SEMICONDUCTOR FABRICATION · PART 3-5

Photolithography: the basics
How light gives a chip its pattern

A perfectly uniform film is only a starting point. To make a working chip, we must decide where material stays, where it is removed and how each new layer lines up with the last. Photolithography makes that possible by turning an optical image into a temporary chemical stencil. This lesson follows the process from coating to inspection, explains why waves limit the image, and shows how resist chemistry, precision machinery and a global network of suppliers work together.

Part 3 · Lesson 3-5 · Intermediate beginner level · Introduction 1-4 is useful preparation · English edition: 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

- Follow a resist pattern from surface preparation to development, inspection and the next fabrication step.
- Use wavelength, numerical aperture and k_1 to estimate printable feature size, and explain the cost in focus tolerance.
- Explain how an acid catalyst makes a chemically amplified resist sensitive to a small exposure dose.
- Distinguish the roles of exposure-tool, track, resist and mask suppliers, and read their market figures on a comparable basis.

1. The lesson in three ideas

- **Lithography makes a temporary stencil.** Light changes a photoresist's chemistry; developer removes selected regions. The remaining resist can protect the material underneath during etching or other processing. A common projection system reduces the mask image to one quarter of its original width and height.
- **A fine image needs optics and chemistry to cooperate.** The Rayleigh relation, $R = k_1\lambda/NA$, links feature size to wavelength, the light-collecting ability of the optics and process optimisation. Chemical amplification supplies another essential ingredient: a useful chemical change from a limited light dose.
- **The supply chain has several distinct markets.** ASML leads exposure equipment by revenue, while tracks, resists, mask writers, mask blanks and pellicles have different supplier structures. A strong position in one segment does not imply leadership in every part of lithography.

2. What is being printed?

A stencil, rather than a finished circuit

The deposition methods in Lessons 3-3 and 3-4 cover a wafer with material. A circuit needs a pattern within that material. Photolithography defines that pattern in a light-sensitive polymer coating called **photoresist**, usually shortened to **resist**.

Think of the resist as a temporary stencil. The openings expose selected parts of the underlying film to the next process. Lithography itself does not normally cut the film or turn it directly into a functioning transistor. **Exposure, development and pattern transfer are separate operations.** Explanation

Lithography is repeated as the chip's layers are built. Stanford's 1999 teaching notes put it at roughly 35% of wafer-manufacturing cost and used an overlay tolerance of about one third of a feature width [1] Reported . Those figures illustrate its importance in that historical setting; they are not universal cost or accuracy rules for today's products.

Positive and negative tone

The two names describe what survives development. With **positive resist**, the exposed regions become removable in the developer. With **negative resist**, the exposed regions remain [11] Reported . The same mask can therefore produce opposite resist patterns.

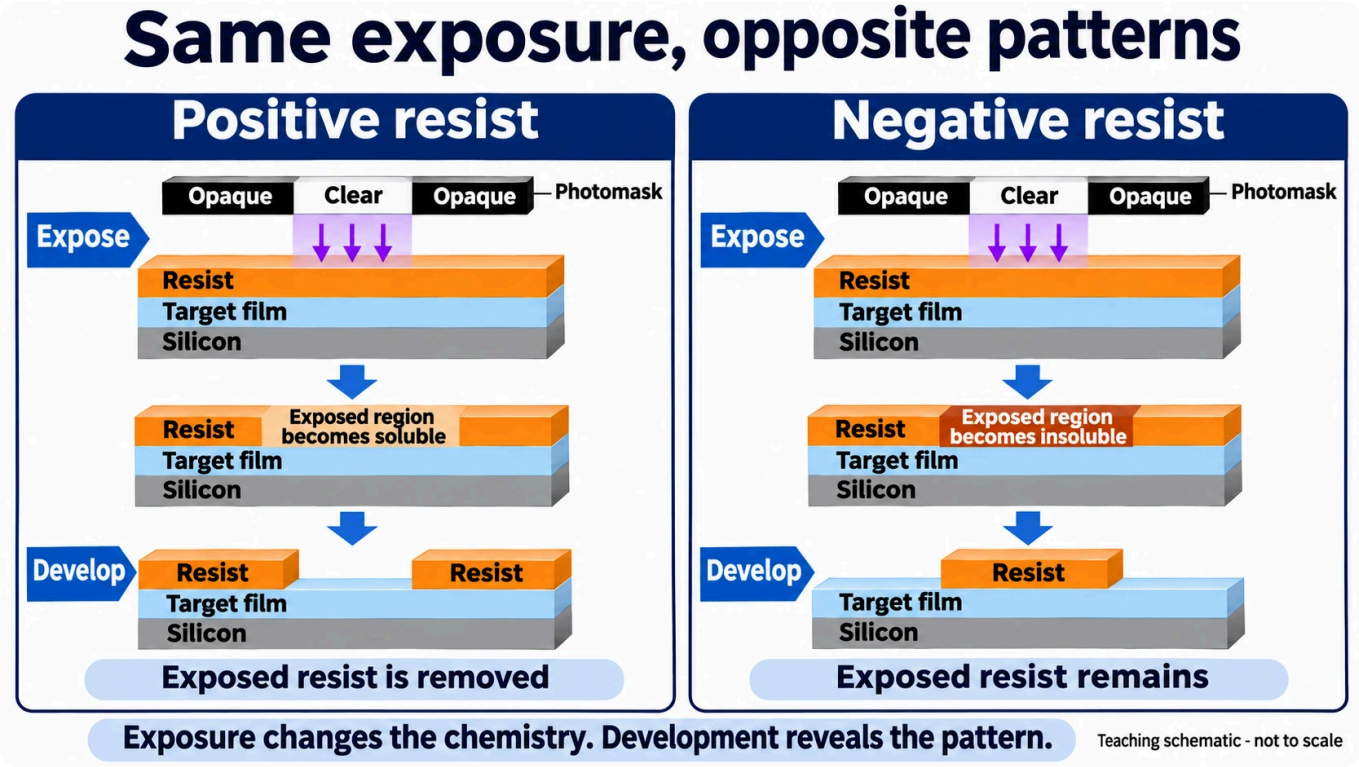


Figure 1 **Positive and negative resist: the same exposure gives opposite patterns** (schematic)

Reading the figure

The light reaches the centre in both panels. Before development, the resist is still a continuous film. Afterwards, the positive-tone centre has gone and the negative-tone centre remains. The pale-blue target film stays intact throughout: **developing the resist is not the same as etching the film**.

3. From a clean surface to a usable stencil

A process sequence with choices

Purdue's resist-technology lecture lists the following processing operations [5] Reported . Real recipes select the steps and conditions to suit the resist and the subsequent fabrication process; they do not simply apply every bake to every product.

1. **Dehydrate the surface.** The lecture gives 150-200 °C in vacuum or nitrogen as an example.
2. **Apply an adhesion treatment**, commonly HMDS.
3. **Coat the resist**, often by spinning the wafer.
4. **Soft bake** to remove solvent.

5. **Expose** the desired image.
6. **Post-exposure bake (PEB)** where the resist chemistry requires it.
7. **Develop, rinse and dry** to reveal the pattern.
8. **Inspect** dimensions and alignment before transferring the pattern.
9. **Stabilise the resist if needed**, using a process-specific hard bake or other treatment.

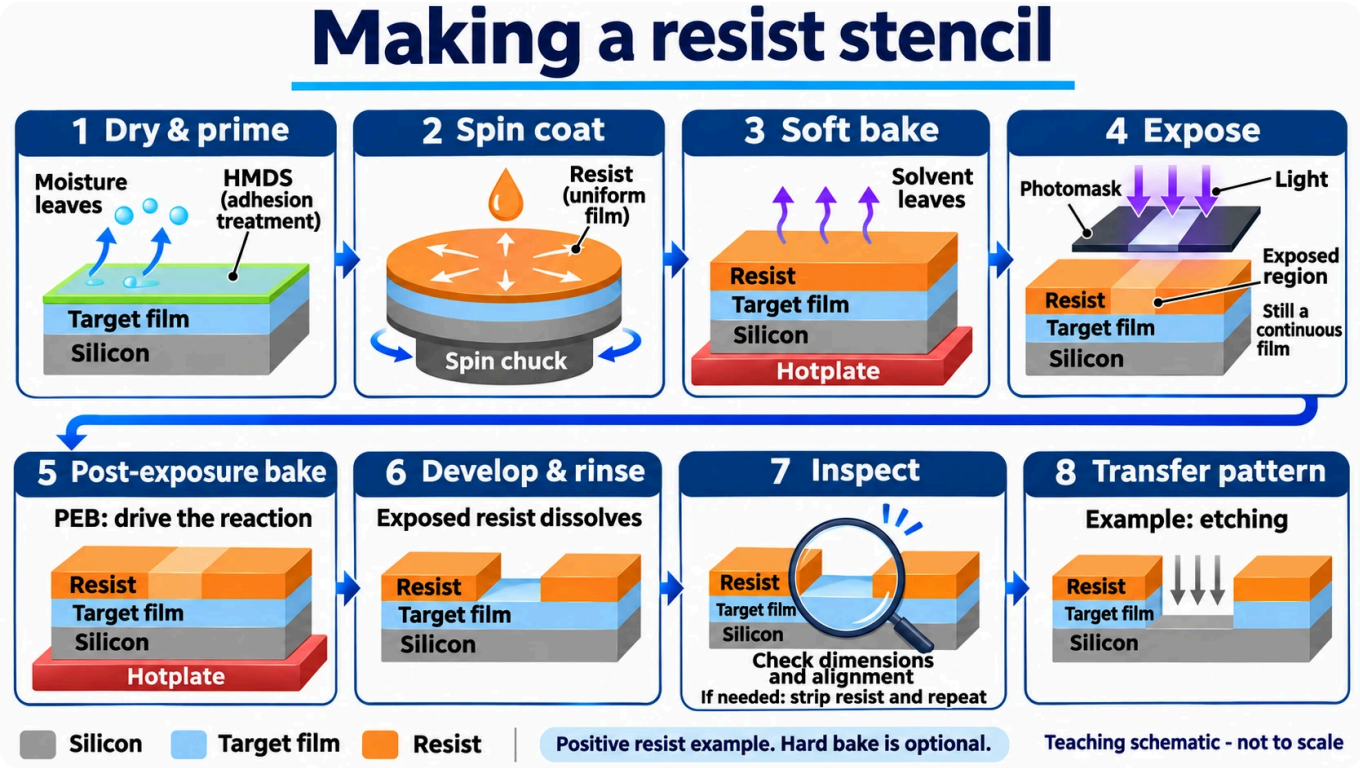


Figure 2 **Making, checking and using a resist stencil** (schematic)

Reading the figure

In scene 4, illumination changes part of the resist but does not open a hole. In this positive-tone chemically amplified example, scene 5 drives the reaction during PEB. Scene 6 removes soluble resist; scene 7 checks the result. Only scene 8 transfers the pattern into the target film. A failed resist pattern can potentially be stripped and repeated before that transfer.

A **hard bake** is optional. MicroChemicals explains that it can improve a developed mask's stability, but may also round its shape or make later stripping more difficult [51] Reported . The aim is a suitable stencil for the next operation, rather than the hottest possible bake.

Why adhesion starts before coating

A silicon-oxide surface is hydrophilic, whereas a novolac-based resist is hydrophobic. **HMDS**, or hexamethyldisilazane, modifies the surface to promote resist adhesion. Vapour treatment is one implementation described in the Purdue lecture [5] Reported . This is surface preparation, not another thick functional layer in the device.

Spin coating: faster rotation, thinner resist

Liquid resist is dispensed near the wafer centre. Rotation spreads it into a thin coating while material is spun off. Stanford's notes give 3,000-6,000 rpm and approximately 0.5 µm film thickness as typical examples [1] Reported . These are illustrative conditions, not a recipe for every resist.

For a given resist and coating regime, thickness scales approximately as the inverse square root of spin speed. MicroChemicals gives typical spin times of 10-20 seconds and notes that only a few per cent of the dispensed resist may remain [31] Reported . Doubling the speed therefore gives about **1/√2 = 0.71 times the thickness**; quadrupling it gives about half Calculation . Formulation, viscosity and solvent evaporation still matter.



Photoresist during spin coating on a silicon wafer, as identified in the Wikimedia Commons description.
Photo: Sei / Wikimedia Commons / CC BY-SA 4.0. Resized and converted to WebP.

Two bakes, two different jobs

The **soft bake** removes solvent from the freshly applied coating. Purdue gives 90-100 °C for 30-90 seconds as an example, reducing residual solvent below 5% [5] Reported .

The **post-exposure bake** comes later. Incoming and reflected light can interfere within the resist, producing standing-wave variations in exposure. Controlled diffusion during PEB can smooth those variations [1] Reported . In a chemically amplified resist, PEB also drives the acid-catalysed reaction that changes solubility. Section 6 explains why this is central to the process.

Developer: selective removal

A common positive-resist developer is aqueous **TMAH**, tetramethylammonium hydroxide, at 2.38% concentration [32] Reported . Assuming a solution density close to 1 kg/L, that is approximately 0.26 mol/L Calculation . Hiroshi Ito's review describes how the 0.26-normal developer established for novolac resists became a continuing constraint on later materials [9] Reported .

TMAH avoids sodium and potassium ions, which are undesirable contaminants in transistor fabrication. Purdue also stresses developer-temperature control, giving a tolerance within 1 °C [5] Reported . The choice of developer and its conditions must match the resist system.

- **Why the room is yellow**

Short-wavelength ambient light could expose sensitive resist unintentionally. Lithography areas therefore often use yellow or orange lighting, as illustrated by the research cleanroom below.



The photolithography area of the London Centre for Nanotechnology cleanroom. The Commons description identifies the orange lighting as protection against unintended short-wavelength exposure. This is a research facility.
Photo: UCL Faculty of Mathematical & Physical Sciences (O. Usher) / Wikimedia Commons / CC BY 2.0. Resized and converted to WebP.

- **Inspect before making the change permanent**

If resist dimensions or alignment are out of specification, it may be possible to strip the resist and repeat the lithography sequence. A patent on resist rework explicitly discusses its economic advantage over scrapping a wafer [35] Reported . Once an incorrect pattern has been etched into the underlying film, replacing the resist will not restore the removed material. This is why inspection belongs before pattern transfer. Explanation

4. Why light limits the image

- **Fine patterns send light out at wider angles**

Light is a wave. After passing through a small opening, it spreads by **diffraction**. A repeating line-and-space mask acts like a grating. For normal incidence in a simplified air-space example, the first diffracted order obeys [1][2] Reported :

$$\sin \alpha = \lambda / p$$

Here p is the pitch and λ the wavelength. Reducing the pitch sends the first-order light out at a larger angle. Forming a periodic image requires interference between collected diffraction orders; zero order alone has no information with which to reproduce the stripes [2] Reported .

Numerical aperture: how much light angle can the optics accept?

Numerical aperture, NA = n sin θ, combines the refractive index n on the image side and the maximum accepted ray angle θ. It describes the optics' ability to collect the light needed for fine detail [1] Reported . It is more informative than lens diameter alone.

In air, n is approximately 1, so NA cannot exceed 1. Purdue describes about 0.93 as a practical dry-lithography limit, corresponding to roughly 68°, and cites a lens assembly weighing about 1,000 kg [2] Reported . These figures describe the systems in that lecture, rather than a weight specification for every exposure tool.

Worked example: the Rayleigh relation

The usual resolution estimate is [1][13] Reported :

$$R = k_1 \times \lambda/NA$$

R is a characteristic printable feature dimension. The factor k_1 depends on the imaging and process conditions. Historical Stanford notes use 0.6-0.8; a 2003 MIT Lincoln Laboratory paper discusses 0.4 for advanced devices and a lower bound of 0.25 for equal lines and spaces in single-exposure optical imaging [1][6] Reported . These values are not interchangeable promises for arbitrary shapes.

With KrF at 248 nm, NA = 0.6 and k_1 = 0.75, R is about 310 nm, conventionally rounded to 0.3 μm in the lecture [1] Reported .

For dry ArF at 193 nm and NA = 0.93:

- k_1 = 0.30 gives 0.30 × 193/0.93 ≈ **62 nm**.
- k_1 = 0.25 gives 0.25 × 193/0.93 ≈ **52 nm**. Calculation

Purdue gives the latter as the dry 193 nm limit under those assumptions [2]. ASML specifies ≤57 nm for its NXT:1470 dry-ArF system [19] Reported . Immersion places water between the final optics and wafer, allowing NA above 1; ASML describes NA = 1.35 [15] Reported . Lesson 3-6 develops that idea.

Better resolution leaves less room for a focus error

A common focus-tolerance relation is [1] Reported :

$$\mathrm{DOF} = \pm k_2 \times \lambda / \mathrm{NA}^2$$

In this lesson the ± convention describes the tolerance on each side of best focus; the total vertical interval is twice that value. Other sources may define DOF using the full interval, so always check the convention.

For KrF, NA = 0.6 and k_2 = 0.5, the Stanford example is about ±0.35 µm. For ArF at 193 nm, NA = 0.93 and the same k_2, the estimate is **±112 nm**, or approximately ±0.11 µm Calculation . NA improves resolution linearly but reduces focus tolerance through its square. Wafer bow and underlying topography therefore become increasingly significant. Planarisation, including CMP in Lesson 3-11, helps keep the resist surface in focus.

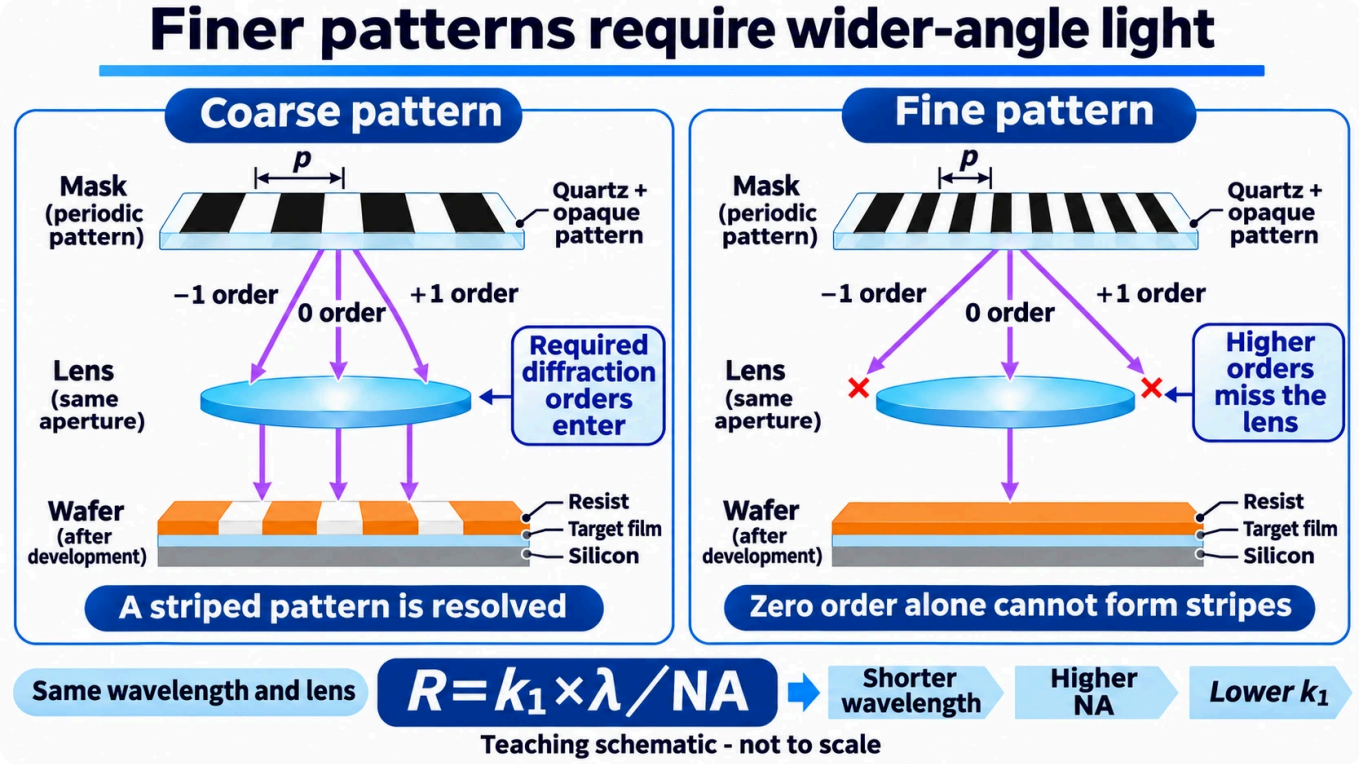


Figure 3 **Diffraction: fine detail needs the wider-angle orders** (schematic)

Reading the figure

On the left, the lens accepts the orders needed to resolve the coarse stripes. On the right, the fine mask sends higher orders beyond the aperture; zero order alone cannot form a striped image. This is a schematic of the imaging principle, not a complete optical ray trace. Shorter wavelength, higher NA and process improvements that lower k_1 are three routes to finer patterns.

The dimension R is not automatically a commercial node name such as “2 nm”. Node names describe technology generations; this equation estimates a feature under particular imaging conditions. Explanation

- **The move to shorter wavelengths**

Source	Wavelength	How the light is produced	Historical manufacturing examples
g-line	436 nm	Mercury lamp; visible blue light	Around 0.8 µm in 1980s 4 Mbit DRAM
i-line	365 nm	Mercury lamp; ultraviolet	Sub-0.5 µm and 0.35 µm in the early 1990s
KrF	248 nm	Krypton-fluoride excimer laser	Around 0.25 µm in the late 1990s
ArF	193 nm	Argon-fluoride excimer laser	Introduced towards the end of the 1990s
EUV	13.5 nm	Tin plasma	Covered in Lesson 3-7

The wavelengths come from the technical sources; the historical production examples are from the Semiconductor History Museum of Japan [1][14][25] Reported . They are examples of adoption, not a statement that older wavelengths disappeared. ASML describes i-line progressing to about 220 nm, and ArF reaching 38 nm with immersion [14][19] Reported . The MIT paper dates the transition to printed dimensions smaller than the exposure wavelength to around 1996 [6] Reported .

5. How an exposure tool covers the wafer

- **Contact, proximity and projection**

Three arrangements help explain how the technology developed [1] Reported :

- **Contact exposure:** the mask touches the resist. It can resolve fine detail, but contact introduces risks of contamination and damage.
- **Proximity exposure:** a small gap avoids direct contact, at the cost of diffraction across the gap.
- **Projection exposure:** optics form an image of the mask on the wafer. This is the main approach for advanced chip fabrication.

In a simplified proximity estimate, $W_{min} \approx \sqrt{(\lambda g)}$, with gap g. For i-line and a 10 µm gap, the Stanford notes give roughly 2 µm [1] Reported . Contact and proximity tools nevertheless remain useful: SUSS supplies mask aligners for research, MEMS, advanced packaging and volume manufacturing [52] Reported . Suitability depends on the product and required dimensions.



MA-6 and MJB-3 mask aligners at LAAS-CNRS in France, under yellow lighting. The machines use contact or proximity exposure, as described on Commons. They illustrate a different application class from a leading-edge production scanner.
Photo: Guillaume Paumier (user:guillom) / Wikimedia Commons / CC BY-SA 3.0. Resized and converted to WebP.

A stepper exposes a field, then moves

Early projection systems included Perkin-Elmer's unity-magnification approach. Later steppers commonly reduced mask dimensions by factors of two to five, making the mask easier to manufacture and reducing the instantaneous optical field [1] Reported . A **stepper** exposes one field, moves the wafer and repeats.

Nikon records its first Japanese-made production stepper shipment in 1980 and an i-line stepper in 1984; Canon also introduced a stepper in 1984 [22][24] Reported . The historical museum estimates that Nikon and Canon together accounted for 70-80% of the exposure-tool market around 1995, linked to the strength of Japan's DRAM manufacturers at the time [24] Reported . That is historical context, not the present market structure.



An AutoStep stepper using 365 nm i-line illumination, identified in the Commons record. The photograph shows research equipment, not a current high-volume production scanner.
Photo: a13ean / Wikimedia Commons / CC BY-SA 3.0. Resized and converted to WebP.

A scanner exposes a moving slit

A **scanner** illuminates a narrow slit and moves the reticle and wafer in synchronisation. In a conventional inverted 4:1 reduction system, they move in opposite directions. The reticle travels four times as far and four times as fast as the wafer, keeping its reduced image matched to wafer motion. Explanation

A historical account describes a lens diameter about 0.7 times that needed by a comparable stepper and a larger effective field in the scan direction. It records Nikon's 1995 NSR-S201A delivery to IBM, with NA = 0.6 and 0.25 µm resolution [26] Reported . Nikon identifies this as the first step-and-scan system in its history [22]; the claim concerns that generation of semiconductor reduction scanners, not every earlier form of scanning optical exposure. Later systems increased NA beyond 0.8 [25] Reported .

Representative DUV specifications include a **26 × 33 mm field**, **4:1 reduction** and a **6-inch reticle** [20][23] Reported . These are examples, not a rule for all lithography platforms. ASML introduced its dual-stage TWINSCAN architecture in 2000, measuring one wafer while exposing another [17] Reported .

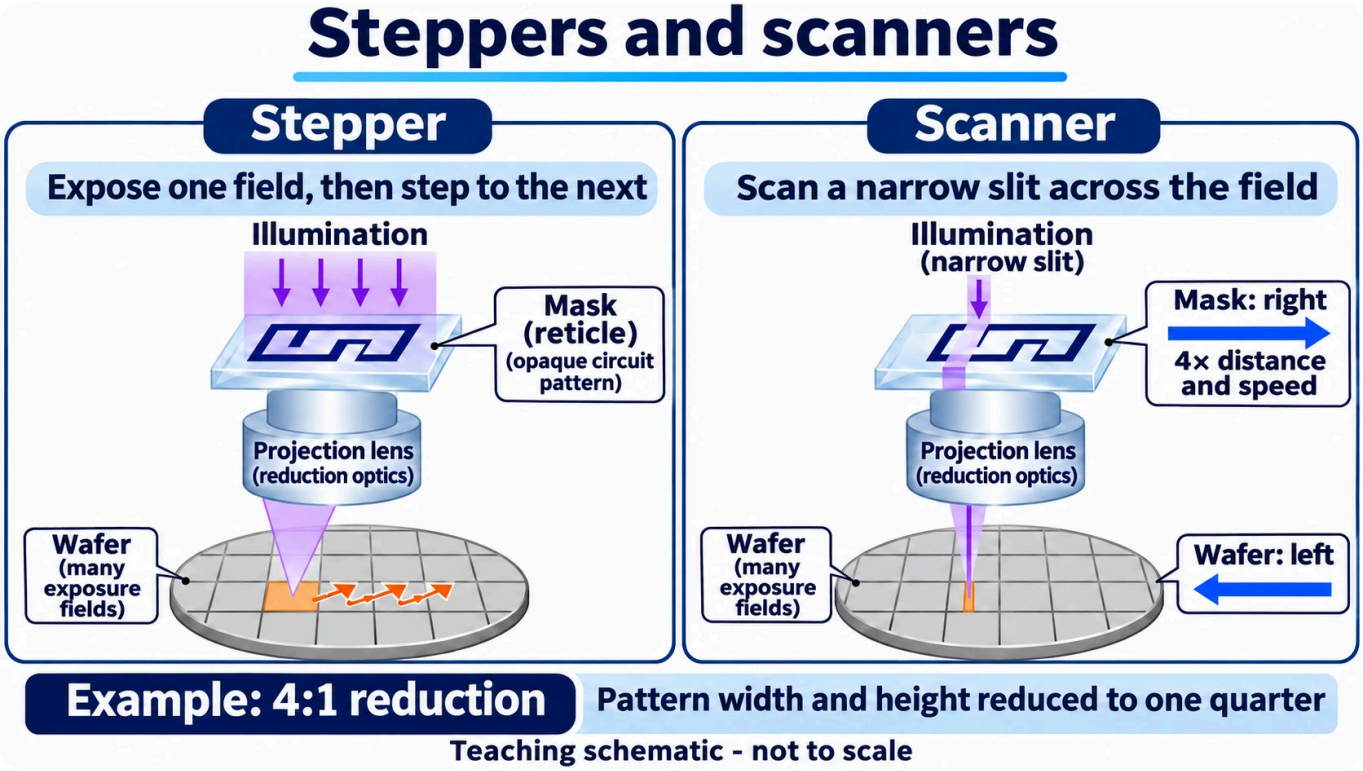


Figure 4 **Step and repeat, or step and scan?** (schematic)

Reading the figure

The upper object is a transparent glass reticle carrying an opaque pattern, not a resist-coated wafer. The projection optics reduce its image. In the scanner example, the reticle moves right while the wafer moves left; the reticle's fourfold travel and speed match the 4:1 image reduction. Only one field is being exposed at a time.

Specifications put the equation to work

System	Source	NA	Specified resolution	Wafers/hour	Indicative k_1
ASML XT:400M	i-line, 365 nm	0.65	≤350 nm	≥245	0.62
Canon FPA-5550iZ2	i-line, 365 nm	0.45-0.57	≤350 nm	Not stated here	0.55
ASML XT:860N	KrF, 248 nm	0.80	≤110 nm	≥260	0.35
ASML XT:1460K	Dry ArF, 193 nm	0.93	≤65 nm	≥205	0.31
ASML NXT:2100i	Immersion ArF, 193 nm	1.35	≤38 nm	295	0.27
Nikon NSR-S636E	Immersion ArF, 193 nm	1.35	≤38 nm	≥280	0.27

Specifications are from manufacturer pages [19][20][23] Reported . The final column is calculated as R × NA/λ, using the quoted resolution value and maximum NA; Canon's example uses 0.57 Calculation . It is an indicative comparison, not a normalised cross-vendor acceptance test. Throughput also depends on the stated test conditions.

The immersion examples give $k_1 \approx 0.27$, close to the single-exposure 0.25 benchmark for equal lines and spaces. At 300 wafers/hour, the average time budget is 12 seconds per wafer Calculation . That is an aggregate throughput measure; dual stages and other tasks can overlap, so it is not the duration of a single exposure.

Overlay: the next layer must land in the right place

Overlay measures how accurately patterns on different layers line up [18] Reported . A narrow line is little use if a contact opening misses it.

The 2022 IRDS roadmap lists leading-edge logic overlay targets of 2.4 nm for 2022, 2.0 nm for 2025 and 1.6 nm for 2028, expressed at 3σ [28] Outlook . These are roadmap requirements, not evidence that every factory has achieved them. Nikon specifies matched-machine overlay of ≤2.1 nm for the NSR-S636E under its stated conditions [20][21] Reported . Tool specifications and roadmap budgets should not be compared as if their definitions were identical.

For scale only, 2 nm is of the order of ten silicon atomic spacings if one uses 0.2-0.3 nm as a rough spacing Interpretation . It is an intuition aid, not an atom-counting definition of overlay.

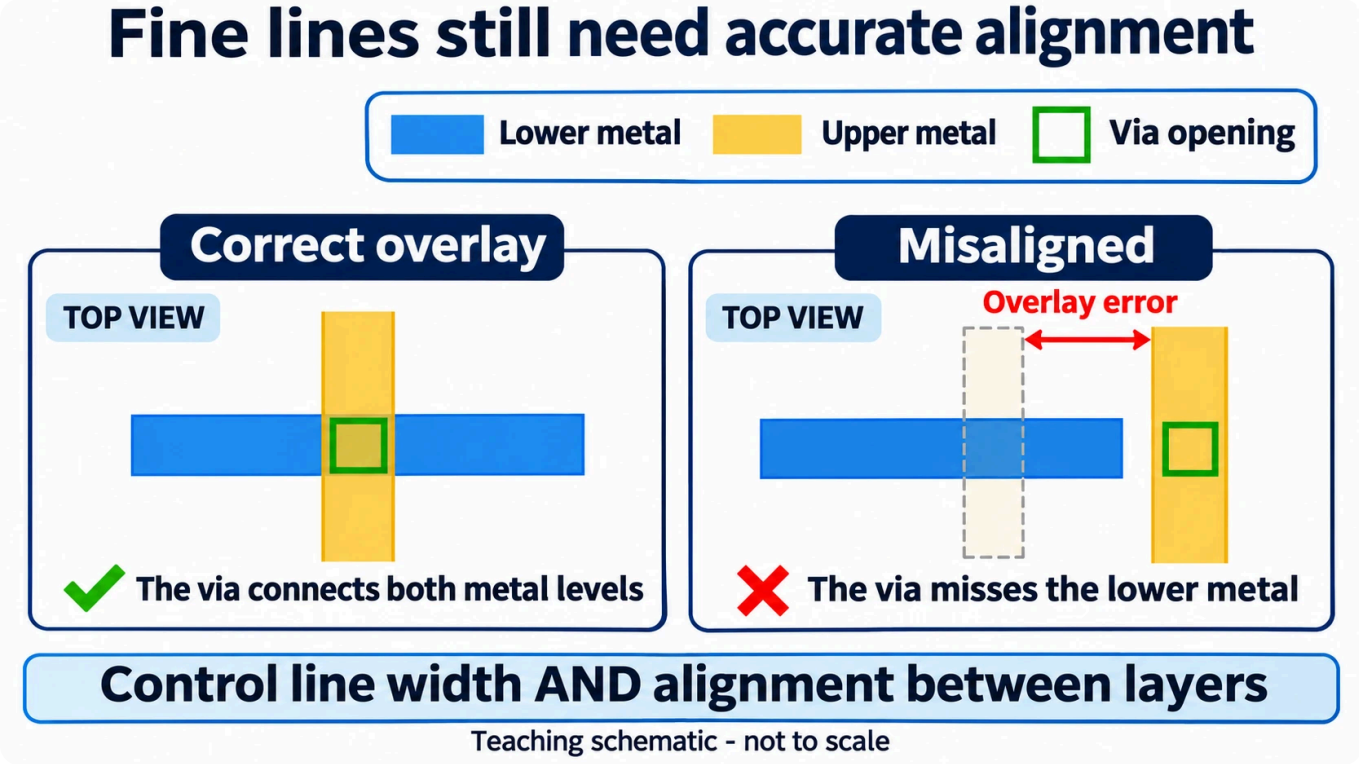


Figure 5 **Fine lines still need accurate alignment** (schematic)

Reading the figure

Blue is the lower metal, gold the upper metal and the outlined square a via opening. In the left panel, both metal levels enclose the via. In the right, the upper metal and via are displaced beyond the end of the lower line. The illustrated failure is a missed connection. **Line width and layer-to-layer position need separate control.**

6. Resist chemistry: getting more work from the light

- **DNQ and novolac: a large change in dissolution rate**

Traditional g-line and i-line resists combine **diazonaphthoquinone (DNQ)** with **novolac resin**. Exposure converts DNQ through photochemistry into a carboxylic-acid product, changing dissolution behaviour [1] Reported . Purdue gives illustrative dissolution rates of about 0.5 nm/s for unexposed DNQ/novolac and 500 nm/s after sufficient exposure, compared with about 5 nm/s for novolac alone [5] Reported . The exposed-to-unexposed ratio in that example is roughly **1,000:1** Calculation .

At 248 nm, however, DNQ/novolac absorbs too strongly to perform adequately. Ito's account identifies this deep-UV absorption problem [8] Reported . The historical KrF account also describes an early source-brightness constraint and a need for roughly ten times the sensitivity of g-line/i-line materials [27] Reported .

Stanford gives a typical photochemical quantum efficiency of about 0.3 for the conventional system [1] Reported . This is an average number of reaction events per absorbed photon. It does not mean one photon performs a fraction of an individual reaction. With a limited light dose, a direct photochemical process can be too slow.

- **Chemical amplification: make a catalyst, then let it work**

Hiroshi Ito, C. Grant Willson and Jean Fréchet at IBM developed the chemical-amplification approach. Ito dates the proposal to 1980 and its report to 1982 [8]; their patent, filed in August 1982, combines an acid-generating photoinitiator with a polymer bearing acid-labile groups [10] Reported .

A positive-tone chemically amplified resist works in three stages [1][11] Reported :

1. **Exposure generates acid** from a photoacid generator, or PAG.
2. **PEB drives deprotection.** The acid catalyses removal of protecting groups from the polymer, making the affected material soluble in the developer.
3. **The acid is regenerated** in the catalytic cycle and can promote further reactions.

An early implementation removed tert-butoxycarbonyl, or tBOC, groups to produce polyhydroxystyrene [11] Reported . Willson's research group explains that a catalyst can promote several hundred solubility-switching events [12] Reported . The amplification is in the number of chemical changes triggered after exposure, rather than a multiplication of the acid molecules.

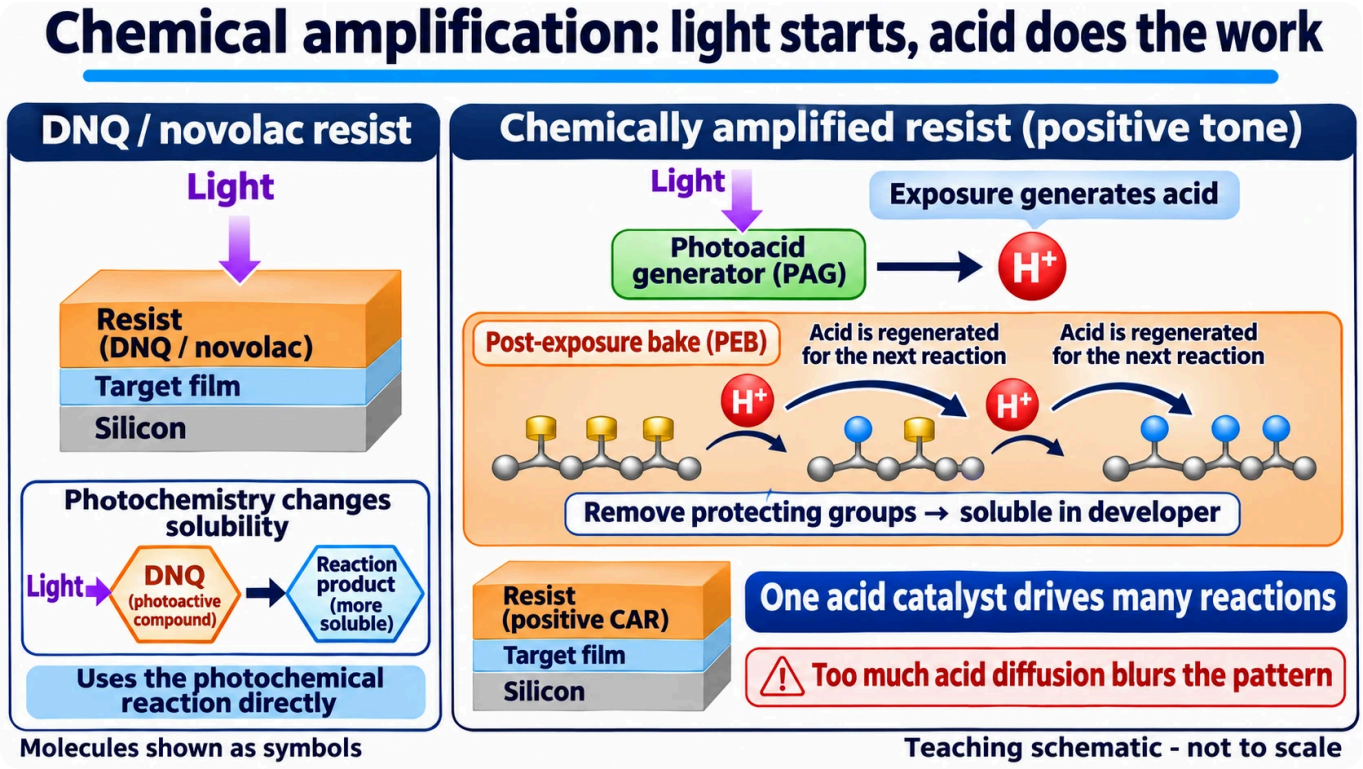


Figure 6 **Chemical amplification: light starts, acid does the work** (schematic)

Reading the figure

The repeated H^+ symbols represent successive stages of a catalytic process. They do not mean the acid reproduces itself. Nor does every incident photon necessarily create one acid molecule. The polymer and protecting groups are symbols, not molecular structures drawn to scale.

Ito describes early chemical amplification as a laboratory curiosity that became valuable quickly: IBM used it in deep-UV processing for 1 Mbit DRAM in the mid-1980s [8] Reported . Later commercial development involved many organisations. The historical museum records TOK's KrF development in 1997 and JSR's collaboration with IBM in 2000 [27] Reported . Willson and Fréchet received the Japan Prize in 2013 for this work [11] Reported .

The price of sensitivity

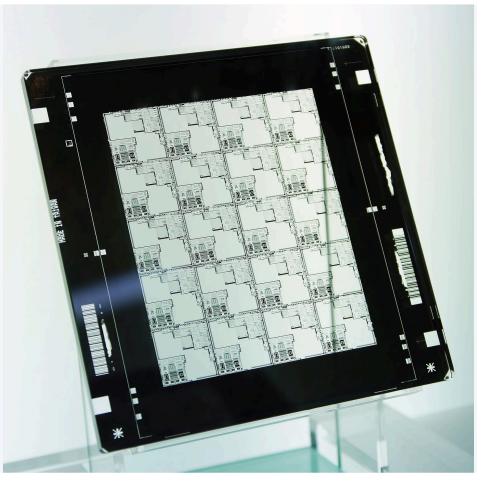
Acid can move beyond the region originally exposed. This creates a trade-off between sensitivity and pattern fidelity; diffusion that was tolerable for larger features becomes significant as features shrink [12] Reported . Basic contaminants such as ammonia can also neutralise acid and change sensitivity, making clean enclosures and chemical filtration important [5][25] Reported .

Purdue's 2016 lecture describes chemical amplification as the prevailing approach for short-wavelength production resists [5] Reported . That historical summary should not be expanded into a claim that every present-day short-wavelength resist has identical chemistry. The 2023 IRDS roadmap anticipates an important continuing role for chemically amplified resists through the 1 nm logic generation, while discussing metal-containing alternatives [29] Outlook . Metal-oxide resists, including Inpria's work, return in Lesson 3-7 [50].

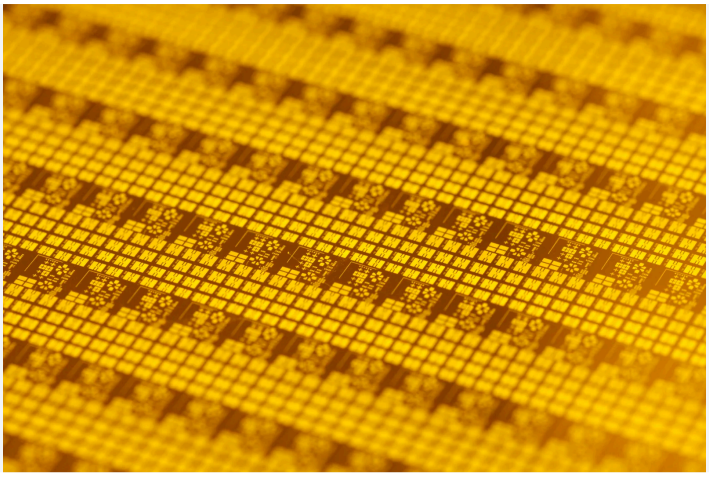
7. Making the mask and light work harder

Reticles and pellicles

A simple transmissive photomask consists of **quartz glass with a patterned opaque chromium film** [2] Reported . A reduction-system mask is commonly called a **reticle**. Its features are larger than the corresponding wafer features, but still require extremely precise manufacture.



A semiconductor photomask with repeated circuit patterns and alignment features, as described in the Commons record.
Photo: Peellden / Wikimedia Commons / CC BY-SA 3.0. Resized and converted to WebP.



An oblique close-up of chromium photomask patterns, photographed under yellow lighting, according to Commons.
Photo: Sei / Wikimedia Commons.JPG) / CC BY-SA 4.0. Resized and converted to WebP.

A particle on a mask can be repeated in every exposure field. A **pellicle** holds a thin protective membrane away from the patterned surface, so dust on the membrane is far from the mask's image plane. IBM's patent describes membrane thicknesses of 0.2-6 µm and separation distances of about 1-125 mm [33] Reported . These are the patent's ranges, not a prescription for a modern tool. The principle is to keep contamination out of focus; it does not make contamination harmless in every circumstance.

Phase shifts improve image contrast

Levenson's IBM patent uses a 180° phase difference between adjacent openings so their light interferes destructively between images [34] Reported . This improves contrast and helps make usable patterns near the imaging limit. It does not remove diffraction.

Purdue discusses attenuated phase-shift masks, including MoSi, as an established approach [3] Reported . A worked example uses a quartz refractive index of 1.56 at 193 nm: a thickness difference of (193/2)/(1.56 − 1) ≈ **172 nm** produces the extra half-wavelength optical-path difference. This is a source example, not a universal mask-etch depth [3].

OPC: change the mask to improve the wafer image

Corners round and line ends shorten in optical imaging. **Optical proximity correction (OPC)** anticipates those distortions by changing the mask: adding corner features, hammerhead-shaped line ends and sub-resolution assist features. The MIT paper illustrates these methods [7] Reported . ASML describes combining mask correction with illumination optimisation [16] Reported .

Off-axis illumination changes which diffraction orders fall within the lens aperture. Purdue presents it as a comparatively simple, low-cost resolution-enhancement technique in its teaching context [3]; the underlying principle is explained in the Stanford notes [1] Reported . “Low cost” here is relative to other imaging improvements, not a claim that an advanced lithography system is inexpensive.

- **Beyond a single exposure**

The 2011 ITRS roadmap placed the practical single-exposure optical limit around 40 nm half-pitch [30] Reported . Read that in its 193 nm optical-lithography context, not as a wavelength-independent limit that also applies to EUV. Purdue discusses splitting a pattern across multiple processing steps to reach an effective k_1 below the single-exposure benchmark [4] Reported . Immersion and multiple patterning are the subjects of Lesson 3-6; 13.5 nm EUV follows in Lesson 3-7.

8. Exposure equipment: different markets within one market

- **Revenue share and shipment count tell different stories**

ASML, based in the Netherlands, has the largest revenue position in exposure equipment. A Japanese Ministry of Economy, Trade and Industry (METI) presentation published in December 2025 reproduces a supplier breakdown of **91% for ASML and 4% for Canon**, based on Global Net data [39] Reported . The slide does not specify the underlying observation year, so these should be read as figures in that presentation, not labelled as verified 2026 market shares.

ASML's 2025 annual report provides a more precisely dated view of its own business [36] Reported :

Exposure technology	Systems	Net system sales (€ million)
High-NA EUV, EXE	4	1,156.9
EUV, NXE	44	10,445.8
ArF immersion	131	10,311.4
Dry ArF	16	427.0
KrF	78	1,001.3
i-line	54	307.3

The table excludes metrology and inspection. ArF immersion leads its exposure-system unit count, while EUV and immersion account for far more revenue than i-line. Dividing sales by systems gives averages of about **€79 million for ArF immersion** and **€5.7 million for i-line** Calculation . Those averages are not catalogue prices.

Canon reported **234 systems in calendar 2025**, comprising 46 KrF and 188 i-line systems [38] Reported . Nikon reported **27 systems in the financial year ended March 2026**, including used equipment: 20 i-line/other, four KrF and three ArF [37] Reported . Nikon also supplies immersion systems, as the specification table shows. The companies' portfolios and reporting periods differ.

Canon's 188 i-line systems exceed ASML's 54 in the same calendar year by more than three times Calculation . That does not contradict ASML's revenue leadership. **Unit count, selling value and the technological application are different measures.** Mature wavelengths remain relevant where the required feature sizes suit power devices, memory processes or packaging [38]. ASML also reported its first XT:260 i-line shipment for advanced-packaging/3D applications in 2025 [40] Reported .

A global customer base

Customers in China accounted for 29.1% of ASML's total net sales in 2025, compared with 36.1% in 2024 [36] Reported . Separately, the SEAJ/SEMI statistics put worldwide semiconductor-manufacturing equipment sales at **US$135.1 billion** in 2025, with **US$49.3 billion** going to China [49] Reported . The latter covers all equipment categories; it is not a lithography-only total.



The lithography area at HP Laboratories in the United States, showing i-line exposure equipment and a wafer track under yellow lighting, according to the Commons description. This is a laboratory installation.
Photo: Alison Chaiken / Wikimedia Commons / CC BY-SA 3.0. Resized and converted to WebP.

9. Tracks, resists and masks: the rest of the lithography system

Tracks make the optical image reproducible

A **coater/developer track** applies resist, performs controlled bakes and develops the exposed wafer. It operates with the exposure tool as part of a lithography cell. KINGSEMI's annual report emphasises this close integration and describes the historical dependence of China's track market on overseas suppliers [41] Reported . That is the company's assessment of its operating environment.

METI's supplier breakdown lists Tokyo Electron at **85%**, SUSS MicroTec at **6%** and KINGSEMI at **5%** for coaters/developers [39] Reported . Their home bases are Japan, Germany and China respectively. As with the exposure breakdown, the underlying year is not identified on the slide.

Tokyo Electron's 2026 integrated report identifies it as the leading track supplier and estimates **100% share in EUV coaters/developers**. It also reports more than 50% fewer resist-coating defects for a newer system relative to its comparison baseline [42] Reported . These are company estimates and product-performance claims, not independently standardised tests of every competing track.

Resists are a separate materials market

Resist suppliers develop formulations for different wavelengths, tones, substrates and process windows. Examples in the cited sources include TOK, JSR/Inpria, Shin-Etsu Chemical, Fujifilm and Merck KGaA. The firms do not all address the same applications with the same chemistry.

METI's summary attributes **78% of photoresist revenue to Japanese suppliers in 2023**, up from 77% in 2021; the separate figure for photomask resists is 65% in 2023 [39] Reported . This documents a substantial concentration of supply. It should not be read as the location where every product is manufactured or used.

TOK's 2026 integrated report gives the following figures from market-research data [43]. The share columns are **2025 shipment-volume measures**; the growth column is a **forecast**, not an achieved result.

Resist application	TOK share by volume	Reported rank	Forecast market CAGR, 2025-2031
EUV	29.3%	1	28.2%
ArF	14.4%	4	7.4%
KrF	33.3%	1	6.1%
g-line/i-line	25.3%	1	3.8%

Shares and ranks: reported estimates Reported . Growth rates: outlook Outlook .

The report estimates the 2025 semiconductor-photoresist market at **US$3.081 billion**, up 12.7%, using SEMI data. It also gives a company-calculated overall share of **26.1%** based on market-research data [43] Reported . Keep that separate from the explicitly volume-based application table. Shin-Etsu describes itself as the second-largest photoresist supplier in its 2025 integrated report, without supplying a numeric share or a detailed third-party basis for that ranking [44] Reported .

Environmental requirements add another design challenge. PFAS are per- and polyfluoroalkyl substances. Germany's **Merck KGaA** reports completing development and starting sample shipments of PFAS-free i-line and KrF resists [45]. **Fujifilm** reports a PFAS-free negative-tone ArF immersion resist, evaluated with Belgium's **imec** for 28 nm-generation interconnect patterning [46] Reported . Sample shipments and demonstrations are important milestones; neither statement by itself proves universal replacement of existing materials.

A mask has its own supply chain

Mask manufacture needs writers, blank substrates, coating materials and protective membranes. These are distinct from both wafer exposure equipment and resist formulation.

Segment	Suppliers or position described in the sources	Basis and qualification
Mask writers	IMS Nanofabrication, Austria: 49%; NuFlare Technology, Japan: 45%	METI breakdown based on Global Net; underlying year not stated [39]
Mask blanks	HOYA; Shin-Etsu Chemical	HOYA describes a very high share without a printed percentage; Shin-Etsu claims second place [47][44]
Pellicles	Mitsui Chemicals, working with ASML technology for EUV	Company history: pellicles launched in 1984; commercial EUV production began in 2021 [48]
Finished photomasks	Suppliers across the mask industry	METI puts Japanese suppliers at 22% of revenue in 2021 and 19% in 2023 [39]

These observations preserve the significant roles of Japanese suppliers while showing why no single country-level percentage describes the whole chain. A mask writer, mask blank and finished mask are different products. A company-ranking claim is also a different kind of evidence from a measured global revenue share.

The practical picture is one of **specialisation and interdependence**: Dutch exposure systems, tracks and materials from several countries, precision mask-making equipment, and customers distributed across the world's fabrication centres. Explanation

10. What comes next, and where materials science fits

- **More resolution needs more than a minor adjustment.** The representative immersion calculations give k_1 near 0.27. Multiple patterning and shorter-wavelength EUV provide routes beyond the single-exposure 193 nm limit.
- **Overlay budgets keep tightening.** The 2022 IRDS roadmap's 2028 logic target is 1.6 nm [28] Outlook . The 2023 update allocates about 40% of the edge-placement-error budget to overlay in its analysis [29] Reported .
- **Chemistry continues to evolve.** IRDS discusses both chemically amplified and metal-containing resists; Inpria, a US-based JSR subsidiary, develops metal-oxide resists [29][50] Reported . Roadmap expectations about future dominance remain forecasts.
- **Environmental performance matters alongside imaging performance.** PFAS-free development by Merck and Fujifilm illustrates efforts to redesign formulations while retaining useful lithographic behaviour [45][46] Reported .
- **Packaging expands the range of useful lithography.** Canon's packaging business and ASML's XT:260 show why mature wavelengths can support advanced products [38][40] Reported .

Opportunities for materials scientists

Lithography combines optics and precision motion with polymer synthesis, photochemistry, surface treatment and contamination control. Important tasks include designing the PAG/polymer/protecting-group system, controlling acid diffusion, reducing trace contaminants, replacing problematic substances and developing mask or pellicle films [12] [25][44–48].

These skills connect to research institutions, material suppliers and equipment makers across the industry. The useful question is which physical or chemical constraint a material solves, followed by how reliably it can do so in a production process.

11. Put the pieces together

Question	Main answer
What does lithography produce?	A patterned resist stencil; etching or another step transfers its openings into the device structure.
Why so many processing steps?	Adhesion, uniform coating, solvent removal, photochemistry, development and inspection each solve a different problem.
What sets the optical scale?	$R = k_1\lambda/NA$; smaller wavelength and higher NA help, but higher NA reduces focus tolerance.
Why move both reticle and wafer?	A scanner sweeps a slit while matching the reticle's reduced image to wafer motion.
Why chemical amplification?	Exposure creates acid; repeated catalytic reactions during PEB change many solubility-switching groups.
Why inspect overlay?	A correctly sized feature can still fail if it misses the previous layer.
Who supplies the process?	Different companies lead exposure tools, tracks, resists, mask writers and mask materials; measures and years must be stated.

Next is **Lesson 3-6: Immersion Lithography and Multiple Patterning**. We will see how water raises usable NA beyond the dry-ArF range, and how splitting a pattern across more than one step creates features beyond a single exposure's limit. Lesson 3-7 then moves to EUV.

12. Check your understanding

1. The same central mask opening is used with positive and negative resist. What remains after development?

▼ **Show answer**

Positive tone removes the exposed centre and leaves the unexposed sides. Negative tone retains the exposed centre. The underlying target film has not yet been etched.

2. Why use HMDS before coating a novolac-based resist on silicon oxide?

▼ **Show answer**

The oxide surface is hydrophilic and the resist is hydrophobic. HMDS modifies the surface to promote adhesion; it is an interface treatment rather than another thick device film.

3. Under the inverse-square-root approximation, what happens if spin speed is quadrupled?

▼ **Show answer**

Thickness becomes approximately $1/\sqrt{4}$, or half its previous value, provided the formulation and coating regime are comparable.

4. Estimate R for 193 nm, NA = 0.93 and k1 = 0.30.

▼ **Show answer**

$R = 0.30 \times 193/0.93 \approx 62$ nm. This is an imaging estimate for those conditions, not a commercial technology-node name.

5. Why does increasing NA make wafer flatness more demanding?

▼ **Show answer**

Focus tolerance scales as λ/NA^2. Increasing NA narrows the permitted vertical range, making bow and topography more significant.

6. Why does the reticle move four times as fast as the wafer in the illustrated scanner?

▼ **Show answer**

Its pattern is reduced 4:1. A reticle displacement must be four times the corresponding wafer displacement, with opposite directions for the inverted image, to keep the image synchronised.

7. What problem did chemical amplification help solve in early KrF processing?

▼ **Show answer**

Conventional DNQ/novolac absorbed deep UV too strongly, while early KrF exposure needed more sensitive materials. Producing an acid catalyst lets a limited exposure trigger many solubility-changing reactions during PEB.

8. Name two ways a chemically amplified resist can lose pattern fidelity or sensitivity.

▼ **Show answer**

Acid diffusion beyond the exposed region can blur edges; basic contaminants such as ammonia can neutralise acid. Both chemistry and environmental control matter.

9. Why is a pellicle held away from the mask pattern?

▼ **Show answer**

Dust on its membrane is displaced from the mask image plane and is therefore defocused. The membrane protects the pattern without placing dust directly in focus.

10. Why can one supplier ship more i-line tools while another leads exposure-equipment revenue?

▼ **Show answer**

Unit count and revenue measure different things. Product mix and average system value matter: an EUV or immersion system and an i-line system contribute very different amounts of revenue. Reporting periods and market definitions must also match.

13. Glossary

Photolithography
Using light and development to form a resist pattern that defines subsequent processing.

Photoresist
A coating whose response to developer changes after exposure and any required processing.

Positive tone
A process in which exposed resist is removed during development.

Negative tone
A process in which exposed resist remains after development.

HMDS
Hexamethyldisilazane; a surface treatment used to improve resist adhesion.

Spin coating
Spreading liquid resist by rotating the substrate.

Soft bake
Heating the coated resist to reduce residual solvent.

Post-exposure bake (PEB)
Heating after exposure; in a chemically amplified resist it drives the catalytic reaction.

Standing wave
A stationary intensity variation caused by interference between incoming and reflected light.

TMAH
Tetramethylammonium hydroxide; a metal-ion-free base used in common aqueous developers.

Rework
Removing an unacceptable resist pattern and repeating lithography before irreversible pattern transfer.

Diffraction
The spreading and angular redistribution of a wave by openings or structures.

Numerical aperture (NA)
n sin θ; the optics' ability to accept the light angles needed for image detail.

Rayleigh relation
The estimate R = k1λ/NA for a characteristic printable dimension.

k1
An imaging/process factor; 0.25 is the single-exposure benchmark for equal lines and spaces.

Depth of focus (DOF)
The allowed range around best focus; check whether a source gives a half-range or full range.

g-line and i-line
Mercury-lamp spectral lines at 436 nm and 365 nm.

Excimer laser
A source used for KrF at 248 nm and ArF at 193 nm.

Stepper
A tool that exposes a field and then steps the wafer to the next field.

Scanner
A tool that exposes through a slit while reticle and wafer move synchronously.

Reticle
The patterned mask used in a projection exposure system.

Overlay
The accuracy of pattern alignment between layers.

DNQ/novolac resist
A traditional resist system combining a photoactive compound with novolac resin.

Chemically amplified resist (CAR)
A resist in which exposure generates a catalyst that drives many later reactions.

Photoacid generator (PAG)
A component that produces acid in response to exposure.

Deprotection
Removing chemical protecting groups to change polymer solubility.

Mask blank
A substrate and coating stack on which the mask pattern will be written.

Pellicle
A protective membrane held away from the mask's patterned surface.

Phase-shift mask
A mask that deliberately changes optical phase to improve image contrast.

Optical proximity correction (OPC)
Altering mask geometry to compensate for imaging distortions.

Off-axis illumination
Angled illumination chosen to improve collection of useful diffraction orders.

Coater/developer track
Equipment that controls resist coating, baking and development alongside the exposure tool.

14. Sources and further reading

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23. **Canon** — FPA-5550iZ2: product specifications (Japanese) — Read source
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31. **MicroChemicals** — Spin-coating of Photoresists; p. 1 — Read source

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15. Claim-to-source guide

This table separates source-reported examples, calculations made in this lesson and forward-looking requirements. Dates remain part of the claim: an older lecture or roadmap should not silently become a claim about every current production line.

Claim or example in the lesson	Supporting source	Evidence type
Historical lithography cost/overlay estimates; spin speeds; standing waves; Rayleigh and focus relations; exposure arrangements; DNQ behaviour	Stanford Chapter 5 [1]	**Reported**; teaching examples with historical scope
Diffraction orders, dry NA ≈0.93 and mask materials	Purdue Lecture 7 [2]	**Reported**
Phase-shift masks, 172 nm quartz example and off-axis illumination	Purdue Lecture 10 [3]	**Reported**; illustrative conditions
Multiple processing steps beyond a single-exposure k1 benchmark	Purdue Lecture 11 [4]	**Reported**
Resist-processing steps, HMDS, bake/developer examples, dissolution rates and contamination sensitivity	Purdue Lecture 5 [5]	**Reported**; 2016 teaching context
Sub-wavelength transition around 1996; k1 examples and equal-line/space lower bound	MIT Lincoln Laboratory [6]	**Reported**
OPC features, including non-printing assist features	MIT Lincoln Laboratory [7]	**Reported**
Early chemical-amplification history and mid-1980s IBM use	Ito [8]; original patent [10]	**Reported**
Standard 0.26-normal developer as a design constraint	Ito [9]	**Reported**
Positive/negative tone, early tBOC chemistry and 2013 prize	Japan Prize Foundation [11]	**Reported**
Repeated catalytic reactions and the diffusion/fidelity trade-off	Willson group [12]	**Reported**
Resolution relation, wavelengths, immersion NA and computational enhancement	ASML technical explanations [13–16]	**Reported**
TWINSCAN introduced in 2000; definition of overlay	ASML [17][18]	**Reported**

Claim or example in the lesson	Supporting source	Evidence type
System specifications, field dimensions, reduction, reticle size and matched-machine overlay	ASML, Nikon and Canon [19–21][23]	**Reported**; vendor-defined conditions
Stepper and scanner milestones; 1990s market context; wavelength and resist adoption	Nikon history [22]; museum accounts [24–27]	**Reported**; historical and attributed priority claims
Overlay requirements for 2022/2025/2028	IRDS 2022 [28]	**Outlook**; roadmap requirements
Future resist roles and overlay contribution to the placement-error budget	IRDS 2023 [29]	**Reported** for the analysis; future roles are **Outlook**
Around 40 nm half-pitch as a practical 193 nm single-exposure limit	ITRS 2011 [30]	**Reported**; technology-specific historical scope
Spin-speed scaling, spin time/material utilisation and developer concentration	MicroChemicals [31][32]	**Reported**
Pellicle ranges, phase-shift principle and resist rework	Patents [33–35]	**Reported**; patent examples are not universal production recipes
ASML 2025 exposure systems/sales and sales to customers in China	ASML Annual Report [36]	**Reported**
Nikon FY ended March 2026 and Canon calendar-2025 system shipments	Company presentations [37][38]	**Reported**; periods and product mix differ
Exposure/track/writer breakdowns; country-based resist and mask shares	METI summary [39]	**Reported** as published; underlying years stated where available
First XT:260 shipment; KINGSEMI's track-market assessment	ASML [40]; KINGSEMI [41]	**Reported** as reported
Track leadership, EUV-track share and coating-defect reduction	Tokyo Electron [42]	**Reported**; company estimates and comparison baseline
TOK application shares/ranks, overall share and market value	TOK [43]	**Reported**; differing measures retained
TOK's cited 2025-2031 application-market CAGRs	TOK / market-research data [43]	**Outlook**
Shin-Etsu ranking; HOYA mask-blank description; Mitsui pellicle history	Company reports [44][47][48]	**Reported** as attributed; no missing percentages invented
PFAS-free resist milestones and metal-oxide resist development	Merck [45], Fujifilm [46], JSR/Inpria [50]	**Reported**; milestones do not imply universal deployment
Worldwide 2025 equipment sales and China purchases	SEAJ/SEMI [49]	**Reported**; all equipment categories

Claim or example in the lesson	Supporting source	Evidence type
Optional hard bake and its possible side effects; mask-aligner applications	MicroChemicals [51]; SUSS [52]	Reported
Spin-speed ratios; approximate TMAH molarity; 62/52 nm resolution; ±112 nm focus tolerance; indicative k1; 12 s/wafer; dissolution ratio; sales-per-system averages and unit-count ratio	Equations and input values explicitly stated in the text	Calculation
Rough comparison of 2 nm with atomic spacings	Assumed spacing of 0.2-0.3 nm	Interpretation ; scale analogy only

English edition completed 7 November 2026. Technical sources include university lectures, original papers, patents, manufacturer documentation and the IRDS/ITRS roadmaps. Company and market figures retain their stated reporting periods and definitions; company estimates and forecasts are identified. The six Image Gen diagrams are teaching schematics: light paths, layer thicknesses, molecular symbols and alignment errors are simplified or exaggerated. Photograph credits and licences appear beside each image.

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