SEMICONDUCTOR FRONT-END · PART 3-8

Plasma Etching How a glowing gas cuts straight down

Lithography creates a pattern in resist. **Etching** transfers that pattern into the material underneath. The challenge is to remove the exposed film without widening the features, consuming the mask or damaging the next layer. Plasma etching brings together two useful capabilities: reactive species provide the chemistry, while electrically accelerated ions help direct removal towards the bottom of a feature. This lesson explains how that combination works, how reactors control it, and how equipment, gases and chamber materials contribute to the process.

Semiconductor Front-End Series · Part 3, Lesson 3-8 · Level ★★★

Suggested preparation: Lessons 3-3 and 3-5 · Updated 7 November 2026

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How to read this lesson

Reported identifies information stated in the cited source, including attributed company estimates; Calculation identifies an estimate worked out in this lesson; Outlook marks forecasts and roadmap requirements; Interpretation marks an illustrative judgement. Standard physical explanations are generally untagged. Figures are schematic and not to scale. Numbered links lead to the supporting sources.

What you will learn

- Explain why an etch can remove material sideways as well as downwards, and distinguish directionality from selectivity.
- Describe how a sheath forms and why positive ions can arrive mainly normal to a wafer surface.
- Connect ion-assisted reactions and sidewall protection to the shape of a finished feature.
- Compare the roles of reactor suppliers, gas producers, chamber-component makers and exhaust systems without treating them as one market.

1. The idea in three steps

- **A mask defines where material may be removed.** An isotropic process can also reach underneath the mask. Fine pattern transfer therefore often calls for directional plasma etching, although wet and other dry processes remain useful elsewhere.
- **Chemistry and ion bombardment do different jobs.** Reactive neutral species help turn the surface into removable products. A sheath accelerates positive ions towards the wafer, helping reactions and clearing protective material at the feature bottom. Passivation suppresses unwanted lateral removal.
- **The recipe is a balance.** Gas composition, pressure, plasma generation, wafer bias and temperature must work together. The equipment is supported by specialised gases, plasma-resistant parts, vacuum pumping and exhaust treatment.

2. Removing material without losing the pattern

Why a liquid etch can widen an opening

Imagine cutting a narrow opening in a stencil, then using it to remove a layer underneath. If the removal proceeds equally in every direction, the exposed layer recedes downwards but also retreats beneath the stencil edges. The opening in the finished layer becomes wider than the opening in the mask. This lateral retreat is **undercut**.

Explanation

Wet etching removes material with liquid chemicals. An important example is silicon dioxide in hydrofluoric acid:

A chemical route for removing oxide

$SiO_2 + 6HF \rightarrow H_2SiF_6 + 2H_2O$

MIT's teaching material gives an example oxide etch rate of roughly 120 nm/min for its stated 6:1 diluted-HF condition, with an oxide-to-silicon selectivity of about 100. Concentration, film properties and temperature affect the actual result [2]. These numbers illustrate a process condition, rather than a universal HF etch rate. Reported

Oxide removal of this kind is **isotropic**: the material can be removed laterally as well as vertically. As feature sizes shrank, the sideways loss became a serious obstacle to accurate pattern transfer. A Semiconductor History Museum account places the growing importance of undercut control around the 3 μm generation in the mid-1970s [10]. Reported

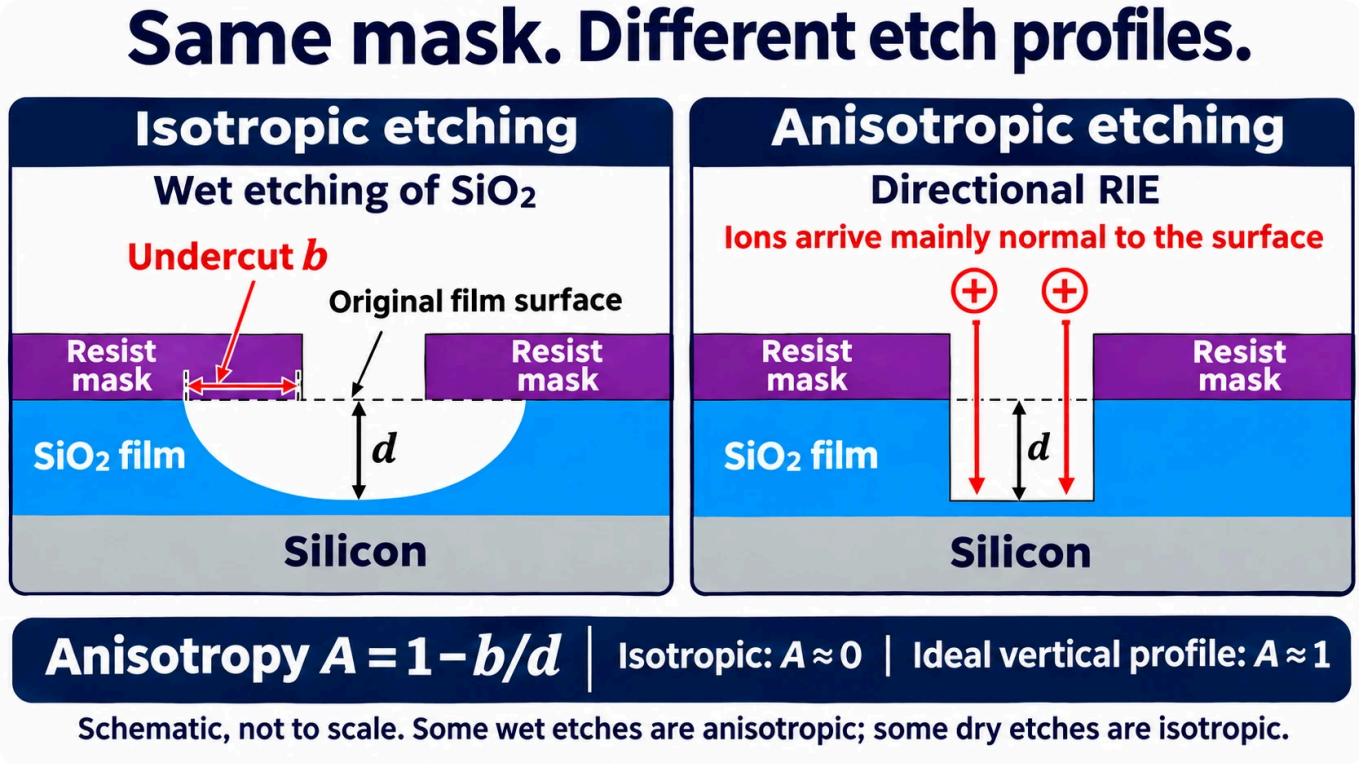


Figure 1 **Isotropic and anisotropic etching through the same mask** (schematic)

Reading the figure

The left-hand cavity extends beneath the mask; the right-hand trench illustrates a directional RIE process. Here, b is the lateral undercut beneath one mask edge and d is the vertical depth measured from the original film surface. The same mask opening can produce very different profiles. These are examples, not a rule that every wet etch is isotropic or every dry etch is anisotropic [1].

- **Two separate questions: which material, and which direction?**

Selectivity is an etch-rate ratio: the rate for the target material divided by the rate for a material we want to preserve, such as the mask or the underlying layer. If a film etches at 100 nm/min and the mask at 5 nm/min, the film-to-mask selectivity is 20:1. Calculation

Anisotropy describes directional dependence. For the simple profile in the figure, one teaching definition is **A = 1 − b/d**. An isotropic profile has b ≈ d and A ≈ 0; negligible undercut gives A ≈ 1 [1]. This measure describes lateral retreat, not every possible aspect of sidewall shape. Reported

MIT gives illustrative selectivities of 20-50 for chemical etching and 1-5 for predominantly physical sputter etching [2]. The broad lesson is that chemistry can distinguish between materials, whereas physical bombardment can provide direction but often removes different materials less selectively. Modern plasma recipes combine the two [1]. Reported

Wet processing still has important roles in cleaning and selective removal. Some wet silicon etches are strongly dependent on crystal orientation and therefore anisotropic. Conversely, a dry process dominated by neutral reactive species can be isotropic. **Wet/dry describes the process medium; isotropic/anisotropic describes the resulting directionality.** [1] Explanation

3. What is inside an etching plasma?

- **A gas with a small population of charged particles**

An electric field transfers energy to electrons. Collisions between energetic electrons and gas molecules can cause excitation, dissociation or ionisation. The result contains electrons, ions, ordinary neutral particles and reactive fragments. This mixture is a **plasma**. Explanation

An aurora, a neon lamp and an etching discharge all involve light emitted by excited particles, although their conditions and purposes differ greatly.



An aurora over Flakstad in Norway's Lofoten Islands, according to the Commons description. Incoming energetic particles excite atmospheric species, which emit light. An etching discharge also emits light when particles are excited, but is engineered to drive controlled surface reactions. **Explanation**

Image: Johannes Groll / Wikimedia Commons / CC0. Resized and converted to WebP.

Most particles in many processing plasmas remain neutral. A University of Texas lecture gives representative capacitively coupled plasma (CCP) ionisation fractions of 10^{-6}-10^{-3} and plasma densities of 10^{8}-10^{10} cm^{-3} [6]. These are teaching ranges for particular classes of discharge, not limits on every CCP tool. **Reported**

The ideal-gas relation provides a useful scale. At about 293 K, the neutral-gas density is approximately $\mathbf{n_g = 3.3 \times 10^{16}\ p}$ cm^{-3}, with p in Torr [4]. At 10 mTorr, that is around 3.3×10^{14} cm^{-3}. An ion density of 10^{10} cm^{-3} would therefore correspond to a fraction of roughly 3×10^{-5}, using a simple singly ionised estimate. **Calculation**

Energetic electrons do not mean a furnace-hot wafer

Electron temperatures of about 2-4 eV appear in Berkeley's CCP examples [4]. Expressed as a temperature scale, 1 eV corresponds to approximately 11,600 K, so 2-4 eV is roughly 23,000-46,000 K. **Calculation**

That does **not** mean the wafer, chamber or entire gas is at that temperature. Electrons are extremely light. In elastic collisions they transfer relatively little energy to heavy particles; in inelastic collisions their energy can excite, dissociate or ionise molecules. Energy is continually supplied and lost, so the electrons and heavy particles need not share one temperature [4][6]. **Explanation**

The wafer nevertheless receives heat from reactions and particle bombardment. A temperature-controlled stage removes or supplies heat. Low-temperature plasma processing therefore means that useful reactive species can be generated without heating the whole gas to the electron temperature; it does not mean that the wafer automatically stays at room temperature. **Explanation**

Reactive does not necessarily mean charged

A fluorine radical, F, is a reactive neutral atom. CF_3 is another example of a reactive fragment. Such species can participate in surface chemistry without being accelerated towards the wafer by the sheath in the way positive ions are.

Simplified reaction sketches are:

CF_4 + electron energy → CF_3 + F + other collision products

Si + 4F → SiF_4 (gas)

These sketches convey dissociation and removal; they are not a complete elementary-reaction mechanism [4].

4. The sheath gives positive ions a direction

- **Electrons reach surfaces much more readily**

The bulk plasma is usually **quasi-neutral**: positive and negative charge densities approximately balance. Where electrons and singly charged positive ions dominate, their number densities are similar. Electronegative gases may also contain negative ions, so quasi-neutrality does not always mean equal electron and positive-ion counts. Explanation

Charge balance does not imply equal particle speeds. An argon ion is approximately 73,000 times heavier than an electron, using argon's approximate atomic mass and the proton-to-electron mass ratio of 1,836.15 [14]. Calculation

A speed comparison, with its assumptions stated

At the same kinetic-energy scale, speed varies as $1/\sqrt{m}$. The electron-to-Ar^+ speed ratio is therefore about $\sqrt{73{,}000} \approx 270$.

If the electrons have a characteristic energy of 2-4 eV while the ion thermal-energy scale is about 0.026 eV, a room-temperature example, the ratio becomes approximately **2,400-3,400**. Calculation

This compares characteristic random motion. It is not a calculation of the directed ion speed after acceleration through a sheath.

Electrons initially escape to surfaces more readily than ions. A potential difference develops that limits electron loss and accelerates positive ions out of the plasma. The plasma potential is consequently higher than the adjacent surface potential [1][6]. Reported

A higher **potential** does not require the entire plasma volume to carry a large excess of positive charge. The bulk remains approximately neutral; substantial charge separation occurs mainly in the boundary layers. Explanation

An electron-poor layer beside the wafer

The boundary region is the **sheath**. Its electric field accelerates positive ions towards the surface. Above a flat wafer, that field is mainly normal to the wafer. If the sheath is sufficiently collisionless, the ions arrive with a strong preference for that direction [1][6]. Reported

The Texas lecture gives illustrative sheath thicknesses of a few millimetres and ion energies of 10-40 eV without a large added bias; additional wafer bias can raise the energy towards 1,000 eV in the examples discussed [6]. These values depend on reactor and operating conditions. Modern recipes choose energies for the material and damage budget rather than aiming for the largest value. Explanation

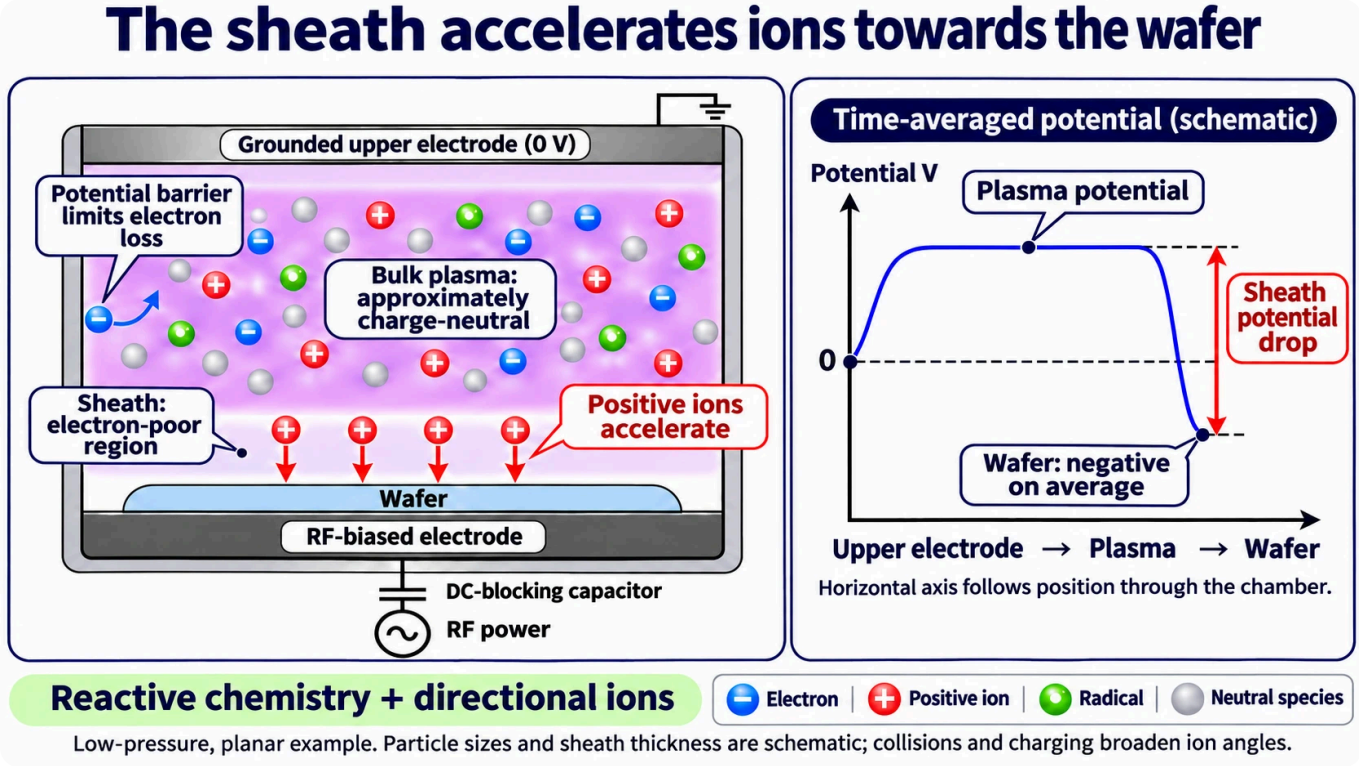


Figure 2 **Sheath acceleration and the potential drop towards the wafer** (schematic)

Reading the figure

The bulk is approximately charge-neutral; the sheath beside the wafer is depleted of electrons. The graph follows a path from the grounded upper electrode through the plasma to the biased wafer, with that path laid out horizontally. It shows a time-averaged concept, not a measured waveform or a scaled sheath thickness. The plasma-to-wafer potential drop accelerates positive ions [1][4][6].

Real ion arrivals have an angular distribution. Collisions, feature geometry and local charging can send some ions towards sidewalls. Directional acceleration is essential, but it does not guarantee a perfectly vertical trench on its own. Explanation

Why an RF electrode can acquire a negative self-bias

In a conventional capacitively coupled RIE arrangement, an RF supply drives the wafer electrode through a **DC-blocking capacitor**. Electrons and ions respond differently over an RF cycle. Charge accumulates until the time-averaged current is consistent with the blocking circuit. In an asymmetric arrangement, the powered electrode can acquire a negative DC offset: **self-bias** [4][6]. Reported

The Berkeley notes describe a sheath-voltage ratio of the form $V_a/V_b = (A_b/A_a)^q$, with experimental q values around 1-2.5 [4]. The smaller electrode tends to have the larger sheath voltage. Placing the wafer there directs more ion acceleration towards it [1][3]. This is an explanatory model, not a universal formula for every modern reactor. Explanation

Why 13.56 MHz appears so often

Many introductory reactor examples use 13.56 MHz [1][4]. The cited US regulations and international frequency-allocation provisions identify 13.56 MHz, with a ±7 kHz band, for industrial, scientific and medical applications [15] [16]. Reported

That allocation helps explain its widespread use, but it is not a special frequency at which every gas becomes a good etchant. Reactors also use other frequencies, microwave excitation, pulsed supplies and combinations of sources. The choice affects power coupling and particle-energy distributions as well as engineering practicality. Explanation

5. Chemistry and ions can do more together

A classic experiment separated the two contributions

In 1979, J. W. Coburn and H. F. Winters at IBM reported work on ion- and electron-assisted gas-surface chemistry [12]. A widely reproduced experiment exposed silicon to xenon difluoride, XeF_2, an argon-ion beam, or both. Separating the chemical supply from the ion beam made it possible to see their combined effect [1][5][6]. Reported

Approximate readings from the Stanford teaching figure give the following scale. These are readings from that illustration, not a new transcription of the original experimental data. Calculation

Exposure	Approximate silicon etch rate
XeF_2 gas alone	0.5 nm/min
XeF_2 and Ar^+ together	5.5-6.7 nm/min
Ar^+ alone	0.2-0.3 nm/min

Adding the separate rates gives only about 0.7-0.8 nm/min. The combined result is much larger: roughly an order-of-magnitude enhancement under those conditions, rather than simple addition [1][5][6]. Explanation

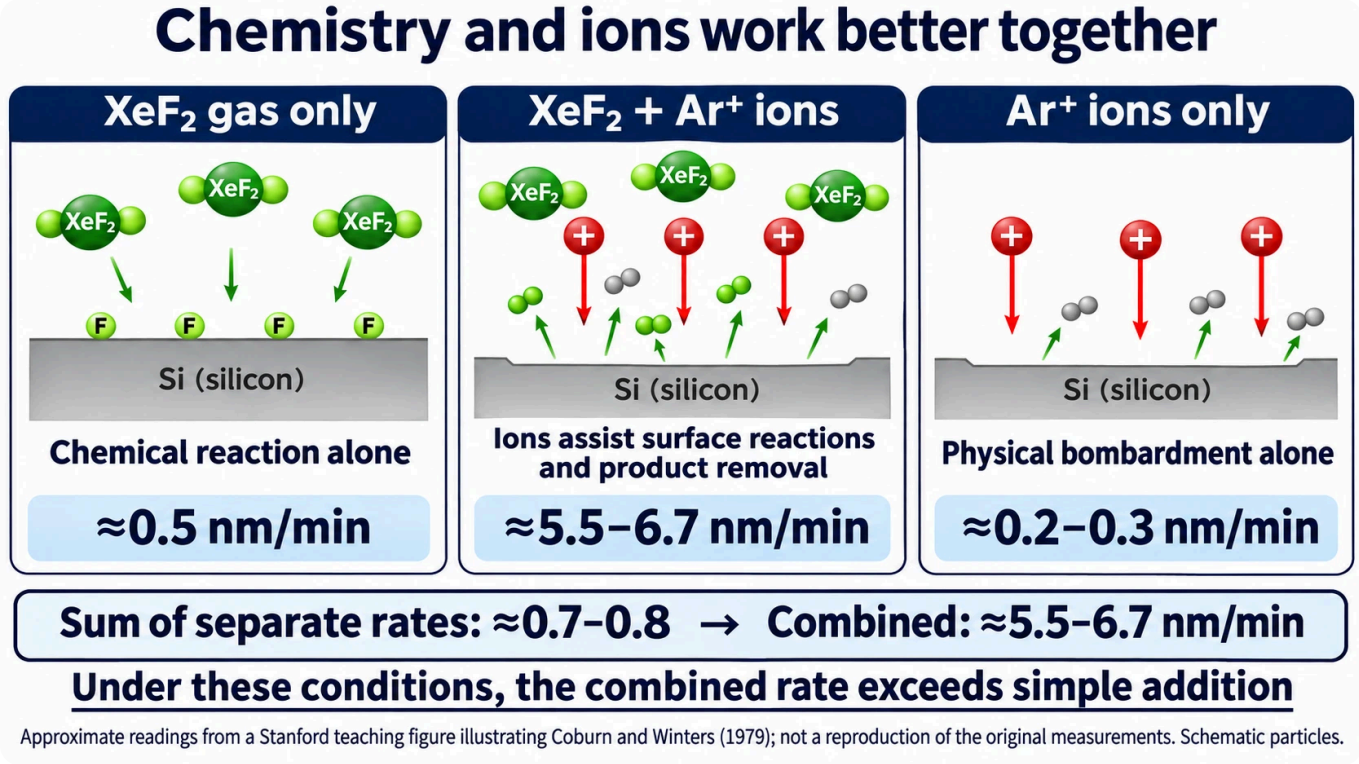


Figure 3 **Comparing gas alone, ions alone and simultaneous exposure** (schematic)

Reading the figure

The middle condition etches faster than the two separate contributions would suggest. Numbers are approximate readings from a teaching figure. Enhancement depends on material, chemistry, ion energy and flux; this is not a universal multiplier or a time-resolved reconstruction [1][12].

Ions can promote surface reactions and help remove layers that inhibit reaction or product desorption [1]. Their effect therefore changes how readily the chemistry proceeds. The ion beam is doing more than physically knocking out an extra, independent quantity of silicon. Explanation

- **Protect the sidewalls while clearing the bottom**

Neutral reactive species can reach sidewalls as well as the bottom of a feature. A useful additional control is **sidewall passivation**: material deposited or formed on the walls suppresses lateral reaction. Carbon-containing gases or mask material can contribute to a polymer-like protective layer [1][6]. Reported

Positive ions arrive preferentially at the bottom and help remove the bottom film or activate the exposed surface. The sidewall receives less direct bombardment, so its protective film can persist. The result depends on balancing film formation, removal and surface reaction. Too little passivation allows widening; too much can stop the etch. Explanation

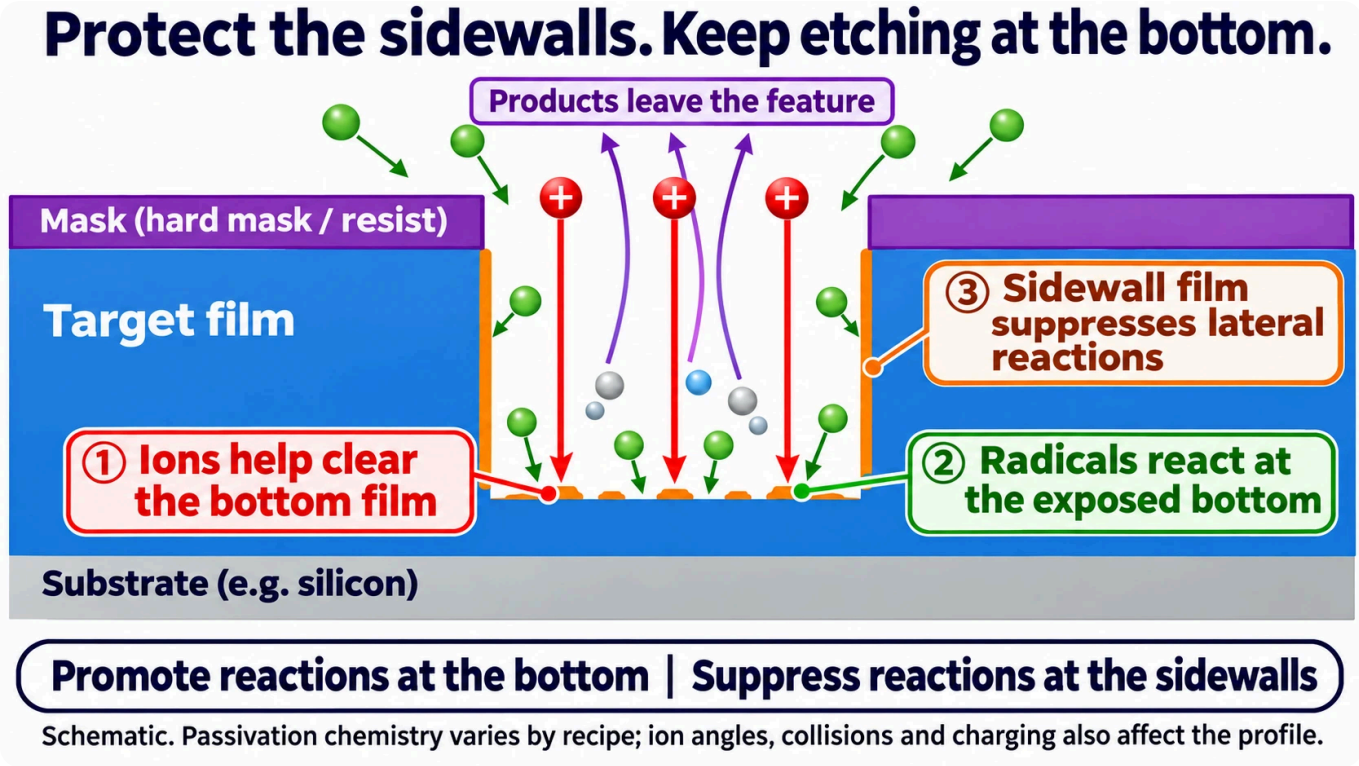
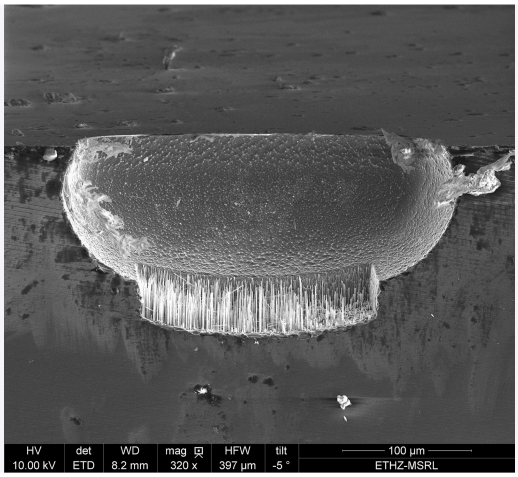


Figure 4 **Combining bottom removal with sidewall protection** (schematic)

Reading the figure

Green particles represent reactive neutral species, red particles positive ions and orange material the protective film. Neutrals also reach the walls, where the film suppresses reaction. At the bottom, ions help clear that film and assist removal. Upward arrows represent products leaving the feature. Geometry and particle counts are schematic [1][6].



Electron micrograph of a deep silicon etch. According to the Commons description, the initial etch without passivation was highly isotropic; opening the C_4F_8 passivation-gas valve produced the intended anisotropic behaviour. The process was not optimised and also produced black silicon. It is an instructive process example rather than a picture of an ideal production profile. **Explanation**

Image: MgerIt / Wikimedia Commons / CC BY 4.0. Resized and converted to WebP.

Four contributions to a useful recipe

- **Reactive species** supply material-dependent chemistry.
- **Positive ions** provide directed energy and assist bottom reactions or film removal.
- **Passivation** suppresses unwanted sidewall removal.
- **Removable products** allow the reacted material to leave the surface and be pumped away.

Gas composition, pressure, source power, wafer bias and temperature determine how these contributions interact.

6. The reaction products must leave

Volatility connects chemistry to the manufacturing route

A chemical dry etch needs products that can leave the surface and be exhausted. Low boiling point is a useful introductory clue, although actual removal depends on vapour pressure, desorption and process conditions [3]. Explanation

Product	Reference property	Source
Silicon tetrafluoride, SiF_4	Boiling point about −86°C	[17]
Silicon tetrachloride, $SiCl_4$	Boiling point 57.57°C	[18]
Copper(II) chloride, $CuCl_2$	Reported decomposition to CuCl at 993°C	[19]
Copper(I) chloride, CuCl	Reported boiling point 1,490°C	[20]

These reference values are not instructions to heat a low-pressure etcher to those temperatures. Their purpose is to show the contrast between readily removable silicon halides and much less volatile copper chlorides. Explanation

Copper is consequently difficult to pattern by conventional chlorine-based RIE under typical interconnect-processing conditions. In **damascene** integration, the pattern is first etched into an insulating layer, then filled with copper; excess copper is removed by polishing [9][21]. This connects the etching lesson to the plating and CMP route introduced earlier. Explanation

Copper removal is not physically impossible. Ion milling and specialised chemical routes exist, with their own issues such as redeposition. The practical point is why conventional subtractive copper patterning is less convenient, not that no dry process can ever remove copper. Explanation

Match the chemistry to the film

The Stanford material gives representative gas families [1]. They illustrate how different targets call for different balances; the recipe names alone do not fix the final profile. Reported

Target	Representative gases	Teaching example
Polysilicon	HBr, Cl_2, Cl_2/HBr/O_2	Directional profiles with useful oxide selectivity
Polysilicon	SF_6, CF_4	More isotropic removal in the cited examples
Silicon dioxide	CF_4/H_2, CHF_3/O_2, C_2F_6, C_3F_8	Directional oxide removal, selective to silicon under appropriate conditions
Silicon dioxide	CHF_3/C_4F_8/CO	Oxide removal with selectivity to silicon nitride in the cited example

- **Why oxide can keep etching while silicon becomes protected**

Fluorocarbon plasmas can both etch and deposit carbon-rich material. The fluorine-to-carbon balance is an important control: lowering it generally favours protective-film formation [3][6]. Reported

In a simplified explanation of oxide-selective etching, oxygen from SiO_2 helps remove carbon as CO. Ion-assisted oxide removal can therefore continue while a more persistent carbon-rich film protects exposed silicon. If deposition becomes too strong, however, even the oxide can stop etching [6]. Explanation

Selectivity can come from different surface balances

Both materials are in the same chamber, but their surface compositions differ. On oxide, carbon removal and ion assistance can keep a reactive surface available. On silicon, a protective carbon-rich layer can persist. The outcome is not determined by the gas alone: it is the balance of deposition, removal and reaction on each material.

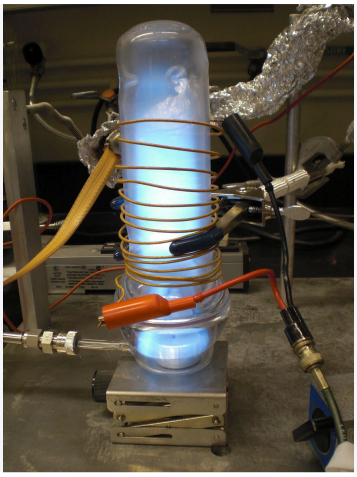
A sketch such as “SiO_2 + fluorocarbon + ion assistance → SiF_4 + CO-containing products” expresses that idea; it is not a balanced elementary reaction [6].

7. Reactor design: more ions, with controlled energy

- **From bulk stripping to directional pattern transfer**

Early plasma tools included barrel reactors, with several wafers placed in a cylindrical chamber. Oxygen-plasma stripping became an important application: organic resist reacts to form mainly volatile products, rather than literally leaving a pile of ash. The historical term is **ashing** [8]. Explanation

A Semiconductor History Museum account records Tokyo Ohka Kogyo's plasma resist-stripping equipment in 1971 and Tokuda's separated-source chemical dry etching equipment in 1978 [8]. These are milestones in that account, not a claim that all plasma-processing development occurred in one country. Reported



An oxygen-plasma cleaner removing carbon contamination from MEMS surfaces. The Commons description gives 100 mTorr and 50 W. Reaction of organic material to form volatile products is also central to plasma resist stripping. **Explanation**

Image: Maxfisch / Wikimedia Commons / CC0. Resized and converted to WebP.

Directional RIE became increasingly important as features shrank. A parallel-plate reactor couples RF power into the discharge and develops a wafer-side sheath. Specialist equipment suppliers, including Applied Materials, Lam Research, Tokyo Electron and the predecessors of today's Hitachi High-Tech, helped industrialise plasma etching [10][22][23]. **Reported**

David Lam's oral history describes a single-wafer polysilicon etcher with load-lock handling, microcomputer control and stored recipes. He also acknowledges earlier single-wafer work at Tegal [22]. The manufacturing advance was not simply producing a plasma: it was making repeatable, controllable wafer processing practical. **Explanation**



A Plasma-Therm 790-series RIE system at the University of Alabama in Huntsville, according to Commons. This is a research installation; production tools differ in scale, automation and configuration. **Explanation**

Image: AlabamaUSA / Wikimedia Commons / CC BY-SA 3.0. Resized and converted to WebP.

The limitation of one control doing two jobs

In a conventional single-frequency CCP, changing the applied power can change both plasma density and the wafer sheath voltage. Raising the ion supply can therefore also raise the ion energy [1][6]. It is difficult to ask for “many ions, but gentle bombardment” when those controls are strongly coupled. **Explanation**

Source designs and bias arrangements developed to make the two quantities easier to adjust separately:

- **ICP, including TCP implementations:** an external RF coil couples energy through a dielectric window to generate plasma. A separate wafer bias adjusts ion bombardment.
- **ECR:** a magnetic field and microwave excitation, commonly 2.45 GHz in the historical examples, efficiently energise electrons through electron cyclotron resonance [11].
- **Dual-frequency CCP:** two RF frequencies provide additional control. In the cited examples, a higher frequency of roughly 27-160 MHz primarily supports density, while a lower frequency of roughly 2-13.56 MHz primarily influences ion energy [5].

Historical high-density systems included Anelva ECR in 1989, Hitachi microwave plasma in 1990, Lam TCP in 1992 and Applied Materials ICP in 1993, as recorded by the Semiconductor History Museum [11]. These approaches coexist; they are not successive versions of one universally best machine. Explanation

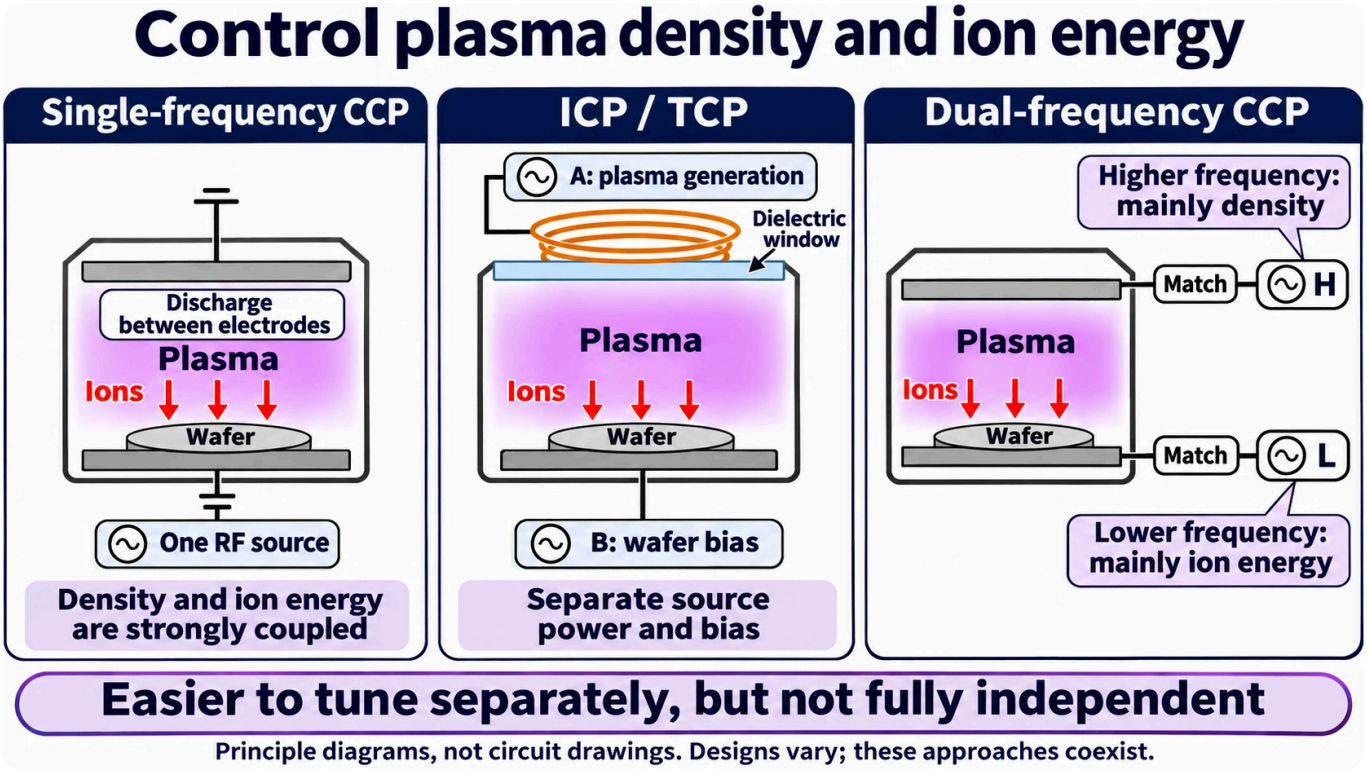


Figure 5 **Single-frequency CCP, ICP/TCP and dual-frequency CCP** (schematic)

Reading the figure

ICP separates coil-driven plasma generation from wafer bias. Dual-frequency CCP also gives more freedom to tune the discharge and ion bombardment. Neither provides perfect independence: source and bias changes can still influence one another. The drawings show functions, not complete electrical circuits [4][5][6][13].

Teaching ranges for ICP include pressures around 1-80 mTorr and ionisation fractions around 10^{-3}-10^{-1} [6]. Density examples span 10^{11}-10^{12} cm^{-3} in the MIT notes, with values up to 10^{13} cm^{-3} discussed in the Texas material [3][6]. Lower pressure can reduce ion collisions in the sheath, helping preserve directionality. These ranges are context, not a requirement that ICP always operate at one density or pressure. Explanation

8. What can go wrong, and when should the etch stop?

A recipe must reproduce the desired profile across different patterns and across the wafer. Several effects interfere with that goal [3][5][7][10]. Reported

Effect	What happens	Why it matters
Loading	A larger exposed area consumes more reactive species	Etch rate can change with the total area being removed
Microloading	Dense and sparse pattern regions receive different effective supplies	Features on one wafer can etch at different rates
Notching	A local recess forms near a feature's base, sometimes driven by charging	The intended sidewall shape is lost
Charging damage	Unequal charge delivery creates electrical stress	Thin device dielectrics can be damaged
Residues and particles	Deposited products or eroded chamber material remain or detach	Defects and contamination reduce yield

The Berkeley notes illustrate charging damage using thin gate dielectrics of 2-20 nm [5]. These are teaching examples, not a description of every current transistor's gate stack. Deep, narrow features add a transport problem: ions and reactive species have increasing difficulty reaching the bottom. Lesson 3-9 follows that issue further. Explanation

- **Watching the plasma for an endpoint signal**

Stopping too early leaves film behind; stopping too late consumes the next layer. **Optical emission spectroscopy (OES)** can monitor light from excited species in the plasma. If the amount of a reaction product changes as a layer clears, its emission can provide an endpoint signal. Explanation

The Texas lecture gives CO emission near 520 nm during oxide etching as an example [6]. A change in that signal can indicate that oxide removal is ending. In practice, signal strength also depends on plasma conditions, exposed area and background chemistry, so endpoint detection is calibrated for the process rather than inferred from glow colour alone. Explanation

9. Atomic layer etching: separate modification from removal

Continuous etching supplies reactive species and ions together. **Atomic layer etching (ALE)** instead separates surface modification and removal into repeated steps, using self-limiting behaviour to control a small amount of removal. It is conceptually related to ALD, introduced in Lesson 3-3, but removes material rather than adding it. Explanation

The 2015 review by Kanarik and colleagues describes ALE in terms of sequential, independent reaction steps with at least one step made as self-limiting as possible [13]. The name does **not** require exactly one atomic plane to disappear in every cycle. Reported

A directional silicon example proceeds as follows [13]:

1. **Modify:** expose silicon to chlorine, producing a thin chlorinated surface region.
2. **Purge:** remove excess reactants and separate the steps.
3. **Remove:** apply suitable argon-ion bombardment to remove the modified region preferentially.
4. **Purge and repeat:** exhaust products and begin the next cycle.

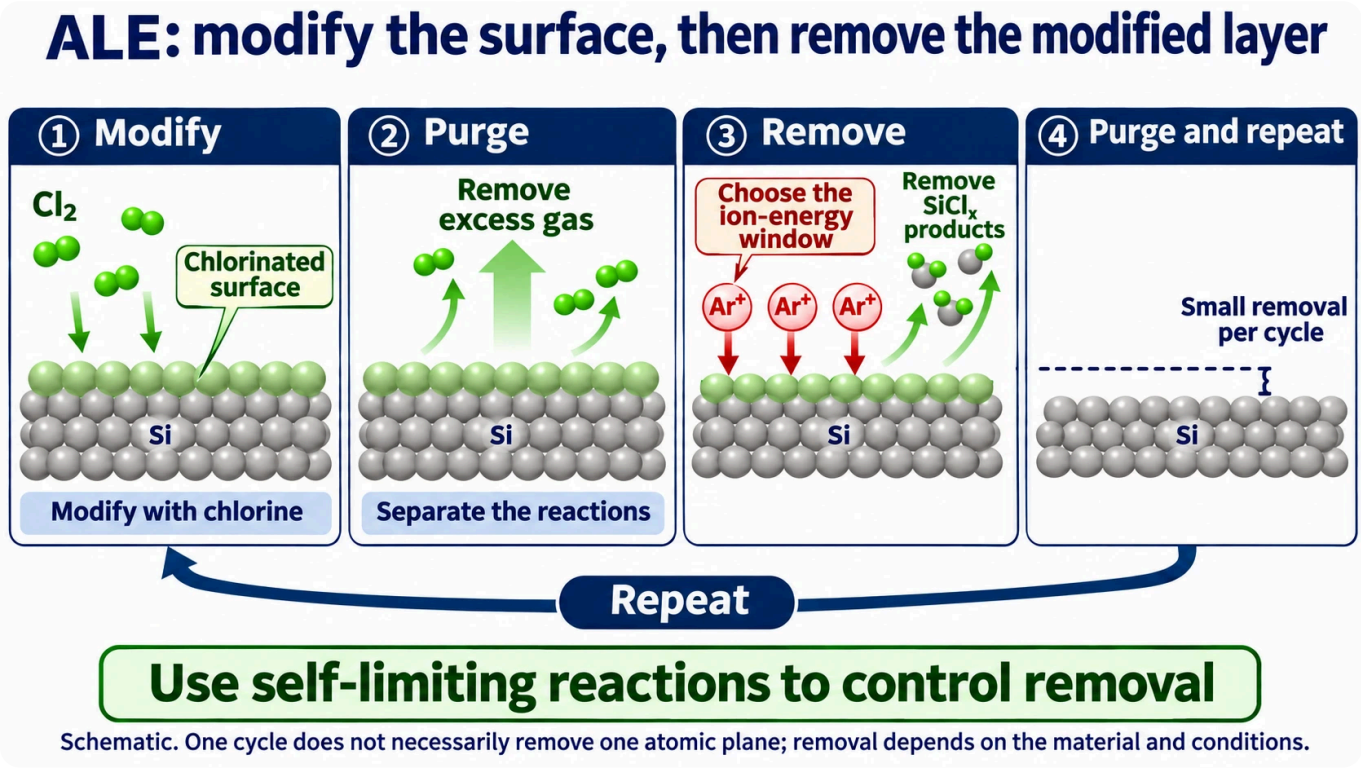


Figure 6 **An ALE cycle: modify, purge, remove, purge** (schematic)

Reading the figure

The spheres indicate a change in surface condition, not an exact crystal structure or atom count. Ion energy is chosen so that the modified layer can be removed without strongly sputtering the underlying unmodified material. Removal per cycle depends on the material and conditions; one cycle is not necessarily one atomic plane [13].

An energy window, rather than simply a shorter etch

The review discusses a silicon example with argon ions around 50 eV, and a 2013 experiment giving approximately 0.7 nm removal per cycle [13]. That result is specific to the reported conditions. It is neither a universal ALE rate nor the thickness of a single silicon atomic plane. Reported

The same review uses bond-energy estimates to explain why chlorination can make removal of the modified region easier: Si-Cl around 4.2 eV, Si-Si around 3.4 eV and a weakened underlying Si-Si bond estimated near 2.3 eV [13]. An incoming ion's energy is not simply matched to one bond energy; energy transfer involves many atoms and collision processes. The useful concept is a **process window** between effective modified-layer removal and excessive attack on the unmodified substrate. Explanation

The paper also discusses ion-induced mixing, with illustrative affected depths of roughly 4 nm at 50 eV and more than 20 nm at higher energies [13]. Carefully chosen cyclic conditions can reduce unwanted damage and variability, but ALE is not automatically damage-free. Throughput, step separation and control remain part of the engineering trade-off. Explanation

10. Fluorinated gases and climate impact

Some gases used for etching or chamber cleaning have high global-warming potentials and long atmospheric lifetimes. The table retains the IPCC AR6 values used in the Japanese edition [24]. It includes several fluorinated-gas families; not every gas listed is a perfluorocarbon. Reported

Gas	100-year GWP, CO_2 = 1	Atmospheric lifetime
CF_4	7,380	50,000 years
C_2F_6	12,400	10,000 years
c-C_4F_8	10,200	3,200 years
CHF_3	14,600	228 years
NF_3	17,400	569 years
SF_6	24,300	1,000 years

On this 100-year metric, emitting 1 kg of CF_4 corresponds to about 7.4 tonnes of CO_2-equivalent. Calculation Gas choice, utilisation, leakage control and exhaust abatement therefore matter alongside etch performance. Changing gas chemistry must still preserve selectivity, profile and process stability. Explanation

The World Semiconductor Council brings together industry associations across major semiconductor-producing regions. Its 2019 statement reported a 32% reduction over the earlier ten-year PFC programme. It also reported that, by 2018, emissions per unit wafer area were 18% below 2010 while absolute emissions had risen by 18% [25]. Reported A more efficient process can therefore coexist with rising total emissions when production grows. Explanation

The 2025 statement commits to a **PFC reduction-rate metric of 85% by 2030**, compared with 82.6% in 2022 [46]. The wording should not be read as a pledge to cut absolute emissions by 85% relative to 2022. The statement also says some semiconductor HFC uses still have no known alternatives, illustrating why substitution and abatement must be assessed application by application [46]. Explanation

11. Equipment suppliers: different technologies and market scopes

- **Read a market table as a defined estimate**

A December 2025 Japanese Ministry of Economy, Trade and Industry (METI) presentation, drawing on Global Net data, gives a global etching-equipment market of **¥2.3383 trillion** and the following shares [26]. The data year is not identified in the reproduced chart; 2025 is the publication year. This table is a sourced snapshot, not an independently established current ranking. Reported

Supplier	Headquarters country	Share in the cited chart
Applied Materials	United States	33%
Lam Research	United States	30%
Tokyo Electron	Japan	20%
NAURA	China	5%
Hitachi High-Tech	Japan	5%
Other suppliers	Various	7%

The three largest entries total 83%. Calculation Market definitions matter: a company's estimate for **plasma etching** need not match a chart for a broader etching-equipment category. Neither market share nor country of headquarters establishes that one supplier is best for every material, feature or customer. Explanation

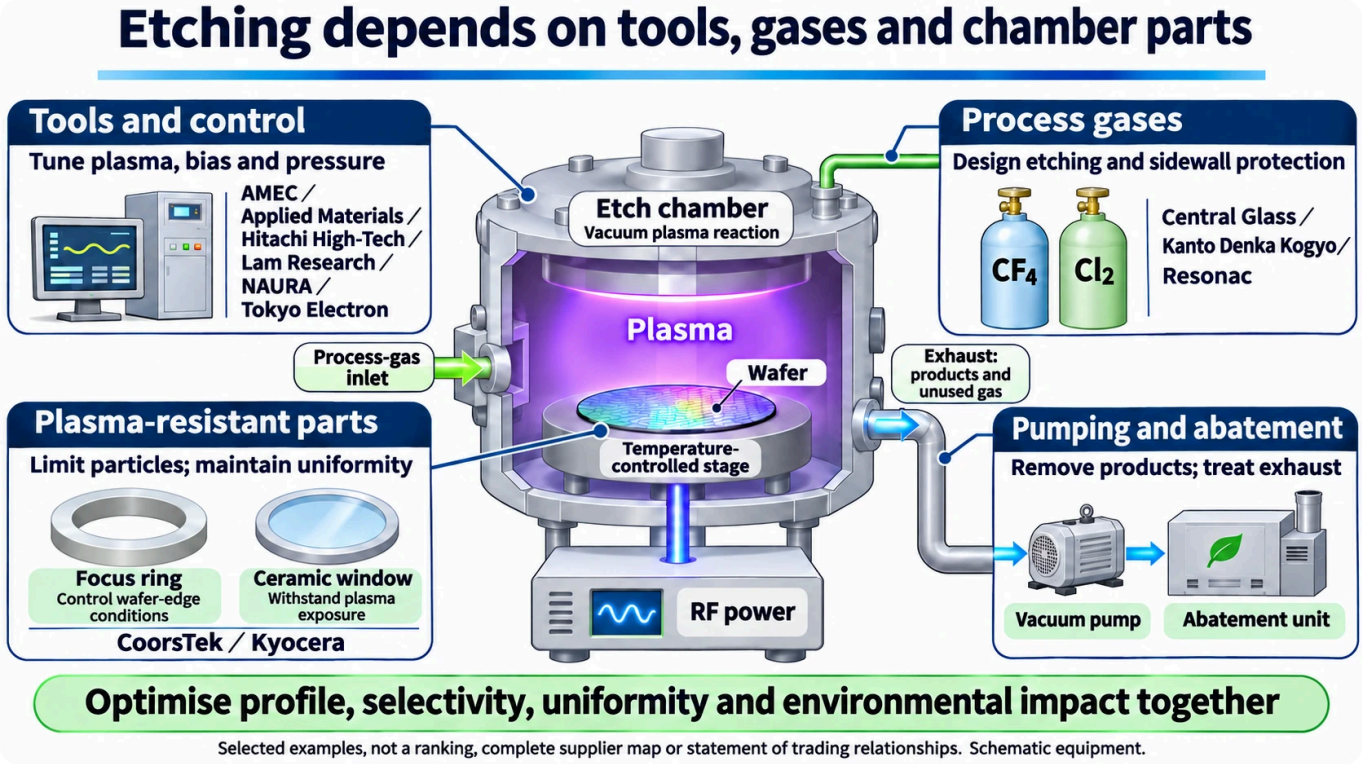


Figure 7 **Equipment, gases, chamber parts and exhaust systems work together** (schematic)

Reading the figure

The chamber is only one part of the process. Equipment controls particle supply and energy; gases enable removal and protection; chamber parts limit contamination and maintain conditions; pumping and abatement handle the exhaust. Company names are selected examples from this lesson. Their order and size do not indicate rank, share, complete coverage or particular trading relationships [23][29][31][34–45].

Supplier profiles, in alphabetical order

AMEC (China). Its 2025 annual report describes both CCP and ICP etching businesses. It reports approximately RMB9.8 billion of etching-equipment revenue, more than 1,000 CCP chambers shipped during 2025, over 5,000 cumulatively and roughly 1,800 cumulative ICP chambers. It also reports CCP sales for overseas production at nodes below 3 nm and dielectric-etch capabilities around 60:1 aspect ratio [35]. These are company-reported milestones; chamber shipments, equipment systems and market share are different measures. Reported

Applied Materials (United States). Etching is part of its broader semiconductor-systems portfolio. Its Sym3 Z Magnum product page describes pulsed-voltage control of ion energy and characterises Sym3 as its fastest-ramping product line [30]. That growth description is the supplier's assessment, not a cross-company performance comparison. Its FY2025 filing reports 30% of company revenue from China, with its two largest customers accounting for about 19% and 15% [29]. Reported

Hitachi High-Tech (Japan). Its microwave ECR products are designed to sustain high-density plasma at low pressure, including conditions at or below 0.1 Pa. The supplier lists conductor-etch applications such as isolation, gates, multiple patterning and interconnect processing [34]. These examples show a particular excitation approach, rather than a claim that ECR is universally preferable to ICP or CCP. Reported

Lam Research (United States). Founded by David K. Lam in 1980, the company records AutoEtch in 1981, conductor TCP in 1992, dual-frequency dielectric etching in 1995 and production ALE products in 2014 [27]. Its FY2026 filing describes conductor and dielectric offerings including Kiyo, Akara, Flex and Vantex, and names Applied Materials, Hitachi and Tokyo Electron among its etch competitors [23]. Reported

Lam's July 2024 announcement states that it introduced cryogenic etching into high-volume production in 2019 and that approximately 1,000 of more than 7,500 of its high-aspect-ratio dielectric-etch chambers used cryogenic technology [28]. The priority wording and installed-base figures are Lam's dated claims. Its FY2026 filing reports 34% of company revenue from China and four major customers each accounting for approximately 12-16% [23]. Reported

NAURA (China). Its 2025 annual report states that etching-equipment revenue exceeded RMB10 billion [36]. That revenue measure should not be directly equated with AMEC's chamber counts or with the share table above without reconciling product scope and reporting periods. Reported

Tokyo Electron (Japan). Its Integrated Report 2026 estimates that it ranks second in plasma etching and first in gas chemical etching [31]. These are company estimates for specified categories and cannot be substituted directly into the broader METI table. Etching accounted for 36% of FY2026 new-equipment sales of ¥1.7754 trillion, implying approximately ¥639 billion on those reported inputs. [31] Calculation

Its product examples include Tactras, introduced in 2006 with configurations up to six chambers, and Episode UL, introduced in 2020 with up to twelve [32][33]. For a cryogenic-etch comparison, the company reports replacing much of the fluorocarbon gas with hydrogen fluoride and reducing per-wafer CO_2-equivalent emissions by 84% and electricity use by 43% relative to its first-generation equipment [31]. These are supplier-reported results for that comparison, not industry-wide reductions. Reported

How to compare these statements fairly

The profiles describe documented roles, products and milestones. They do not use the amount of detail available for each company as a measure of capability. Revenue geography is company-wide unless otherwise stated; chamber counts are not system counts; node labels and aspect ratios do not by themselves define equivalent processing tasks. Procurement decisions require application-specific results, not a single league table.

12. Gases and parts: the rest of the process ecosystem

Process-gas suppliers

A gas must do more than react quickly. It must support the required selectivity and sidewall balance, arrive at suitable purity and remain manageable in delivery and exhaust systems. The following companies are examples covered by the source material, listed alphabetically rather than by nationality or market position. Explanation

- **Central Glass** describes high-purity fluorinated-gas production, a multipurpose plant completed in 1988 and its CEG range of next-generation etching gases [41]. Reported
- **Kanto Denka Kogyo** identifies gases including C_4F_6, COS and CH_3F in its semiconductor portfolio [37]. It reports adoption of KSG-14 for Kioxia's 3D NAND hole etching and adoption of KSG-5 by Samsung Electronics from 2025 as a CF_4 alternative, with a claimed GWP below 1 [38][39]. These are named supplier announcements, not evidence that the gases replace every use of CF_4. Reported
- **Resonac** announced plans to begin high-purity hydrogen-fluoride gas production in Tokuyama during 2026 in addition to Kawasaki, citing demand from advanced processes including cryogenic etching [40]. The cited announcement is a plan; it is not used here as confirmation that the new line is already operating. Reported

These examples demonstrate significant Japanese participation in specialised gases. They are not a complete census of international gas supply, and no worldwide ranking is inferred from this selection. Explanation

Chamber-component suppliers

Plasma attacks exposed chamber surfaces as well as the intended wafer material. Erosion can change the local process and generate contaminating particles. Materials must therefore withstand the chemistry while meeting thermal, electrical and mechanical requirements. Explanation

- **CoorsTek (United States)** lists focus rings, showerheads and windows for etching, with materials including CVD silicon carbide, yttria and yttria coatings, and single-crystal silicon focus rings. A focus ring helps maintain the process conditions around the wafer edge [45]. Reported
- **Kyocera (Japan)** describes plasma-resistant ceramics for semiconductor equipment, including electrostatic chucks and chamber components. It emphasises low particle generation, heat resistance and electrical properties [44]. Reported

A longer-lived part is useful only if it also preserves the required process conditions. Material purity, erosion products, surface condition and replacement intervals can all affect wafer results. Pumping and exhaust abatement complete the system by removing products and treating unused or harmful gases. Explanation

A dated example of supply-chain policy

In July 2019, Japan changed its export-licensing treatment for hydrogen fluoride, fluorinated polyimide and resist supplied to South Korea, requiring individual licensing in the specified cases. In March 2023, the three items again became eligible for the specified bulk-licensing treatment [42][43]. These historical changes illustrate why highly specialised materials can become supply-chain issues. They are not a statement of today's complete export-control rules. Reported

Where materials engineering contributes

- Design gas chemistry that balances removal, protection and climate impact.
- Purify and deliver chemicals without introducing device contaminants.
- Develop ceramics, coatings and rings that resist erosion and particle formation.
- Improve resist and hard-mask survival during pattern transfer.
- Improve gas utilisation and exhaust treatment while retaining the required profile.

These tasks connect chemistry and materials science directly to the electrical performance and yield of finished devices.

13. What comes next?

Three pressures shape further development: thinner margins for damage and dimensional error, deeper and narrower features, and lower environmental impact. ALE addresses controlled removal; high-aspect-ratio and cryogenic etching address difficult three-dimensional structures; lower-impact chemistries and abatement address emissions [13][28][31][46]. Explanation

Those goals interact. A gentler process may be slower. A protective film that preserves sidewalls can restrict transport to the bottom. A lower-GWP gas must still deliver the right reaction products and selectivity. Lesson 3-9 builds on these principles to examine deep-feature etching. Explanation

14. Recap

Question	Key idea
Why does a mask opening widen?	Isotropic removal reaches beneath the mask as well as down into the film.
How is material selectivity obtained?	Different materials react or retain protective films differently.
What does the sheath do?	Its potential drop gives positive ions directed energy towards the surface.
Why combine ions and chemistry?	Ion assistance can make reactions and product removal much more effective than either contribution alone.
How are sidewalls preserved?	Passivation remains where direct ion assistance is weaker.
Why does volatility matter?	Chemical products must leave the surface; this helps explain copper damascene integration.
Why use separate source and bias controls?	They make particle supply and ion energy easier to tune, although coupling remains.
What distinguishes ALE?	Sequential surface modification and removal exploit self-limiting behaviour.
What supports the reactor?	Specialised gases, resistant parts, vacuum pumping and exhaust abatement.
How should company claims be read?	Keep the source, date, product scope, comparator and reporting unit attached.

15. Check your understanding

1. A wet oxide etch removes material equally quickly in all directions. Why does the finished opening become wider than the mask opening?

   ▼ Show answer

   The etch reaches laterally beneath the mask while also moving downwards. That undercut changes the transferred dimensions even though the mask opening itself has not changed.

2. What is the difference between selectivity and anisotropy?

   ▼ Show answer

   Selectivity compares the removal rates of different materials. Anisotropy describes directional dependence. A process can be selective without being directional, or directional without being very selective.

3. If the electrons have a temperature of several electronvolts, why is the entire chamber not at tens of thousands of kelvin?

   ▼ Show answer

   The discharge is not in thermal equilibrium. Light electrons transfer relatively little energy to heavy particles in elastic collisions, while inelastic collisions drive excitation, dissociation and ionisation. The wafer still receives heat and needs temperature control.

4. Can the bulk plasma be approximately neutral while its potential is positive relative to the chamber wall?

   ▼ Show answer

   Yes. Potential difference and net charge density are different quantities. The bulk can remain quasi-neutral while charge separation in the boundary sheath establishes a potential barrier that limits electron loss and accelerates positive ions.

5. Why can plasma etching remove material at the bottom of a trench while leaving its walls protected?

   ▼ Show answer

   Ions arrive mainly normal to the wafer and help clear the bottom film or activate bottom reactions. A protective film can remain on the less-bombarded sidewalls. Neutral chemistry alone would not guarantee that profile, and real ion angles are spread out.

6. What did the Coburn-Winters experiment reveal?

   ▼ Show answer

   Under the reported conditions, simultaneous XeF_2 exposure and argon-ion bombardment etched silicon much faster than the sum of their separate rates. Ion assistance changes the effectiveness of the surface chemistry rather than simply adding an independent sputter rate.

7. Why are conventional copper interconnects commonly formed by damascene processing?

▼ **Show answer**

Copper chlorides are not readily volatile under typical processing conditions, making conventional chlorine-based subtractive RIE difficult. Damascene etches the pattern into an insulator, fills it with copper and removes the excess by polishing.

8. How can a fluorocarbon recipe etch oxide preferentially to silicon?

▼ **Show answer**

The balance between carbon-film deposition and removal differs on the two surfaces. Oxygen in the oxide helps remove carbon as CO while ion assistance sustains etching; a carbon-rich protective film can persist on silicon. Too much deposition can stop oxide removal too.

9. What do ICP with wafer bias and dual-frequency CCP improve, and what do they not guarantee?

▼ **Show answer**

They make plasma generation and ion energy easier to adjust separately. Source and bias remain coupled to some extent, so the controls are not perfectly independent.

10. Why is neither one ALE cycle nor a supplier's market rank enough to define a process?

▼ **Show answer**

ALE removal per cycle depends on its material and conditions; it is not necessarily one atomic plane. A market rank depends on category, year and methodology, and does not establish performance for a particular etch application.

16. Glossary

Etching
Removing exposed material to transfer a mask pattern or selectively remove a layer.

Wet etching
Removal using liquid chemicals; it may be isotropic or depend on crystal orientation.

Dry etching
Removal without a liquid bath, using gas-phase chemistry, energetic particles or both; not every dry process uses plasma.

Isotropic etching
Removal at approximately the same rate in different directions.

Anisotropic etching
Removal that depends on direction; often used to obtain a mainly vertical profile.

Undercut
Lateral removal beneath the edge of an etch mask.

Selectivity
The target material's etch rate divided by the rate for a material to be preserved.

Plasma
A mixture containing mobile charged particles together with neutral species.

Ionisation fraction
The fraction of gas particles that are ionised, under the stated definition.

Radical
A reactive atom or molecular fragment, often neutral, such as F or CF3.

Electron temperature
A measure of the electrons' characteristic random energy; 1 eV corresponds to about 11,600 K.

Sheath
A boundary region with charge separation and a strong potential gradient beside a surface.

Plasma potential
The electric potential of the plasma, commonly above adjacent surface potentials in the examples discussed.

Self-bias
A DC voltage offset that can develop on an RF-driven electrode under appropriate circuit and asymmetry conditions.

ISM frequency
A frequency designated for industrial, scientific and medical applications, such as 13.56 MHz.

Reactive ion etching (RIE)
Plasma etching that combines reactive chemistry with ion bombardment to control removal and directionality.

Sidewall passivation
A protective surface layer that suppresses lateral reactions during an etch.

F/C ratio
Fluorine-to-carbon ratio, used as one guide to fluorocarbon etching and film-formation behaviour.

Damascene
Forming interconnects by filling patterned dielectric recesses with metal and removing excess metal.

Ashing
Plasma removal of organic material, usually through formation of volatile reaction products.

Capacitively coupled plasma (CCP)
A discharge sustained by capacitive coupling from RF-driven electrodes.

Inductively coupled plasma (ICP)
A discharge sustained by inductive RF coupling, usually from an external coil; TCP is a related supplier terminology.

Electron cyclotron resonance (ECR)
Resonant electron heating using microwave excitation and a magnetic field.

Loading
A change in process behaviour with the total exposed area or material load.

Microloading
Local etch differences associated with pattern density or geometry.

Notching
An unwanted recess near the base of a feature, sometimes caused by charging.

Endpoint detection
Monitoring a signal that indicates when the intended layer removal is complete.

Atomic layer etching (ALE)
Cyclic surface modification and removal that exploit self-limiting behaviour for controlled small increments.

Global warming potential (GWP)
Climate impact per unit mass relative to CO2 over a stated time horizon.

Focus ring
A component around the wafer edge that helps control local plasma and etching conditions.

17. Sources and further reading

Reference numbers are shared with the Japanese edition. English descriptions identify the cited documents; some originals are in Japanese or Chinese. Dated teaching ranges and company announcements retain their original context.

1. **J. D. Plummer, M. D. Deal and P. B. Griffin (Stanford EE212; hosted by the University of Washington)** — Class Handout 27: Etching, Chapter 10 (1999-2000; PDF pp. 1-17) — Read source
2. **MIT OpenCourseWare** — 6.152J Micro/Nano Processing Technology: Lecture 16, Wet Etching (2005; pp. 8-9, 16) — Read source
3. **MIT OpenCourseWare** — 6.152J: Lecture 17, Dry Etching (2005; pp. 1-5, 18, 22, 26, 28) — Read source
4. **M. A. Lieberman, UC Berkeley** — A Short Course on the Principles of Plasma Discharges and Materials Processing, Day 1 (2015; PDF pp. 10-17, 24, 63, 97-98) — Read source
5. **M. A. Lieberman, UC Berkeley** — The same course, Day 2 (2015; PDF pp. 90, 98, 112-113, 133) — Read source
6. **S. Sirard, Lam Research / University of Texas at Austin** — Introduction to Plasma Etching, Day 1 (2017; pp. 10-11, 15, 17, 23, 26, 28-30, 38, 40, 53-61) — Read source
7. **S. Sirard, Lam Research / University of Texas at Austin** — Introduction to Plasma Etching, Day 2 (2017; pp. 11, 14) — Read source
8. **Semiconductor History Museum of Japan** — Use of isotropic plasma etching in the late 1970s (English historical account) — Read source
9. **Semiconductor History Museum of Japan** — Adoption of damascene for copper interconnects in the late 1990s (English) — Read source
10. **Semiconductor History Museum of Japan** — Introduction of anisotropic plasma etching, RIE, in the early 1980s (English) — Read source
11. **Semiconductor History Museum of Japan** — High-density plasma, ECR and ICP, for etching and CVD in the early 1990s (English) — Read source
12. **J. W. Coburn and H. F. Winters, IBM Research Laboratory** — Ion- and electron-assisted gas-surface chemistry: An important effect in plasma etching, Journal of Applied Physics 50, 3189-3196 (1979; experimental illustration discussed via refs. 1 and 5) — Read source
13. **K. J. Kanarik et al.** — Overview of atomic layer etching in the semiconductor industry, Journal of Vacuum Science & Technology A 33, 020802 (2015; Sections I-IV) — Read source
14. **NIST** — CODATA 2022: proton-electron mass ratio — Read source
15. **US Electronic Code of Federal Regulations** — 47 CFR 18.301: Operating frequencies for ISM equipment — Read source
16. **US Electronic Code of Federal Regulations** — 47 CFR 2.106: Table of Frequency Allocations, including international footnote 5.150 — Read source
17. **PubChem, US National Institutes of Health** — Silicon tetrafluoride, CID 24556: boiling-point data — Read source
18. **PubChem, US National Institutes of Health** — Silicon tetrachloride, CID 24816: boiling-point data — Read source
19. **PubChem, US National Institutes of Health** — Cupric chloride, CID 24014: thermal-property data — Read source
20. **PubChem, US National Institutes of Health** — Cuprous chloride, CID 62652: boiling-point data — Read source
21. **K. Saraswat, Stanford EE311** — Copper Interconnect (lecture notes; pp. 3, 5, 7) — Read source
22. **Computer History Museum / SEMI** — Oral History of David K. Lam (recorded 2004; pp. 3-5) — Read source
23. **Lam Research** — Form 10-K, fiscal year ended June 2026 (pp. 4, 6-7, 11, 24, 70) — Read source
24. **IPCC** — AR6 Working Group I, Chapter 7 Supplementary Material, Table 7.SM.7 (PDF pp. 17, 21) — Read source
25. **World Semiconductor Council** — Joint Statement of the 23rd Meeting (Xiamen, May 2019; pp. 4-5) — Read source
26. **Japan, Ministry of Economy, Trade and Industry** — Future direction of semiconductor and digital industry strategy (23 December 2025; p. 5; Japanese; chart based on Global Net data) — Read source
27. **Lam Research** — Company history — Read source
28. **Lam Research** — Lam Research Introduces Lam Cryo 3.0 Cryogenic Etch Technology to Accelerate Scaling of 3D NAND for the AI Era (31 July 2024) — Read source

29. **Applied Materials** — Form 10-K, fiscal year ended October 2025 (pp. 7, 30-31) — Read source
30. **Applied Materials** — Sym3 Z Magnum Etch (product page) — Read source
31. **Tokyo Electron** — Integrated Report 2026 (PDF pp. 11, 15, 20, 55, 83; Japanese edition) — Read source
32. **Tokyo Electron** — Tactras series (product page; Japanese) — Read source
33. **Tokyo Electron** — Episode UL series (product page; Japanese) — Read source
34. **Hitachi High-Tech** — Microwave ECR etching systems (product page; Japanese) — Read source
35. **AMEC** — Annual Report 2025 (pp. 25, 32, 42-43, 55; Chinese) — Read source
36. **NAURA** — Annual Report 2025 (p. 19; Chinese) — Read source
37. **Kanto Denka Kogyo** — Securities Report, 118th reporting period (p. 27; Japanese) — Read source
38. **Kanto Denka Kogyo** — KSG-14 (product page; Japanese) — Read source
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40. **Resonac** — Strengthening production of high-purity hydrogen-fluoride gas for semiconductors (25 June 2026; Japanese) — Read source
41. **Central Glass** — Electronic materials (product page; Japanese) — Read source
42. **Japan, Ministry of Economy, Trade and Industry** — Amendment to export-licensing treatment for South Korea (1 July 2019; Japanese) — Read source
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46. **World Semiconductor Council** — Joint Statement of the 29th Meeting (22 May 2025; bilingual English/Japanese; GHG and HFC sections) — Read source

18. Claims and evidence

Claim or group of claims	Supporting source	Treatment
Pattern transfer, directionality, selectivity, undercut and A = 1 − b/d; wet/dry exceptions; reactive species and sidewall protection; example gas families	Stanford EE212 [1]	Introductory models and process examples
HF oxide chemistry, approximate 120 nm/min and 100:1 example; chemical versus sputter selectivity ranges	MIT wet etching [2]	Conditions from a teaching example, not universal rates
Early wet/dry processing, loading, ICP density, removable products and fluorocarbon selectivity	MIT dry etching [3]	Teaching material and explanatory synthesis
Electron energy, gas-density relation, RF self-bias, electrode-area scaling and 13.56 MHz examples	Lieberman Day 1 [4]	Example discharge conditions; simple models qualified
Ion-assisted enhancement, charging, notching and dual-frequency examples	Lieberman Day 2 [5]	Teaching examples; damage dimensions are historical
Weak ionisation, sheath acceleration, CCP/ICP ranges, ion-assisted chemistry, carbon films and CO endpoint example	Sirard Day 1 [6]	Representative conditions, not equipment specifications
Macroloading and microloading	Sirard Day 2 [7]	Process concepts
Barrel reactors, stripping, early Japanese equipment milestones and endpoint monitoring	History Museum [8]	Dated historical account, not an exclusive global first claim
Copper RIE difficulty and damascene adoption	History Museum [9]; Stanford copper notes [21]	Conventional integration explained; no claim that copper cannot be dry-etched
Undercut at the 3 µm generation, RIE industrialisation and processing challenges	History Museum [10]	Historical account
ECR, ICP and TCP equipment milestones in 1989-1993	History Museum [11]	Selected milestones, not a complete global timeline
Coburn-Winters authorship and experiment	Original paper [12], illustrations in [1][5][6]	Approximate diagram readings identified separately
ALE definition, modified-layer removal, energy-window explanation and reported 0.7 nm/cycle experiment	Kanarik et al. [13]	Material- and condition-specific research examples
Mass ratio used in electron/argon comparison	NIST [14]	Physical constant plus approximate argon mass
ISM frequency allocation	Regulations [15][16]	Cited frequency provisions, not a complete regulatory guide
Silicon and copper halide thermal properties	PubChem [17–20]	Reference properties, not reactor temperature instructions
Single-wafer automation, load-lock, recipes and earlier Tegal work	David Lam oral history [22]	Attributed retrospective
Lam product families, competitors and company revenue/customer distribution	Lam FY2026 filing [23]	Company-wide fiscal-year figures where stated
GWP values and atmospheric lifetimes	IPCC AR6 [24]	Stated 100-year metric
Historical PFC targets, intensity and absolute emissions	WSC 2019 [25]	Dated collective industry report
¥2.3383 trillion market and supplier-share table	METI / Global Net [26]	Data year not identified; publication year is 2025
Lam history and cryogenic-etch introduction/installed base	Lam [27][28]	Supplier milestones and dated claims
Applied Materials revenue geography and customers; Sym3 features	FY2025 filing and product page [29][30]	Company figures and supplier product description
Tokyo Electron market estimates, etch sales mix and cryogenic environmental comparison	Integrated Report 2026 [31]	Category-specific supplier estimates; first-generation comparator retained

Claim or group of claims	Supporting source	Treatment
Tactras and Episode UL configurations	Tokyo Electron products [32][33]	Supplier descriptions
Microwave ECR conditions and applications	Hitachi High-Tech [34]	Supplier description
AMEC revenue, CCP/ICP chambers and reported applications	AMEC 2025 report [35]	Company claims; chambers distinguished from systems
NAURA etching-equipment revenue	NAURA 2025 report [36]	Company-reported business revenue
Kanto Denka gases and named adoption announcements	[37–39]	Supplier statements, not universal substitution claims
Additional hydrogen-fluoride production	Resonac [40]	June 2026 plan, not an assumed completion
Fluorinated-gas production and CEG products	Central Glass [41]	Supplier description; no global rank inferred
Japan-South Korea licensing changes in 2019 and 2023	METI [42][43]	Historical policy example
Plasma-resistant ceramics and chamber components	Kyocera [44]; CoorsTek [45]	Selected supplier examples
PFC reduction-rate goal and HFC substitution limitations	WSC 2025 [46]	Industry metric distinguished from an absolute-emissions baseline cut
20:1 worked selectivity, gas-density estimate, ionisation estimate, temperature equivalence, mass/speed ratios, diagram-rate comparison, 83% total, implied Tokyo Electron revenue and CF4 CO2-equivalent	Stated inputs and arithmetic in the text	This article's calculations
Links between reaction chemistry, passivation, transport, damage, integration and the supply ecosystem	Sources above plus explanatory reasoning	Teaching synthesis, not additional measured results

Updated 7 November 2026. Physics and chemistry draw on university teaching materials and original research. Company figures and product capabilities are attributed to the named reports and announcements; market estimates retain their scope and limitations. Historical teaching ranges are examples, not specifications for every modern reactor. References match the numbering of the Japanese edition. English prose and diagram text were written for this edition.

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