SEMICONDUCTOR FRONT-END · PART 3-1

Wafer Cleaning
Small contaminants. Very large consequences.

A wafer may look spotless and still be too dirty to make a reliable chip. This lesson explains how fabs remove particles, metals, organic residues and unwanted oxide—and why drying can be harder than washing. It connects the chemistry and physics to the tools, high-purity chemicals and water systems that support a global manufacturing industry.

Semiconductor Front-End Series · Part 3-1 · Intermediate introduction · Helpful background: Lessons 1-4 and 2-2 · Updated 6 November 2026

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How to read this lesson

Begin with the main text. The shaded physics boxes add optional detail and worked estimates. Figures are conceptual and not to scale. Numbered links lead to the supporting sources.

What you will learn

- Explain why cleaning is repeated throughout chip fabrication, and identify four main classes of contamination.
- Describe how chemistry, electrical interactions and liquid motion remove contaminants without damaging the wafer.
- Explain drying-induced pattern collapse, and connect the technical challenges to equipment, chemicals and ultrapure-water suppliers.

1. The lesson in three ideas

- **Cleaning prepares the surface for what comes next.** It removes particles, metals, organic residues and, where necessary, native oxide. Advanced processes may have to control particles only a few nanometres across.
- **Removing contamination is only half the task.** The process must also preserve valuable material and fragile structures. Even the liquid left after rinsing can pull narrow features together as it dries.
- **Performance depends on a whole supply chain.** Tool design, chemical purity, water treatment, measurement and delivery all matter. The goal is a clean, undamaged surface achieved with less water, solvent and waste.

2. Where cleaning fits in fabrication—and in the global industry

A repeated step in a repeated sequence

A chip is built through many cycles of deposition, lithography, etching and surface preparation. The order varies with the device and layer; the important point is that the wafer repeatedly returns for cleaning. A Japanese Ministry of Economy, Trade and Industry (METI) overview describes semiconductor manufacturing as involving more than **1,000 process steps** [4] Reported .

Part 3 examines these operations one at a time. Each lesson asks two connected questions: **how does the process work, and what must its suppliers deliver?**

Supplier location and customer location are different measures

A chart of equipment suppliers does not tell you where that equipment is installed. Supplier statistics commonly classify sales by the manufacturer's headquarters; customer statistics classify spending by the location of the receiving fab. Neither measure, by itself, describes every location in which a multinational company manufactures or conducts research.

The following historical snapshots help establish that distinction. Supplier regions are listed alphabetically.

Supplier category	China	Europe / EMEA*	Japan	United States	Other regions	Source
Manufacturing equipment, FY2021	9%	22%	31%	35%	South Korea 2%; Taiwan 1%	METI, 2023 [4]
Manufacturing equipment, 2023	5%	27%	28%	36%	4%	METI, 2025 [3]
Key components and materials, FY2021	3%	10%	48%	9%	Taiwan 16%; South Korea 13%	METI, 2023 [4]
High-purity cleaning chemicals, 2023	5%	7%	59%	—	30%	METI, 2025 [3]

The FY2021 source uses EMEA: Europe, the Middle East and Africa. The 2023 source uses its own regional categories. Figures from different years and underlying surveys are not a consistent time series. The 2023 values are read from METI's charts; a dash means that no separate category is shown, not necessarily zero. Rounded materials shares total 99%; cleaning-chemical shares total 101%.

Customer markets have a different distribution. In the table below, equipment destinations are listed in descending order of equipment billings. Values are rounded to one decimal place in **US$ billion**.

Customer region	Equipment, 2025	Equipment growth vs 2024	Materials, 2025
China	49.3	0%	15.6
Taiwan	31.5	+90%	21.7
South Korea	25.8	+26%	11.2
North America	10.9	−20%	6.2
Japan	9.5	+22%	6.8
Rest of world	5.2	+25%	7.5
Europe	2.9	−41%	4.2
World total	**135.1**	**+15%**	**73.2**

Equipment figures come from SEAJ and SEMI [1]; materials figures come from SEMI [2] Reported . Totals may differ from the sum of rounded rows.

China was the largest equipment market for the sixth consecutive year in 2025. Taiwan's equipment spending rose 90%, supported by advanced-logic investment, moving it ahead of South Korea for the first time in three years [1]. Taiwan was also the largest materials market for the sixteenth consecutive year [2] Reported .

Taken together, these data show an interdependent industry: major equipment suppliers are based in the United States, Japan and Europe, while much of the equipment is installed in China, Taiwan and South Korea. Japan's substantial share of key materials is also clear. Its domestic equipment purchases represented about **7%** of worldwide billings in 2025—9.52 ÷ 135.06 ≈ 0.070 Calculation . A supplier's home market and its customer base can therefore look very different.

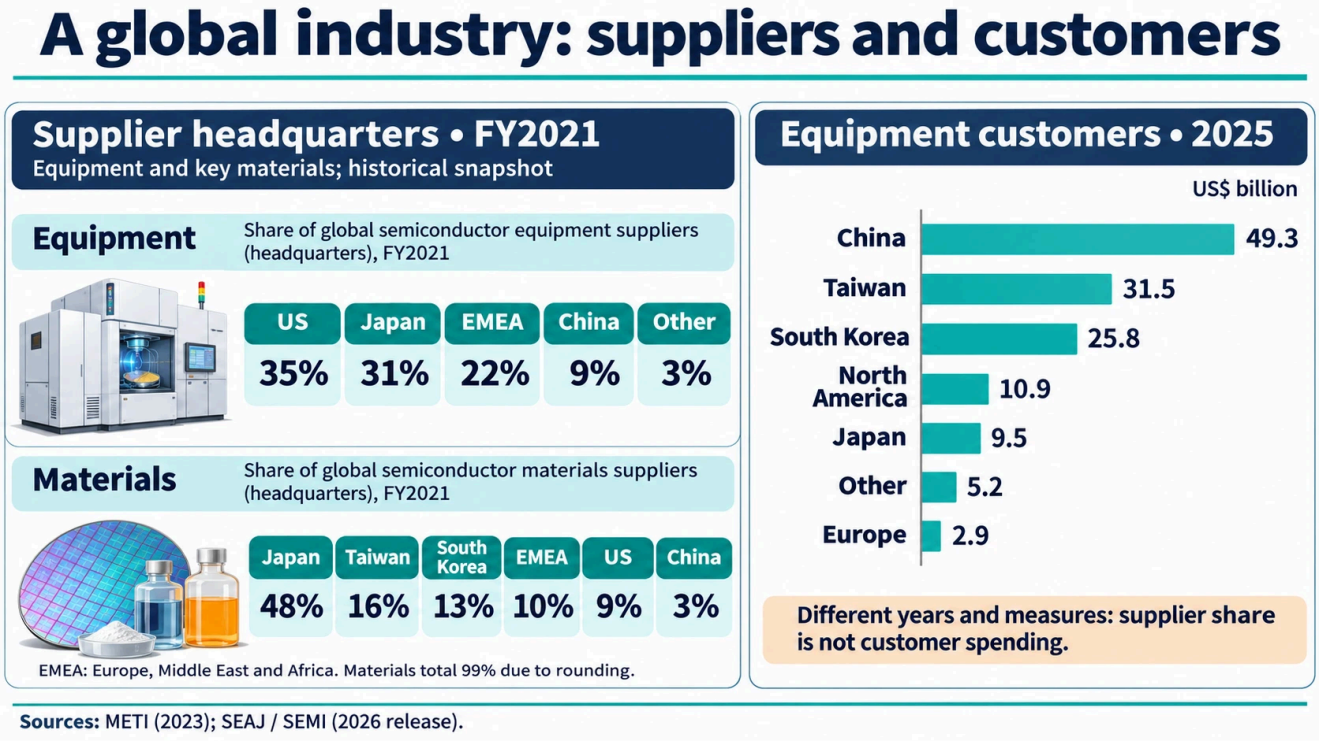

Figure 1 **A global industry: suppliers and customers** (schematic)

Reading the figure

The supplier panel is a FY2021 snapshot, not a current market ranking. The customer panel shows 2025 equipment billings. EMEA includes the Middle East and Africa. No single region's share represents the whole supply chain.

- **Many disciplines contribute**

Semiconductor manufacturing draws on far more than electronics. A polymer scientist, a ceramic engineer and an analytical chemist can all contribute to the same wafer process.

Expertise	Material or component	Where it is used
Polymer and organic chemistry	Photoresists; polishing pads	Lithography; chemical–mechanical polishing (CMP)
Colloid and surface chemistry	Slurries; cleaning formulations	CMP; residue removal
Inorganic chemistry	High-purity acids and other process chemicals	Wet cleaning and etching
Organometallic chemistry	ALD and CVD precursors	Thin-film deposition
Ceramics and coatings	Electrostatic chucks; plasma-resistant parts	Wafer handling and process chambers
Metals	Sputtering targets	Metal-film deposition
Glass and quartz	Mask substrates; furnace tubes	Lithography and thermal processing
Optics and analytical science	Inspection and measurement systems	Defect detection and process control

Examples in the supporting sources include ADEKA's deposition precursors [12], Fujibo's polishing pads [7], JSR's CMP and cleaning materials [6], JX Advanced Metals' targets [10], Kyocera's yttria components [9], Lasertec's mask inspection systems [15], NGK's ceramic chucks [8], Shin-Etsu's mask blanks [13], Stella Chemifa's chemicals [11], TOK's photoresists [5] and Tosoh's quartz glass [14] Reported . These are illustrative product examples from the source set, not a complete international supplier list or a ranking.

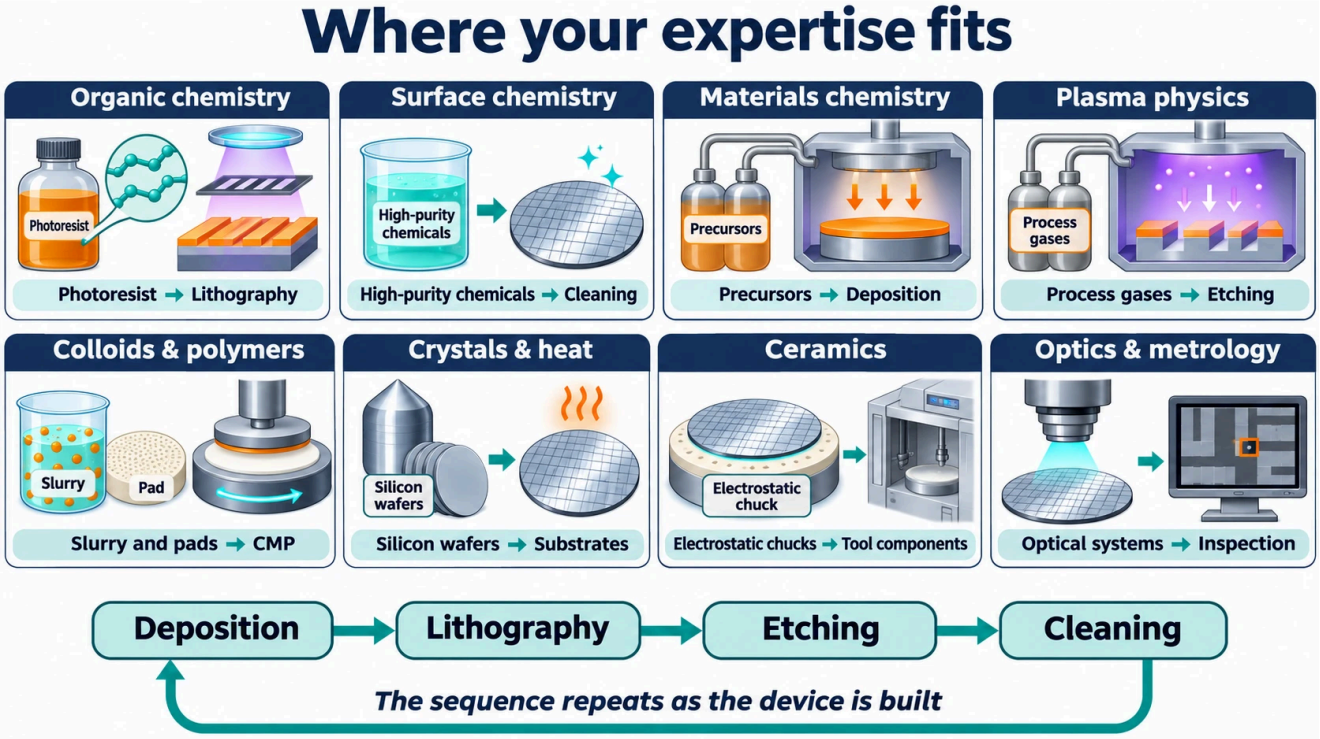

Figure 2 **Where your expertise fits** (schematic)

Reading the figure

The arrows show examples, not exclusive career paths. Developing a process normally involves several disciplines, and cleaning appears between many of the steps shown.

3. Why the wafer keeps coming back for cleaning

- **The next process inherits the previous surface**

A 1999 paper by researchers at imec describes cleaning as the most frequently repeated operation in integrated-circuit fabrication [16]. A Lam Research patent gives an example in which cleaning accounts for roughly 20% of process steps [17] Reported . That is a historical illustration, not a fixed percentage for every fab in 2026.

The reason is straightforward. Deposition can leave particles; etching can leave reaction products; resist removal can leave organic residues. A new film or contact must be formed on the intended surface, rather than on whatever the previous operation happened to leave behind Explanation .

- **Four main classes of unwanted material**

Contaminant	Typical sources	Why it matters
Particles	Tool components, liquids, air or earlier processing	Can bridge conductors, obstruct features or create film defects
Metals	Chemicals, equipment and handling	Can increase leakage or degrade insulating layers
Organics	Resist residue, airborne molecules and containers	Can interfere with adhesion, wetting or chemical reactions
Native oxide	Silicon exposed to oxygen and moisture	Can obstruct a contact or interfere with the next growth step

SCREEN's process overview identifies these types of contamination [18]. The effects summarised here explain the general process concerns Explanation . **Oxide is not automatically contamination:** an oxide film may be deliberately required. The process determines whether it should remain.

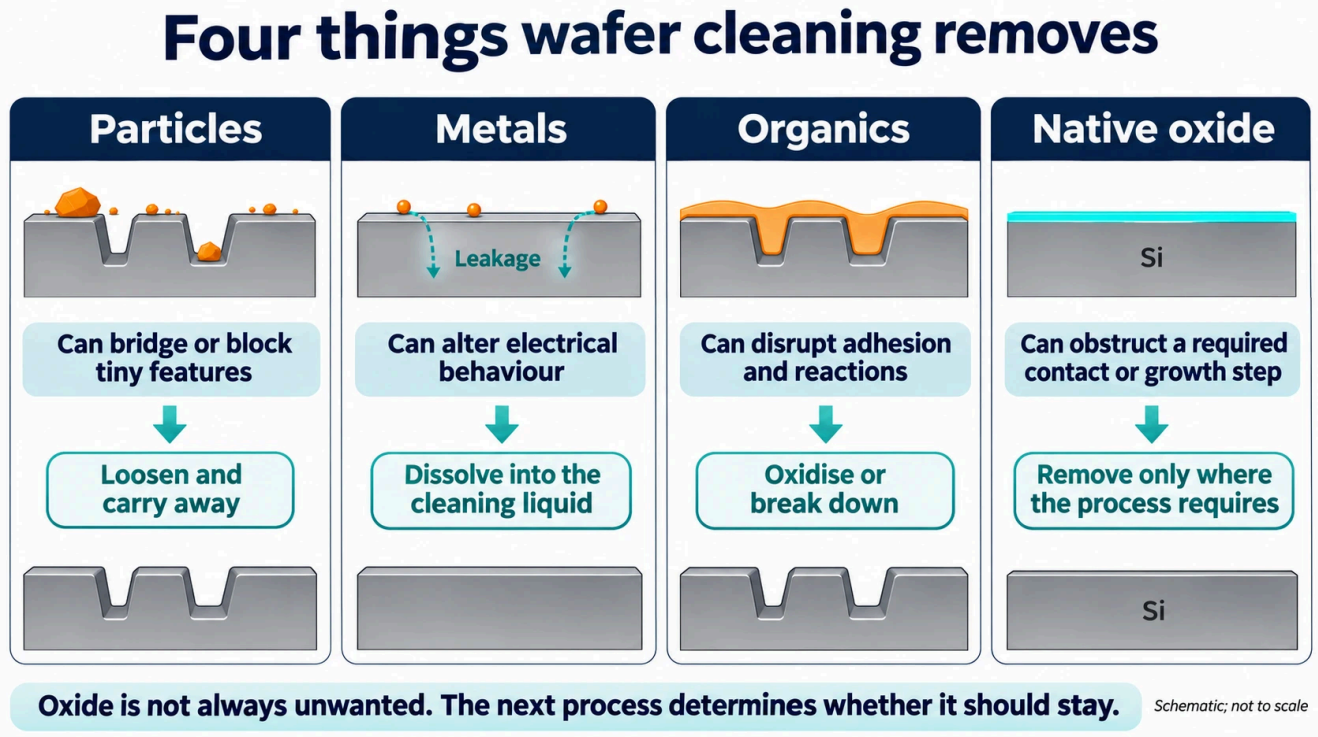

Figure 3 **Four things wafer cleaning removes** (schematic)

Reading the figure

The drawings are not on a common scale. A dust particle, a dissolved ion and a thin surface film should not be interpreted as objects of similar size.

University teaching material hosted by nanoHUB highlights transition-metal contaminants such as copper, iron, nickel, chromium, cobalt and molybdenum, as well as alkali metals such as sodium, potassium and lithium [19]. Calcium, also relevant to contamination control, belongs to the alkaline-earth group rather than the alkali metals.

Why a few nanometres can matter

The 2024 International Roadmap for Devices and Systems (IRDS) discusses critical, electrically active particles at **3.0 nm**, within a framework relating particle size to logic half-pitch. It notes that relevant particle sizes have fallen below 5 nm [20] Reported .

This is a roadmap-based requirement under particular assumptions. It does not mean that every 3 nm particle destroys every device. Material, electrical activity and landing position all affect the outcome.

For a sense of scale, 3 nm spans roughly a dozen silicon nearest-neighbour spacings if each is taken as 0.24 nm Calculation . At this scale, the boundary between a particle, a precursor to a particle and a large molecule becomes less clear—a difficulty also discussed by IRDS [20].

4. Cleaning with chemistry

RCA cleaning: a foundation, rather than a single immutable recipe

Werner Kern and colleagues at RCA developed chemistry that still underpins many wet-cleaning processes. Kern's retrospective dates the start of the research to 1961 and the publication to 1970 [21]. The 1999 imec paper describes RCA cleaning as developed in 1965 [16]. These dates refer to different accounts of its development; they should not be treated as contradictory dates for one event.

The familiar pair is **Standard Clean 1 (SC-1)** and **Standard Clean 2 (SC-2)**.

Chemistry	Main ingredients	Main purpose	Underlying idea
SC-1	Aqueous ammonia, hydrogen peroxide and water; alkaline	Particle and organic removal	Slight surface etching loosens attachment; electrical interactions can reduce redeposition
SC-2	Hydrochloric acid, hydrogen peroxide and water; acidic	Metal removal	Metal-containing species are dissolved and stabilised in solution, including through complex formation; silicon and oxide etching is relatively small under normal cleaning conditions

These mechanisms are described in the nanoHUB lecture [19] Reported . A complex is a metal ion bound to surrounding molecules or ions; forming soluble complexes helps keep removed metal in the liquid.

SC-1: loosen, repel, then carry away

A useful explanation separates three contributions.

1. **Loosen the contact.** Peroxide oxidises the surface while alkaline chemistry causes slight dissolution. This can undermine a particle's attachment. The balance depends on concentration, temperature and surface state; oxidation and dissolution need not proceed at identical rates.
2. **Make return less favourable.** In suitable alkaline conditions, a silica particle and an oxide surface can both become negatively charged. Like charges repel, reducing the tendency to reattach.
3. **Remove the released particle from the area.** Liquid motion carries it away. Detachment alone is not the same as successful removal from the wafer.

The first two mechanisms are described in the lecture and cleaning literature [19][22]. Zeta potential is a useful indicator of electrical behaviour in a liquid: it is the potential at the slipping plane, not the surface charge itself.

The 1999 imec paper reports a change of sign around pH 2–2.5 for silicon and silicon oxide under the conditions it discusses [16]. Surface preparation and solution chemistry matter, so that value should not be applied to every particle or surface. The repulsion argument works when the relevant surfaces have the same sign of charge.

- **Other useful chemistries**
  - **Dilute hydrofluoric acid (DHF)** removes native silicon oxide, described in the teaching example as about **1.0–1.5 nm** thick. The cited lecture uses a 50–100-fold dilution example. The treated silicon can become hydrogen-terminated and hydrophobic, rather than the hydrophilic oxide surface present beforehand [19].
  - **Sulphuric acid–peroxide mixture (SPM)** oxidises organic residues. The lecture gives sulphuric-acid/peroxide ratios of **2:1 to 4:1** and temperatures of **100–130°C** as examples [19].
  - **Ozonated water** uses ozone dissolved in high-purity water to help remove organics. The imec paper discusses hydroxyl-radical chemistry and an approximately **20 ppm** room-temperature solubility example. Avoiding sulphuric acid can simplify the subsequent rinse [16]. Ozone solubility is condition-dependent; the quoted value is not a universal maximum.

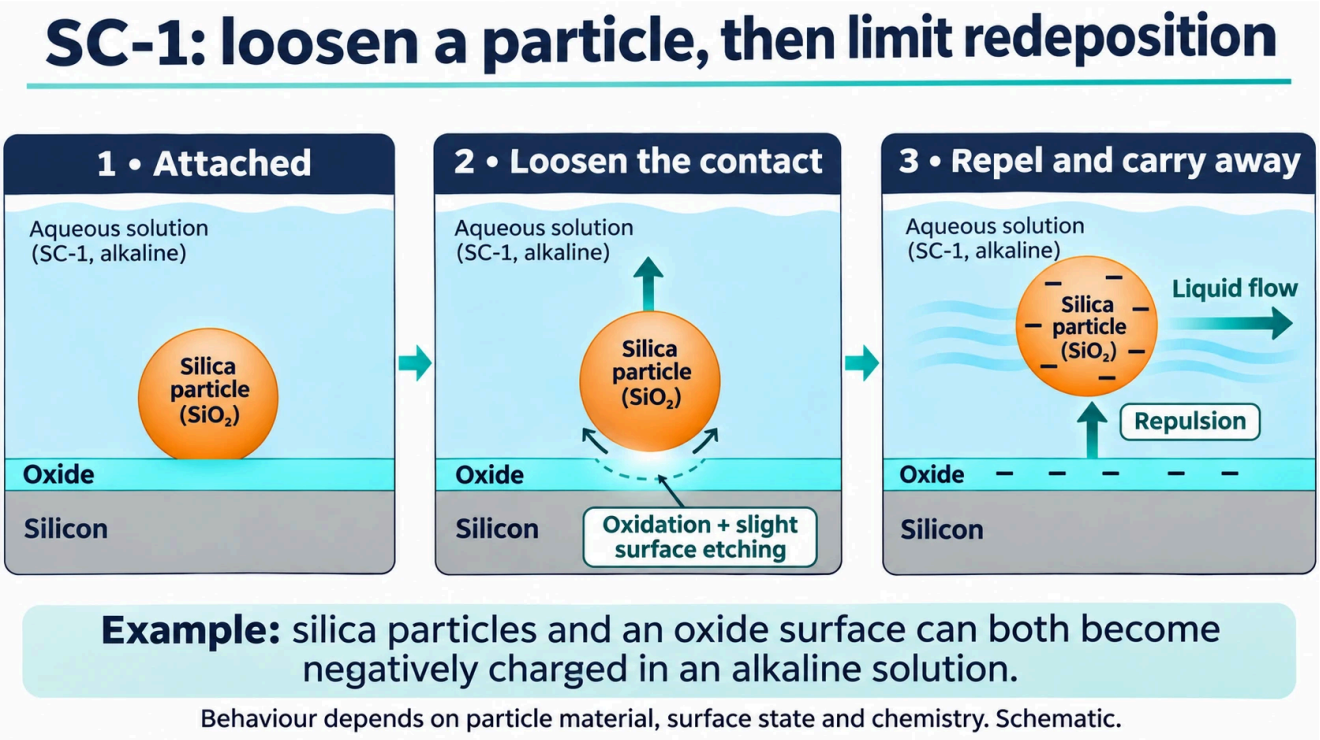

Figure 4 **SC-1: loosen a particle, then limit redeposition** (schematic)

Reading the figure

Not all particles become negatively charged in the same liquid. The illustration explains one useful case, rather than a guarantee that a detached particle cannot return.

Process conditions are examples

The concentrations, ratios and temperatures above describe cited teaching examples. Production conditions depend on the material, film thickness, contamination and equipment; they are not a universal cleaning sequence.

5. Adding physical removal

Chemistry is often combined with controlled motion of the liquid or direct contact.

Megasonic cleaning uses acoustic energy around **1 MHz**. It can increase liquid motion near the surface, reduce transport limitations in the boundary layer and help detach particles. Acoustic streaming and bubble behaviour, including cavitation under some conditions, contribute to the response [19] Reported . A brush scrubber instead uses mechanical contact; cleaning brushes and water are among the physical methods described by SCREEN [18].

Stronger removal is useful only while the device survives. A 2013 report discusses damage to structures below 30 nm when using physical techniques such as megasonics and sprays, and the importance of chemical removal [22]. This is evidence from that study, not a present-day 30 nm limit for every tool. The continuing engineering problem is to apply enough action to release a contaminant without breaking the feature underneath it.

6. Batch and single-wafer processing

Batch cleaning treats many wafers together in a bath. It can share chemicals across a group of wafers and offers productive processing for suitable steps. An ACM Research patent describes an example near **400 wafers per hour**, recirculated chemistry and SPM above **90°C** [24]. These are particular conditions, not a benchmark for all batch tools.

A shared bath also needs careful contamination management: material removed from one wafer must not be transferred to another. An Applied Materials patent discusses cross-contamination as a reason for using single-wafer processing [23].

Single-wafer cleaning typically dispenses liquid onto a wafer rotating in a process chamber. It provides control of chemistry, flow and processing time wafer by wafer. A tool may contain many chambers operating in parallel, so single-wafer processing is not automatically slower overall.

The two approaches coexist. Throughput, footprint, chemical use and contamination performance depend on the tool configuration and recipe. A quoted throughput from one machine should not be compared with another without checking the processing conditions.

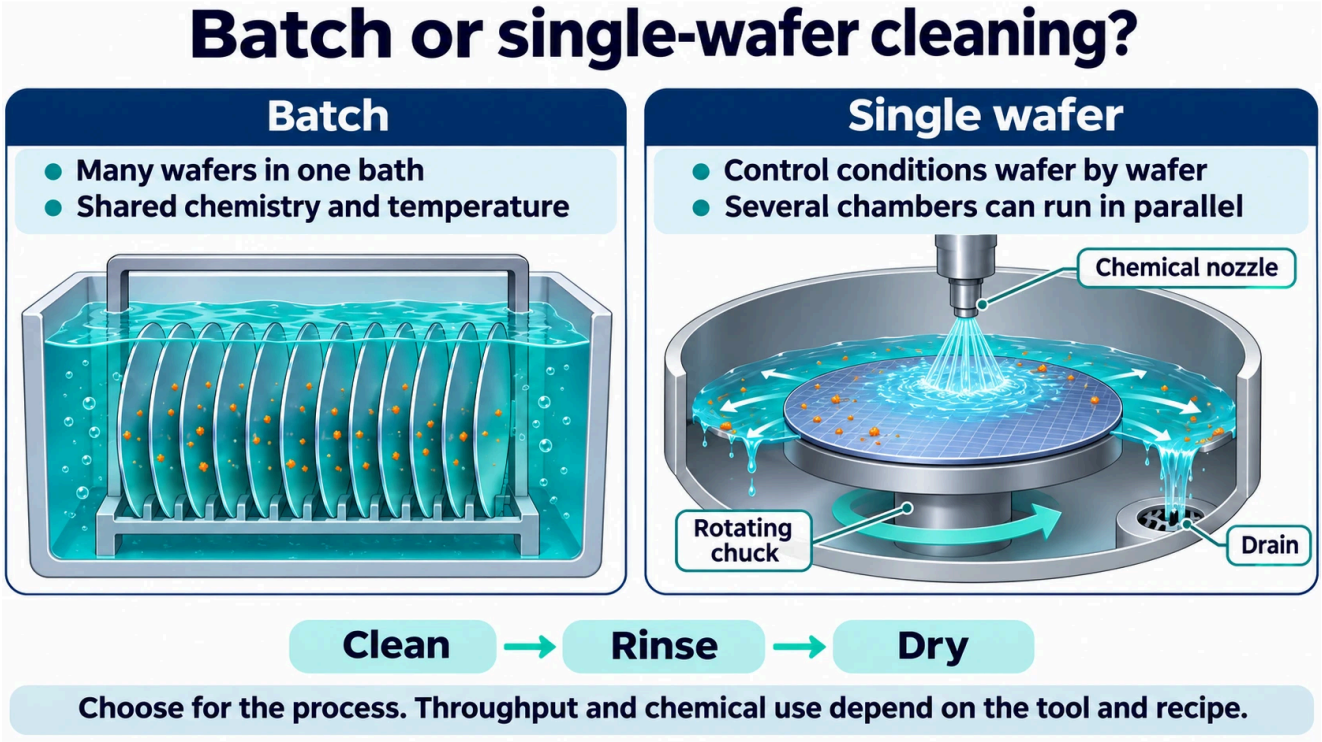

Figure 5 **Batch or single-wafer cleaning?** (schematic)

Reading the figure

One chamber processes one wafer at a time in the right-hand drawing; the complete tool can contain several chambers. The common sequence is cleaning, rinsing and drying, even though its implementation differs.

7. Why drying is a process in its own right

- **Preventing watermarks**

A droplet can leave dissolved or suspended material behind as it evaporates. Such **watermarks** are a defect concern discussed in a Siemens–IBM patent [28]. Drying must remove the liquid without simply concentrating its contents on the surface.

Marangoni drying uses a difference in surface tension. In a typical arrangement, IPA vapour is introduced near the surface as a wafer is withdrawn from water. IPA enrichment lowers the local surface tension; the resulting gradient helps draw water away from the wafer and towards the bulk liquid [16][28]. The aim is to remove the water film rather than evaporate isolated droplets in place.

- **When a rinse liquid pulls structures together**

As a liquid dries between narrow features, its curved surface—the **meniscus**—can generate a pressure difference. If forces are unbalanced, slender structures bend towards one another and may stick. This is **pattern collapse**.

A nanometre-scale gap can generate a large local pressure difference

A simplified model in a Tokyo Electron research abstract relates the pressure difference to surface tension and geometry [25]:

$$\Delta P \approx 2\gamma \cos\theta / S$$

Here γ is surface tension, θ is the contact angle measured through the liquid, and S is the gap width. For a sidewall of height H and depth D, the corresponding simplified force estimate is:

$$F \approx \Delta P \times H \times D$$

Take water with γ = **0.073 N/m**, a **20 nm** gap and θ = **0°**:

$$\Delta P \approx 2 \times 0.073 / (20 \times 10^{-9}) \approx 7.3 \text{ MPa} \approx 72 \text{ atm}$$

This is a **local capillary pressure difference**, not a pressure applied to the whole wafer. A net bending force depends on the difference between conditions on the two sides of a feature. Whether it collapses also depends on its stiffness, dimensions and support.

Replacing water with IPA at **22 mN/m**, while holding the other assumptions fixed, gives about **2.2 MPa** Calculation. Moving the contact angle towards 90° reduces the cosine term in this model. It does not remove every possible force or guarantee that collapse cannot occur. The cited study reports a **1.7-fold** improvement in a collapse-limit aspect ratio with its surface-modification approach relative to IPA drying [25]; that result belongs to the study's conditions.

Two further approaches aim to avoid a liquid–gas interface during the final removal stage:

- **Sublimation drying:** a suitable drying material is supplied, solidified and then removed directly as vapour. A SCREEN patent describes a liquid containing a sublimable material and a controlled drying-gas supply [26]. This should not be read as a general instruction to freeze the rinse water.
- **Supercritical drying:** temperature and pressure are managed so that drying proceeds without forming the liquid–gas boundary responsible for capillary loading. Tokyo Electron announced a supercritical-drying system in December 2020, identifying collapse even with low-surface-tension alcohols as a growing difficulty [27].

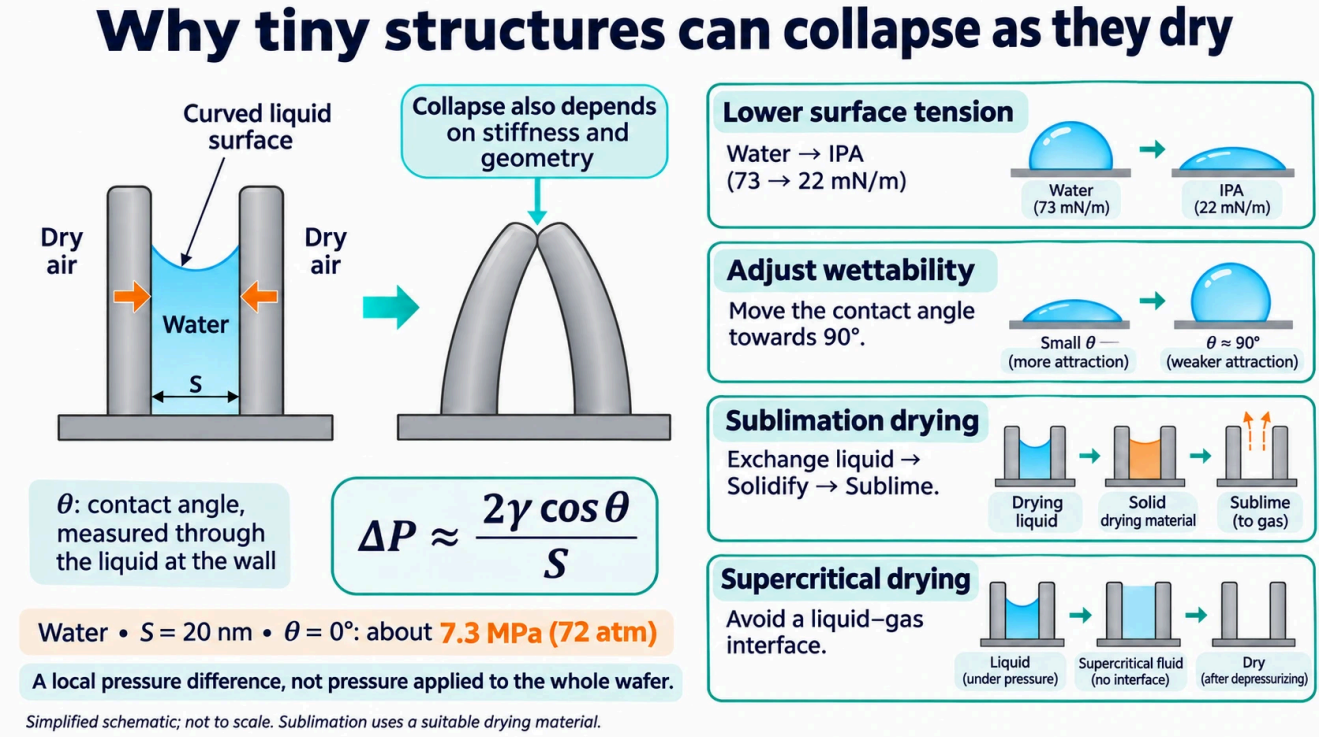

Figure 6 **Why tiny structures can collapse as they dry** (schematic)

Reading the figure

The numerical example assumes a 20 nm gap and zero contact angle. The liquid is deliberately shown on only one side of each pillar. Symmetric liquid on both sides would require considering both loads, rather than simply assuming an inward net force.

8. The water and chemicals must not become the contamination source

- **Ultrapure water**

Rinsing removes chemicals and released contaminants. It cannot do that reliably if the rinse water introduces new contamination.

The 2013 International Technology Roadmap for Semiconductors (ITRS) describes ultrapure water in terms of contaminants approaching or falling below available detection limits. It discusses revisiting definitions involving **1 ppt** for critical metals and **10 ppt** for other metals [29]. These are historical specification discussions, not a complete current water specification for every fab.

The 2024 IRDS report raises the possibility that organic contamination below **500 ppt** can include nanoscale material that passes very fine filters [20]. Purity therefore involves more than a single number: different contaminants need different measurement and removal methods.

Kurita's process material shows multiple treatment stages, including clarification and filtration, reverse osmosis, degassing, ultraviolet oxidation, ion exchange and ultrafiltration [30]. Each removes a different part of the contamination burden.

What “12N” does—and does not—mean

Stella Chemifa's 2026 material lists high-purity hydrofluoric-acid grades from **9N**, associated with impurity levels of 1 ppb or less, to **12N**, associated with 1 ppt or less [31] Reported .

The purity grade is distinct from the concentration of HF in an aqueous product. It does not mean that an HF–water mixture contains only a trillionth water. Nor can the grade be compared directly with 11N polysilicon without checking which impurities, limits and measurement definitions are covered.

For scale, **1 ppt by mass is one gram in one million metric tonnes of water**: $1\ g / 10^{12}\ g = 10^{-12}$ Calculation . The demanding part is maintaining that cleanliness through the tank, container, pipework, filter and point of use.

9. The equipment supplier landscape

Cleaning equipment is supplied by companies with different product portfolios and customer bases. The table is **alphabetical by company**, not a league table. The quoted figures are also not directly comparable: some concern cleaning revenue, some an entire business segment, and some a company's own market estimate.

Supplier	Headquarters / operating context	Examples in the source set	What the cited disclosure says
ACM Research	United States; business concentrated in China	Single-wafer and batch cleaning	Cleaning revenue of US$626 million in 2025 [38]
Lam Research	United States	EOS, DV-Prime; Coronus bevel plasma processing	Cleaning products appear within a broader equipment portfolio [36]
SCREEN	Japan	SU single-wafer systems; FC-3100 batch system; scrubbers	Claims leading shares in three cleaning categories, based on its own 2025 research [32]
SEMES	South Korea	BLUEICE PRIME and other cleaning tools	Describes itself as Korea's largest equipment supplier; company-wide annual business around KRW3 trillion [37]
Tokyo Electron	Japan	CELLESTA single-wafer and EXPEDIUS batch systems	Estimates its global cleaning-equipment position as third [34]

Different ways to compete

ACM Research reported 2025 revenue of **US$901 million**, including **US$898 million** from mainland China; cleaning contributed **US$626 million**, or **69.5%**. It estimated an addressable wafer-cleaning equipment opportunity of about US$7.3 billion and named competitors including Lam, NAURA, SCREEN, SEMES and Tokyo Electron. Its filing also records the December 2024 addition of its Shanghai and Korean subsidiaries to the US Entity List [38]. These figures describe a geographically concentrated business and a regulatory constraint, rather than the entire Chinese equipment industry.

Lam Research illustrates how cleaning sits within a wider process portfolio. Its filing lists cleaning systems as well as bevel plasma processing [36]. The source does not provide a directly comparable stand-alone cleaning share. A bevel tool also serves a different job from a general wet-cleaning tool; product names alone do not establish equivalence.

SCREEN reports a number-one position in single-wafer cleaning, batch cleaning and spin scrubbers, based on its own 2025 market research [32]. Its semiconductor production equipment segment recorded **JPY485.9 billion** in revenue for the year ended March 2026 [35]; that is not a cleaning-only figure.

The company dates its single-wafer cleaning development to **1983**. Its SU-3400 can accommodate **24 chambers**, arranged in four stacks of six, and advertises throughput up to **1,200 wafers per hour** [33]. The FC-3100 uses high-concentration IPA and reduced-pressure drying to address watermarks and pattern collapse [39]. Chamber parallelisation, compact layout and wafer handling provide plausible explanations for productive single-wafer operation Interpretation ; the advertised throughput remains dependent on the process conditions.

SEMES supplies cleaning equipment alongside other tool families [37]. Its company-wide scale is useful context, but it cannot be treated as cleaning revenue or converted into a cleaning market share.

Tokyo Electron combines deposition, coater/developer, etching and cleaning products [34]. Its CELLESTA platform supports up to **20 cleaning chambers**; the CELLESTA-i MD description emphasises IPA delivery for drying fragile patterns [40]. Such a portfolio can help address interactions between adjacent process steps Interpretation .

Cleaning accounted for **9%** of Tokyo Electron's new-equipment sales in the year ended March 2026 [34]. Applying that rounded share to JPY1,775.4 billion gives approximately **JPY160 billion** Calculation . This is an estimate from a rounded product mix, not a separately audited cleaning-revenue line. Its reported leading positions in diffusion and coater/developer equipment do not imply the same ranking in cleaning [34].

10. Chemical suppliers, water systems and reliable delivery

Specialist suppliers and concentrated markets

METI's 2025 overview attributes approximately **59%** of the 2023 high-purity cleaning-chemical market to Japan-headquartered suppliers [3]. This is a substantial share of a defined chemical category, rather than of all cleaning inputs or all water systems.

The following examples illustrate chemical production and water-system capabilities; they are not an exhaustive global supplier list.

- **Hydrofluoric acid:** Stella Chemifa reports combined high-purity HF capacity of **105,000 tonnes a year** across facilities in Kitakyushu, Osaka and Singapore, with shipments of **73,800 tonnes** in FY2025 [31]. Japan's Small and Medium Enterprise Agency describes Morita Chemical's first domestic HF production in 1918 and a highly concentrated Japanese supply base in its 2018 profile [41]. The date and market context matter; the profile is not a 2026 global share table.
- **Hydrogen peroxide:** Mitsubishi Gas Chemical reports a leading global position in super-pure hydrogen peroxide. It describes locating this production close to customers, unlike a feedstock-oriented location strategy for methanol [42]. Proximity can support stable supply and careful quality control; headquarters location alone does not describe its production network.
- **Ultrapure-water systems:** Kurita reported **JPY171.8 billion** of electronics-market revenue for the year ended March 2026 [45]. Organo reported **JPY108.0 billion** of electronics-industry revenue for the same period and described advanced-logic projects, including a 2 nm fab in Japan [46]. These are revenue categories with their own scopes, not directly comparable global water-market shares. Organo's account also describes its early delivery of an electronics-industry ultrapure-water system in Japan.

Across suppliers, high purity must be **measurable, maintainable and consistently delivered**. Analytical capability, compatible containers, clean distribution and customer qualification can be as important as making a pure chemical in the first place Interpretation .

A historical example of supply-chain exposure

In July 2019, Japan changed its export-licensing treatment of fluorinated polyimide, photoresist and hydrogen fluoride supplied to South Korea, requiring individual licensing in place of the previous broad treatment [43]. In March 2023, it restored eligibility for the relevant bulk-licensing arrangements [44].

The example shows how a process chemical can become a supply-chain issue. These dates describe the cited policy changes, rather than a statement of the complete current export-control rules. The technical lesson is the importance of supply continuity and qualification when a fab depends on a tightly specified material Interpretation .

11. What becomes harder next

Cleaning must advance alongside the structures it protects.

- **Removal with very little material loss.** Gate-all-around structures expose several materials at once. imec discusses highly selective isotropic etching as an important challenge [47]. A method that removes a little surface to release contamination becomes harder to use when almost no surface loss is acceptable.
- **Drying taller, thinner features.** High-aspect-ratio structures increase the need to manage capillary loading or avoid the final liquid–gas interface [26][27].
- **Control beyond the front surface.** IRDS identifies wafer edges, bevels and backsides as important contamination-monitoring and control areas [20].
- **Cleaner surfaces for hybrid bonding.** imec emphasises very flat, clean surfaces when joining wafers at fine interconnect pitches [48]. A particle can become a bonding defect rather than merely a surface blemish.
- **Measurement that keeps pace.** IRDS identifies a gap between critical-particle sizes and available particle metrology [20]. Being unable to detect a contaminant does not establish its absence.
- **Lower resource use.** IRDS discusses recycling, reclaiming and reusing ultrapure water [20]. SCREEN describes development of IPA–water separation to reduce organic waste [49]. The challenge is to reduce consumption while preserving process control.

Opportunities for materials specialists

Potential contributions include more selective cleaning formulations, lower-surface-tension liquids, surface treatments, sublimable drying materials, cleaner containers and pipework, improved separation membranes, and chamber coatings that shed fewer particles. Process performance depends on chemistry, polymers, ceramics and analysis working together.

12. What to remember—and what comes next

Question	Key point
Why clean so often?	Every operation leaves a surface that the next operation must use.
What is removed?	Particles, metals, organics and oxide where oxide is unwanted.
How does removal work?	Chemical reaction, electrical interactions and controlled physical transport.
Why is drying difficult?	A liquid meniscus can bend slender structures; watermarks can leave residues.
What makes the industry demanding?	Surface preservation, purity, measurement and delivery must all work together.
How should supplier claims be read?	Keep years, product categories, revenue scopes and self-reported rankings distinct.

The next lesson, **3-2: Oxidation and heat treatment**, turns from removing unwanted surface material to deliberately growing a useful oxide. It asks how oxygen reacts with silicon inside a hot furnace, and how that reaction can be controlled.

13. Check your understanding

1. Why can a supplier-share chart look very different from a regional equipment-spending chart?

▼ Show answer

The first commonly groups companies by headquarters; the second groups equipment purchases by the location of the receiving fab. They measure different sides of a global supply chain and may also use different years and product definitions.

2. Name four classes of material removed in wafer cleaning. Is native oxide always unwanted?

▼ Show answer

Particles, metals, organic residues and native oxide. Oxide is removed only where the next process requires it; useful oxide layers are deliberately retained or grown.

3. Why can SC-1 reduce particle redeposition?

▼ Show answer

Slight surface etching can loosen attachment. Under suitable conditions, a silica particle and oxide surface have the same sign of charge and repel. Liquid flow must then carry the particle away. The behaviour depends on materials and chemistry.

4. What changes when DHF removes native oxide from silicon?

▼ Show answer

It exposes a surface that can become hydrogen-terminated and hydrophobic, rather than the hydrophilic oxide-covered surface present before treatment.

5. Does processing one wafer per chamber mean a single-wafer tool must have low throughput?

▼ Show answer

No. Many chambers can operate in parallel. Overall throughput also depends on processing time, handling and tool configuration; batch and single-wafer figures require comparable conditions.

6. Estimate capillary pressure for water in a 20 nm gap with zero contact angle. What changes if IPA is substituted?

▼ Show answer

With $\Delta P \approx 2\gamma\cos\theta/S$ and $\gamma = 0.073$ N/m, the result is about 7.3 MPa, or 72 atm. At 0.022 N/m, the IPA estimate is about 2.2 MPa. This is a local pressure difference in a simplified model, not a whole-wafer pressure or a complete collapse prediction.

7. What do sublimation and supercritical drying have in common?

▼ Show answer

They can avoid a liquid–gas interface during the final removal stage. Sublimation removes a suitable solid directly as vapour; supercritical drying uses a controlled temperature–pressure path without forming the meniscus responsible for capillary loading.

8. How can you describe Japan's cleaning-chemical strength accurately without making a claim about the whole industry?

▼ Show answer

State the category, year and measure: METI attributes about 59% of the 2023 high-purity cleaning-chemical market to Japan-headquartered suppliers. It is not a share of every cleaning input or of all semiconductor manufacturing.

14. Glossary

Supplier share
A market share grouped here by the manufacturer's headquarters, not by every manufacturing location.

Customer market
Purchases grouped by the location of the receiving fab.

Particle
A small piece of material that can contaminate a wafer or liquid.

Killer particle
A particle capable of causing device failure under the relevant process and design conditions.

Native oxide
A thin oxide that forms when silicon encounters oxygen and moisture.

RCA cleaning
A family of cleaning methods developed at RCA, including SC-1 and SC-2.

SC-1
An alkaline ammonia–peroxide–water clean used for particles and organics.

SC-2
An acidic hydrochloric-acid–peroxide–water clean used for metals.

DHF
Dilute hydrofluoric acid, used to remove silicon oxide.

SPM
Sulphuric acid–peroxide mixture, used to oxidise organic residues.

Ozonated water
High-purity water containing dissolved ozone.

Zeta potential
Electrical potential at the slipping plane in a liquid; an indicator of electrical interactions.

Isoelectric point
The pH at which zeta potential is zero for the specified surface and solution conditions.

Complex
A metal ion bound to surrounding molecules or ions.

Hydrophilic / hydrophobic
Readily wetted by water / resistant to wetting by water.

Megasonic cleaning
Cleaning assisted by high-frequency acoustic energy, often around 1 MHz.

Cavitation
Formation and collapse or oscillation of bubbles in a liquid.

Brush scrubbing
Physical cleaning using a brush in contact with the surface.

Batch processing
Treating multiple wafers together, for example in a common bath.

Single-wafer processing
Treating one wafer at a time in each process chamber.

Cross-contamination
Transfer of unwanted material between wafers, fluids or process locations.

Chamber
A controlled process space within a tool.

Watermark
Residue or surface damage associated with liquid drying on the wafer.

Marangoni drying
Liquid removal driven by a surface-tension gradient, commonly using IPA near a water surface.

Pattern collapse
Bending and sticking of slender features, including during liquid removal.

Surface tension
The interfacial property entering capillary forces; water and IPA are approximately 73 and 22 mN/m in the cited example.

Contact angle
Angle at the solid–liquid–gas contact, measured through the liquid.

Aspect ratio
Feature height divided by width.

Sublimation drying
Removing a suitable solid drying material directly as vapour.

Supercritical drying
Removing fluid along a suitable path that avoids a liquid–gas interface.

Ultrapure water
Water with tightly controlled contamination, often close to measurement limits for specified impurities.

ppt
Parts per trillion; 10 to the power of −12 as a fraction.

Reverse osmosis
Pressure-driven membrane separation used to remove dissolved contaminants.

Isotropic etching
Etching that proceeds in all directions rather than favouring one direction.

Bevel
The shaped edge region of a wafer.

Hybrid bonding
Joining dielectric surfaces and metal interconnects in the same bonding structure.

Entity List
A US export-control list; restrictions depend on the applicable rules and transaction.

Customer-proximate production
Locating production near the customers that consume the product.

15. References and supporting material

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16. Claims and supporting sources

Claim or topic	Supporting material and limits	Type
Equipment billings by region; US$135.1bn total; China and Taiwan positions	SEAJ / SEMI [1]	Reported
Materials market US$73.2bn and regional destinations; Taiwan as largest market	SEMI [2]	Reported
2023 equipment and high-purity cleaning-chemical supplier shares	METI 2025, chart readings [3]	Reported
FY2021 equipment and key-material shares; more than 1,000 manufacturing steps	METI 2023 [4]	Reported
Examples connecting materials disciplines to products	Company product pages [5–15]; examples, not a global ranking	Reported
Repeated cleaning; RCA development account; pH example; ozonated water; Marangoni effect	Heyns et al., 1999 [16]; conditions and publication date retained	Reported
Approximately 20% of steps in the patent example	Lam patent [17]; not a universal current fab ratio	Reported
Contamination categories and physical cleaning methods	SCREEN process overview [18]	Reported
Cleaning chemistry, metal contaminants, DHF and SPM teaching conditions, acoustic mechanisms	nanoHUB lecture [19]; recipes described as examples	Reported
Few-nanometre critical particles; organic contamination; edge and backside control; metrology and water reuse	IRDS 2024 [20]; roadmap conditions retained	Reported
RCA research began in 1961; paper published in 1970	Kern retrospective [21]	Reported
Surface etching and particle–substrate interactions; damage below 30 nm in the study	Lee et al., 2013 [22]; not a current universal tool limit	Reported
Cross-contamination as a reason for single-wafer processing	Applied Materials patent [23]	Reported
Batch example around 400 wafers/hour, recirculation and hot SPM	ACM patent [24]; particular conditions	Reported
Capillary model, 73 and 22 mN/m example values; surface-treatment result of 1.7×	Watanabe et al., 2013 [25]; simplified geometry and study conditions	Reported
Solidification of a sublimable-material liquid and removal as vapour	SCREEN patent [26]	Reported
Supercritical-drying system announced in December 2020	Tokyo Electron [27]	Reported
Watermarks and IPA-assisted Marangoni drying	Siemens / IBM patent [28]	Reported
Ultrapure-water definitions and historical metal-limit discussion	ITRS 2013 [29]	Reported
Multiple stages in ultrapure-water production	Kurita [30]	Reported

Claim or topic	Supporting material and limits	Type
HF grades, 105,000 t/year capacity and FY2025 shipments of 73,800 t	Stella Chemifa [31]	Reported
Leading positions in three cleaning categories	SCREEN [32]; own market research, 2025	Reported
1983 development; up to 24 chambers and 1,200 wafers/hour	SCREEN SU-3400 [33]; advertised capability, recipe-dependent	Reported
Estimated third position in cleaning; portfolio; 9% of new-equipment sales	Tokyo Electron Integrated Report [34]; own estimates and rounded product mix	Reported
JPY485.9bn semiconductor equipment segment revenue	SCREEN results [35]; not cleaning-only revenue	Reported
Cleaning and bevel products in a broader portfolio	Lam Form 10-K [36]	Reported
Company scale and cleaning product examples	SEMES corporate overview [37]; company-wide scope	Reported
ACM sales, geography, cleaning mix, market estimate and subsidiary Entity List additions	ACM Form 10-K [38]; company figures and market estimate	Reported
Reduced-pressure IPA drying; up to 20 chambers and IPA-delivery approach	SCREEN FC-3100 [39]; Tokyo Electron CELLESTA [40]	Reported
Morita history and the concentrated supply base described in 2018	Japanese SME Agency [41]; historical scope	Reported
Super-pure hydrogen-peroxide position and customer-proximate strategy	Mitsubishi Gas Chemical [42]; company account	Reported
2019 licensing change and March 2023 amendment	METI announcements [43][44]; historical events	Reported
Electronics-related revenues of JPY171.8bn and JPY108.0bn; Organo projects	Kurita [45]; Organo [46]; scopes kept separate	Reported
Selective isotropic etching and flat, clean bonding surfaces	imec [47][48]	Reported
Development of IPA–water separation	SCREEN technology highlights [49]	Reported
Approximately 7% domestic equipment purchases; atom-spacing comparison; 7.3/2.2 MPa; 1 ppt mass analogy; approximately JPY160bn TEL cleaning estimate	Arithmetic shown in the text using stated source values and assumptions	Calculation
Reasons for parallelisation, process-portfolio benefits and quality-delivery capabilities	Editorial interpretation, identified as such in the text	Interpretation
Surface preparation, transport, preservation, wetting and supply-chain implications	General teaching explanation; simplified figures are not quantitative process simulations	Explanation

Updated 6 November 2026. Market figures retain their stated years and definitions; company rankings are attributed to the companies making the claims. Historical papers and patents explain particular mechanisms and examples, rather than universal limits for current equipment. Calculations and interpretation are identified separately from reported evidence.

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