Semiconductor Technology from A to Z

Dry Etching

Overview

General

In wet chemical etching, layers are generally removed isotropically, yet an anisotropic etch profile is particularly important for small structures. Dry etch processes are well suited for this, offering sufficient selectivity. These processes enable reproducible, uniform etching of most layers used in semiconductor manufacturing. Besides anisotropic etch profiles, isotropic ones can also be achieved. Despite the high equipment costs and sequential single-wafer processing, dry etching has established itself over wet chemical etching.

Key parameters in dry etching

Dry etch processes are described by a small number of key parameters, which are also the target parameters of every process development effort.

Etch rate r
: The etch rate describes the material removed per unit time and is expressed, for example, in nanometers per minute or Ångström per second.

$$r=\frac{Etch\ removal\ \Delta z}{Etch\ time\ \Delta t}$$

Anisotropy factor f
: The anisotropy factor describes the ratio of the horizontal etch rate r_h to the vertical etch rate r_v.

$$f=1-\frac{r_h}{r_v}$$

For pattern transfer, strongly anisotropic processes are desired, i.e. etching only in the vertical direction, so that the resist mask is not undercut. For anisotropic etch processes, $f \to 1$, and correspondingly, for isotropic processes, $f \to 0$.

Selectivity S_{jk}
: The selectivity S_{jk} between material j and material k describes the ratio of the etch rates of two materials, e.g. of the layer to be patterned (j) and the resist mask (k).

$$S_{jk}=\frac{r_j}{r_k}$$

Whether a high or a low selectivity is desired depends on the particular process. When patterning layers, the value should be as high as possible, i.e. the layer to be patterned is removed faster than the resist mask. In reflow etchback, the

selectivity has to be 1 in order to planarize topographies uniformly.

Uniformity U
: Uniformity describes how evenly the material removal occurs – across a single wafer, from wafer to wafer, and from batch to batch. It is expressed as the spread of the etch rate relative to its mean value.

$$U=\frac{r_{max}-r_{min}}{r_{max}+r_{min}}\cdot 100\,\%$$

Aspect ratio A
: The aspect ratio is the ratio of etch depth z to feature width b. It describes how slender a trench or hole is.

$$A=\frac{z}{b}$$

As the aspect ratio increases, the etch rate decreases, because the etch species have more difficulty reaching the bottom of the structure and the reaction products are less readily transported away. This effect is known as aspect ratio dependent etching (ARDE), or RIE lag. Today it is the decisive limitation when etching deep structures, such as the memory holes in 3D NAND flash, which have aspect ratios exceeding 50:1. Typical profile defects in such etches include bowing (bulging widening in the upper region), twisting (deep holes tilting relative to one another), and microtrenching (excessive removal at the bottom corners).

Loading effect
: The etch rate depends on the total exposed area: a large area to be etched consumes more reactive species, so the etch rate decreases. Macro-loading affects the entire wafer or batch, while micro-loading affects the immediate vicinity of a single structure.

Since the etch rate depends on the state of the equipment, the gas flow, and the loading, an etch process in manufacturing is not controlled by a fixed time, but by endpoint detection. For this purpose, a spectrometer monitors the optical emission of the plasma (optical emission spectroscopy, OES) – when a layer is etched through, the intensity of characteristic lines changes because different reaction products are formed – or an interferometer measures the remaining layer thickness. Once the endpoint has been detected, a short, defined overetch time follows to reliably remove residues across the entire wafer.

Dry etch processes

In dry etch processes, gases are excited by high-frequency alternating fields, typically at 13.56 MHz and 2.45 GHz. At a pressure between 0.1 Pa and 100 Pa,

the mean free path of the particles is a few millimeters to centimeters.

Modern tools separate the generation of the plasma from the acceleration of the ions: a high-frequency generator (e.g. 13.56 MHz or 60 MHz, coupled in inductively or via microwaves) sets the charge carrier density and thus the etch rate, while a second, low-frequency generator (e.g. 400 kHz to 2 MHz) at the wafer electrode sets the ion energy and thus the physical component of the etch. This allows both quantities to be adjusted largely independently of one another. In addition, the plasma is frequently pulsed to reduce charge buildup and profile defects in deep structures.

There are generally three different types of dry etching, which are described in more detail on the following page:

- Physical dry etching: physical removal of the wafer surface by accelerated particles
- Chemical dry etching: reaction between gas and the wafer surface
- Chemical-physical dry etching: physical etching with a chemical component

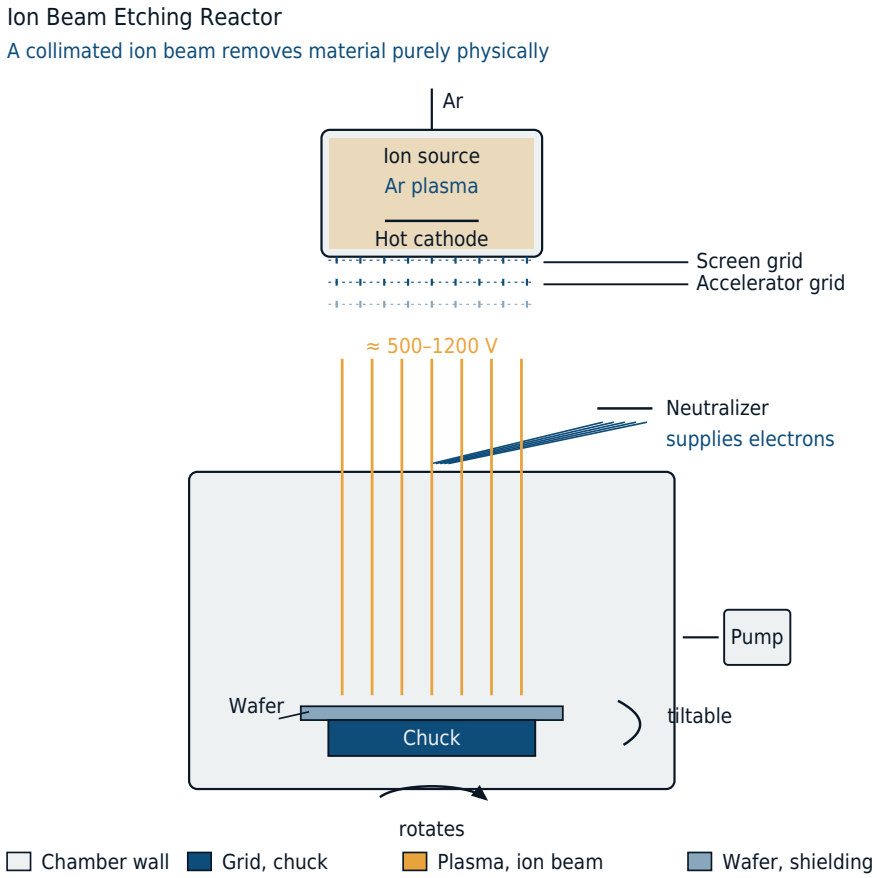
A more recent development is atomic layer etching (ALE). Here, the chemical activation of the surface and the actual removal step are separated in time and repeated cyclically, so that only one or a few atomic layers are removed per cycle. The amount removed is thus controlled not by the etch time but by the number of cycles – a prerequisite for devices whose layer thicknesses are only a few nanometers, such as gate-all-around transistors.

Dry etch processes

Ion beam etching

Ion beam etching (IBE) is a purely physical dry etch process. Here, argon ions are directed onto the wafer as a collimated ion beam with an energy of 1–3 keV. Due to the energy of the particles, they knock material out of the surface. The ions are generated in a source separated from the process chamber and extracted through a grid system; the working pressure is below 0.1 Pa, so that the ions retain their direction all the way to the wafer. The wafer is held perpendicular or tilted relative to the ion beam in the process chamber, and the etch proceeds in a completely anisotropic manner. The selectivity is only low, since the accelerated ions do not distinguish between materials. The gas and the material knocked out are extracted by the pump system; however, particles also deposit on the chamber walls and on vertical edges of the wafer itself, since the removed material does not transition into the gaseous state.

To prevent particle deposition, a reactive gas is introduced into the chamber in addition to argon. This gas reacts with the argon ions, resulting in a physical etch process with a chemical character. The gas then reacts partly with the surface, but also with the material knocked out by the physical component, to form a gaseous reaction product. If the reactive gas is already added within the ion source, this is called reactive ion beam etching (RIBE); if it is introduced only in front of the wafer, it is called chemically assisted ion beam etching (CAIBE).



With this process, almost all materials can be etched. Due to the perpendicular irradiation, removal at vertical edges is very low (high anisotropy).

Because of its low selectivity and low etch rate (low ion density in the beam), ion beam etching no longer plays a role in patterning silicon and silicon compounds. It is, however, indispensable for materials that do not form volatile reaction products and are therefore hardly etchable by chemical means:

- magnetic layer stacks, such as the tunnel elements of MRAM memory cells

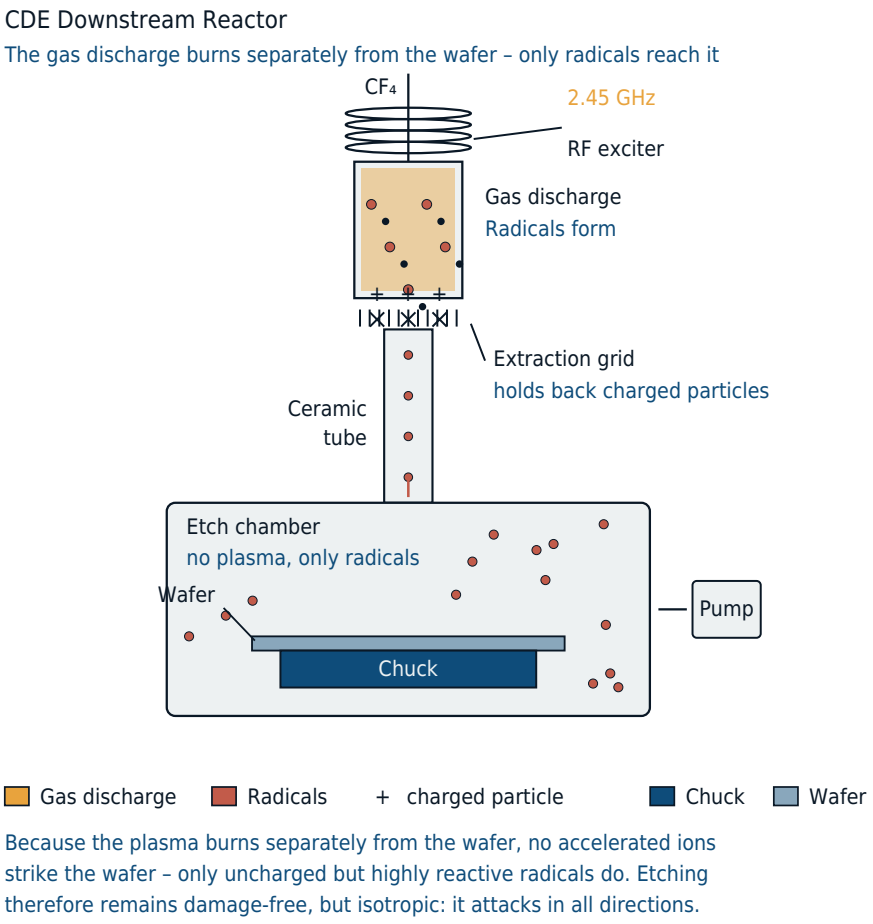
made of CoFeB and MgO, as well as read heads and magnetic field sensors
- noble metals such as platinum, iridium, and ruthenium
- piezoelectric and ferroelectric layers such as PZT
- lithium niobate and similar crystals in integrated photonics

The tiltable, rotating substrate holder is a significant advantage here: the angle of incidence can be used to set the sidewall angle of the structure and to remove redeposited material from the sidewalls – for layer stacks made up of many different materials, a result that cannot be achieved with plasma chemical processes. Since insulating substrates would charge up under ion bombardment, the source operates with a neutralizer that adds electrons to the beam.

Plasma etching

Plasma etching is a purely chemical etch process (chemical dry etching, CDE). Its advantage is that the wafer surface is not damaged by accelerated ions. Because of the freely moving gas particles, the etch profile is isotropic, which is why plasma etching is mostly used for removing entire layers at a high etch rate.

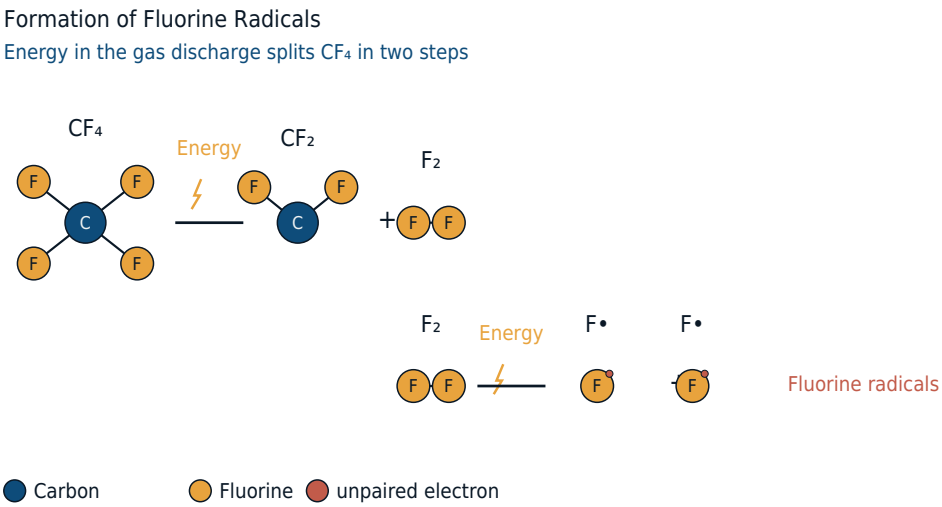
One type of equipment used for plasma etching is the downstream reactor. Here, a plasma is generated by impact ionization through the application of a high-frequency voltage (e.g. 2.45 GHz). The space where the gas discharge occurs is separated from the wafer, and the gas reaches the wafer via a ceramic tube.



In the gas discharge zone, various species are formed through collisions between the gas molecules, including radicals. Radicals are molecules with a broken bond, made highly reactive by an unpaired outer electron. As a neutral gas, tetrafluoromethane CF_4 (also known as carbon tetrafluoride), for example, is introduced and broken down by the alternating voltage into CF_2 and a fluorine molecule F_2. Fluorine can likewise be split off from CF_4 by adding oxygen:

$$2CF_4 + O_2 \rightarrow 2COF_2 + 2F_2$$

The fluorine molecule can then be split into two individual fluorine atoms by the energy present in the gas discharge zone: fluorine radicals (radicals are uncharged particles; a single fluorine atom has nine protons in its nucleus and nine electrons in its electron shell).



In addition to the neutral radicals, further particles are formed, some of them charged ($CF4^+$, $CF3^+$, $CF2^+$, ...), which are all carried together through the gas tube to the etch chamber. Charged particles are either intercepted by an extraction grid or recombine back into neutral molecules on the way. The fluorine radicals, too, are partly recombined again. Nevertheless, enough radicals reach the etch chamber, where they react with the wafer surface. Neutral particles do not take part in the reaction and, like the resulting reaction products, are extracted by the pump system.

Examples of layers etched using the CDE process:

Silicon: $Si + 4F \rightarrow SiF_4$
Silicon dioxide: $SiO_2 + 4F \rightarrow SiF_4 + O_2$
Silicon nitride: $Si_3N_4 + 12F \rightarrow 3SiF_4 + 2N_2$

Present-day relevance

Purely chemical dry etching is unsuitable for patterning layers, because the isotropic profile undercuts the mask. As a remote or downstream process – the plasma burns separately from the wafer, and only long-lived neutral radicals reach it – it fulfills clearly defined tasks in manufacturing, however:

- Resist removal (ashing): oxygen radicals burn off the photoresist after etching or implantation into CO_2 and H_2O.
- Chamber cleaning: nitrogen trifluoride NF_3 is dissociated in an upstream plasma source; the fluorine radicals remove deposits from process chambers without the chambers having to be opened.
- Selective etchback: radical processes based on NH_3 and NF_3 remove native oxide and thin nitride layers without causing damage – even inside contact

holes, which a directional etch can only reach with difficulty.
- Channel release: in nanosheet or gate-all-around transistors, silicon-germanium is removed isotropically and selectively against silicon in order to release the channel layers. Here, the isotropy that is a nuisance in patterning is deliberately exploited.

Reactive ion etching

In reactive ion etching (RIE), the etch characteristics – selectivity, etch profile, etch rate, uniformity, reproducibility – can be precisely adjusted through the gases used and the process parameters (generator power, pressure, electrode spacing, gas flow). Both an isotropic and an anisotropic etch profile are possible. This makes RIE, a chemical-physical etch process, the most important etch process for patterning various layers in semiconductor manufacturing.

Inside the process chamber, the wafers sit on an electrode fed with an alternating voltage (RF electrode). Impact ionization generates a plasma containing free electrons and positively charged ions. When the RF electrode is at a positive voltage, electrons accumulate on it and, due to the work function, cannot leave it during the positive half-cycle; the electrode thus charges up negatively to as much as 1000 V (bias voltage). The slow ions, which could not follow the fast alternating voltage, now move toward the negatively charged electrode carrying the wafers.

If the mean free path of the ions is long, the particles strike the wafers at nearly perpendicular incidence due to their velocity. Material is thereby knocked out of the surface by the accelerated ions (physical etching), while some particles also react chemically with the substrate. Vertical sidewalls are not struck, so no removal occurs there and the etch profile remains anisotropic. The selectivity is not very high because of the physical removal component, and in addition the wafer surface is damaged by the accelerated ions. This damage later has to be repaired by thermal treatment.

The chemical component of the etch occurs through the reaction of free radicals with the wafer surface and with the physically removed material, so that this material, unlike in ion beam etching, cannot redeposit on the chamber walls or on the wafers. As the pressure is increased, the mean free path of the particles decreases, so that many collisions occur between particles on their way to the wafer, continuously changing their direction. Directional etching of the wafer surface then no longer occurs; the etch process takes on a more chemical character, the etch profile becomes isotropic, and the selectivity increases.

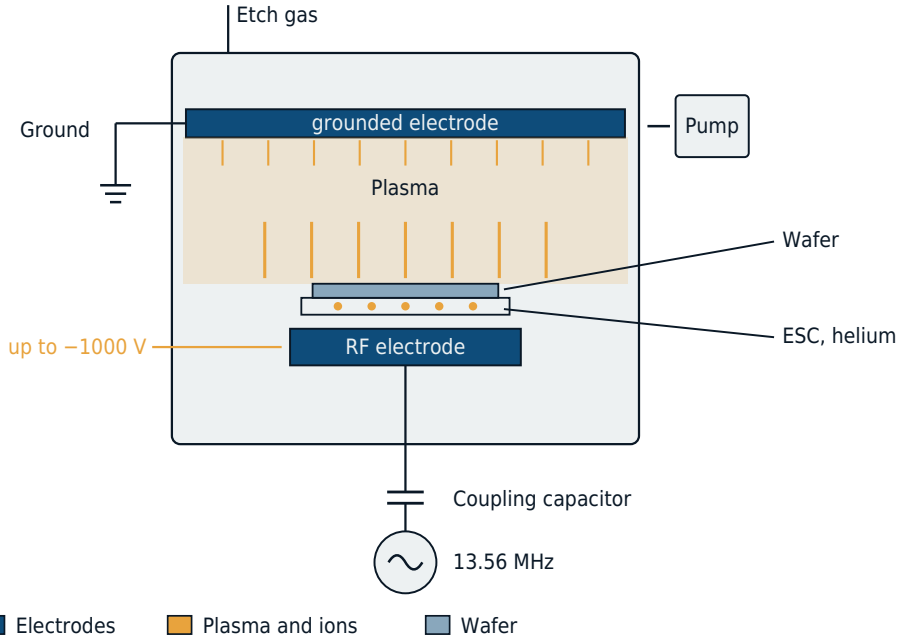
The hexode design etched several wafers simultaneously on a six-sided carrier. Such batch tools are today only of historical interest, because uniformity and

endpoint can no longer be controlled with sufficient precision across many wafers.

Today, etching is carried out exclusively on a single-wafer basis in a parallel-plate configuration. The wafer rests on an electrostatic chuck (ESC), which holds it flat and thermally couples it to the temperature-controlled electrode via helium on the wafer backside. This allows wafer temperatures to be set from about −100 °C up to over 100 °C – temperature is one of the most effective control parameters for selectivity and profile.

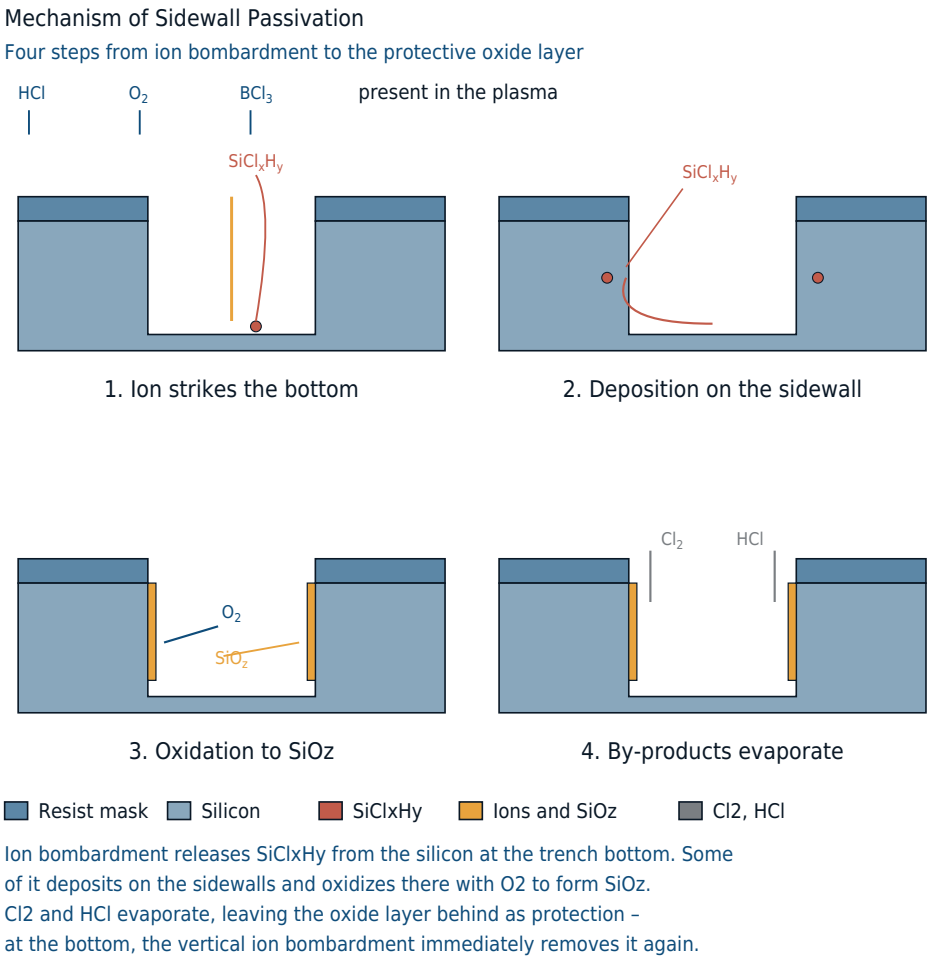
Reactive Ion Etching

Parallel-plate design: the wafer sits on the RF electrode



Because the lower electrode is smaller than the upper one, it charges negatively relative to the plasma. This accelerates the positive ions perpendicular to the wafer, removing material directionally – the etch profile becomes anisotropic.

An anisotropic etch profile is achieved in silicon etching through passivation of the sidewalls. Here, oxygen in the process chamber reacts with silicon released from the wafer surface to form silicon dioxide, which grows on the vertical sidewalls. An oxide layer on horizontal surfaces is removed by ion bombardment, allowing the etch to proceed further into the depth.



The etch rate depends in every case on the pressure, the power of the RF generator, the process gases, the gas flow rate, and the wafer or electrode temperature.

Anisotropy increases with rising RF power, decreasing pressure, and decreasing temperature. The uniformity of the etch is determined by the gases, the electrode spacing, and the electrode material. If the electrode spacing is too small, the plasma is not distributed evenly within the chamber, leading to non-uniformity. As the spacing increases, the etch rate decreases, since the plasma is spread over a larger volume. Carbon was formerly used as the electrode material: since fluorine and chlorine gases also remove carbon, the electrode causes a uniform loading of the plasma, so that the wafer edge is not stressed more than the wafer center. Today, electrodes made of silicon, silicon carbide, or quartz are common; the chamber parts facing the plasma are coated with yttrium oxide or aluminum oxide to prevent particles and metallic contamination.

Further developments of reactive ion etching

The classic RIE reactor couples plasma density and ion energy through the same electrode: more power simultaneously means more etch rate and more damage. Today's generations of equipment decouple these two quantities and extend the process in several directions.

High-density plasma sources
: In inductively coupled plasma (ICP, also TCP) tools, a coil above a dielectric window generates the plasma; in ECR tools, a microwave in a magnetic field does so. The ion energy is set separately via a bias generator at the wafer electrode. The result is high etch rates at low ion energy, i.e. less damage, at pressures well below 1 Pa.

Multi-frequency tools
: For etching dielectrics, capacitively coupled reactors operate with two or three generators of different frequencies on the same electrode, in order to set ion density, ion energy, and energy distribution separately. For deep structures, bias voltages of several kilovolts are used.

Pulsed plasma
: If the supplied power is pulsed in the kilohertz range, charge buildup in deep structures decays between pulses. This reduces profile defects such as bowing and notching and improves selectivity.

Deep etching (DRIE, Bosch process)
: In deep reactive ion etching, very short etch steps using SF_6 alternate cyclically with passivation steps using C_4F_8. This produces trenches with aspect ratios above 30:1 and depths of several hundred micrometers. The cyclic sequence leaves a wavy sidewall (scalloping). The main applications are micromechanical devices (MEMS) and through-silicon vias.

Cryogenic etching
: At wafer temperatures around −100 °C, reaction products condense on the cold sidewalls and passivate them, while ion bombardment keeps the bottom clear. This yields smooth, vertical sidewalls without scalloping. For several years, this process has also been used in volume production for etching the memory holes in 3D NAND flash: at depths of around 10 µm and aspect ratios above 50:1, the low temperatures allow etch chemistries that do not work at room temperature, and roughly double the etch rate of conventional dielectric processes.

Atomic layer etching (ALE)
: Surface activation and removal are split into separate, self-limiting half-steps and repeated cyclically. The removal per cycle is on the order of one atomic layer, controlled via the number of cycles. ALE is used wherever individual nanometers determine functionality, such as in releasing channels and etching gate structures.

Selectivity and etch rate can be strongly influenced by the etch gases used. For silicon and silicon compounds, chlorine and fluorine are primarily employed.

Etch gases used in dry etching

Processes do not necessarily run with a single gas mixture and constant etch parameters throughout. Native oxide on polysilicon, for example, can first be removed with a high etch rate and low selectivity. The polysilicon is then etched with high selectivity to the underlying layer. Real-world recipes therefore consist of several steps with different gas mixtures, powers, and pressures.

The following table gives an overview of gases used in dry etching.

Layer	Process gases	Remark
SiO_2, Si_3N_4	CF_4, O_2	F etches Si, O_2 removes carbon (C)
	CHF_3, O_2	CHF_3 acts as a polymer, increased selectivity against Si
	CHF_3, CF_4	
	CH_3F, CH_2F_2	improved selectivity of Si_3N_4 against SiO_2
	C_2F_6 / SF_6	
	C_3F_8	increased etch rate compared to CF_4
	C_4F_6, C_4F_8 + O_2, Ar	standard chemistry for deep structures (contact holes, memory holes in 3D NAND); the carbon-rich molecules form a polymer layer on the mask and sidewall, O_2 controls its thickness
	BCl_3, Cl_2	no contamination by carbon (C)
	$SiCl_4$, Cl_2 / HCl, O_2 / $SiCl_4$, HCl	
Poly-Si	HBr / Cl_2 / O_2	improved selectivity against photoresist and SiO_2; standard chemistry for gate structures
	SF_6	high etch rate, good selectivity against SiO_2
	NF_3	high etch rate, isotropic
	HBr, Cl_2	
	HBr, NF_3, O_2	higher selectivity against SiO_2
monocrystalline Si	BCl_3, Cl_2 / HBr, NF_3	
	SF_6 / C_4F_8 SF_6, O_2	deep etching: cyclic in the Bosch process, or at low temperatures in the cryogenic process
	Cl_2	isotropic etching
Al alloys	BCl_3	only low etch rate, additionally binds residual moisture and native Al_2O_3
	BCl_3 / Cl_2 / CF_4	anisotropic etching
	BCl_3 / Cl_2 / CHF_3	improved sidewall passivation
	BCl_3 / Cl_2 / N_2	higher etch rate, no carbon contamination

W, TiN, Ti	SF_6 / NF_3	etchback of tungsten in contact holes
	Cl_2, BCl_3	barrier and metal gate layers

Historically, bromine-containing chlorofluorocarbons such as CF_3Br were also used for monocrystalline silicon. As ozone-depleting substances, they are banned under the Montreal Protocol and have been replaced in manufacturing by HBr mixtures.

Metallization: why copper is not etched

Etching of aluminum alloys has become less important with the transition to copper interconnects. Copper does not form compounds with chlorine or fluorine that are volatile at process temperature and can therefore practically not be dry-etched. Instead, in the damascene process, the trench is first etched into the dielectric, copper is then deposited, and the excess is removed by chemical mechanical polishing. Aluminum continues to be patterned for bond pads as well as in power and analog technology.

Climate impact of the process gases

The perfluorinated etch and cleaning gases are chemically extremely stable – precisely the property that makes them useful in the process. In the atmosphere, they are therefore barely broken down and act as very potent greenhouse gases. According to the sixth IPCC report, the 100-year global warming potentials are around 7,400 for CF_4, around 12,400 for C_2F_6, around 14,600 for CHF_3, around 17,400 for NF_3, and around 25,000 for SF_6. Based on current estimates, CF_4 remains in the atmosphere for several tens of thousands of years.

On the manufacturing side, the exhaust of every tool is treated individually (point-of-use abatement), either thermally, catalytically, or in a plasma torch. Reactive gases such as NF_3 are broken down by more than 99 %, but CF_4 only partially; moreover, it is also formed as a decomposition product of other fluorine compounds. The contribution is therefore reduced primarily at the process level itself: by replacing C_2F_6 with NF_3 for chamber cleaning, lower gas flows, shorter etch times, and processes such as cryogenic etching with a higher etch rate. Regulatorily, these substances are covered by the EU regulation on fluorinated greenhouse gases; in addition, a restriction on PFAS is being discussed under REACH, with exemptions and long transition periods so far for semiconductor manufacturing.

Special Case: Bosch Process (Deep Reactive Ion Etching)

An important advancement of reactive ion etching is the Bosch process (DRIE), which uses a cyclic alternation of etch and passivation steps to achieve

extremely high aspect ratios with nearly vertical sidewalls – significantly more than continuous etching could achieve.

Since it is used primarily in microsystems technology to pattern deep trenches and to singulate MEMS devices, it is described in detail in the Micromechanics section: DRIE: Deep Reactive Ion Etching.

Reactor Types

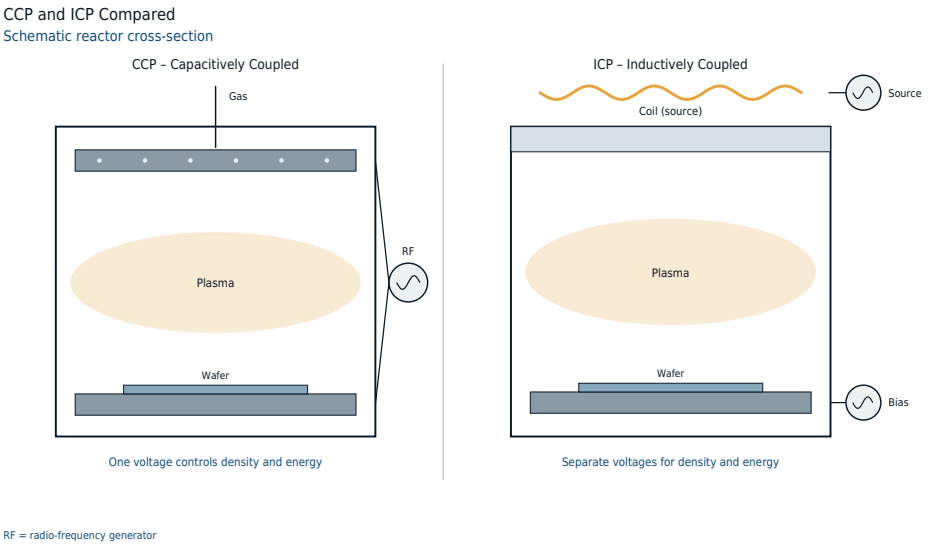
General: Structure of a Dry Etch Tool

Every dry etch tool consists of the same basic components: a process chamber, a gas inlet – often designed as a so-called showerhead directly above the wafer for uniform gas distribution – a pumping system made up of a turbomolecular pump and a backing roughing pump for the required vacuum, RF coupling for plasma generation, and the wafer chuck.

How these components are implemented in detail differs strongly between reactor types – and largely determines which processes a given tool can perform.

Reactor Types: CCP and ICP in Practice

As described in the Deposition section, in capacitively coupled reactors (CCP) the same voltage determines both ion density and ion energy – the two cannot be set independently. Inductively coupled reactors (ICP) separate these two quantities using a separate bias voltage at the wafer electrode.



This separation matters especially for etching: a high etch rate needs many reactive species, i.e. a high ion density, while a clean anisotropic profile needs controlled, not too high, ion energy. The construction differs accordingly: CCP reactors often use silicon or SiC electrodes as consumable material to avoid metal contamination of the wafer; the chamber walls are usually anodized aluminum, which must withstand the aggressive fluorine and chlorine radicals. In ICP reactors, the coil sits outside a dielectric chamber window made of quartz or ceramic, through which the alternating field can penetrate.

The achievable ion density with ICP is typically 10 to 100 times higher than with CCP – the main reason why ICP is the standard today for demanding etch processes with high aspect ratios.

Electron Cyclotron Resonance (ECR)

In ECR reactors, a combination of microwave coupling – usually at 2.45 GHz – and a magnetic field generates very high plasma densities at particularly low pressure. The microwave frequency is tuned precisely to the electron cyclotron resonance frequency in the magnetic field, enabling very efficient energy transfer.

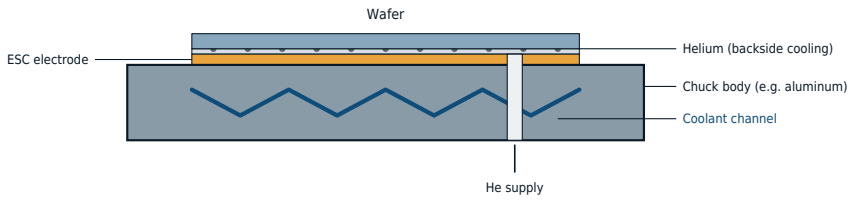
Historically, ECR was an important precursor to today's ICP technology, but has largely been displaced by ICP due to the more complex and expensive equipment – additional magnetic coils, a microwave source instead of a simple RF generator. It is still used in niche applications that require particularly low ion energies combined with high density, for example with especially damage-sensitive layers.

Wafer Chuck: Temperature Control and Electrostatic Clamping

The electrostatic chuck (ESC) holds the wafer flat and mechanically stable during the process, without mechanical clamps that could damage or shadow the wafer edge.

Physically, the ESC behaves like a capacitor: the DC voltage at the electrode charges one side of the thin dielectric, while an opposite mirror charge builds up on the wafer backside. The resulting electrostatic attraction presses the wafer against the surface. For simple Coulomb-type chucks, the applied voltage alone is enough; Johnsen-Rahbek chucks additionally use a slightly conductive dielectric layer and achieve considerably higher clamping forces – though with a slower release after the process, since the charge first has to dissipate.

Wafer Chuck: Clamping and Cooling
Schematic cross-section



Electrostatic clamping via DC voltage at the electrode

ESC = Electrostatic Chuck

Since there is no convection in vacuum, targeted backside cooling with helium gas – fed through fine channels between the chuck and the wafer backside – provides the necessary heat transfer. This temperature control is critical: etch rate, selectivity and profile shape all depend strongly on wafer temperature, which is why modern chucks regulate temperature to within a few degrees, both throughout the process and across the wafer.

Compound Semiconductors and High-k Materials

Why These Materials Are a Special Case

The gas overview in the Dry etch processes chapter covers the standard materials of silicon manufacturing: silicon, silicon dioxide, silicon nitride, polysilicon and aluminum. Some material systems, however, cannot be etched

well – or at all – with the same chemistries, either because they are too chemically inert, or because the resulting reaction products are not volatile enough at process temperature.

III-V Compound Semiconductors (GaAs, InP, GaN)

III-V semiconductors such as gallium arsenide, indium phosphide or gallium nitride cannot be etched with fluorine chemistry – the resulting fluorides are not volatile enough at process temperature. Chlorine chemistry (BCl_3, Cl_2) is used instead, forming volatile chlorides with the group III elements.

One challenge is that the different elements of a compound react at different rates – for GaAs, for example, the chemistry must be tuned so that gallium and arsenic are removed at comparable rates. Otherwise the surface becomes depleted of one element, and etching stalls or the surface roughens.

Silicon Carbide (SiC)

Silicon carbide is chemically extremely inert – the very property that makes it valuable for high-temperature and power applications makes it significantly harder to pattern. Dry etching SiC requires fluorine chemistry, usually SF_6-based, with considerably higher ion energy than for silicon, in order to break the strong Si-C bonds.

Etch rates are correspondingly lower, and the mask erodes faster – for deep structures, the mask thickness must therefore be more generous than for comparable silicon processes.

High-k Dielectrics (HfO_2 and Others)

Hafnium oxide (HfO_2) and related high-k materials, which replace classic silicon dioxide as the gate dielectric in modern gate stacks, form only poorly volatile reaction products with fluorine or chlorine compounds. Etching is usually done with BCl_3-based chemistries, often assisted by a stronger physical component – i.e. ion bombardment – to mechanically remove the reaction products from the surface rather than relying purely on chemical volatilization.

The process windows are narrow, since the extremely thin high-k layers – often just a few nanometers – do not tolerate over- or under-etching.