SF ₆ , Platen	C ₄ F ₈	C ₄ F ₈



What parameter is missing? The duration of each step



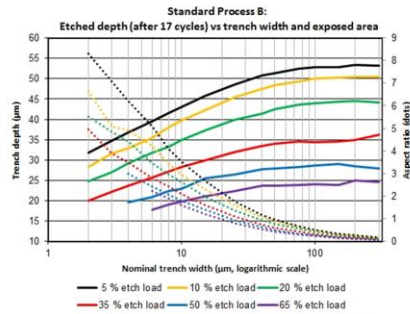
Etching of materials: Silicon and the Bosch process



Important design parameters for the Bosch process:

Silicon etch by fluorine does not require an ion bombardment -> the etch process is limited by etchant diffusion. Therefore, the achieved depths will depend on two factors:

- Etch load: What percentage of the substrate is etched?
- Aspect ratio dependent etching to be achieved



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We saw earlier that the etching of silicon by fluorine occurs spontaneously (the reaction is in fact exothermic). This means that it will be limited by etchant diffusion. As such, two effects will have to be considered in the design phase:

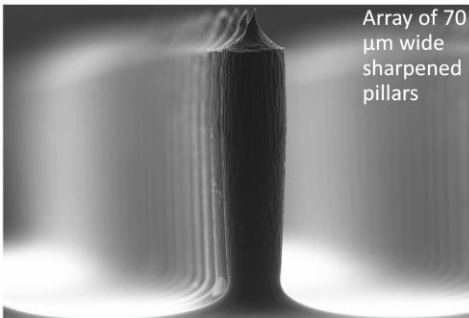
1. Etch load (acronym 'open area', 'loading effect')
2. Aspect ratio dependent etching (acronym 'rie lag')

They are both illustrated by the graph in the top right corner that shows how deep trenches are obtained when etching a silicon wafer with 20 % etch load. The width of the trenches vary and so does the pitch to maintain 20% etch load. (the 2 µm trenches have pitch 10 µm, the 30 µm have pitch 150 µm etc.) It is seen that the narrow trenches are less deep – because of the limited transport of reactants and reaction products. At some width (100-150 µm), this limitation stops and the obtained depth remains essentially constant. Looking at the graph with log scale makes it easier to see.

At 10 % etch load, all trenches are deeper because of the higher etchant concentration (with a smaller area to etch there will be more fluorine available per area). The trend continues in both directions – towards higher and lower etch load.

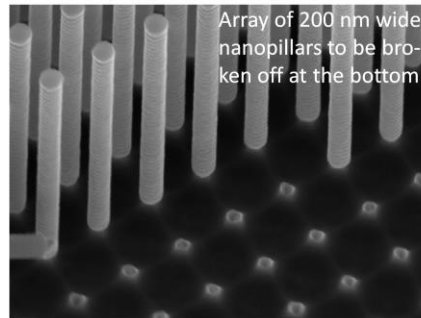
Mixing isotropic steps with anisotropic steps:

25 minutes of isotropic etching
44 minutes of anisotropic etching



Structures realised by Thor Emil Andersen, DTU Nanotech

45 cycles of anisotropic etching
The last etch step is twice as long



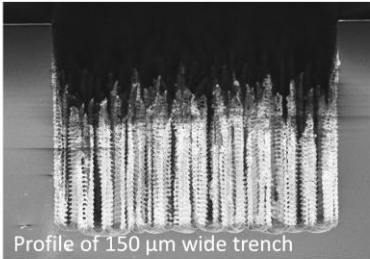
The tunability of the Bosch process allows you to combine several steps with a varying degree of isotropy to achieve excellent structures.

To the left, an array of sharpened pillars almost 300 μm tall have been achieved. First, however, an isotropic step has underetched the circular mask at the top to sharpen the final tip.

Less obvious in the right picture, an array 200 nm diameter pillars has been made. This required some 45 cycles of Bosch processing. To make sure that the pillars will break off only at the bottom, the duration of the last etch step has been doubled. The result may not be visible by looking at the pillars themselves but in the lower part of the image where the pillars are broken off (scraped off with a knife or screwdriver) makes it clear that all pillars must have the same length.

When the Bosch process is not perfect:

Question: Any suggestions to what might have gone wrong below?

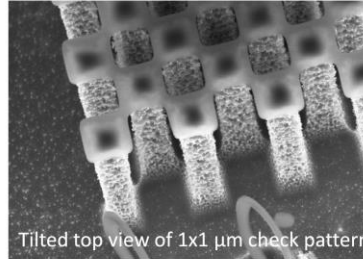


Profile of 150 μm wide trench

Possible answers:

The dep is too dominant – possible solutions:

- Reduce duration of dep
- Extend break
- Reduce C_4F_8 in dep
- Increase platen power in break
- Reduce pressure in break



Tilted top view of 1x1 μm check pattern

Possible answers:

The Etch is too dominant – possible solutions:

- Reduce duration of etch
- Lower electrode temperature
- Increase C_4F_8 in dep
- Reduce platen power in break



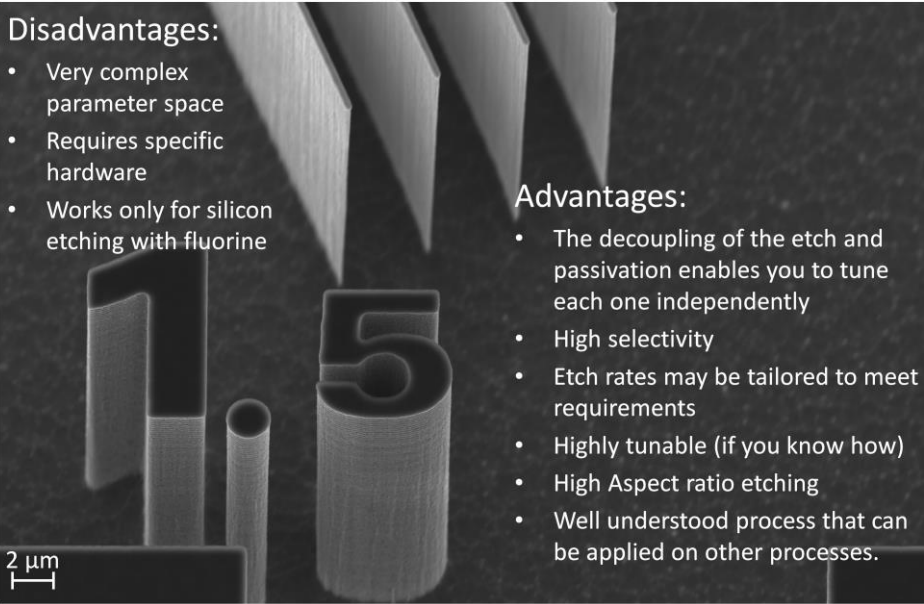
The Bosch process is not perfect: Here are SEM images two examples of poor process results. Can you come up with a reason and suggest some solutions?

Disadvantages:

- Very complex parameter space
- Requires specific hardware
- Works only for silicon etching with fluorine

Advantages:

- The decoupling of the etch and passivation enables you to tune each one independently
- High selectivity
- Etch rates may be tailored to meet requirements
- Highly tunable (if you know how)
- High Aspect ratio etching
- Well understood process that can be applied on other processes.



1. Motivation: Why bother about dry etching?
2. Etch Plasmas
3. Etch Mechanisms
4. Etch characteristics
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“Etch characteristics” will introduce some of the requirements you will have for the performance of the etch.

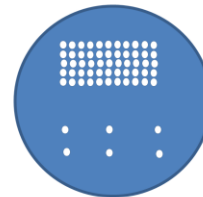
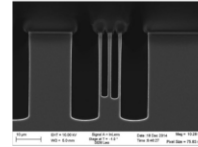
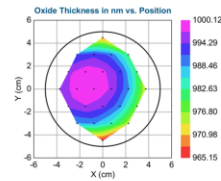
1. Motivation: Why bother about dry etching?
2. Etch Plasmas
3. Etch Mechanisms
4. Etch characteristics
 - Etch rate
 - Etch Profile
 - Selectivity
5. Process Tuning
6. Equipment for dry etching at Danchip



We will look at the etch rate requirements, the etch profile requirements and the selectivity requirements.

Etch Characteristics: Etch Rate

- **Etch rate**
 - Preferable high for deep etch – many samples
 - Preferable low for etching thin layer, to have good control over the etch depth.
- **Etch rate uniformity over the sample**
 - Preferable same etch rate all over the sample.
- **Aspect ratio dependent etch rate**
 - Different etch rates for different aspect ratios.
- **Loading effect**
 - High loading areas etch slower than low loading areas.



Let us first start with the etch rate

Etch rate: How fast will the etch be. You maybe ask for a high etch rate because you need to etch all the way through you wafer and you have 30 wafers. Or you may ask for a low etch rate because you need to etch only 30nm \pm 5nm's. **Question:** what happens if you etch 30nm with an etch rate of 1 μ m/min? **Answer:** The reproducibility will be very bad – you cannot hit the 30nm \pm 5nm's.

Etch rate uniformity over the sample: You may need to etch through a 2 μ m thick silicon oxide and stop on a 50nm silicon nitride. **Question:** What can happen if the etch uniformity is not good? **Answer:** To get through SiO₂ on the whole wafer the etch will break through the silicon nitride in some regions of the wafer unless the selectivity is very high.

Aspect ratio dependent etch rate: Aspect ratio dependent etch rate is when the etch rate changes when the aspect ratio increases (above 1), like you see on this image. The aspect ratio is the depth of a structure divided by the width.

Question: When can aspect ratio depend etch be a problem?

Answer: There can be many answers to this question but one would be when etching a SOI wafer. Etching the silicon layer down to a thin oxide layer without breaking through the SiO₂ and with notching in the bottom of the trench.

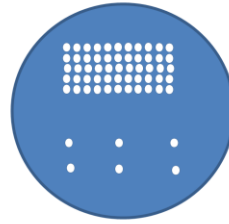
Loading effects:

This image illustrates a wafer with high loading in the top part (many holes to be etched) and low loading in the bottom part (a few widely distributed holes to be etched). Here the etch rate can be lower in the high loading area than in the low loading area. That is called the loading effect.

Etch Characteristics: Loading effect

Question: How can you obtain the same etch rates in the high loading area and the low loading area?

- A. When the etch rate is limited by the number of reactive species?
- B. Or when the etch is limited by ion bombardment?



Answer: B

Limited by reactive species:

Low loading has more species/Area high loading => **Not equal etch rates**

Limited by ion bombardment:

Enough species for all areas and ion bombardment is uniformly distributes => **Etch rate equal in low and high loading areas.**



A **question** for can be:

When will the etch rate be the same in the high loading area and the low loading area:

- A. When the etch rate is limited by the number of reactive species?
- B. Or when the etch is limited by ion bombardment?

The Answer is : B

When the etch rate is **limited by reactive species**, then areas with low loading will have more species per area than the high loading areas and therefore achieve a higher etch rate.:

When the etch rate is **Limited by ion bombardment**: There are enough species for all areas and since the ion bombardment is uniformly distributed: the etch rate is equal in low and high loading areas.

Extra question:

So where will the loading effect be highest:

- A. In a silicon etch - etching with SF_6 ?
- B. Or a silicon etch etching with Cl_2 ?

Answer: A

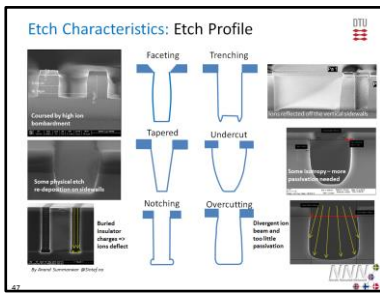
As the SF_6 etch is not very dependent on ion bombardment it will most likely be in the reactive species limited regime.

The Cl_2 is much more dependent of the ion bombardment and can at least be tuned to be in the ion limiting regime.

1. Motivation: Why bother about dry etching?
2. Etch Plasmas
3. Etch Mechanisms
4. Etch characteristics
 - Etch rate
 - Etch Profile
 - Selectivity
5. Process Tuning
6. Equipment for dry etching at Danchip



We now move on to the etch profile.



Now let us take a look at the various etch profiles you may get.

a) Faceting:

- a) Faceting of the mask is a result of ion bombardment. Sputter rates are typically higher with an angle to the surface rather than with normal incident. The corners of the mask will easily erode creating an angle and will then be sputtered faster than the rest of the mask. This results in faceting of the mask.
- b) In a deep etch this faceting will be transferred to the etched layer. That has happened in the etch you see in the top left corner.
- c) You also see a bow on the sidewall. This is being created due to deflection of ions from the sloped surface.

b) Trenching:

- a) Trenching is also a result of ion bombardment. This happens due to ions being reflected on the sidewall when either the sidewall is a little off from vertical or the impinging ions can be a little off normal to the surface for other reasons. This can lead to enhanced etch rate near the edge as can be seen in the top right image.

c) Undercut:

- a) Undercutting is a result of isotropic etching. The right middle image is in between isotropic and anisotropic etch – some passivation is taking place, but not enough. **Q:** How would you improve the anisotropy here? **A:** More passivating chemistry in the plasma – and/or higher ion energy.

d) Tapered:

- a) A tapered etch profile is normally created by reposition on the side wall. This can be formed by either polymers created by the plasma chemistry and sputtered of the horizontal plane or it can be re-deposition of non-volatile material that has been sputtered off. The middle left image shows a tapered sidewall in an silicon oxide etch – so this is most likely formed by re-deposition of polymers on the sidewalls.

e) Notching:

- a) This can happen when one layer is etched down to an isolating layer (that could be etching silicon down to a buried SiO₂ layer). When reaching the SiO₂ – the SiO₂ layer may charge up and can deflect the positive ions against the sidewall – this will remove the passivation layer and the lateral etching will take place if using isotropic etch chemistry.
- b) The lower left image is showing a silicon etch made with a Bosch process that is etched down to a SiO₂ layer.

f) Overcutting:

- a) This can happen when etching down in a trench/hole with an isotropic etch chemistry combined with a passivating chemistry. Then it can happen that the passivation gets thinner when the trench gets deeper and at some point it is not thick enough and the etching will start having a lateral component.
- b) Or divergent ion flux. – The images in the lower right corner shows a Si etch with SF₆ and O₂ with a high mask load. This will be a species limited regime, so there is maybe too little sidewall passivation in a regime where the ion bombardment is important. This will lead to a significant effect of a divergent ion flux. Therefore it has a more rounded etch shape.

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Selectivity is the last etch characteristics that we will introduce you to.

- **Selectivity:** higher etch rate in one material over the etch rate in another material.
- **High etch rate:** Material to be etched (blue)
- **Low etch rate:** Masking layer (brown) or underlying layer (pink)
- **How to create etch rate selectivity:**
 - Choice of gasses
 - Process parameters
 - Platen power
 - Process temperature



Examples: Etching silicon

- Mask: Photo resist
 - Keep sputter rate down (low platen power)
 - Run a fluorocarbon process (e.g. Bosch) that makes polymers. This protects the mask (and sidewalls)
- Mask: Aluminum
 - Use fluorine gas, not chlorine. Keep sputter rate down.
- Mask: Silicon oxide
 - Use SF₆ at low power (or Chlorine).
 - Silicon etches spontaneously without ionbombardment
 - Silicon oxide needs a high ionbombardment to etch fast.
- What if you need to etch SiO₂ down to silicon?

Read the slide!

Selectivity: Example: SiO₂ etch over Si. Select gas.



Compound	Boiling point [°C]	Temperature required to get a vapor pressure of 1 Torr [°C]	Volatile at low pressure?	Bond	Bond Energy [kJ/mol]
SiF ₄	-86	-144	Yes	Si-Si	327
SiCl ₄	58	-63	Yes	Si-F	540
SiBr ₄	154	-	Yes	Si-Cl	456
CO ₂	-78	-134	Yes	Si-Br	343
SO ₂	-10		Yes	Si-O	798
SOCl ₂	76		Yes	C-O	1076
SOF ₂	24		Yes	Si-N	439
SOBr ₂	138		yes	Si-C	435
				S-O	521
				S-F	343
				Al-Al	186
				Al-Cl	494

These look good:

- SF₆
- CF₄
- CHF₃
- C₄F₈

Use fluorocarbon gases to create selectivity

Example of question: What gas or gasses would be good for SiO₂ etching?
Give them time to suggest and explain.

Solution:

First take a look at what compounds with Si that will be volatile. And what compounds with volatile with O.

All compounds in the table are volatile at low pressure. Then what gasses do we need?
SF₆, CF₄, CHF₃ or C₄F₈ look okay from the volatility point of view.

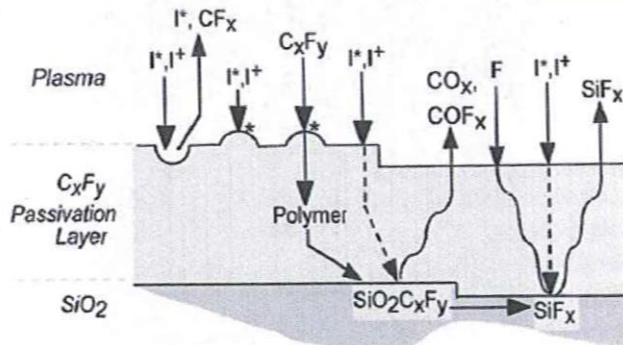
Selectivity: Example: SiO_2 etch over Si. Creating selectivity with fluorocarbon gases (CF_4 , CHF_3 , C_4F_8)

Reactions take place in F-C etching

- Deposition of fluorocarbon layers
- Etch of fluorocarbon layer
- Etch of substrate material

Polymer layer on Si > Polymer layer on SiO_2

 Si etch rate < SiO_2 etch rate



A.Sankaran and M.J. Kushner, Appl. Phys. Lett. 82, 1824 (2003)

Etching SiO_2 with a good selectivity to silicon

The trick is to use fluorocarbon gases (like CF_4 , CHF_3 and C_4F_8).

There are three reactions taking place in fluorocarbon (F-C) etching

1. Deposition of fluorocarbon polymer layers
2. Etch of fluorocarbon layer
3. Etch of substrate material

It has been reported that the polymer layer that forms on Si is thicker than the polymer that forms on SiO_2 (how much thicker depends on the process parameters). This leads to lower etch rate in Si than in the SiO_2 layer.

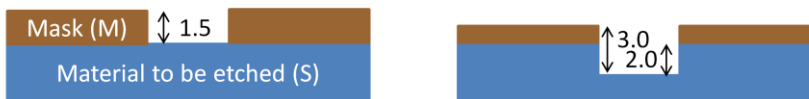
A thicker polymer decreases the etch rate due to reduction of ion energy through the polymer, reduction of reactive fluorine through the layer and reduction of diffusion of the etch product out of the layer.

The reason of the etch rate difference is probably because the etching of SiO_2 consumes the polymer during etching (carbon reacts with the oxygen to form CO_x , which is volatile and evaporates. The Fluor reacts with the silicon atoms and makes volatile SiF_x).

Etch pure silicon the reaction to SiF_x will soon be lacking F and the carbon will not react and therefore the polymer will not be consumed during the etch and will stay thicker than on the SiO_2 .

The process parameters can be tuned to get a high selectivity.

Selectivity to the mask



$$\text{selectivity to the mask} = \frac{\text{Etch rate (S)}}{\text{Etch rate (M)}} = \frac{\text{Etch depth (S)}}{\text{Etch depth (M)}}$$

Example:

Stylus profiler measurement of mask **before etch**: 1.5 μm

Stylus profiler measurement **after etch**: 3.0 μm

Remove mask

Stylus profiler measurement of **etched material**: 2.0 μm

What is the selectivity to the mask?

$$\text{selectivity to the mask} = \frac{2.0\mu\text{m}}{1.5\mu\text{m} - (3.0 - 2.0)\mu\text{m}} = 4$$



First: let's look at how to measure the selectivity:

The blue is the material to be etched. The brown is the masking material. After the etch both layers have been etched. The selectivity is then defined as the etch depth (or etch rate) of the material to be etched over the etch depth (or etch rate) of the masking material.

Let's do a small example:

Let us say we measure the mask thickness before etch – for example by using a stylus profiler and we find that the thickness is 1.5 μm

After the etch we measure the profile again and find a step height of 3.0 μm

We then remove the mask and measure the etch depth of the material we wanted to etch and find a depth of 2.0 μm

Question: what is the selectivity to the mask then?

Answer: 4

You may use this the other way around to calculate how thick a masking layer is required to be able to etch down to a certain depth in your material – but remember that if you get mask faceting you may need a thicker layer to avoid getting angled sidewalls.

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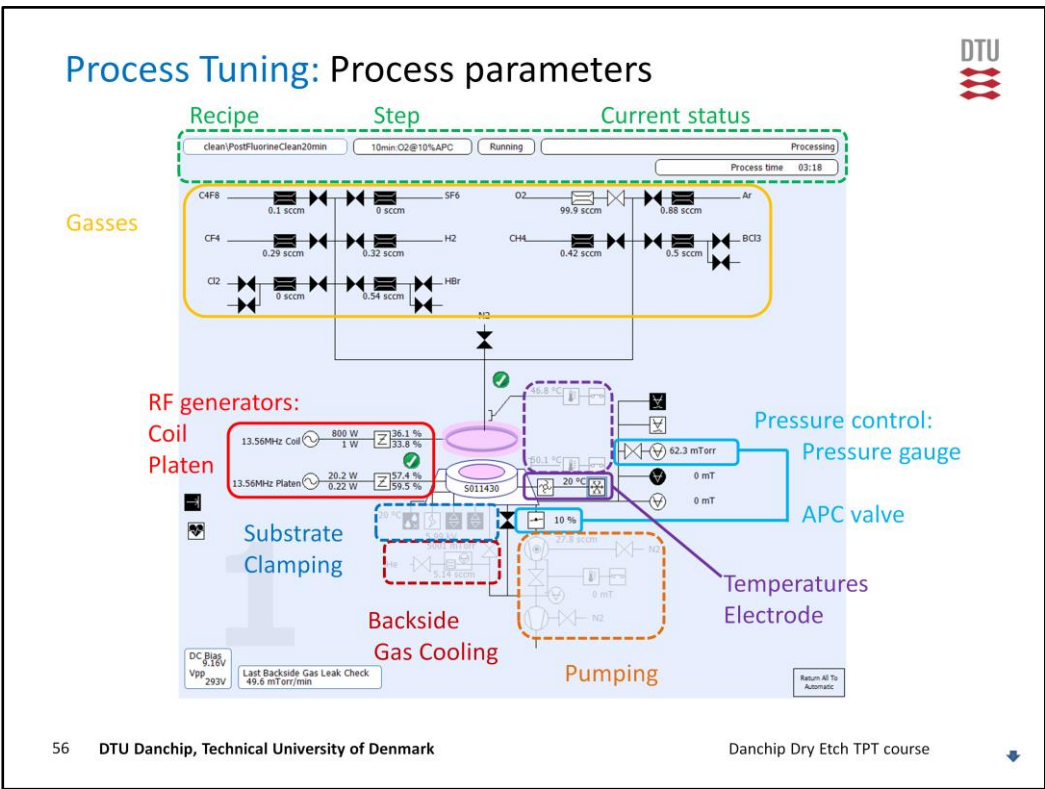
Process tuning or optimizing the etch process is not always straight forward. In this section, we will go through some practical tuning issues with the hardware and also go through the process parameters to give you an understanding of how they affect the etch results.

1. Motivation: Why bother about dry etching?
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4. Etch characteristics
5. Process Tuning
 - What **gas(es)** to select ✓
 - Setting of **Pressure**
 - Setting of **power (coil and platen)**
 - Setting **gas flows**
 - Setting the platen **Temperature**
 - Chamber conditioning
 - RF matching
6. Equipment for dry etching at Danchip



We have talked about how to select the most appropriate gas or gasses.

In the next part we will go through the effect for the other process parameters: Pressure, power, gas flow rates and temperature.



This is a screen dump from one of our ICP's. It shows the process chamber in which an oxygen clean is running. Most of our dry etchers have the same graphical user interface and will look the same although there are differences in connected gas lines, RF generators and heaters. One can divide the parameters shown here into two groups – the actual process parameters and those that must be regarded as constants.

Gas:

The gasses connected may vary – here only oxygen is flowing at 100 sccm. The gases may flow freely within the flow range determined by the MFC. Some are interlocked.

Pressure:

To be able to change the pressure while keeping all other process parameters (RF, gas flow, temp) fixed, one must have a way of changing the pumping speed. This is done by the so called APC (Automatic Pressure Control) valve that sits between the process chamber and the turbo pump; it is capable of varying the opening towards the turbo pump thus enabling control of the pumping speed. The pressure may then be controlled in two ways: With fixed pressure (determined by the pressure gauge) or with fixed APC.

The range of possible pressures is determined by the range on the pressure gauge and the total gas flow.

Substrate temperature:

The platen temperature may be varied in a limited range, the various process chamber temperatures may not.

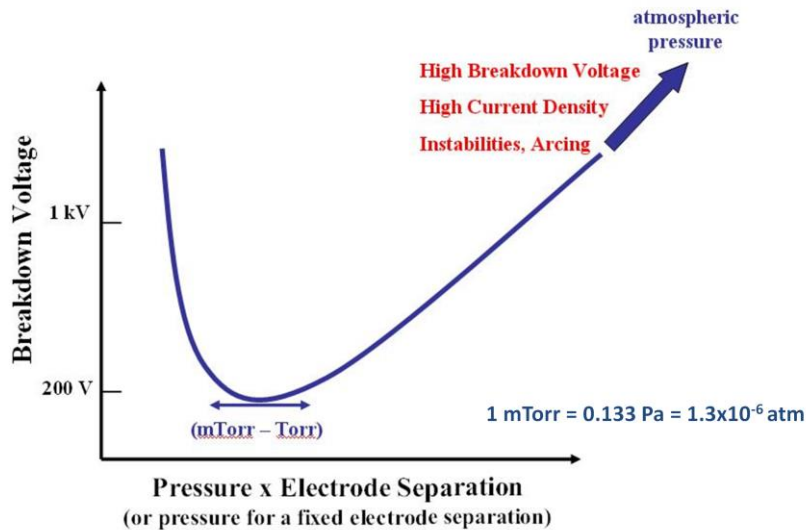
RF generators:

The RF generators, and usually in particular the coil generator, are responsible for maintaining the plasma. They may be given any value between a minimum of being able to sustain a plasma to the maximum output.

The group of fixed parameters includes: Substrate clamping, Backside gas cooling of the substrate, Chamber heaters and Pumping.

Process Tuning: Pressure and Power

Discharge- Paschen curve

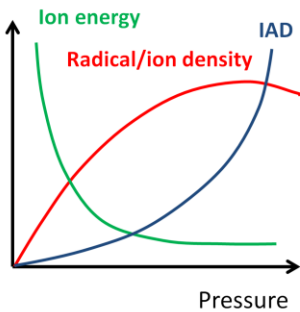


<http://www.wikiwand.com/en/Microplasma>

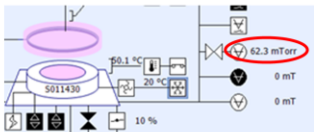
The Paschen curve shows the relationship between the breakdown voltage you need to create a plasma and the chamber pressure or as in this case pressure times electrode separation. In the chambers we have, we need to operate in the mTorr range. Typically between 1 mTorr and a few hundred mTorr.

It is worth noting that when we work in very low pressure regime we need to have high power to start the beam or if we work at low power we need a high pressure to start the plasma. This can in some systems be overcome by using a strike pressure, where the plasma is started at a higher pressure e.g. 10-20 mTorr and then after a few seconds the pressure is lowered to maybe 3 mTorr. If it gets too low it will not be able to sustain the plasma.

Process Tuning: Pressure



- Increasing Pressure
 - Higher density of reactive species and ions => higher etch rate.
 - Lower Ion energy due to smaller mean free path of ions => lower etch rate for reactions requiring high ions energy.
 - Higher IAD (Ion Angular Dispersion)
- Questions:
 - When will a high pressure be valuable?
 - An isotropic etch
 - In Bosch process during passivation and during etch
 - Question ->



Pressure:

The pressure controls the amount of gas for the ionization and creation of reactive species. So for a higher pressure the plasma contains a higher density of reactive species and ions. This will lead to a higher etch rate.

One draw back from high pressure is: Lower mean free path of the ions in the dark space. This gives more ion scattering which leads to a higher IAD (Ion Angular Dispersion. IAD gives non-directional etching.

If the pressure gets too high the radical/ion density goes down again due to recombination and electrons not having energy enough to sustain the plasma.

Questions:

When will a high pressure be valuable?

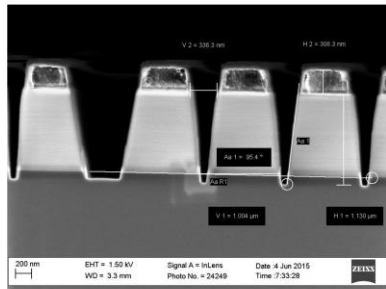
1. In an isotropic etch because the density of the reactive species is large. This gives a high etch rate. The ion energy and ion directionality is not used.
2. In a Bosch process during passivation and etch step. The etch step is isotropic. And the passivation set is also independent of the ion energy and the deposition rate will be higher at higher radical density.

Process Tuning: Pressure

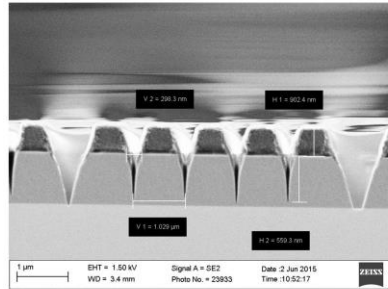


SiO₂ etch: All parameters are the same except the pressure.

Lowest pressure



Highest pressure



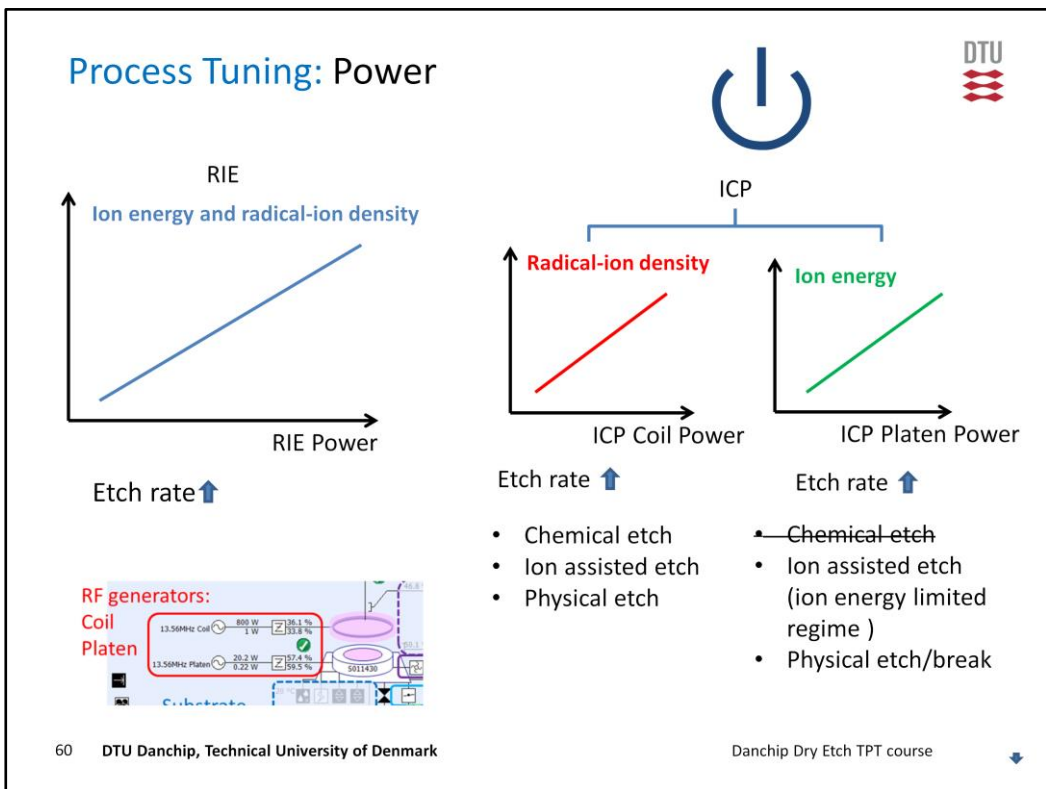
Question: Which one is the high pressure and which one is low pressure?

Answer: The one to the right has the highest pressure. The ions are less directional due to the lower mean free path at higher pressure.



Take a look at the two images. Which one is the high pressure and which one is low pressure?

Answer: The one to the right has the highest pressure. The ions are less directional due to the lower mean free path at higher pressures. Therefore they have problems reaching the bottom of a narrow trench. If you take a look at the resist left on the top of the oxide it looks like the selectivity to the resist is a little better at high pressure. This can be due to lower ion energy. This gives a lower bombardment of the resist mask.



Power

The parallel plate RIE system and the ICP with combined coil power and platen power should be considered separately with regards to the effect on the process results.

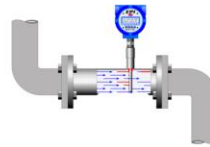
For the RIE:

- Higher power gives
 - higher etch rate due to higher plasma density and
 - higher ion bombardment energy
- May damage the mask giving low selectivity.

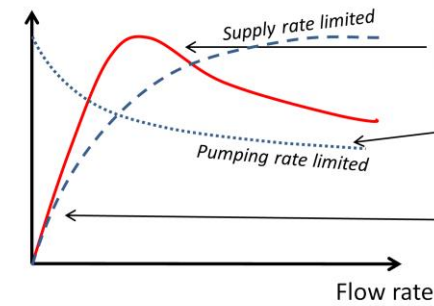
ICP Power is divided in coil power and Platen power:

- Higher coil power
 - higher plasma density
 - Gives higher etch rate (more reactive species and more ions)
- Higher Platen power
 - Gives directionality
 - higher ion bombardment energy
 - Increasing etch rate in ion limited regimes and for reactions needing higher energy
 - Needed in break through steps – to break through the polymer layer in the Bosch process or the polymer in a continues etch/passivation etch
 - Damage mask

Process Tuning: Gas flows



Etch rate *At constant pressure*



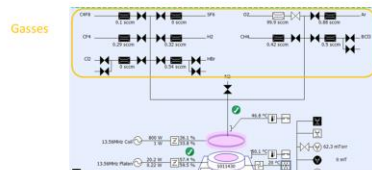
Enough gas + gas residence time is long.

Residence time is short:
Reactive species are pumped out
before they react.

Limited by the amount of gas

NB! Flow rates can affect selectivities and passivation

- Flow ratios
 - SF_6/O_2 for Si etch
 - CF_4/CHF_3 for SiO_2 etch
- Gas residence time can affect which neutrals are formed – this can affect selectivity.



Gas flow rates:

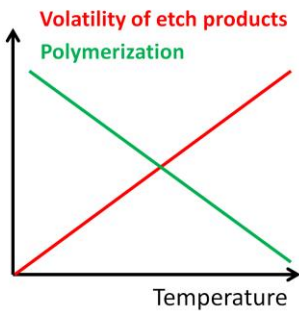
The gas flow rates also have an effect on the process results. We can first take a look at how the total flow rate effects the etch rate at constant pressure.

- At low flows the etch rate is limited by the amount of gas.
- At higher gas flow there is enough and the gas residence time is long enough for the reactive species to react.
- At even higher flow rates the gas/reactive species are pumped out before it has time to react with the surface – giving lower etch rates.

Note that flow rates can also have an effect on selectivities:

- The flow rate ratio can make the chemistry more or less passivating and this can affect the substrate etch rate and masking etch rate differently and affect the etch profile. This can for example be the case for SF_6/O_2 ratio in Si etching or CF_4/CHF_3 in SiO_2 etching.
- The gas residence time can also affect what reactive species are formed - this can also affect selectivity, for example the selectivity between Si and SiO_2 etch in a fluor/carbon chemistry.

Process Tuning: Platen Temperature



Platen temperature affects:

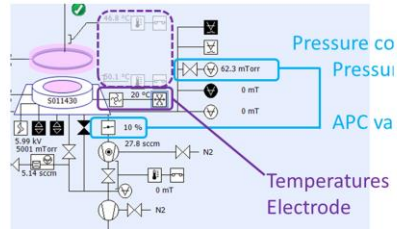
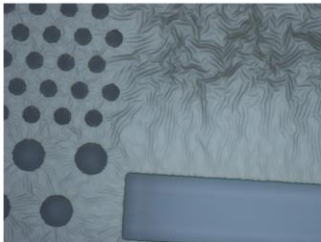
- Volatility of the etch products
- Polymerization of neutral species
 - Protects sidewalls
 - Protects mask
- Deformation of layers that cannot withstand the heat

When is low temperature needed?

When is high temperature needed?

What material would you suggest to etch at elevated temperature?

Resist mask deformation by UV-radiation and heat



Platen/sample temperature:

The Temperature has some effect on the process as well.

First of all it affects the volatility of the etch products. As the temperature goes up, the volatility goes up. This can make the etch rate go up.

The electrode temperature also affect the polymerization degree. Normally the polymerization goes down as the temperature increases. The polymerization protects the sidewalls and in some cases the mask so a higher temperature can give less steep sidewalls and affect the selectivity. High temperature can also deform layers that cannot withstand the heat.

When is low temperature needed?

When having layers that cannot withstand the heat.

Heat is often a problem for a resist mask. UV-radiation combined with heat can make the resist curl, leading to a rough edge.

When is high temperature needed?

What Material would you suggest to etch at elevated temperature?



Compound	Boiling Point [°C]	Temperature required to get a vapor pressure of 1 Torr [°C]
SiF ₄	-86	-144
SiCl ₄	58	-63
SiBr ₄	154	-
CO ₂	-78	-134
AlCl ₃	181 ^α	100
AlF ₃	1291 ^α	1238
MoF ₆	35	-66
TiCl ₄	136	-14
WF ₆	17	-71
InCl	608	175 ^β

^α Sublimation. ^β at 5 mtorr.

Compound	Boiling Point [°C]	Temperature required to get a vapor pressure of 1 Torr [°C]
GaCl ₃	200	48
GaF ₃	1000	-
AsF ₅	-53	-118
AsCl ₃	130	-11
CrF ₂	>1300	-
CrCl ₃	1300 ^α	-
CrO ₂ Cl ₂	117	-18
AgF	1160	-
AgCl	1550	-
NiF ₂	1000 ^α	-
NiCl ₂	987	671

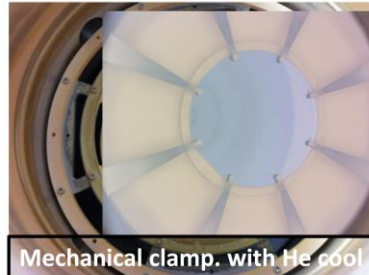
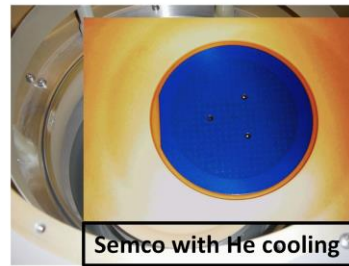
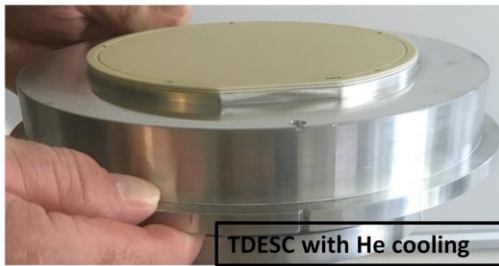
63 DTU Danchip, Technical University of Denmark

Danchip Dry Etch TPT course

When is high temperature needed?

- When reaction products are volatile only at elevated temperature
- Question: take a look at the etch product volatility. What material would you suggest to etch at elevated temperature?
- Answer: InP in Chlorine chemistry.

Process Tuning: How are the wafers cooled/heated?



Here you see some images of the clamping/cooling systems in the dry etchers.

To the right is shown a TDESC (Thick Dielectric Electro Static Chuck). The wafer is positioned on the ceramic surface. The part in the lower left image is positioned underneath the chuck in the upper image. At the edge 5 pins may lift the wafer to enable transfer of the wafer. The wafer is electrostatically clamped to this chuck during processing. The chuck is cooled or heated by a liquid running inside the chuck. To transfer the heat between the chuck and the wafer He gas is let in underneath the wafers from below. It comes out of the middle hole and goes through the pinholes and spreads to the recess at the edge of the chuck. The He is set to a pressure of 10 Torr. This will keep a He pressure underneath the wafer while He will leak out at the edge. The He leak up rate is measured before the etch starts and if it is too high the wafer is not properly clamped and the process will fail.

This ceramic chuck is quite robust and can withstand a O_2 plasma but with any particles on the chuck the wafer cannot clamp properly and you will see high He leak up rates. Therefore it is important that your wafers have clean backside when you process them in the system. Particles or resist on the back side is NO good!

The Semco chuck to the upper right also clamps the wafer electrostatically. Here the pins are close to the middle of the wafer and this is where the He comes out. The surface of the chuck is a softer polymer material and therefore it CANNOT withstand a plasma – so no chamber cleaning without a wafer with this chuck. The surface is check patterned allowing He diffusion underneath the wafer while it still stays clamped. With this chuck you also get problems with clamping if there are any particles on the chuck or on the back side of your wafer.

A third chuck we have is the mechanical clamping chuck. Here the chuck material is aluminum. An O-ring is at the edge of chuck. Everything else is made of ceramic. A basket with ceramic fingers are pressed down on the wafers to keep it down. This allows a high He pressure underneath. These fingers will cover some of the edge of your wafer. The last image shows a wafer being mechanically clamped in this system. This chuck also needs to be covered during all processing – including cleaning.

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 - What **gas(es)** to select
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 - Setting of **power (coil and platen)**
 - Setting **gas flows**
 - Setting the platen **Temperature**
 - Chamber **conditioning**
 - **RF matching**
6. Equipment for dry etching at Danchip

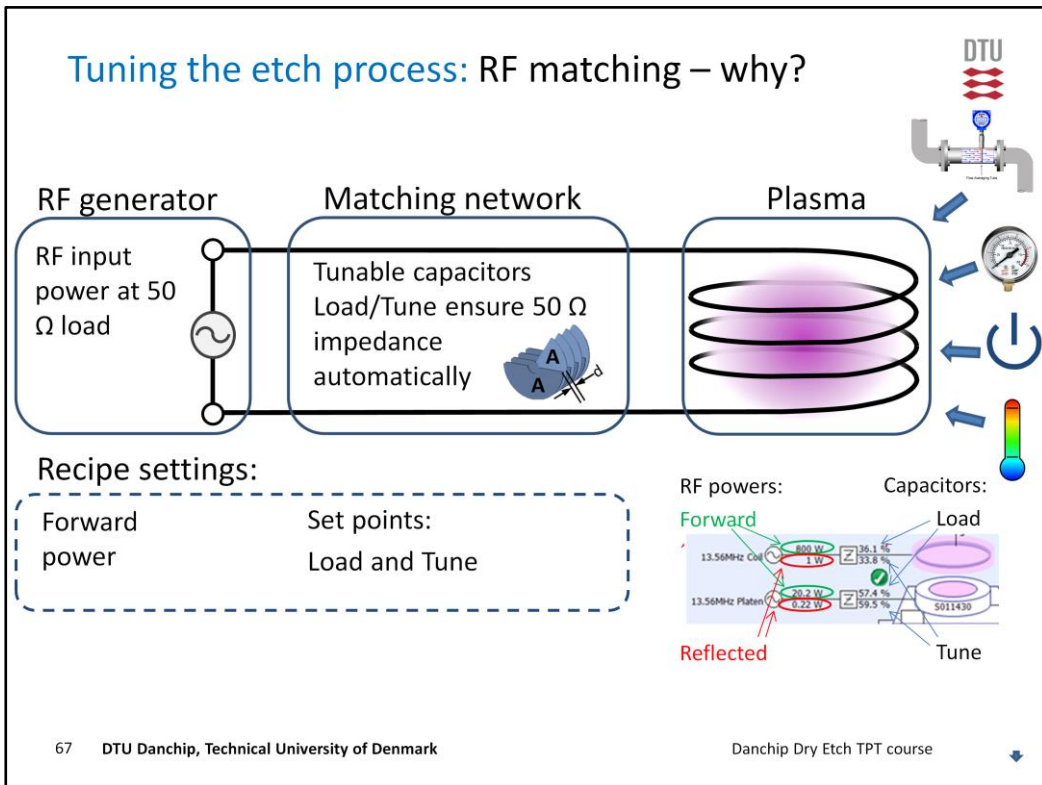


We are now done with process settings but there are still a few important issues to ensure a good stable process. That is the chamber conditioning and RF matching.

- What do we mean by the chamber condition?
 - The degree of polymer/layer build up on the chamber walls
 - The content of the polymer/layers: C, F, Cl, Br
 - Temperature on the sample during process (not the same as set point)
 - You can call it a "memory effect" of previous processing
- Why is it affecting the process results?
 - The layer on the walls interacts with the plasma chemistry.
 - Unstable temperature on the sample during the process or from run to run leads to variations.
- How can this be overcome?
 - Chamber cleaning with O₂ plasma
 - Conditioning run with O₂ plasma + process recipe: to stabilize temperature and chamber chemistry.



See text on the slide.



RF generators in AC circuit with a load:

One cannot just connect an RF generator to a coil, put a certain power through and expect a plasma generated absorb all energy. It is not possible: At RF frequencies even cables become inductors so circuits must be carefully constructed. Here, the coil of an ICP is shown but the RIE setup is equivalent.

Most power RF generators are designed to transfer power into a 50 ohm load. This means that the circuit, in addition to the coil with some inductance and resistance, will also require tunable capacitors in order to produce a 50 ohm impedance. If the impedance is off, part of the power will be dissipated as **Reflected Power** for instance localized heating of RF cables due to standing waves. Therefore, the capacitances of the capacitors Load and Tune must be carefully chosen to minimize the reflected power.

Effects of the plasma:

Once a plasma has been ignited in the process chamber by the coil, an electron current will be induced in the conductive part of the plasma so as to oppose the RF magnetic field. As a result of the coupling between the coil and the plasma, the inductance of the coil changes. This, in turn, changes the impedance of the generator circuit and hence causes reflected power

RF matching network:

Therefore, in order to maintain the impedance matching, the two capacitances of the two capacitors, Load and Tune, need to change. This is taken care of by the RF matching network that will automatically detect changes in impedance and adjust the Load and Tune capacitors to ensure impedance matching.

Tuning the etch process: RF matching – how?



All process recipes have two RF matching modes :

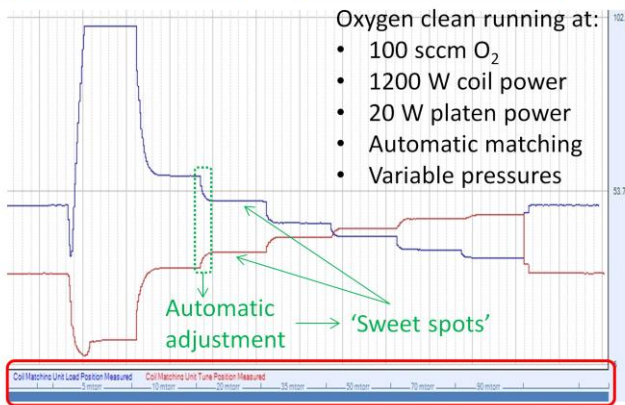
- Automatic
- Manual

All recipes must have **correct** set points for

- Load
- Tune

for each RF generator.

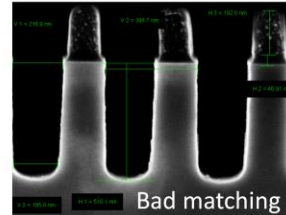
The automatic matching will ensure correct RF matching *only* if the set points have been correctly chosen.



Oxygen clean running at:

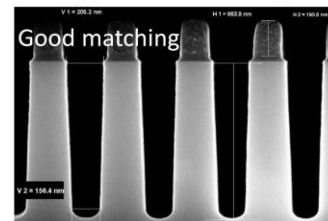
- 100 sccm O₂
- 1200 W coil power
- 20 W platen power
- Automatic matching
- Variable pressures

Automatic adjustment → 'Sweet spots'



Bad matching

Same recipes - different set points



Good matching

Danchip Dry Etch TPT course

68 DTU Danchip, Technical University of Denmark

Automatic matching:

Although one has the possibility of running with manual/fixed matching – it should **NEVER** be done. The processes will simply not work.

RF matching parameters in a process recipe:

The set points (in percentages of full capacitance) for the Load and Tune should be chosen with care: Set Tune 5% below and Load 5% above the sweet spot. From these set points the RF matching network should be able to find a minimum of reflected power – the **Sweet spots**.

Example: Oxygen clean at different pressures:

A data log with Load and Tune values of an oxygen clean with fixed RF power and gas flow run at different pressures is shown. The automatic matching changes Load/Tune as the pressure changes.

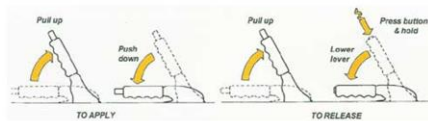
Why RF matching is important:

If the processes are not correctly matched:

- The power assumed to be transferred to the plasma is not correct
- The power will get dissipated in capacitors/cables/RF generator → not good.

Typically you have two types of recipes:

- Standard recipes or some that have already been optimized:
 - > No problem! The matching set points in the recipe will ensure that the automatic matching works correctly. Keep an eye on the reflected power anyway!
- Development recipes or if you are optimizing your own recipes:
 - > Always verify correct RF matching! Don't hesitate to ask us.
 - Failure to verify correct matching corresponds to driving your car without checking whether the hand brake is still on:
 - You will be able go somewhere – at lower performance
 - In the end, the power that was not transferred to the plasma will cause serious hardware malfunction as it is dissipated in generator/matching units etc.



In most cases one can narrow it down to two typical situations when you are processing at a dry etch tool:

1. You are either using **preexisting recipes** – either standard recipes or some that have been used extensively and have been well studied:
2. Or you are trying to **develop new recipes** or optimize the performance of old ones.

1. Motivation: Why bother about dry etching?
2. Etch Plasmas
3. Etch Mechanisms
4. Etch characteristics
5. Process Tuning
6. Equipment for dry etching at Danchip



At last a overview of our dry etch equipment is given to let you know what the instruments are best suited for.

Equipment for Dry Etching at Danchip:



	RIE2	III-V RIE	ASE	AOE	DRIE 1+2	ICP metal	III-V ICP	IBE
Purpose								
Type								
Allowed materials (Look it up in LM)								
Clamping and sub. Size								
Temp.								
Gasses								
Endpoint detection								

This is an overview of the dry etch equipment we have at Danchip. We have two RIE systems – parallel plate systems and 6 ICP's and a an IBE (Ion Beam Etch) with is pure physical sputtering with Ar-ions.

	RIE2	III-V RIE	ASE	AOE	DRIE 1+2	ICP metal	III-V ICP	IBE
Purpose	Si, SiO ₂ , SiN etch on Si -with some metals. -with sensitive back sides	-SiO ₂ , SiN, polymer etching on III-V materials	-Polymer on Si -Si	-SiO ₂ on Si -SiN on Si -Quartz	-Si etching	-Al, Cr, Ti, W, Mo, Si, SiN, SiO ₂ (thin),	InP at 180°C GaAs, GaN,	Materials that do not form volatile products
Type	Parallel plate	Parallel plate	ICP incl. Bosch	ICP	ICP incl. Bosch	ICP	ICP	Ion Beam Etcher
Allowed materials (Look it up in LM)								
Clamping and sub. Size								
Temp.								
Gasses								
Endpoint detection								↓

Purpose and type of the etchers at Danchip:

RIE2: This is a parallel plate plasma etcher. It is used for Si based etching. For etching samples with some metal on – and for etching samples with sensitive backsides.

III-V RIE: This is a parallel plate plasma etcher. It is dedicated for III-V based etching and for SiO₂, SiN and polymer etching on III-V materials

ASE: This is an ICP. It is for polymer etching and Si etching.

AOE: This is an ICP designed of dielectric etching. It is used for dielectric etching of SiO₂ and SiN.

DRIE1+2: Two highly advanced ICP’s. These are for Si etching only.

ICP Metal: This is an ICP. It is primarily for etching of metals that makes volatile products with the etching gasses. Also some Si, SiO₂ and SiN etching on 6” wafers.

III-V ICP: This is an ICP. It is dedicated for III-V based etching. Etching of III-V materials that form volatile products with the etching gasses between 20 degrees and 180 degrees. Therefore very suitable for InP etching.

IBE: This is our Ion Beam etcher. It etches physically with bombarding the sample with Ar+ ions. CHF₃ can be added to bombard with more reactive ions.

	RIE2	III-V RIE	ASE	AOE	DRIE 1+2	ICP metal	III-V ICP	IBE
Purpose	Si, SiO ₂ , SiN etch on Si -with some metals. -with sensitive back sides	-SiO ₂ , SiN, polymer etching on III-V materials	-Polymer on Si -Si	-SiO ₂ on Si -SiN on Si -Quartz	-Si etching	-Al, Cr, Ti, W, Mo, Si, SiN, SiO ₂ (thin),	InP at 180°C GaAs, GaN,	Materials that do not form volatile products
Type	Parallel plate	Parallel plate	ICP incl. Bosch	ICP	ICP incl. Bosch	ICP	ICP	Ion Beam Etcher
Allowed materials (Look it up in LM)	Si based + Up to 5% other materials	III-V based materials	Si based +Al	Si based +Al (+Cr)	Si based	Si based + Al, Cr, Ti, W Mo	III-V based + Al	Almost All
Clamping and sub. Size								
Temp.								
Gasses								
Endpoint detection								↓

Allowed materials:

Not all materials are allowed in all the chambers and that can put a limit to what samples you can etch in the different chambers.

- RIE2 is the only chamber where we allow most materials BUT limited to 5% coverage of the sample or of a 4" wafers. That is about 4 cm². That can for example we gold or silver. That does NOT mean that you may try to etch gold in the chamber. It just means that you may have some gold on you sample when etching e.g. silicon. You may want to etch down to a gold layer or something like that.
- III-V materials may only enter the III-V RIE and the III-V ICP.
- ASE, AOE and the DRIEs are for silicon based etching. However Al is allowed for masking material in the ASE and the AOE. In the AOE Chromium is also allowed for masking because it gives less re-deposition problems than aluminum and is therefor sometimes need for SiO₂ etching. Please ask for allowance for this as we want to keep the Cr contamination as low as possible.
- In the 'ICP metal' silicon based materials are allowed and then we allow metals that form volatile etch product. These or Al, Cr and Ti for chlorine chemistry and W, Mo, Nb for fluorine chemistry.
- In the IBE you can have almost any material in the chamber and etching it.

Always take a look in the cross contamination sheets of the instrument. You find it in LabManager.

	RIE2	III-V RIE	ASE	AOE	DRIE 1+2	ICP metal	III-V ICP	IBE
Purpose	Si, SiO ₂ , SiN etch on Si -with some metals. -with sensitive back sides	-SiO ₂ , SiN, polymer etching on III-V materials	-Polymer on Si -Si	-SiO ₂ on Si -SiN on Si -Quartz	-Si etching	-Al, Cr, Ti, W, Mo, Si, SiN, SiO ₂ (thin),	InP at 180°C GaAs, GaN,	Materials that do not form volatile products
Type	Parallel plate	Parallel plate	ICP incl. Bosch	ICP	ICP incl. Bosch	ICP	ICP	Ion Beam Etcher
Allowed materials (Look it up in LM)	Si based + Up to 5% other materials	III-V based materials	Si based +Al	Si based +Al (+Cr)	Si based	Si based + Al, Cr, Ti, W Mo	III-V based + Al	Almost All
Clamping and sub. Size	None 4" (6")	None 4"	Electrostatic: 4"	Electrostatic: 4"	Electrostatic: 4"+6"	Electrostatic: 6"	Mechanical: 4"	Mechanical: 2" to 8"
Temp.	20°C	20°C	-10°C to 20°C	-10°C to 60°C	-20°C to 30°C	-10°C to 50°C	20°C to 180°C	-20°C to 30°C
Gasses								
Endpoint detection								↓

Clamping, substrate sizes and temperature:

The two RIE's are running with a platen temperature of 20 degrees Celsius and the samples are not clamped to the electrode. This means that the sample is not cooled very well (if at all). This works because the plasmas in the RIE's are low density plasmas that do not get so hot. The advantages of this is small samples can lie on a carrier without getting over heated. Also wafers with sensitive backside wafers with structures backsides can be processed without problems.

Most of the ICP's have electrostatic clamping. This gives the possibility of backside cooling of the wafer with He which improves the heat transfer a lot. This is very important for ICP etching with resist masks. If they are not cooled during etching they will get affected as explained earlier. Normally it has to be cooled to zero degrees or below. This can make it a challenge to etch with resist mask in the III-V ICP. Notice that the ICP metal is fixed at 6". Carriers can be used but there can be an issue that bad heat transfer.

The III-V ICP has mechanical clamping. This was chosen due to the high temperature range, that is not working will for the electrostatic clamping. Please notice that the III-V ICP can be used at 180 degrees for Indium etching, but it cannot go lower than approximately 20 degrees.

The IBE also has mechanical clamping. This system is build for 8" wafers but has different carriers for 6", 4" and 2" wafers which allow cooling of the wafers. Cooling is also important in the IBE.

	RIE2	III-V RIE	ASE	AOE	DRIE 1+2	ICP metal	III-V ICP	IBE
Purpose	Si, SiO ₂ , SiN etch on Si -with some metals. -with sensitive back sides	-SiO ₂ , SiN, polymer etching on III-V materials	-Polymer on Si -Si	-SiO ₂ on Si -SiN on Si -Quartz	-Si etching	-Al, Cr, Ti, W, Mo, Si, SiN, SiO ₂ (thin),	InP at 180°C GaAs, GaN,	Materials that do not form volatile products
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Clamping and sub. Size	None 4" (6")	None 4"	Electrostatic: 4"	Electrostatic: 4"	Electrostatic: 4"+6"	Electrostatic: 6"	Mechanical: 4"	Mechanical: 2" to 8"
Temp.	20°C	20°C	-10°C to 20°C	-10°C to 60°C	-20°C to 30°C	-10°C to 50°C	20°C to 180°C	-20°C to 30°C
Gasses	CF ₄ , SF ₆ , CHF ₃ , H ₂ , O ₂ , Ar, N ₂	CHF ₃ , CH ₄ , H ₂ , O ₂ , Ar	SF ₆ , O ₂ , C ₄ F ₈ , CO ₂ , Ar	SF ₆ , O ₂ , C ₄ F ₈ , CF ₄ , H ₂ , He	SF ₆ , O ₂ , C ₄ F ₈ , Ar	SF ₆ , O ₂ , C ₄ F ₈ , CF ₄ , H ₂ , BCl ₃ , Cl ₂ , HBr, Ar	SF ₆ , O ₂ , CF ₄ , H ₂ , CH ₄ , BCl ₃ , Cl ₂ , HBr, Ar	Ar, CHF ₃ , O ₂
Endpoint detection								↓

Here is an overview of the gasses connected on the systems.

- RIE2: Here we have F-containing gasses which are good for etching of Si, SiO₂, silicon nitrides and in principle also a few metals like W, Nb, and a few others. Hydrogen, Oxygen, Argon and Nitrogen are gasses that are typically add to the fluorine chemistry. This can be used to change passivation degree of a fluorocarbon plasma. Oxygen can also be used for etching carbon and polymers. N₂ and Ar are mainly used to dilute the gas and especially Argon is easily ionized and this will increase the sputter rate.
- The III-V RIE also have F-gas for SiO₂ etching with some of the same additive gasses – but then it also has Methane that is used for etching InP and InGaAs. Etching with methane is a dirty process that creates a lot of polymer in the chamber. The etch rates of InP and InGaAs with methane are very low compared to etching with chlorine at elevated temperatures.
- ASE: The ASE was originally for etching silicon with the Bosch process. After we got the DRIE (Pegasus) CO₂ was added and the idea was to use it for polymer etching. At the moment it still does a lot of silicon etching but also some polymer etching.
- AOE: The AOE has fluorocarbons for SiO₂ etching, SF₆ for etching silicon masking layers (to mask the SiO₂). He is used to dilute the gas to decrease the residence time for the gas. This helps to improve the selectivity between SiO₂ and a resist mask.
- DRIE1+2: The DRIE's have gasses dedicated silicon etching, specially the Bosch process but continued processes are also done here.
- ICP metal: ICP metal has almost all our gasses installed. Almost anything that form volatile etch products can be etched here except Indium containing materials, since the temperature cannot be increased to 180 degrees. However the Bosch process does not work well on this system and process stability can be an issue when mixing chlorine and fluorine gasses in the same chamber. We prefer to have chlorine processes in this chamber.
- III-V ICP: The III-V ICP has almost the same gasses as the ICP metal, but it is primarily dedicated etching of III-V materials. We try to separate the III-V materials process line from the silicon based process line.
- IBE: The IBE only has Argon, CHF₃ and O₂. It is mainly Argon that is being used for sputtering. CHF₃ can be valuable especially for sputter etching SiO₂. O₂ can be used for cleaning polymers from a sample.

Temperature and clamping:

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Clamping and sub. Size	None 4" (6")	None 4"	Electrostatic: 4"	Electrostatic: 4"	Electrostatic: 4"+6"	Electrostatic: 6"	Mechanical: 4"	Mechanical: 2" to 8"
Temp.	20°C	20°C	-10°C to 20°C	-10°C to 60°C	-20°C to 30°C	-10°C to 50°C	20°C to 180°C	-20°C to 30°C
Gasses	CF ₄ , SF ₆ , CHF ₃ , H ₂ , O ₂ , Ar, N ₂	CHF ₃ , CH ₄ , H ₂ , O ₂ , Ar	SF ₆ , O ₂ , C ₄ F ₈ , CO ₂ , Ar	SF ₆ , O ₂ , C ₄ F ₈ , CF ₄ , H ₂ , He	SF ₆ , O ₂ , C ₄ F ₈ , Ar	SF ₆ , O ₂ , C ₄ F ₈ , CF ₄ , H ₂ , BCl ₃ , Cl ₂ , HBr, Ar	SF ₆ , O ₂ , CF ₄ , H ₂ , CH ₄ , BCl ₃ , Cl ₂ , HBr, Ar	Ar, CHF ₃ , O ₂
Endpoint detection	Endpoint detection	LASER endpoint	None	None	Optical multiple λ	Optical multiple λ	Optical + LASER	SIMS ↓

Endpoint detection:

RIE2 has an optical endpoint system that looks at the plasma. It looks to find light at a fixed wavelength. In the plasma excitations take place followed by relaxation and emission of light. The wavelength of the emitted light depends on the atom being excited.

III-V RIE has a LASER endpoint system. This sends in light on the surface of the sample and detects the reflected light. With an oxide on an absorbing material for example there will be interference of the light reflected from the surface of the sample and the light reflected in the interface between the oxide and the absorbing material. This interference patterned will change as the oxide gets thinner.

Motivation: Contents of the Dry Etch Tool Package Training course



Today:

1. Motivation: Why bother about dry etching?
2. Etch Plasmas
3. Etch Mechanisms
4. Etch characteristics
5. Process Tuning
6. Equipment for dry etching at Danchip

Later:

7. Hands-on training at dry etch equipment.
 - This requires that you have watched the two sets of screen cast videos.



Now we are done with today's lecture.

The next thing is the hands-on training at the dry etch equipment. Please remember that this requires that you have watched the screen cast videos before the training.

Thank you for your attention!!!

