SEMICONDUCTOR FRONT-END · PART 3-6

# Immersion Lithography and Multiple Patterning Extending the reach of 193 nm light

How can a chip factory keep making smaller features without changing the wavelength of its light? Two ideas transformed 193 nm lithography. Put ultrapure water between the last lens and the wafer, and the optics can deliver a wider range of light angles. Divide a difficult pattern between several operations, and the final features can be packed more closely than a single exposure allows. This lesson follows both ideas from their physics to the moving water, surface chemistry, thin films and alignment that make them work in production.

Semiconductor Front-End Series · Part 3-6 · Level: intermediate
Suggested preparation: Part 3-5 · Updated 7 November 2026

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## How to read this lesson

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

### What you will learn

- Explain how water allows numerical aperture to exceed one without changing photon energy.
- Connect immersion defects to fluid handling, temperature control and resist surface chemistry.
- Distinguish splitting a pattern between exposures from multiplying lines with sidewall spacers.
- Identify the equipment and materials involved, and understand why resolution and overlay appear in export-control rules.

## 1. The lesson in three ideas

- **Immersion changes what the optics can deliver.** Water has a refractive index of about 1.44 at 193 nm. Replacing the air gap below the final lens allows production scanners to reach NA 1.35. A practical single-exposure benchmark became roughly 40 nm half-pitch. Achieving that performance required control of bubbles, droplets, contamination and the resist-water interface.
- **Multiple patterning separates a difficult task into easier ones.** LELE puts alternating features on different masks and combines their results. SADP and SAQP create extra lines from films left on the sides of temporary cores. The price is additional processing: overlay is central to LELE, while spacer thickness, etching and cut placement become crucial in self-aligned flows.
- **These technologies remain part of a wider manufacturing system.** ASML and Nikon supply immersion scanners; deposition, etch, resist and process-control suppliers make the rest of the flow possible. ASML reported 131 ArF immersion systems sold in 2025. Advanced immersion equipment also became subject to increasingly detailed export-licensing requirements from 2023 onwards [29][37][38]. Reported

## 2. Why an air gap became a limit

Part 3-5 introduced the Rayleigh relationship:

$$R = k_1 \lambda / NA, \text{ with } NA = n \sin \alpha$$

Here R is a measure of the smallest printable feature, λ is the light's free-space wavelength, n is the refractive index of the medium at the wafer side, and α is the largest half-angle collected by the imaging system. The process factor $k_1$ represents how effectively the optics and patterning process are used. Explanation

If the space beneath the lens contains air, n is approximately one. Since sin α cannot exceed one, neither can NA. Real optics stop short of this geometric limit: Purdue University's teaching material uses about **0.93** as a practical value [2]. Reported

In the early 2000s, the industry was developing 157 nm lithography as the next step after 193 nm ArF. ASML's account of that period describes a troubled roadmap and a December 2001 conference at which its researchers considered immersion as an alternative [6]. Instead of changing the light source, immersion changed the material through which the light travelled on its final approach to the wafer. Explanation

## 3. What water changes, and what it does not

### A shorter wavelength inside the liquid

At 193 nm, water's refractive index is approximately **1.44**. Light travels more slowly in it, so the distance between successive wave crests becomes smaller [2]:

$$\text{Wavelength in water} \approx 193 / 1.44 \approx 134 \text{ nm}$$

That is a wavelength **inside the material**. The light's frequency does not change at the boundary, and neither does the photon energy E = hv. Burn J. Lin's review makes this frequency point explicitly [1]. It explains why immersion could build on the existing 193 nm materials platform. It does not mean an unchanged resist is automatically suitable for contact with water: leaching and surface behaviour still need attention. Explanation



Refraction makes a pencil appear to change direction where it enters water. The same optical principle underlies the change in light propagation in an immersion system; the glass is an everyday analogy, not a model of the scanner. Description based on the Commons file record.
Image: Meganbeckett27 / Wikimedia Commons / CC BY-SA 3.0. Resized and converted to WebP.

### Keeping high-angle light in the image

A fine pattern diffracts light into different directions. Forming a faithful image requires the optical system to deliver the relevant light to the resist. At sufficiently large angles, light in the final lens cannot enter an air gap: it undergoes **total internal reflection** instead. MIT Lincoln Laboratory explains that inserting a liquid lets light which would otherwise be reflected back reach the resist [8]. Reported

Water therefore gives the lens a usable path for a wider angular range. This is another way of understanding why immersion increases NA. The shorter in-medium wavelength and the higher n in NA = n sin α are connected descriptions of the same optical change; they must not be counted as two independent resolution gains.
Explanation

### The physics: getting beyond NA = 1

Snell's law relates the angles on the two sides of a boundary:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

For fused silica at 193 nm, take n ≈ 1.56. At a silica-air interface, a ray with sin θ > 1/1.56 cannot propagate into the air. This corresponds to an angle greater than about **40° from the normal**, not 40° from the surface [2]. Reported

With water on the other side, the image-side quantity n sin θ can exceed one. Lin gives the example of keeping sin θ = 0.93 and changing the medium to water: 1.44 × 0.93 ≈ **1.34** [1]. Reported

For a simple resolution comparison, use $k_1$ = 0.27 and λ = 193 nm: Calculation

- Dry, NA 0.93: R ≈ 0.27 × 193 / 0.93 ≈ **56 nm**.
- Immersion, NA 1.35: R ≈ 0.27 × 193 / 1.35 ≈ **39 nm**.

This example reduces the feature size by roughly 30%. The cited ASML and Nikon production-scanner specifications both give resolution of **38 nm or better** [3][4]. These figures describe the imaging capability under specified conditions; they are not chip-node names.

## Focus latitude depends on the comparison

Water can also provide more **depth of focus** when the comparison is made at the **same resolution**. Lin reports a worked example with a 96% increase, and the Purdue material also describes the equal-resolution benefit [1][2]. Reported

That does not mean every higher-NA process has more focus margin. Spending the optical gain on finer features makes focus control harder. Holding resolution fixed and improving focus latitude is a different choice from pushing NA to print the smallest possible pattern. Explanation

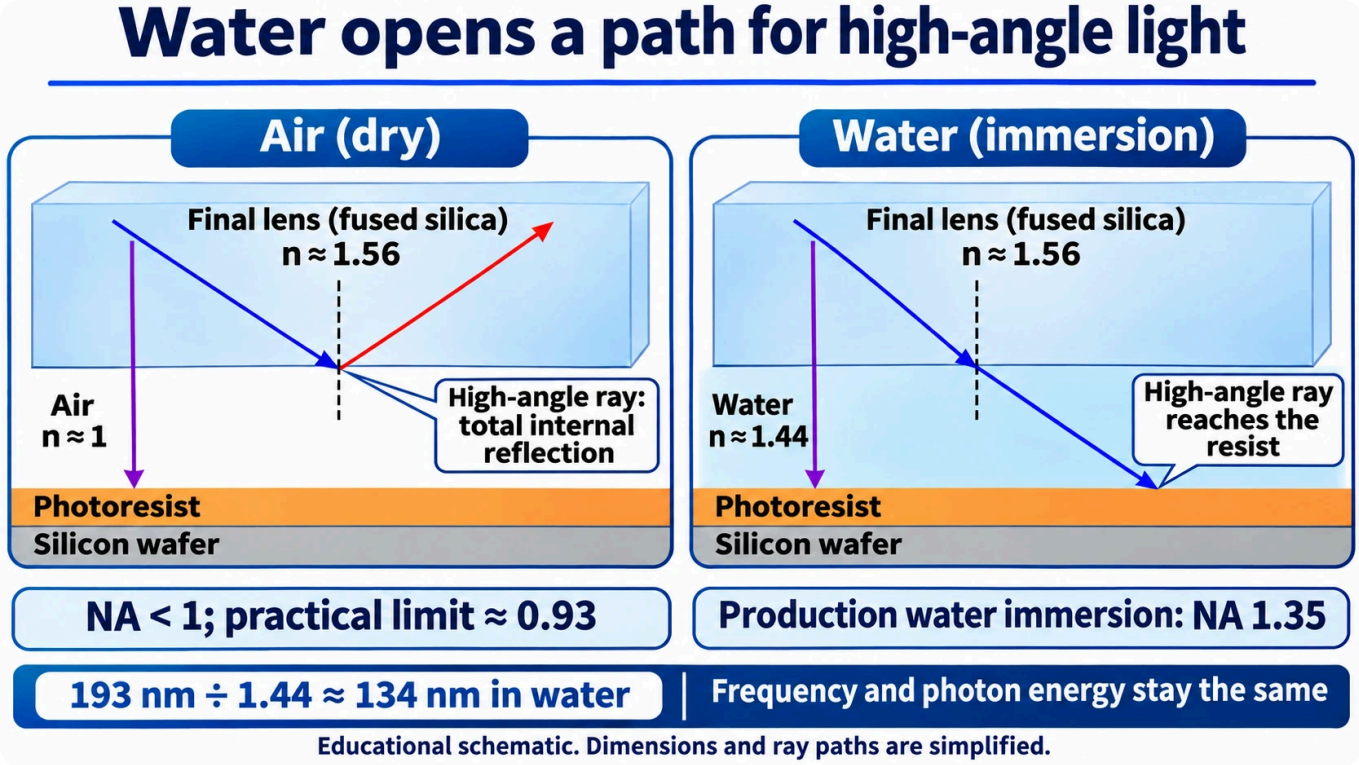



**Figure 1** **How water opens a path for high-angle light** (schematic)

### Reading the figure

The left panel shows a high-angle ray reflected back into the final lens. In the right panel, water allows that ray to reach the resist. The purple arrows represent a near-normal path that can propagate in both cases. The lens, water gap and ray angles are simplified for teaching; the drawing is not an optical design or a scale drawing.

## 4. From an established idea to production tools

Immersion was familiar in microscopy long before it became a semiconductor production method. ASML's history traces descriptions of its lithographic use to IBM in the 1980s [6]. A patent filed in 1980 describes filling the gap between a projection lens and the wafer with a transparent liquid whose index matches the resist [12]. MIT Lincoln Laboratory began research into immersion with NA above one in 2000 [8]. Reported

**Burn J. Lin and colleagues at TSMC** helped establish the route towards practical use. Lin's review brings together his 2002 and 2004 analyses of immersion's advantages and experiments with immersion equipment [1]. Reported

The equipment milestones came quickly. ASML announced the TWINSCAN XT:1250i in December 2003, describing it as the industry's first immersion lithography system. Its historical account records working 90 nm chips made by TSMC with early ASML immersion equipment in late 2004, followed by production use of the XT:1700Fi in 2006 at NA 1.2 [6]. Reported

**Nikon** introduced the NA 1.07 NSR-S609B in 2005 and describes it as the first production scanner to break the NA 1.0 barrier [10]. It shipped an NA 1.30 immersion scanner for 45 nm production in 2007 [9]. These milestones use the companies' own descriptions of the equipment category and stage of adoption; an announcement, a working chip and a production tool are different milestones. Explanation



The headquarters of lithography-equipment manufacturer ASML in Veldhoven, the Netherlands. Description based on the Commons file record.
Image: A ansems / Wikimedia Commons / Public domain. Resized and converted to WebP.

## 5. Making water behave on a moving wafer

### A local pool, not a wafer-sized bath

A production scanner moves its wafer stage rapidly. Water has to remain in the exposure region while the surface beneath it moves. Purdue's lecture illustrates the timing pressure with less than a second available per shot in a 100-wafer-per-hour example [2]. It is an illustration of the engineering challenge, not a specification for every production scanner. Reported

ASML describes using an **immersion hood** around the final lens to control the local pool. Its historical account says that improvements ultimately allowed stage speed to triple while defects fell by an order of magnitude [6]. Reported

The wafer is not submerged in a tank and then drained for every exposure. Water is supplied and recovered locally near the final lens, with the hood maintaining the liquid region as the stage moves. Explanation

### Bubbles, droplets and particles

Lin groups immersion defects into printed bubbles, watermarks, printed particles and particles deposited from above. His discussion links bubbles to disturbed flow, describes typical micrometre-scale bubbles and notes that smaller bubbles can dissolve in sufficiently degassed water. Escaped liquid can remain on the surface and produce watermarks; the wafer-edge region is another difficult place for fluid control [1]. Reported

The practical distinction matters: removing dissolved gas, preventing droplet escape and limiting particles address different mechanisms. A cleaner liquid alone does not solve every problem. Explanation

- **The resist is part of the fluid system**

Water can extract resist components, including the **photoacid generator (PAG)** used in chemically amplified resists. JSR's 2008 technical report identifies two linked requirements: suppress this **leaching**, which can contaminate the optics, and make the surface shed water effectively [11]. Reported

One approach adds a protective **topcoat** above the resist. Another builds low leaching and suitable surface behaviour into a resist designed for use without a separate topcoat. For its reported topcoat, JSR gives a **69° receding contact angle** and PAG leaching reduced to **one-hundredth or less** of the comparison level [11]. These are results for the material studied, not universal requirements. Reported

The receding contact angle describes the edge of a droplet as it retreats. A suitable surface helps water move away without leaving droplets that later dry into defects. The coating must also fit the subsequent development process: protection during exposure cannot come at the expense of reliable pattern formation. Explanation

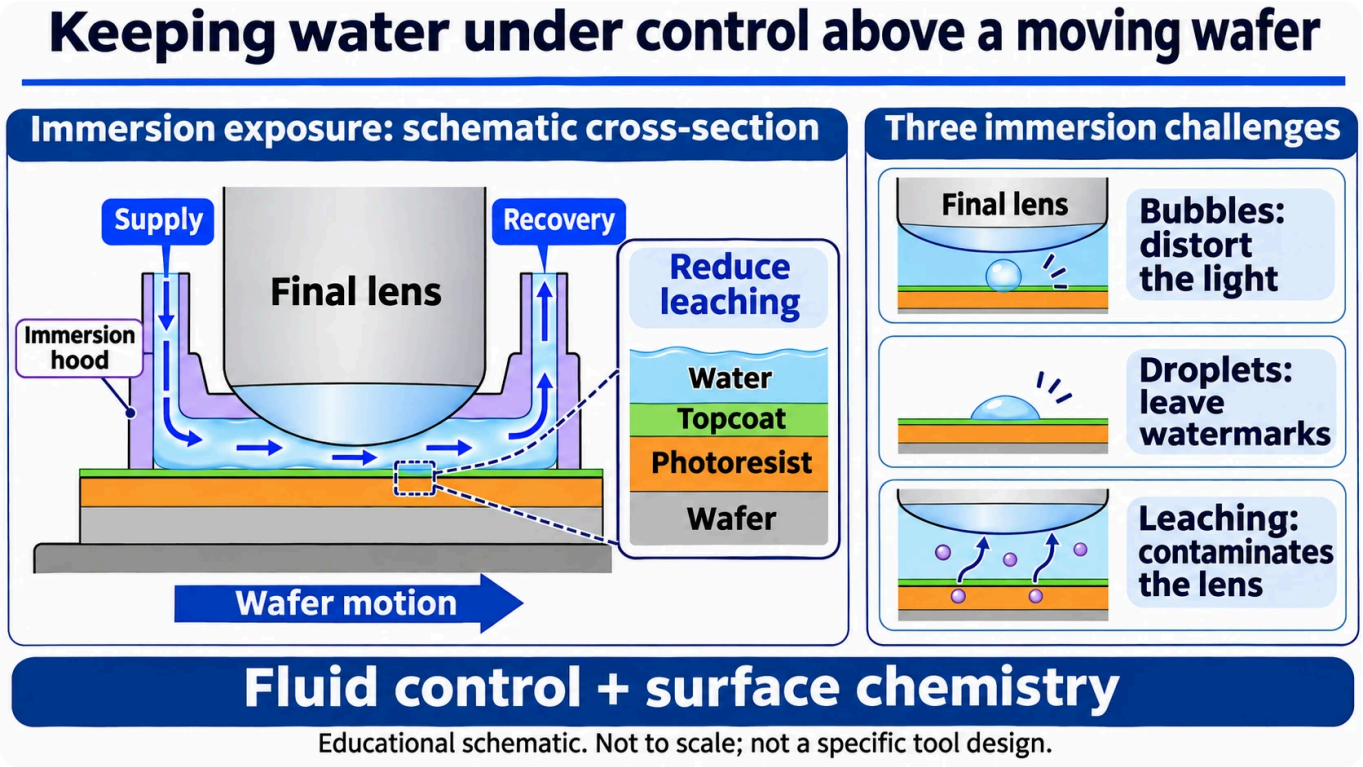



**Figure 2** **Fluid handling and surface chemistry work together** (schematic)

### Reading the figure

The blue arrows show supply and recovery around a local water region; the wafer moves underneath. Green is the topcoat, orange the resist and grey the wafer. The small cards distinguish bubbles in the optical path, residual droplets and resist components entering the liquid. The arrangement illustrates functions, not the internal construction of a particular scanner.

### The physics: why a tenth of a degree can matter

Water's refractive index changes with temperature. A 2003 simulation study by Boston University and MIT Lincoln Laboratory used dn/dT ≈ −100 ppm/°C at 193 nm. To hold the index within ±10 ppm of its design value, the authors estimated temperature control within **±0.1°C** [7]. Reported

Using the paper's ppm convention, 100 ppm/°C × 0.1°C = 10 ppm. Calculation A ppm change can refer to an absolute index increment or a change relative to a reference index; this example retains the source's notation rather than switching between conventions.

This is a result under the study's assumptions, not a common temperature specification for all scanners. Its broader lesson is that small temperature changes alter the optical path and can disturb the image. Absorption of the exposure light can itself heat the liquid [2].

- **Why production water immersion settled at NA 1.35**

The cited ASML and Nikon scanners use **NA 1.35** [3][4][5]. Water made NA above one possible, but water also constrains how far it can go. Reported

For propagating light through this optical stack, the lowest-index material sets a ceiling. Researchers at Rochester Institute of Technology identify water at about **1.44**, below fused silica at about **1.56** and resist at about **1.75** [13]. Lin's calculation with a practical angular limit sin θ = 0.95 gives 1.44 × 0.95 = **1.368** [1]. Reported

Higher-index liquids were investigated. A 2009 paper describes the industry's decision to discontinue that development as a matter of timing rather than a fundamental impossibility [14]. In a later review, MIT Lincoln Laboratory's Mordechai Rothschild explains the difficulty of combining high index with low absorption; liquids reached an index around 1.65, but the development was judged unattractive relative to the alternatives [15]. Reported

The industry retained water immersion and pursued further density through multiple patterning and EUV. Improving the fluid was only one possible route through a much larger cost-and-timing decision. Explanation

## 6. Building a pattern that one exposure cannot print

- **First, distinguish width from pitch**

**Pitch** is the centre-to-centre distance between repeating lines. **Half-pitch** is half that distance. Only when lines and spaces have equal width does half-pitch also equal the line width. A chip's process-node label is a separate naming convention. Explanation

The 2011 ITRS roadmap used about **80 nm pitch, or 40 nm half-pitch**, as the practical single-exposure benchmark for 193 nm immersion at NA 1.35. The Japanese STRJ's 2009 report gives a similar limit for simple line-space patterns [16][19]. These are historical benchmarks for that exposure technology, not a limit applying to all wavelengths or every pattern type. Reported

IRDS describes multiple patterning as using more than one exposure for a pattern, or a sequence of deposition and removal operations to increase pattern density. ITRS distinguishes two broad approaches: **pitch splitting** and **spacer patterning** [16][17]. Reported

- **LELE: print alternating lines separately**

Imagine a row of closely spaced lines. Put the first, third and fifth on one mask, and the second, fourth and sixth on another. Each mask now contains a less crowded pattern. Combining the two results produces the dense array. Explanation

In **LELE**, the sequence is lithography, etch, lithography, etch. The first pattern is transferred, a new resist is applied, and the second pattern is exposed and etched. **LFLE** instead freezes the first resist pattern before the second lithography step and a subsequent etch [16][19]. Reported

The two patterns must land in the right places. If the second set of lines shifts sideways, line widths can remain unchanged while the spaces become alternately wider and narrower. Purdue's lecture identifies overlay error as a contributor to final pattern variation [18]. STRJ reports requirements for double-patterning overlay error to be no more than about half the corresponding single-patterning value [19]. Reported

### The design problem: two colours are not always enough

Assign a colour to each mask. Features too close to be printed together must receive different colours. UC San Diego researchers formulate this as a layout-decomposition problem [20]. Reported

Now imagine three features, each too close to both the others. Colour A red and B blue. C cannot be red because it is close to A, or blue because it is close to B. This triangle is the simplest **odd cycle**, which cannot be coloured with two colours. The layout needs a change, a permissible split or an additional patterning solution [20]. Lin also discusses closely packed holes requiring three masks [1]. Reported

This is why multiple patterning reaches back into chip design. Layout software has to assign features to manufacturable groups; the mask set cannot simply be chosen after an arbitrary layout has been drawn. Explanation

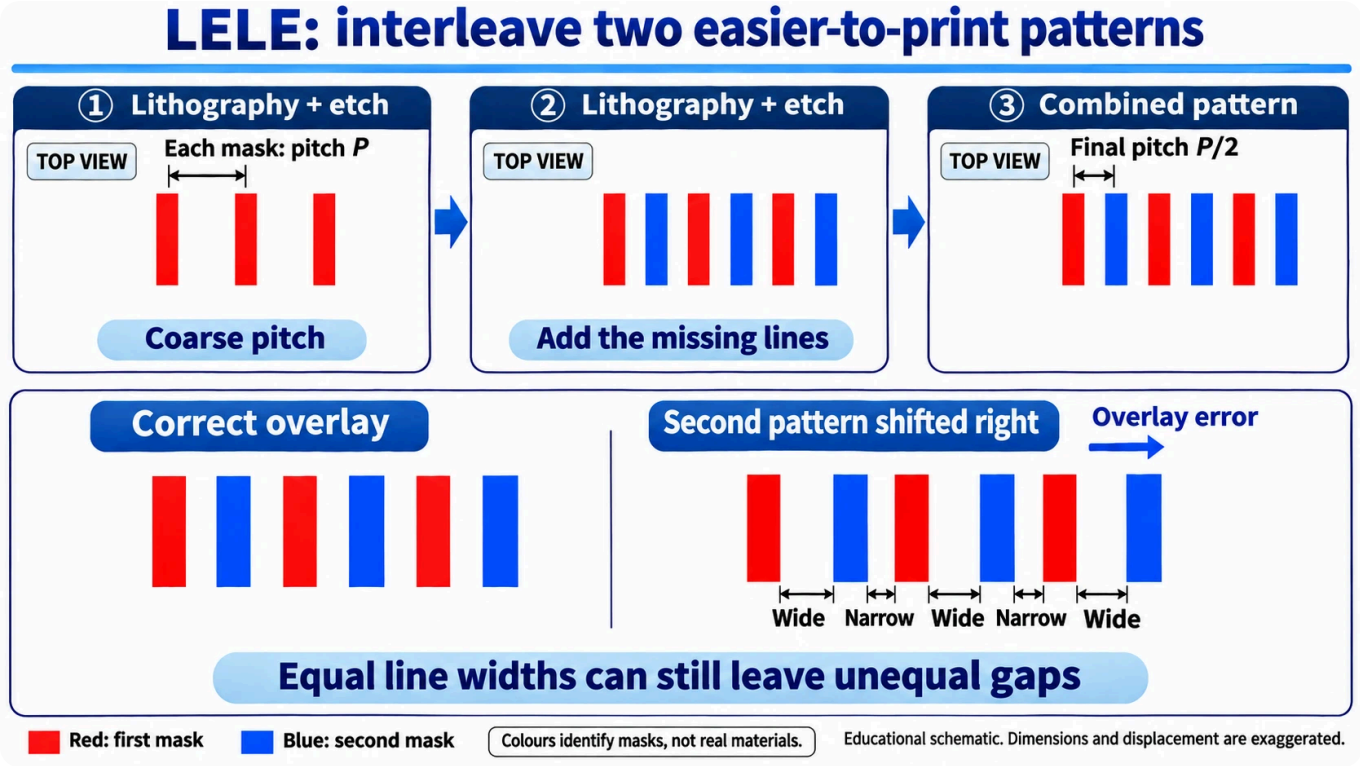



**Figure 3** **LELE: interleaving patterns makes overlay critical** (schematic)

### Reading the figure

Red and blue identify the two masks, not different physical materials. Each mask has pitch P; the combined array has pitch P/2. In the lower-right example, the blue pattern shifts to the right. The red-to-blue gap widens and the next blue-to-red gap narrows. This is a spacing error even if every line has the same width.

## SADP: use the two sides of a temporary core

**Self-aligned double patterning (SADP)** creates extra lines through thin-film processing. The temporary core is called a **mandrel**. A film deposited around it becomes a **spacer** on each side [19]. Reported

1. Use lithography to form an array of mandrels.
2. Deposit a conformal film over the tops, sidewalls and exposed floor. ALD or suitable CVD processes can provide the coating.
3. Etch back directionally, clearing horizontal surfaces while retaining material on the vertical sidewalls.
4. Remove the mandrels selectively. Two sidewall lines remain for each original core. Explanation

The principal controls on the remaining line width are **spacer thickness and the etch process**. The original lithography still matters: mandrel width and placement affect the positions and spacing of the final lines. Uniform half-pitch does not emerge from an arbitrary core geometry. Explanation

Purdue lists tight linewidth control, reduced dependence on a second exposure's overlay and low edge roughness among SADP's advantages, alongside extra process cost [18]. Lam Research explains that the deposited film itself becomes the patterning mask and sets critical dimensions [24]. Reported

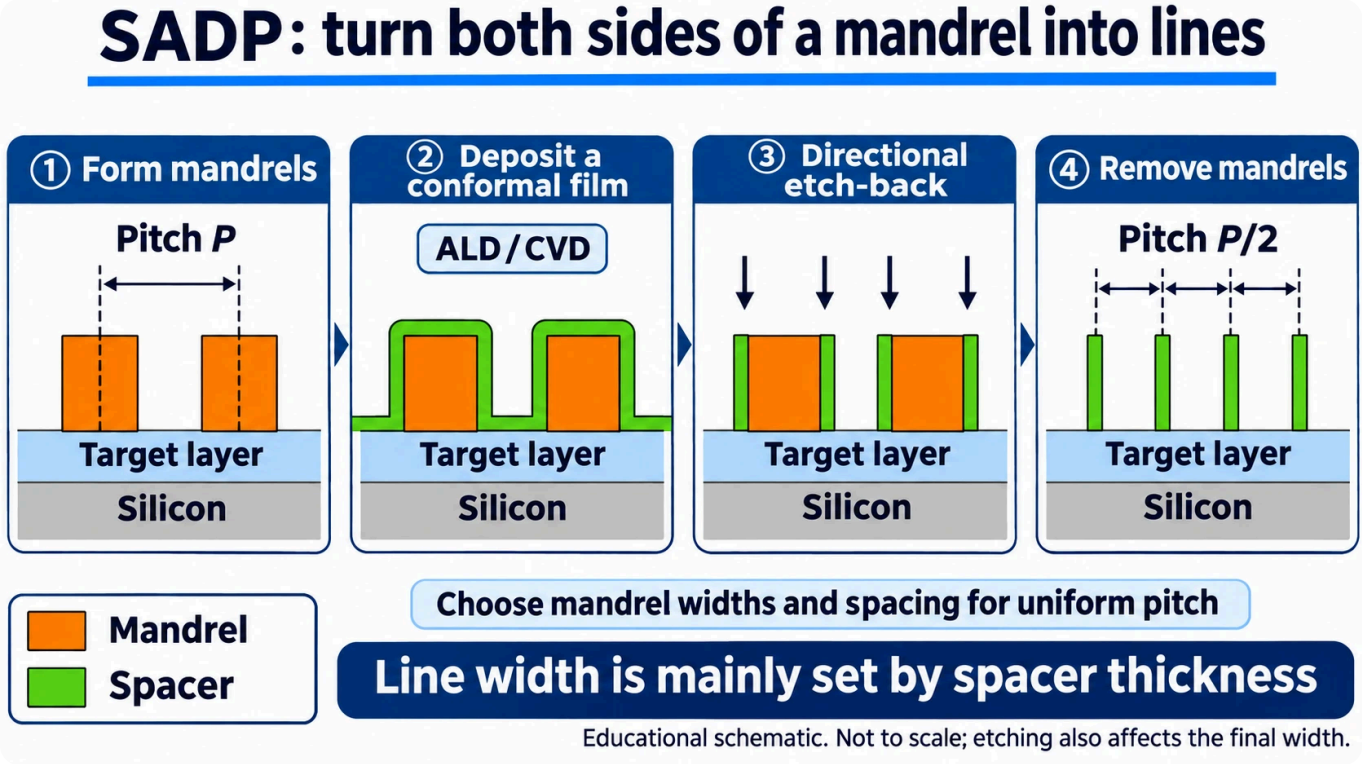



**Figure 4** **SADP: turn sidewall films into a denser line array** (schematic)

### Reading the figure

Orange mandrels receive a green coating. After the horizontal coating and then the cores are removed, green sidewalls remain. The blue target layer has not yet been patterned in this simplified sequence: the spacers can act as a mask for later transfer. Thickness, etching and the initial core geometry all need control.

## SAQP: repeat the process from deposition onwards

**Self-aligned quadruple patterning (SAQP)** performs a second round of spacer formation. The first spacers become the next set of cores. Deposit another film, etch it back and remove those cores to leave four lines for each starting mandrel [16]. Reported

imec describes a 193 nm immersion flow starting with an ASML NXT:1970i and using two spacer-patterning rounds to reach four times the line density, at **16 nm half-pitch** [21]. Its 2019 discussion considers a further doubling, **SAOP**, for eightfold multiplication at still tighter pitches, while stressing the resulting process complexity [22]. Reported

As an idealised arithmetic example, starting with 40 nm half-pitch gives about **20 nm after SADP** and **10 nm after SAQP**. These are density-scaling calculations, not guaranteed production specifications. Calculation Lin separately discusses pitch splitting reducing an effective $k_1$ from 0.3 to 0.15 and a prospective 19 nm half-pitch [1]. Reported

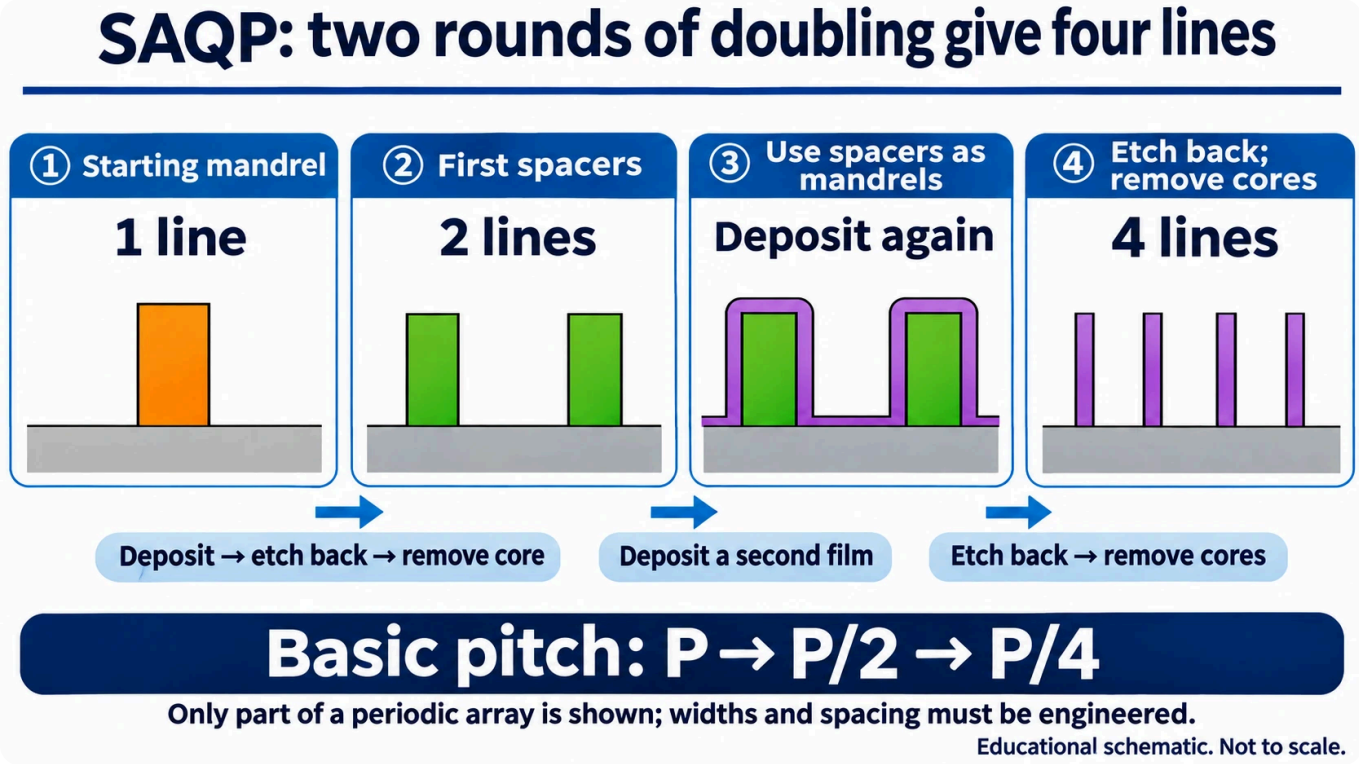



**Figure 5** **SAQP: two rounds of spacer formation** (schematic)

### Reading the figure

The orange core becomes two green sidewall lines. Those green lines then receive the purple film. A second etch-back and core-removal sequence leaves four purple lines. Repeating only the removal steps would not multiply the pattern: a new deposition is essential. Real integration also includes material choices and transfers through hard masks; the drawing shows only part of a periodic array.

## Dense lines still need useful ends

A spacer follows the outline of its core. Around the end of a mandrel, that outline can form a loop. Producing a useful circuit therefore requires more than creating closely spaced straight sections: unwanted parts must be removed and line ends placed accurately. Explanation

ITRS includes a **cut mask** in the spacer-patterning flow [16]. imec's example shows how a block layer for immersion-based SAQP wiring can require three masks and three lithography/etch operations [21]. Work by University of Texas and imec researchers describes highly regular one-dimensional layouts in which metal lines are formed and then cut where they are not needed [23]. Reported

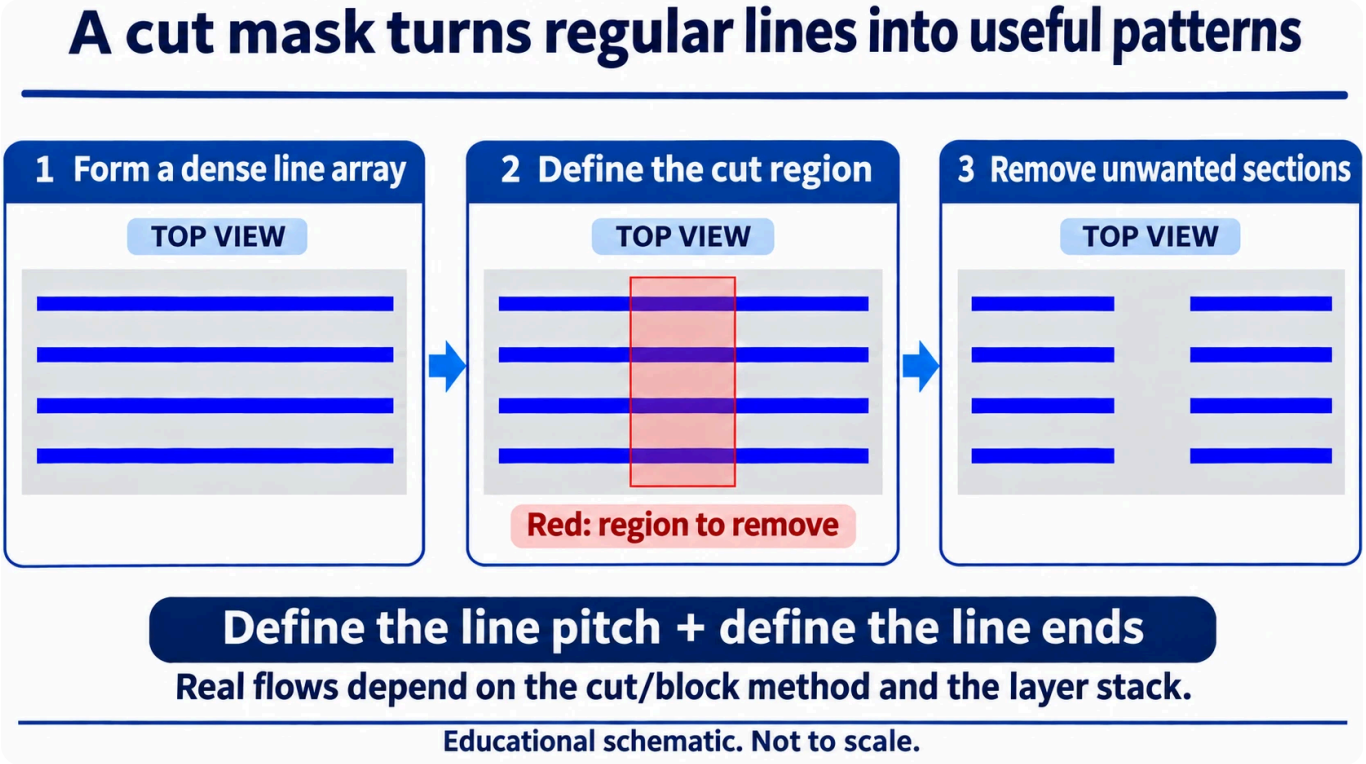
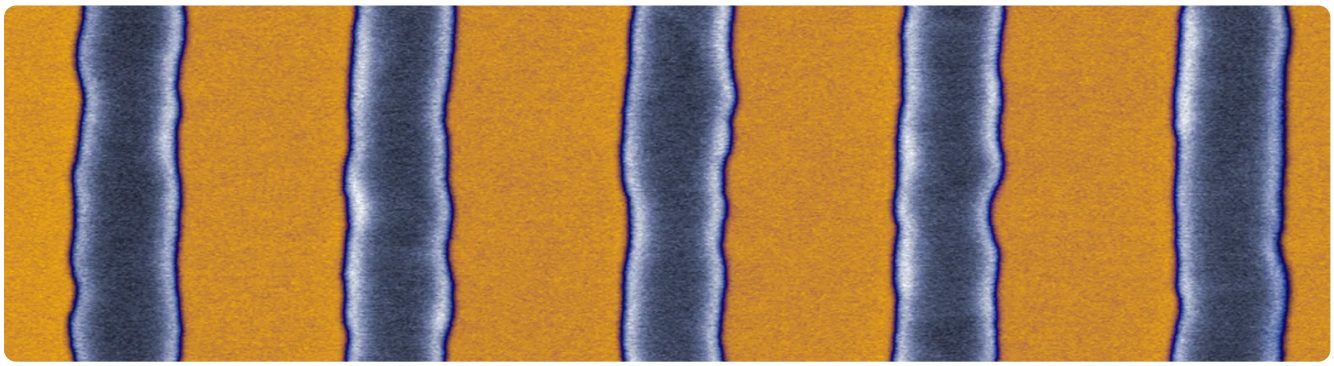



**Figure 6** **Cut masks define where a line must stop** (schematic)

### Reading the figure

The central red window marks the material to remove. The gaps in the right-hand panel correspond to that same window. Making the pitch small and placing the line ends are separate tasks. Actual cut and block flows depend on the stack, mask polarity and transfer method; the illustration isolates their purpose.



A colourised scanning-electron-microscope image of a silicon reference line about 100 nm wide. The irregular edge illustrates why pattern quality involves more than an average width. Description and credits follow the Commons record: B. Bunday, SEMATECH / K. Talbott, NIST. Image: National Institute of Standards and Technology / Wikimedia Commons.jpg) / Public domain. Resized and converted to WebP.

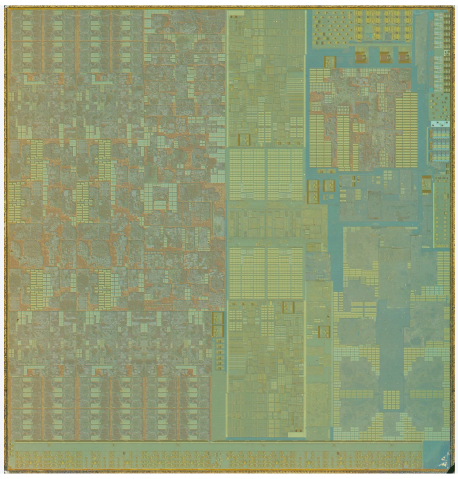
## 7. Where it was used, and what it cost

### From memory arrays to logic

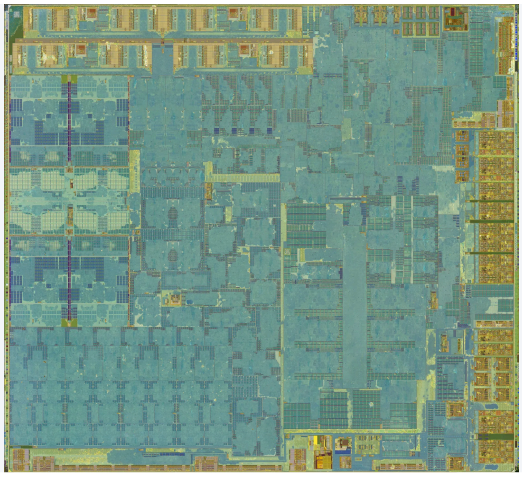
The regular layouts of memory made them an early setting for spacer patterning. STRJ's report records shipments of NAND products at **32 nm half-pitch** using spacer double patterning by 2008 [19]. ASM says its plasma ALD was originally introduced for spacer-defined double patterning in DRAM and planar NAND [25]. Reported

In logic, **Intel's 2017 presentation** described its 10 nm technology as the first use of SAQP. It reported fin pitch falling from 42 to 34 nm and minimum interconnect pitch from 52 to 36 nm, crediting SADP and SAQP as essential to the scaling [26]. The first-use wording is Intel's claim, and the pitch values are distinct from the 10 nm node label. Reported

**TSMC's 2016 annual report** highlighted overlay, defect reduction and patterning robustness in 7 nm development. For 5 nm, it discussed using EUV to reduce the complexity of multiple patterning [27]. Its 2019 N7+ announcement described commercial EUV production and 15–20% higher density than the original N7 [27]. The comparison is consistent with the original N7 preceding the EUV version; it does not mean EUV alone accounts for every change between the processes. Interpretation



The Core i3-8121U Cannon Lake processor die, photographed after removal of the interconnect stack to reveal the polysilicon level, using 5× microscopy according to the Commons record. The die photograph provides device context; individual SAQP steps cannot be read directly from this overview.
Image: FritzchensFritz / Wikimedia Commons / CC0. Resized and converted to WebP.



The processor used in the LCD Steam Deck, photographed after delayering to the polysilicon level with 5× microscopy. The process attribution and preparation follow the Commons filename and description.
Image: FritzchensFritz / Wikimedia Commons / CC0. Resized and converted to WebP.




The package of the same processor bears the markings DIFFUSED IN TAIWAN and MADE IN TAIWAN, as documented in the Commons record. The first marking refers to wafer fabrication.
Image: FritzchensFritz / Wikimedia Commons / CC0. Resized and converted to WebP.

## Resolution gives way to placement

Once two operations contribute neighbouring features, their relative position can matter as much as either operation's resolution. ASML's account identifies overlay as a key enabler of further scaling with multiple patterning [6]. Reported

There is also a financial cost. ITRS estimated that a two-mask set could cost about **1.5 times** as much as one mask, including data, inspection and repair overheads [16]. Purdue's simplified double-patterning example uses two masks per critical layer and halves lithography throughput; Lin discusses the extra process, equipment and mask burden [1][18]. These are comparisons of the affected patterning operations, not statements that every factory's total output must fall by half. Explanation

**Edge placement error (EPE)** brings together the consequences at the feature boundary. IRDS discusses local linewidth and edge variation alongside more global errors such as overlay [28]. EPE is a combined placement measure, not a rule that all separate error numbers should simply be added arithmetically. Explanation

## 8. The equipment and materials ecosystem

### Immersion scanners

The Netherlands' **ASML** reports the following ArF immersion system sales [29]:

| Calendar year | Systems sold | System sales, € million |
|---|---|---|
| 2023 | 125 | 9,017.4 |
| 2024 | 129 | 9,667.0 |
| 2025 | 131 | 10,311.4 |

Reported

In its 2023 history, ASML said approximately 80% of its more than 1,100 immersion shipments had been NXT systems [6]. Its product material reports demonstrated productivity above **6,000 wafers per day**, equivalent to more than 250 per hour averaged over a full day [30]. Calculation Its annual report describes immersion tools serving both single and multiple patterning, alongside EUV tools used for other layers of the same chip [29]. Reported

Japan's **Nikon** also supplies immersion scanners. Its NSR-S636E was announced for release in January 2024 [4]. Nikon's reported ArF immersion unit sales, including used systems, were 4, 11, 3 and 0 in the fiscal years ended March 2023, 2024, 2025 and 2026 respectively. Its May 2026 presentation forecast 3 for the year ending March 2027 [31]. Reported The last figure is a forecast. Outlook The reporting periods and treatment of used equipment differ from ASML's table, but the figures show a substantial difference in scale. Explanation

Canon's 2025 unit breakdown lists KrF and i-line systems without an ArF category [32]. This is a distinction between product portfolios; total lithography sales alone do not indicate a supplier's immersion position. Explanation

### The rest of the process matters just as much

The spacer route shifts part of the dimensional-control task from optical exposure to film formation and removal. Equipment and materials contributions can be grouped by function:

- **Deposition and etch:** Lam Research describes film-defined dimensions in multiple patterning and lists hard spacer materials for critical patterning among the applications of its Striker ALD platform [24][33]. ASM links the introduction of plasma ALD to spacer-defined double patterning [25].
- **Process integration:** Tokyo Electron discusses evaluating combinations of EUV and multiple patterning to balance patterning performance and cost [34].
- **Modelling and control:** KLA describes simulation software for multiple-patterning optical lithography and EUV in its annual filing [35].
- **Resist and surface protection:** JSR's work includes immersion topcoats and a 2010 non-topcoat, self-freezing ArF resist for double patterning. It reports minimising defects such as watermarks without a separate topcoat in that material system [11][36]. Reported

## 9. Why export rules refer to overlay as well as resolution

This section follows the introduction and expansion of selected controls. The dates matter: the cited Dutch, US and Japanese provisions have different scopes, destinations and legal structures. It is an explanation of the technology and the cited measures, rather than a complete shipment-classification guide.

### The Dutch measures of 2023 and 2024

ASML announced on 30 June 2023 that Dutch rules would require export licences for advanced immersion DUV systems, including the NXT:2000i and subsequent immersion models, when exported from the Netherlands outside the EU. The rules took effect on **1 September 2023** [37]. Reported

The 2023 regulation includes a wavelength of 193 nm or longer, a legally defined **minimum resolvable feature (MRF) of 45 nm or less**, and **dedicated chuck overlay (DCO) of 1.50 nm or less** [38]. The 2024 amendment added the DCO range **above 1.50 nm up to and including 2.40 nm** [39]. ASML said the change meant it would seek Dutch rather than US licences for NXT:1970i and NXT:1980i shipments [40]. Reported

DCO concerns overlay evaluated on the same lithography system under the defined measurement conditions. MRF is calculated using the regulation's definition. Neither should be substituted casually with a chip-node label or a headline figure from a product brochure. Explanation

The Dutch government described the measure as case-by-case licensing, rather than an export ban [41]. The amendment's explanatory material estimated nine initial applications and five per year thereafter [39]. Separately, ASML reported in January 2024 that some licences for 2023 shipments of the NXT:2050i and NXT:2100i had been partially revoked, affecting a small number of customers in China [42]. Reported

### US and Japanese provisions

The US Bureau of Industry and Security's October 2023 rule separated relevant overlay ranges into DCO of 1.50 nm or less, and above 1.50 nm up to 2.4 nm, explaining the revision in terms of advances in immersion lithography [43]. Reported

The cited Japanese ministerial ordinance includes equipment using wavelengths of 193 nm or longer where **0.25 × wavelength [nm] / NA ≤ 45** and the **maximum same-system overlay value is 2.4 nm or less**, subject to the provision's full terms and exceptions [44]. Reported Overlay alone is therefore not the whole criterion.

### Customers and the wider supply chain

ASML's 2025 annual report says its non-EUV business remained broadly at the previous year's level, supported mainly by mainstream business in China; its company-wide sales share for customers in China was 29.1%, a different measure from immersion-only sales [29]. Reported

China's **KINGSEMI** reports domestic development of coating and developing equipment for immersion applications [45]. **SMIC** identifies tighter controls as a risk to procurement of controlled equipment in its annual report [46]. Neither statement by itself establishes the availability of a domestically supplied immersion scanner. Explanation

The overall picture is a connected one: scanner suppliers in the Netherlands and Japan, supporting equipment and materials across several countries, customers worldwide, and overlapping national controls. The relevant capability is the whole manufacturing flow, not a single machine viewed in isolation. Explanation

## 10. What still needs to improve

- **Choosing the right flow for each layer.** ASML describes EUV as simplifying some complex immersion multiple-patterning flows [29]. IRDS's 2023 discussion nevertheless expects multiple patterning to remain relevant, including alongside EUV [28]. A shorter wavelength does not remove every design and integration constraint.
- **Tighter placement control.** The roadmap discussed in Part 3-5 gives a projected 1.6 nm logic overlay requirement for 2028. Outlook ASML reports a 15% improvement in on-product overlay for the NXT:2150i relative to its predecessor [30]. Reported A roadmap target and a product-to-product improvement are different kinds of number.
- **Avoiding unnecessary patterning steps.** Applied Materials' 2023 pattern-shaping announcement claimed savings of about **US$250 million in capital equipment per 100,000 wafer starts per month** and **US$50 per wafer** for each EUV double-patterning step replaced [47]. Reported These are the supplier's estimates for the stated application, not general savings for all layers.
- **Energy as well as step count.** IRDS's 2022 discussion warns that fewer process steps with EUV do not automatically mean lower energy use, because the exposure equipment itself consumes substantial energy [17]. Reported

### Where materials expertise makes a difference

These processes depend on surfaces and films as much as on lenses. Useful materials work includes:

- Designing water-shedding surfaces that remain compatible with development [11].
- Limiting resist-component leaching and optical contamination [11].
- Depositing uniform, durable spacer films with suitable etch selectivity [24][25][33].
- Integrating cuts, blocks and pattern transfer while controlling feature-edge placement [21][28].

In SADP and SAQP, film thickness becomes a principal control on line width. This is a direct connection to the ALD and CVD processes in Part 3-3: deposition helps extend what lithography can manufacture.

## 11. Recap and the next lesson

| Question | Key idea |
|---|---|
| Why did dry optics reach a limit? | NA = n sin α cannot exceed one in air; a practical dry value was about 0.93. |
| What does water change? | At 193 nm, n ≈ 1.44 allows NA 1.35. The in-water wavelength is about 134 nm, while frequency and photon energy stay unchanged. |
| What about focus? | Immersion can improve focus latitude when compared at the same resolution; pushing to finer resolution is a separate trade-off. |
| What made immersion difficult? | A moving local water region, bubbles, escaped droplets, leaching and temperature-dependent optical properties. |
| Why stop at water? | Water limits the index of the stack; higher-index fluids faced materials, timing and investment challenges. |
| How does multiple patterning help? | LELE interleaves exposures; SADP and SAQP multiply sidewall lines. Cuts create the required ends. |
| What is the price? | More masks and processing, tighter placement control and additional cost. EPE captures the result at feature edges. |
| Who supplies the flow? | ASML and Nikon provide immersion scanners; international suppliers provide deposition, etch, resists, integration and control. Advanced equipment is also subject to export rules. |

**Next: Part 3-7, EUV lithography.** Moving from 193 nm to 13.5 nm changes far more than a number in the resolution equation. The light is strongly absorbed by air and glass, so the system needs a plasma source, a vacuum light path and reflective optics.

## 12. Check your understanding

1. Why can a dry imaging system not have image-side NA above one?

▼ **Show answer**

NA = n sin α. Air has n approximately one and sin α cannot exceed one. Real dry systems stop short of that limit; the teaching example uses about 0.93.

2. What is the wavelength of 193 nm light inside water with refractive index 1.44? Does a photon gain energy?

▼ **Show answer**

The in-water wavelength is approximately 193/1.44 = 134 nm. Frequency and photon energy do not change at the boundary. Water contact can still affect resist chemistry and leaching.

3. With k1 = 0.27, compare NA 0.93 and NA 1.35 at 193 nm.

▼ **Show answer**

R = k1λ/NA gives about 56 nm for dry optics and 39 nm for immersion. These are illustrative resolution calculations, not process-node labels.

4. Name three defects or contamination mechanisms introduced by immersion.

▼ **Show answer**

Bubbles can disturb the optical path; residual droplets can leave watermarks; particles or components leached from the resist can contaminate the process or optics.

5. What does an immersion topcoat need to do?

▼ **Show answer**

Limit contact and component leaching, help the surface shed water, and remain compatible with resist processing and removal during development. A high receding contact angle is useful, but the full process compatibility matters too.

6. Why did production water immersion settle around NA 1.35?

▼ **Show answer**

Water, with n about 1.44 at 193 nm, is the lowest-index material in the relevant stack. Practical collection angles bring the usable limit to roughly 1.37. Higher-index liquids were explored but not adopted for the next production step.

7. Why does LELE place such demanding requirements on overlay?

▼ **Show answer**

Neighbouring lines are formed in different exposures. A shift between them directly changes the alternating spaces, even if individual line widths are perfect.

8. Why can three mutually conflicting features not be assigned to two masks without another change?

▼ **Show answer**

Each feature must have a different colour from both neighbours. A triangle is an odd cycle, which cannot be two-coloured. The layout or decomposition needs to change, or another patterning solution is required.

9. What principally controls the width of the sidewall lines in SADP?

▼ **Show answer**

Spacer thickness and the subsequent etch process. Mandrel geometry still affects where the lines land and how evenly they are spaced; self-aligned does not mean independent of lithography.

10. Starting from 40 nm half-pitch, what do ideal doubling and quadrupling give?

▼ **Show answer**

About 20 nm for SADP and 10 nm for SAQP. SAQP includes a second deposition, etch-back and core-removal sequence. These are idealised density calculations, not a production guarantee.

# 13. Glossary

**Immersion lithography**
Exposure through a liquid between the final lens and the wafer. Production ArF tools use water to achieve NA above one.

**Refractive index**
The ratio of the speed of light in vacuum to its phase velocity in a material. Water has n about 1.44 at 193 nm.

**Snell's law**
The refraction relationship n1 sin θ1 = n2 sin θ2, with angles measured from the surface normal.

**Total internal reflection**
Reflection back into a higher-index medium when the incident angle exceeds the critical angle for a lower-index neighbour.

**In-medium wavelength**
The free-space wavelength divided by the refractive index. Changing it does not change frequency at the boundary.

**Immersion hood**
The assembly controlling local liquid supply and recovery around the final lens.

**Watermark**
A defect associated with residual liquid left on the wafer surface.

**Topcoat**
A protective film above the resist, designed to control water contact, leaching and surface behaviour.

**Receding contact angle**
The contact angle at the edge of a withdrawing liquid droplet; relevant to water shedding.

**Leaching**
Transfer of resist components into the immersion liquid.

**High-index immersion**
An investigated route using fluids of higher refractive index than water; it was not adopted as the next production extension.

**Multiple patterning**
Increasing pattern density through multiple exposures or sequences of film deposition and removal.

**Pitch splitting**
Dividing a dense pattern into less crowded sets that are formed separately and combined.

**LELE**
Lithography-etch-lithography-etch; a pitch-splitting sequence with two lithography and etch rounds.

**LFLE**
Lithography-freeze-lithography-etch; the first resist pattern is stabilised before the second lithography step.

**Colouring / decomposition**
Assigning features to masks while respecting printing-distance constraints.

**Mandrel**
A temporary core around which a spacer film is deposited.

**Spacer**
Film retained on a sidewall after etch-back, used to define a denser pattern during transfer.

**SADP**
Self-aligned double patterning; one spacer-formation round doubles line density.

**SAQP**
Self-aligned quadruple patterning; two spacer-formation rounds give fourfold line density.

**Cut mask**
A mask used to define unwanted line sections or the required line ends.

**Edge placement error (EPE)**
Deviation of a feature boundary from its intended position, incorporating local dimensional variation and placement effects such as overlay.

**Dedicated chuck overlay (DCO)**
A same-system overlay metric evaluated under defined conditions; used among the technical criteria in the cited export rules.

## 14. Sources and further reading

The reference numbering matches the Japanese edition. Source-language notes identify material published in Japanese, Dutch or Chinese. Supplier first-use claims and forecasts retain their attribution.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2. **M. Qi (Purdue University / nanoHUB)** — ECE695Q Lecture 10: Resolution Enhancement Techniques (2016; slides 24, 26–28, 32–34) — Read source
3. **ASML** — TWINSCAN NXT:2000i and NXT:2100i product information — Read source
4. **Nikon** — Nikon Releases the NSR-S636E ArF Immersion Scanner (6 December 2023) — Read source
5. **ASML** — Lithography principles: Lenses and mirrors — Read source
6. **ASML** — How immersion lithography saved Moore's Law (2 August 2023) — Read source
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9. **Nikon Precision** — Nikon Ships World's First 45 nm Production Immersion Scanner (28 February 2007) — Read source
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24. **Lam Research** — Lam's New Etch and Deposition Products Control Process Variability to Enable Advanced Multiple Patterning (7 July 2014; company release) — Read source
25. **ASM International** — Annual Report 2025 (PDF p. 22) — Read source
26. **K. Mistry (Intel)** — Intel 10 nm technology, Technology and Manufacturing Day (2017; slides 6, 13, 34; copy hosted by Milwaukee School of Engineering) — Read source

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47. **Applied Materials** — Applied Materials' Innovative Pattern-Shaping Technology Reduces the Cost, Complexity and Environmental Impact of Chipmaking (28 February 2023) — Read source

The TSMC N7+ production announcement is the second document cited in reference 27. Reference 46 links directly to the filed annual report rather than the exchange homepage.

## 15. Claims and evidence

| Claim or group of claims | Supporting source | Treatment |
|---|---|---|
| Unchanged frequency; NA 1.34 example; equal-resolution focus benefit including a 96% example; defect categories; practical NA 1.368; three-mask hole pattern; effective k1 and 19 nm half-pitch discussion | Lin [1] | Reported analysis |
| Dry NA about 0.93; water index 1.44 and 134 nm in-medium wavelength; critical angle; fluid timing and heating | Purdue Lecture 10 [2] | Teaching examples |
| Production specifications: NA 1.35 and resolution 38 nm or better | ASML [3]; Nikon [4] | Product specifications |
| Water enables NA above one; production immersion NA 1.35 | ASML [5] | Supplier explanation |
| Early roadmap, IBM history, ASML and TSMC milestones, immersion hood development, stage speed and defect improvements, NXT shipment share and importance of overlay | ASML [6] | Supplier historical account |
| dn/dT assumption and ±0.1°C estimate for ±10 ppm index control | Baek et al. [7] | Historical simulation, not a universal specification |
| Propagation of otherwise internally reflected light; research beginning in 2000 | MIT Lincoln Laboratory [8] | Research account |
| NA 1.30 scanner for 45 nm production | Nikon [9] | Company announcement |
| NSR-S609B, NA 1.07, 2005 and first-use claim | Nikon [10] | Supplier historical account |
| Leaching, optical contamination, water shedding, 69° receding angle and PAG reduction | JSR [11] | Material-specific study |
| Liquid between projection lens and wafer | US4346164 [12] | Patent disclosure |
| Index constraints of water, fused silica and resist | RIT researchers [13] | Research explanation |
| High-index immersion development discontinued; timing argument | Zimmerman et al. [14] | Research account |
| Index/absorption difficulty and approximately 1.65 fluid index | Rothschild [15] | Retrospective analysis |
| Historical single-exposure benchmark, pitch splitting, spacers, LELE/LFLE, cut mask, mask cost and repeated spacer doubling | ITRS 2011 [16] | Roadmap and process analysis |
| Multiple-patterning definition and the distinction between fewer steps and lower energy | IRDS 2022 [17] | Roadmap analysis |
| Overlay-induced variation, SADP strengths and costs, simplified throughput comparison | Purdue Lecture 11 [18] | Teaching examples |
| Approximate 40 nm half-pitch benchmark, spacer process, early NAND use and overlay requirements | STRJ 2009 [19] | Dated roadmap report |
| Conflicting features require different masks; odd cycles are not two-colourable | Kahng et al. [20] | Layout-decomposition research |
| Fourfold multiplication to 16 nm half-pitch; multi-mask block patterning | imec 2017 [21] | Research demonstration |
| SAOP and long, complex immersion flows | imec 2019 [22] | Research outlook |
| Regular one-dimensional wiring and cuts | Lin, Pan et al. [23] | Design/process research |
| Deposited spacers serve as patterning masks and define critical dimensions | Lam [24] | Supplier process explanation |
| Plasma ALD introduced for spacer-defined double patterning | ASM [25] | Company report |
| SAQP first-use claim, fin and interconnect pitches at Intel 10 nm | Intel [26] | Company presentation |

| Claim or group of claims | Supporting source | Treatment |
|---|---|---|
| TSMC development priorities, EUV simplification and N7+ density comparison | TSMC [27] | Company reports |
| EPE and the continuing role of multiple patterning with EUV | IRDS 2023 [28] | Roadmap analysis |
| ArF immersion units and revenue, combined use with EUV, non-EUV business and China sales context | ASML annual report [29] | Period-specific company figures |
| More than 6,000 wafers/day and NXT:2150i overlay improvement | ASML [30] | Supplier performance claims |
| Nikon immersion unit sales and following-year forecast | Nikon [31] | Historical results; forecast labelled separately |
| Canon unit-sales categories | Canon [32] | Company portfolio breakdown |
| Striker ALD spacer applications | Lam Form 10-K [33] | Company filing |
| Evaluation of EUV/multiple-patterning combinations | Tokyo Electron [34] | Company report |
| Optical and EUV lithography simulation | KLA Form 10-K [35] | Company filing |
| Non-topcoat self-freezing ArF resist | JSR [36] | Product-development announcement |
| Dutch licensing from September 2023 and NXT:2000i onward | ASML [37] | Dated announcement |
| MRF, DCO and same-system definition | Dutch Gazette 2023 [38] | Cited regulatory criteria |
| Added DCO range and estimates of licensing applications | Dutch Gazette 2024 [39] | Dated amendment and explanatory estimates |
| NXT:1970i and 1980i licensing | ASML [40] | Dated announcement |
| Outside-EU scope and case-by-case licensing | Dutch government [41] | Dated government explanation |
| Partial revocation affecting some NXT:2050i and 2100i shipments | ASML [42] | Dated announcement |
| US DCO ranges | BIS [43] | Cited 2023 rule |
| Japanese wavelength, resolution-expression and overlay conditions | e-Gov [44] | Cited ordinance; full terms and exceptions apply |
| Coating/developing equipment for immersion | KINGSEMI [45] | Company report |
| Procurement risk under tighter controls | SMIC [46] | Company risk disclosure |
| Pattern-shaping capital and per-wafer savings | Applied Materials [47] | Supplier estimates for stated conditions |
| 134 nm in water; 56/39 nm resolution examples; ppm-temperature arithmetic; daily-to-hourly conversion; ideal SADP/SAQP half-pitches | Stated source inputs and equations in the text | This article's calculations |
| The inference about original N7 and interpretation of the process comparison | TSMC comparison [27] and explanatory reasoning | Interpretation, not an additional measured result |

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