SEMICONDUCTOR FRONT-END · PART 3-7

EUV Lithography Drawing circuits with light that air absorbs

The finest layers of an advanced chip can be printed with light at a wavelength of just 13.5 nm. Yet this light cannot travel through an ordinary lens, or even through a long path in air. Making it useful required an entirely different exposure system: a laser-driven tin plasma, a vacuum light path, exceptionally smooth multilayer mirrors and a reflective mask. This lesson connects those engineering choices to the small number of photons available to form each tiny feature, then follows EUV from early experiments to the international equipment and materials ecosystem behind it.

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

In this lesson

1. The lesson in three ideas
2. Why the wavelength is 13.5 nm
3. An optical system built around absorption
4. Making the light from tin
5. How an experiment became a production technology
6. High-NA: more resolution, tighter constraints
7. Why fewer photons can mean more variation
8. Resists and pellicles: materials become decisive
9. Throughput and electrical energy
10. Scanners, key components and chipmakers
11. The materials and inspection ecosystem
12. What still needs to improve
13. Recap and the next lesson
14. Check your understanding
15. Glossary
16. Sources and further reading
17. Claims and evidence

How to read this lesson

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

What you will learn

- Explain why EUV needs a vacuum light path and multilayer mirrors instead of lenses.
- Trace the energy path from a laser through tin plasma to useful exposure light.
- Connect photon energy and photon-count variation to patterning defects and exposure dose.
- Describe High-NA's benefits and constraints, and identify the roles of equipment, materials and inspection suppliers.

1. The lesson in three ideas

- **A shorter wavelength changes the whole machine.** EUV lithography uses 13.5 nm light. Strong absorption in air and glass leads to a vacuum light path, reflective optics and a reflective mask. Even carefully engineered mirrors lose light: ten reflections at 67% reflectivity leave only about 2% of the starting power.
- **Making enough useful photons is difficult.** A laser turns tiny tin droplets into plasma. The useful EUV conversion is only a fraction of the laser energy. Each EUV photon carries about fourteen times the energy of an ArF photon, so the same exposure energy contains fewer photons. Their random arrival, together with material and chemical variation, becomes important at small feature sizes.
- **Production depends on a network of specialised capabilities.** ASML supplies EUV scanners, ZEISS supplies their key optics and TRUMPF provides the powerful CO2 laser technology. Mask materials, resists, coating and developing, inspection and pellicles come from a broader ecosystem, with major contributions from Japanese, European and US companies.

2. Why the wavelength is 13.5 nm

A large step down from 193 nm

Parts 3-5 and 3-6 showed how 193 nm ArF immersion, with NA 1.35, reached a practical single-exposure benchmark around 40 nm half-pitch. Further density could be built through multiple patterning, but at the cost of additional masks, deposition, etching and placement control. Shortening the wavelength offered another route. Explanation

EUV's **13.5 nm** wavelength is about **one-fourteenth** of 193 nm. ASML specifies **13 nm resolution** for its NA 0.33 EUV platform [11]. Reported Rearranging the Rayleigh relationship gives:

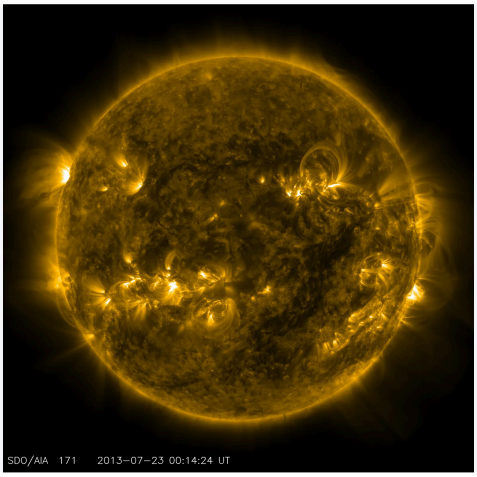
$$k_1 = R \times NA / \lambda = 13 \times 0.33 / 13.5 \approx 0.32$$

Calculation The shorter wavelength permits much finer single-exposure features without pushing k_1 as low as in the most aggressive ArF processes. A scanner's resolution is not the same thing as a chip's process-node name or the dimensions of a complete transistor. Explanation

The source and the mirror had to agree

There was no reason to choose 13.5 nm in isolation. A practical wavelength needed both a usable source and optics that could reflect it effectively. IRDS emphasises multilayer-mirror reflectivity in the wavelength choice [1]. ASML's historical account describes investigations across roughly 4–40 nm before settling on the region suited to a tin-plasma source [9]. Reported

The source-development literature shows the useful match between tin's emission spectrum and molybdenum/silicon mirror performance [4]. The selected wavelength is where two technologies could work together: producing the light and transporting enough of it to form an image. Explanation



NASA's Solar Dynamics Observatory recorded this view at 17.1 nm. Coronal loops follow the Sun's magnetic structure, as described in the Commons record. This is another part of the EUV spectrum, not the 13.5 nm exposure wavelength.
Image: NASA/SDO and the AIA, EVE, and HMI science teams / Wikimedia Commons / Public domain. Resized and converted to WebP.

3. An optical system built around absorption

Why the light path must be in vacuum

Air and solid materials strongly absorb EUV. A long path through ordinary air would lose the light; a glass lens would absorb it rather than focus a useful transmitted beam. ASML and imec therefore describe a vacuum system using reflective optics [10][16][20]. Reported

Strong absorption does not mean that no light can ever pass through any thickness of material. An extremely thin membrane can still transmit a useful fraction, which is why a pellicle is possible. A lens-sized thickness of glass is a very different proposition. Explanation

A mirror made from many weak reflections

An ordinary single interface reflects too little near-normal-incidence EUV to make a useful imaging mirror. Instead, alternating thin layers of **molybdenum and silicon (Mo/Si)** create reflections that add through interference. The layer spacing is engineered so that contributions returning from different depths reinforce one another.
Explanation

A 1998 Lawrence Livermore National Laboratory paper describes **40 Mo/Si pairs**, with a **6.89 nm period**: approximately 2.8 nm of Mo and 4.1 nm of Si. It reports routinely achieving **67.5% reflectivity at 13.4 nm**, while pursuing higher performance [3]. Reported

Those are a research example, not the layer count of every current mirror. ASML's general description of its EUV optics refers to mirrors with **more than 100 material layers** [16]. A pair contains two layers; the example and the modern description should not be treated as identical specifications. Explanation

The physics: why the period is roughly half a wavelength

Consider light entering and returning from a layer one period, d, deeper into the stack. At normal incidence, the simplest geometric approximation adds an extra path of 2d. If that equals a wavelength, the returning waves can reinforce:

$$2d \approx \lambda, \text{ so } d \approx \lambda/2 \approx 6.75 \text{ nm for } \lambda = 13.5 \text{ nm}$$

Calculation This is close to the cited 6.89 nm period [3], but it is only a first explanation. Accurate design includes complex refractive indices, absorption, angle, interface quality and reflection phase. Dividing the wavelength by two is not a complete mirror recipe. Each constituent layer is only a few nanometres thick, on the order of tens of atomic dimensions. Explanation

The physics: ten good mirrors still lose most of the light

Fomenkov and colleagues give an example with ten reflections between the **intermediate focus** and the wafer. At 67% reflectivity per reflection, the remaining fraction is:

$$0.67^{10} \approx 0.018, \text{ or about } 2\%$$

Even 70% reflectivity gives only $0.70^{10} \approx 0.028$, about 3% [4]. Calculation Much of the unreflected light is absorbed, adding heat to the optics.

The reference point matters. The 2% starts with the light available at the intermediate focus. It is neither the fraction of all plasma emission reaching the wafer nor the electrical efficiency of the whole machine. This optical loss is one reason the source needs so much power and the mirrors need thermal control. Explanation

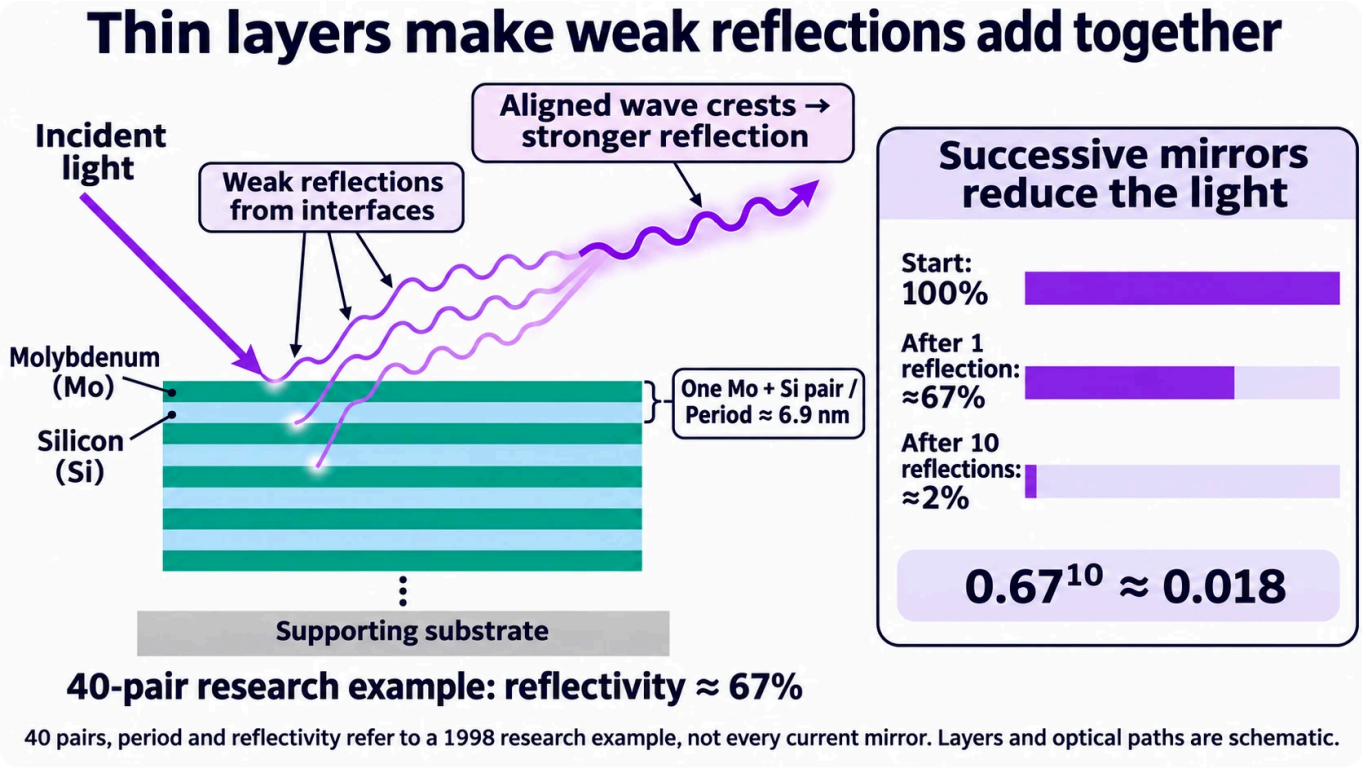
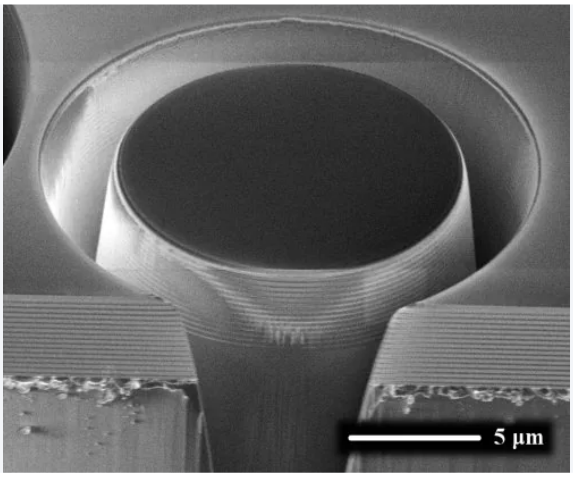


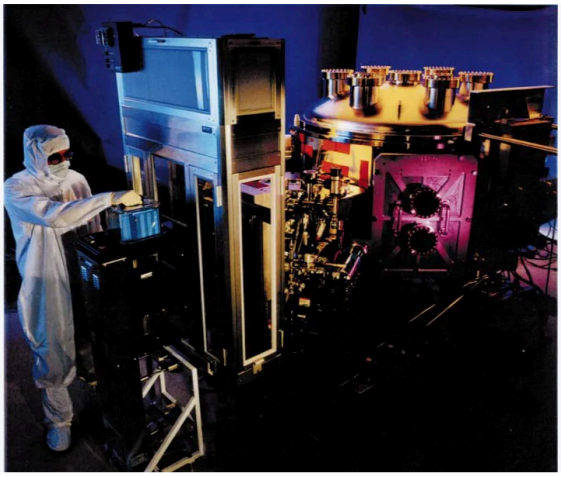
Figure 1 **Multilayers strengthen reflection; successive mirrors reduce available light** (schematic)

Reading the figure

On the left, weak contributions from different interfaces add together. A photon is not gaining energy by bouncing serially between the layers. On the right, useful power decreases as light encounters successive mirrors. The 40-pair stack is the historical research example; the drawing does not specify the architecture of a production scanner [3][4].



This dielectric mirror uses alternating tantalum-oxide and silicon-oxide layers for visible/infrared applications, according to the Commons record. It is not an EUV Mo/Si mirror. It illustrates the idea of building a reflector from a carefully controlled stack of films.
Image: Geepster (English Wikipedia) / Wikimedia Commons / Public domain. Resized and converted to WebP.



Lawrence Livermore National Laboratory equipment for depositing very low-defect thin films for EUV lithography, as described in the Commons record. This is coating equipment, not an exposure scanner.
Image: Lawrence Livermore National Laboratory / Wikimedia Commons / Public domain. Resized and converted to WebP.

Surface quality and a reflective mask

The mirror surface must be extraordinarily smooth. ZEISS illustrates this by imagining a mirror expanded to the size of Germany: its cited surface-height variation would be about **0.1 mm**. The company describes a conventional EUV projection-optics assembly with around **20,000 parts** and a mass of roughly **two tonnes** [25]. These comparisons communicate precision and scale rather than an optical drawing. Reported

The **mask, or reticle, is also reflective**. An absorber pattern sits above a multilayer reflector; the difference between covered and uncovered areas creates the image. The conventional NA 0.33 system reduces the mask pattern by a factor of four [10]. A paper on mask effects discusses, for example, an approximately **80 nm tantalum-based absorber** [6]. Reported

Illumination arrives obliquely, typically around **6° from the normal** in the cited conventional geometry. This separates incoming and outgoing light but makes absorber thickness important. Shadowing and other wave-optical effects can change printed dimensions depending on feature orientation. The same paper discusses penetration of roughly 50 nm into the multilayer [6]. These **mask 3D effects** motivate new absorber materials and computational correction [1]. Reported

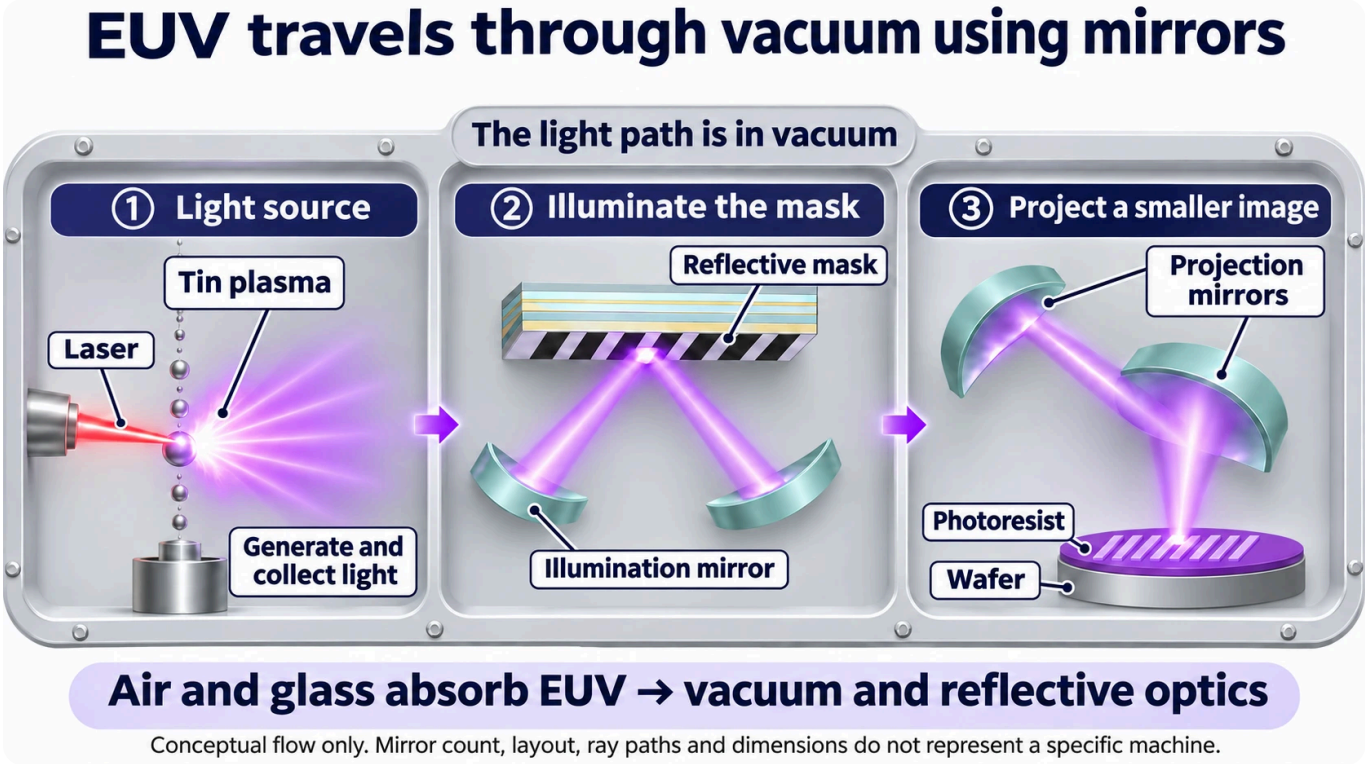


Figure 2 **The EUV system: generate, illuminate, then project** (schematic)

Reading the figure

The source generates and collects light. Illumination optics deliver it to the patterned reflector, and projection optics form a smaller image on the resist. The black absorber pattern is on the reflective face. The three modules explain the sequence rather than reproduce an actual ray trace. Vacuum means greatly reduced gas pressure; the source can still use controlled low-pressure hydrogen for contamination management [4][10].

4. Making the light from tin

- **Two pulses, repeated 50,000 times a second**

The source is called **laser-produced plasma (LPP)**. ASML describes the following sequence [15]:

1. Launch molten tin droplets about **25 µm** in diameter at about **70 m/s**.
2. Strike a droplet with a lower-intensity pulse to flatten and expand it.
3. Deliver a stronger pulse to vaporise the prepared tin and create a hot, EUV-emitting plasma.
4. Repeat about **50,000 times per second**. Reported

The cited source-development paper describes a **10.6 µm CO2 laser** [4]. ASML characterises the plasma temperature as about forty times the Sun's surface temperature [9]. The long-wavelength laser is an energy input: it is the tin plasma, not the laser beam itself, that provides the 13.5 nm exposure light. Explanation

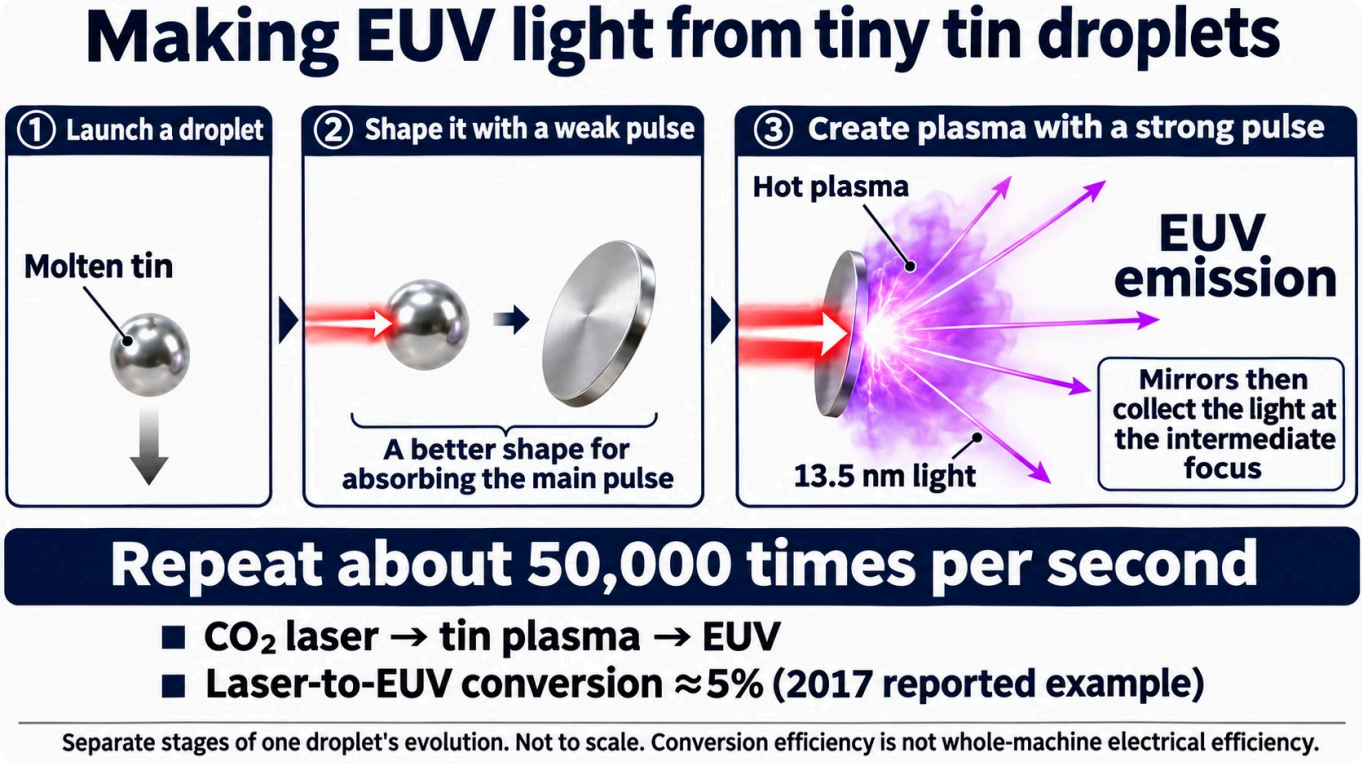


Figure 3 **From a tin droplet to EUV emission** (schematic)

Reading the figure

The panels separate stages in the evolution of a droplet. The weaker pulse improves the target shape before the main pulse arrives. Purple makes the invisible EUV emission visible for teaching. Collection optics subsequently gather part of the emitted light at the intermediate focus. The geometry and timing are schematic [4][15].

- **Conversion efficiency is only one part of the energy chain**

The 2017 source paper reports average **laser-to-EUV conversion efficiency around 5%**, with 6% demonstrated in development tests. After collection and spectral-purity losses, its example required more than **20 kW of laser output** to obtain **200 W at the intermediate focus** [4]. Reported

It helps to distinguish three stages: electricity powers the laser; the laser heats tin to produce radiation; collection and spectral selection deliver useful EUV. The 5% figure describes the middle conversion under the paper's conditions, not all three stages combined. Explanation

For a unit-conversion example, 20,000 W divided into 50,000 pulses per second is **0.4 J per pulse**. Separately, 250 W at the intermediate focus and the same repetition rate is **5 mJ per pulse**. Calculation These are illustrative conversions using different output examples, not a matched pair of measurements from which to infer efficiency.

Power and contamination had to improve together

ASML's retrospective describes early sources below 10 W and a prolonged difficulty passing 80 W [13]. It connects the later 250 W milestone with processing 125 wafers per hour [9]. The **2023 IRDS** update reports 600 W at intermediate focus and work towards 1 kW [1]. These are dated milestones, rather than a claim that 600 W is the limit of every current system. Reported

The source also ejects tin ions and debris that can damage or contaminate the **collector mirror**. Fomenkov and colleagues identify collector lifetime as a critical issue and describe hydrogen to slow ions, together with hydrogen-radical chemistry to remove deposited tin [4]. Reported

Gigaphoton has investigated magnetic control of tin ions; its 2015 paper reports 140 W burst output at 50 kHz [5]. Burst output, sustained output and power measured at different locations are not interchangeable performance measures. Explanation

5. How an experiment became a production technology

Early reduction imaging at NTT

An important starting point was **Hiroo Kinoshita's work at NTT in Japan**. In his own account, work on one-to-one X-ray imaging led him around 1983 to pursue reduction imaging with multilayer-coated optics. After difficult alignment experiments at the Japanese high-energy physics laboratory, he produced line-space patterns in **1985** and presented the result at the **Japan Society of Applied Physics in autumn 1986** [7]. Reported

Tsuneyuki Haga's later history places the beginning of the NTT programme around 1984 and the first report of pattern transfer in 1986 [8]. Kinoshita recalls a sceptical initial reception and an international EUVL meeting near Mount Fuji in 1993 [7]. ASML also recognises the 1986 work in its history [9]. The dates distinguish the beginning of research, the experiment and its public presentation. Explanation

National laboratories, industry consortia and equipment development

In the United States, **EUV LLC**, led by Intel, Motorola and AMD, partnered with Lawrence Livermore, Sandia and Lawrence Berkeley national laboratories. The 1997 announcement described a **three-year, US$250 million** cooperative research programme, then the largest agreement of its kind for the US Department of Energy [17]. Reported

ASML subsequently integrated the technology into commercial exposure equipment. It records shipping demonstration systems to Albany and imec in **August 2006**, shipping the NXE:3300 in **2013**, investing more than **€6 billion over 17 years** in EUV development, and acquiring source company Cymer [10]. Its annual-report history identifies the 2018 NXE:3400B as the first high-volume EUV model able to process more than 100 wafers per hour [27]. Reported

The result came from successive research, component and system-development efforts across countries. The early proof of imaging was essential, but so were source power, masks, resists, inspection and the economics of operating a production scanner. Explanation

Adoption in chip production

Samsung announced the start of production using its **7LPP EUV process in October 2018**. It said some layers requiring up to four ArF masks could be made with one EUV mask, reducing the overall mask count by about 20% in that process [18]. TSMC's **2019 N7+ announcement** described high-volume commercial EUV production [19]. ASML identifies the Galaxy Note10, released in 2019, among the first commercial products using EUV-made chips [9]. Reported

More than thirty years separate Kinoshita's 1985 experiment and the 2018–2019 production milestones. Calculation Claims about a first machine, first production process and first customer product refer to different achievements.

6. High-NA: more resolution, tighter constraints

Increasing NA from 0.33 to 0.55

High-NA EUV keeps the 13.5 nm wavelength and increases numerical aperture to **0.55**. ASML gives **8 nm resolution**, compared with 13 nm for its NA 0.33 platform [11]. Reported The implied process factor is:

$$k_1 = 8 \times 0.55 / 13.5 \approx 0.33$$

Calculation ASML describes the geometric scaling opportunity as features about 1.7 times smaller and potential transistor density around 2.9 times higher [12]. That is an imaging/scaling opportunity, not a guarantee that a complete chip's density or performance rises by 2.9 times. Explanation

ZEISS describes the High-NA projection optics as more than **40,000 parts** weighing approximately **12 tonnes** [24]. Reported

Different reduction in the two directions

Simply enlarging the optical angles creates problems at the reflective mask. ASML explains that the larger angles would reduce reticle reflectivity. Its solution is **anamorphic imaging**: reduce the pattern by **four times in one direction and eight times in the other** [12]. Reported

Keeping the established reticle format then gives a **26 mm × 16.5 mm** wafer exposure field, half the area of the conventional **26 mm × 33 mm** field. Large dies can require field stitching or other design approaches; larger-mask options have also been discussed [1]. Reported

The wafer and reticle stages must move faster to support productivity. ASML's 2024 explanation gives accelerations of **8 g** for the wafer stage and **32 g** for the reticle stage [12]. These describe acceleration, not a stage speed or a load applied to the finished chip. Explanation

The physics: focus margin becomes shallower

At fixed wavelength and proportionality factor, depth of focus scales approximately as λ/NA². Raising NA from 0.33 to 0.55 gives:

$$\text{DOF ratio} = (0.33 / 0.55)^2 = 0.36$$

Calculation Thus the simple comparison gives about 36% of the former focus depth. IRDS discusses the need for resist thinner than **20 nm** in High-NA processes [1]. Reported A thinner film helps focus and pattern transfer but can absorb fewer photons at a given material absorption strength. That connects the optical design directly to the next section's statistical problem. Explanation

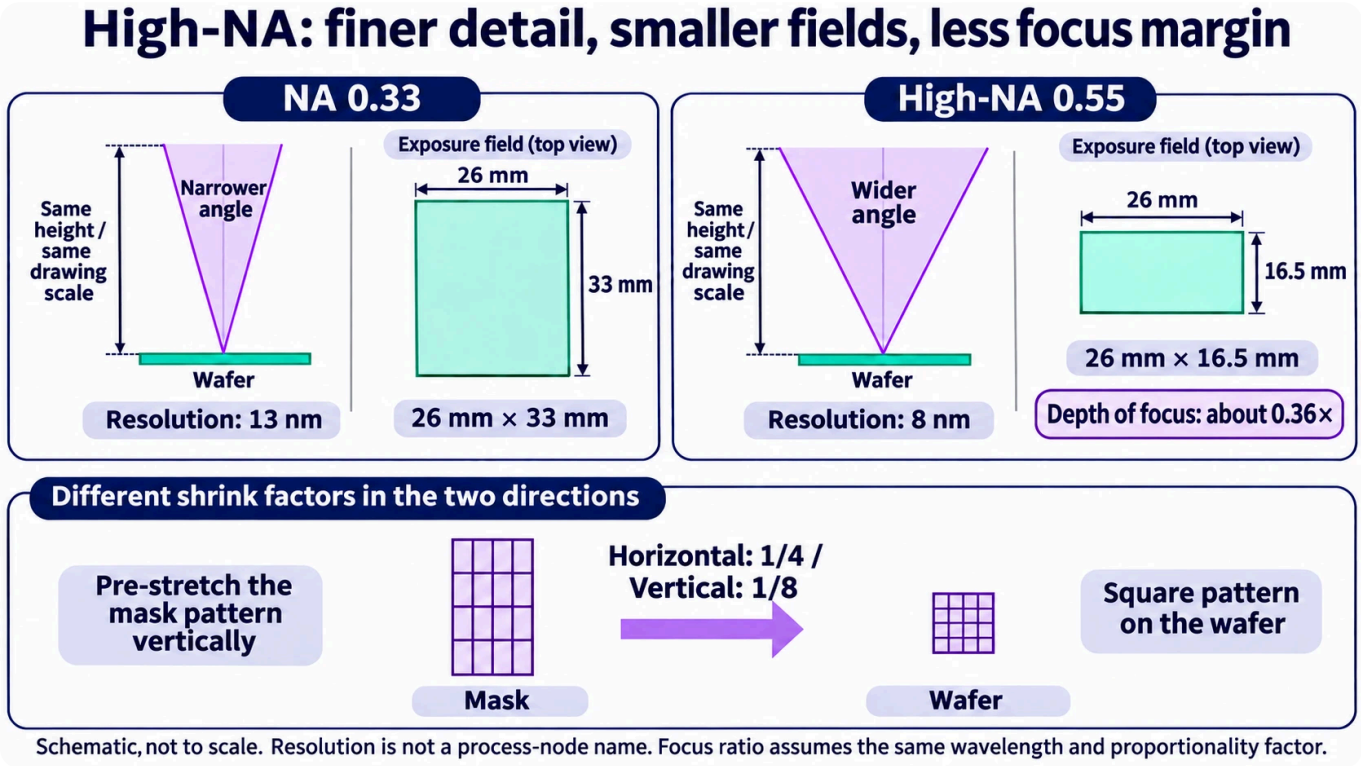


Figure 4 **High-NA trades a wider angular range for tighter field and focus constraints** (schematic)

Reading the figure

The top-view fields have the same width; the High-NA field has half the height. The cones are a conceptual angular comparison, not actual working distances. In the lower example, the mask pattern is stretched vertically to compensate for unequal reduction and produce square cells on the wafer. The mask and wafer symbols use different illustrative scales. The focus ratio assumes the same wavelength and coefficient [1][11][12].

7. Why fewer photons can mean more variation

Count photons, not just millijoules

Photon shot noise exists in ArF lithography too. EUV makes it more demanding because the same exposure energy contains fewer photons. imec links stochastic EUV printing failures to line breaks, bridges and missing or merged holes [20]. Reported

The physics: a photon-count example

Using E = hc/λ and NIST's constants [26], the photon energies are approximately **92 eV at 13.5 nm** and **6.4 eV at 193 nm**. An EUV photon therefore carries about fourteen times as much energy. Calculation

Take an incident dose of **30 mJ/cm²** and an area of **10 nm × 10 nm**. The energy delivered to that area is 3×10^{-14} J. Dividing by photon energy gives approximately: Calculation

- **2,000 EUV photons**.
- **29,000 ArF photons**.

For independent arrivals described by a Poisson model, mean count N has standard deviation √N. The relative standard deviation is 1/√N: about **2.2% for the EUV count** and **0.6% for the ArF count**. Calculation

These are incident counts. Only some photons are absorbed in the resist, and electron transport and chemical reactions add further variation. The calculated 2.2% is not a linewidth variation or a defect rate. It illustrates one statistical contribution to the complete process [1][20]. Explanation

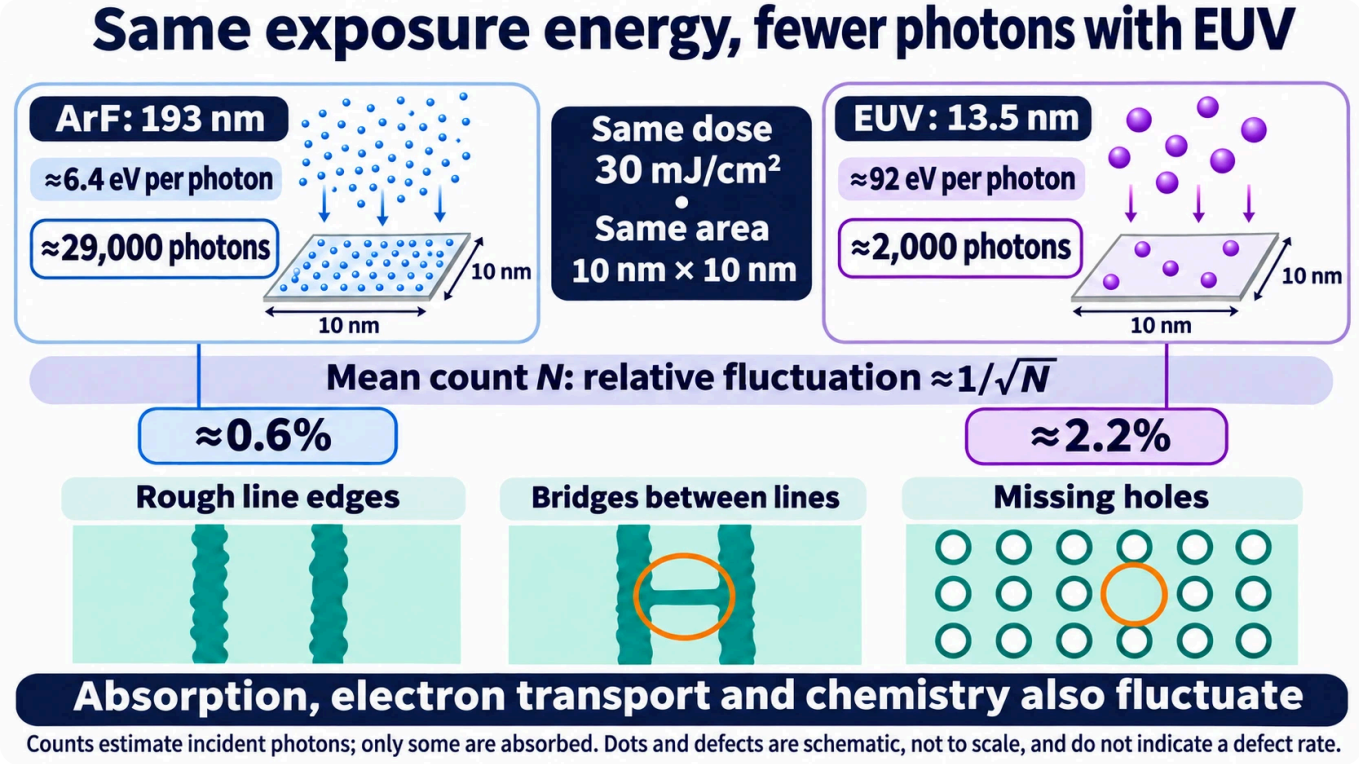


Figure 5 **Equal dose does not mean equal photon count** (schematic)

Reading the figure

The dots represent the difference in count, not the actual number of photons drawn to scale. The bottom examples show rough edges, a bridge and a missing hole. They are possible failure shapes, not measured defect frequencies at the stated dose. Both photon statistics and the material's response matter [1][20][26].

- **More dose costs time unless the source improves**

Increasing dose can reduce some stochastic failures, but at the same source power it takes longer to expose a wafer. The 2023 IRDS discussion describes rising dose requirements, including an expectation of about a threefold increase over four generations, and notes the difficulty of thin, weakly absorbing resists [1]. Reported

IRDS 2022 gives examples including 40 nm-pitch holes at **60 mJ/cm²** and 13 nm line-space features at **50 mJ/cm²** [2]. imec's 2018 work contrasts a 20 mJ/cm² productivity target with higher doses needed to suppress failures [20]. These are dated examples with different patterns and process conditions, not one universal EUV dose specification. Explanation

The practical trade-off is among resolution, defect performance, sensitivity and throughput. More source power, better absorption and more efficient resist chemistry can all help; none removes the need to control variation. Explanation

8. Resists and pellicles: materials become decisive

Absorbing more of the available light

The **2023 IRDS roadmap** expected chemically amplified resists to remain important at least to the 1 nm logic generation, while identifying metal-containing materials as promising alternatives. It discussed metal-oxide resist adoption around later nodes and the transition to NA 0.55 [1]. These are the roadmap's expectations at publication, not an observation that every manufacturer follows one timetable. Outlook

JSR announced its acquisition of US metal-oxide-resist developer **Inpria for US$514 million in 2021** [22]. Lam Research introduced a **dry resist** approach in 2020, forming the film from vapour rather than spin-coating a liquid. In January 2025 it announced adoption by a leading memory manufacturer for advanced DRAM and claimed chemical use five to ten times lower than conventional liquid processes [23]. Reported

These developments address several linked needs: useful absorption, thin-film uniformity, controlled reactions, pattern transfer and material consumption. A more strongly absorbing material alone is not a complete solution to every stochastic defect. Explanation

A protective membrane that the light crosses twice

A **pellicle** catches particles before they reach the mask. Separating the particles from the mask plane makes them less likely to print sharply, though it does not make every particle harmless [14]. Explanation

ASML's **2022 account** describes its then-leading membrane as only **13 nm thick**, able to withstand temperatures up to **500°C** in high vacuum. It also stresses that no material transmits all 13.5 nm light: a pellicle consumes part of the photon budget [14]. Reported

imec and Mitsui Chemicals announced a partnership in 2023 to commercialise **carbon-nanotube (CNT) pellicles**, reporting transmission of at least **94%** and the ability to withstand EUV power levels above **1 kW** [21]. The partnership combined research and industrial development; its announcement was not a claim that every scanner already used that membrane. Explanation

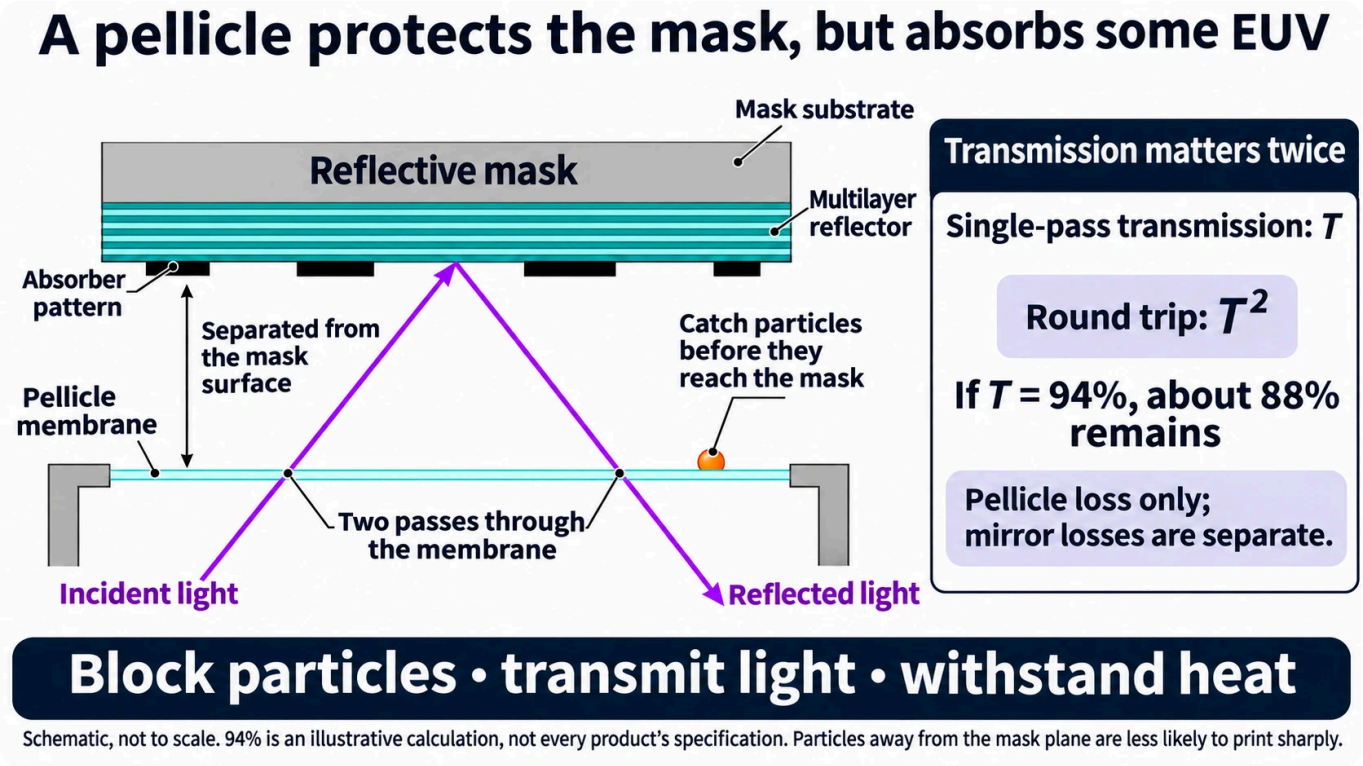


Figure 6 **Pellicle protection and the two-pass transmission penalty** (schematic)

Reading the figure

The beam passes through the membrane on its way to the mask and again after reflection. If each pass transmits a fraction T, the two-pass factor is T². For an illustrative T = 0.94, 0.94² = 0.8836: about 88% remains. Calculation This is the pellicle contribution only. Mirror and mask losses are separate; the drawing exaggerates film thickness and spacing [14][21].

9. Throughput and electrical energy

ASML's cited product information gives the following specifications [11]. Dose is included because a wafers-per-hour figure without its exposure conditions can be misleading.

System	NA	Resolution	Wafers/hour	Specified dose
NXE:3400B	0.33	13 nm	≥125	20 mJ/cm²
NXE:3400C	0.33	13 nm	≥170	20 mJ/cm²
NXE:3600D	0.33	13 nm	≥160	30 mJ/cm²
NXE:3800E	0.33	13 nm	≥220	30 mJ/cm²
EXE:5000	0.55	8 nm	≥110	50 mJ/cm²
EXE:5200B	0.55	8 nm	≥175	50 mJ/cm²

The figures span different generations and operating conditions. They are not a controlled head-to-head comparison. Explanation

ASML's **2025 annual report** gives **5.5 kWh per wafer exposure** for the NXE:3800E, down 57% from its 2018 reference of 12.8 kWh. Its power table puts NXE systems at approximately **1.2–1.4 MW**, against around **0.15–0.17 MW** for ArF immersion systems [27]. Reported The resulting power ratio is roughly seven to ten. Calculation

Power in MW and energy per exposed wafer in kWh are different measures. Neither is the energy needed to manufacture an entire chip through all its layers. A complete comparison also includes the process steps avoided or added. IRDS's 2022 discussion warns that EUV's shorter flow does not automatically produce an energy saving over multiple patterning [2]. Explanation



Large ASML transport containers in Tainan, Taiwan, in the Commons record. Complex lithography equipment is shipped as separated modules; the containers give a sense of the logistics involved rather than the size of an individual optical component.
Image: 4300streetcar / Wikimedia Commons / CC BY 4.0. Resized and converted to WebP.

10. Scanners, key components and chipmakers

ASML's system business

ASML states in its 2025 annual report that it is the world's only manufacturer of EUV lithography systems [27]. Its historical filings show the growth of reported EUV system sales [27][28]:

Year	Systems sold	System sales, € million	Revenue per system, calculated
2015	1	70.5	—
2017	11	1,101.5	About €100 million
2019	26	2,799.7	About €110 million
2021	42	6,284.0	About €150 million
2023	53	9,124.0	About €170 million
2025	44 NXE + 4 High-NA	10,445.8 + 1,156.9	About €240 million NXE; €290 million High-NA

Units and revenue follow the reports. The following year's report restated 2017 revenue to €1,084.2 million. The averages shown are simple revenue/unit calculations, not quoted machine prices; configuration, sales mix and revenue recognition affect comparisons. Explanation

ASML's 2025 report expected High-NA use in high-volume manufacturing from **2027** [27]. This is an attributed forecast, distinct from delivery of development tools or initial customer qualification. Outlook

The optics and laser are specialised businesses

ASML identifies **Carl Zeiss SMT** in Germany as its sole source for key optical components, under an exclusive arrangement. It acquired a **24.9% interest** in Carl Zeiss SMT's holding company in 2017 [27]. ZEISS reports delivering more than **300 EUV optical systems** for volume manufacturing [25]. Reported

TRUMPF, also based in Germany, provides the powerful CO2 laser technology. Its 2024/25 annual report gives EUV business sales of **€724 million**, compared with €943 million in the previous year [29]. ASML reports approximately 5,100 suppliers overall [27]. These company figures describe different scopes and should not be added as though they were shares of one market. Explanation

Adoption beyond the first logic processes

- **Samsung and TSMC:** the 2018 and 2019 production milestones discussed in Section 5 [18][19].
- **SK hynix:** announced volume production of EUV-based 1a DRAM in 2021 [40].
- **Intel:** announced assembly of the EXE:5000 at its Oregon R&D site in 2024, describing it as the first commercial High-NA system. The reported machine mass was 165 tonnes [42].
- **Micron:** announced in 2023 a plan to bring EUV-based memory volume manufacturing to Hiroshima, describing this as Japan's first such introduction by a semiconductor company [41].
- **Rapidus:** reported delivery of an NXE:3800E to Chitose in December 2024 and successful exposure and development on 1 April 2025 [43].

These statements concern different stages: a plan, equipment arrival, first patterning and volume production are not equivalent. The Japanese first-use wording in Micron's and Rapidus's announcements also concerns different scopes. Explanation

11. The materials and inspection ecosystem

Mask substrates and coatings

An **EUV mask blank** combines a very stable substrate with a low-defect reflective multilayer and absorber material before the circuit pattern is written. **AGC** says it began development in 2003 and volume production in 2017, and describes its integrated capability from glass to coating as unique among EUV mask-blank suppliers [30]. Its 2020 release set targets of more than ¥40 billion in EUV mask-blank sales and 50% share for 2025; those were targets, not evidence here that they were achieved. Explanation

HOYA describes a high mask-blank market position in its 2025 integrated report while noting the possibility of EUV customers moving towards multiple suppliers [31]. These are company descriptions with their own market definitions. Reported

Inspecting with the relevant wavelength

Some EUV mask defects cannot be assessed adequately using a different illumination wavelength. **Lasertec** describes its EUV mask-blank defect-inspection equipment as an industry standard and its advanced mask-inspection position as strong, without a numerical share in the cited company profile [32]. Reported

Inspection also needs EUV light. **Ushio** reported initial production acceptance of a tin-based EUV source for mask inspection in 2019 [33]. **Gigaphoton** also describes LPP-EUV sources for inspection applications [34]. An inspection source and a high-throughput scanner source serve different requirements. Explanation

Coating, developing and resist chemistry

Tokyo Electron estimates a **100% share of EUV coater/developers** in its cited report [35]. That is a specifically defined equipment category and a supplier estimate, not a share of all EUV equipment. Explanation

For **EUV photoresists**, Tokyo Ohka Kogyo reports **29.3% and a leading position in 2025**, citing Fuji Chimera Research Institute data [36]. **Fujifilm** announced sales of negative-tone EUV resist and developer in 2024 [38]. **JSR/Inpria** and **Lam Research** contribute the metal-oxide and dry-resist approaches discussed in Section 8 [22][23]. These examples cover different material platforms and do not form a ranking of interchangeable products.
Explanation

Pellicles and their commercialisation

Mitsui Chemicals says it began commercial EUV pellicle production under an ASML licence in 2021. Its cited 2026 update describes commissioning a CNT-pellicle production plant and customer evaluation [39]. Its partnership with Belgium's imec links membrane research to qualification and supply [21]. Reported

The ecosystem has substantial Japanese strengths in mask blanks, inspection, tracks, resists and pellicles, alongside the European system, optical and laser businesses and US materials/process contributions. Recognising these roles is more informative than treating a scanner's country of origin as the origin of every technology inside it.
Explanation

Function	Examples discussed here	Basis of the description
EUV scanners	ASML, Netherlands	Sole-manufacturer statement [27]
Projection and illumination optics	Carl Zeiss SMT, Germany	ASML sole-source statement; ZEISS deliveries [25][27]
Powerful CO2 lasers	TRUMPF, Germany	Company business reporting [29]
Mask blanks	AGC and HOYA, Japan	Company capability and market descriptions [30][31]
Mask inspection and its light sources	Lasertec, Ushio, Gigaphoton, Japan	Company equipment and source accounts [32][33][34]
Coating and developing	Tokyo Electron, Japan	Supplier's EUV-track share estimate [35]
Resist platforms	TOK, Fujifilm, JSR/Inpria, Lam Research	Material-specific reports; Japan/US development and supply [22][23][36][38]
Pellicles	Mitsui Chemicals, Japan; imec research, Belgium	Commercialisation and partnership accounts [21][39]

A Japanese Ministry of Economy, Trade and Industry presentation gives ASML **91% of worldwide lithography-equipment revenue**, using Global Net data [37]. That broader market figure is separate from EUV-only supply and from material or component shares. Explanation

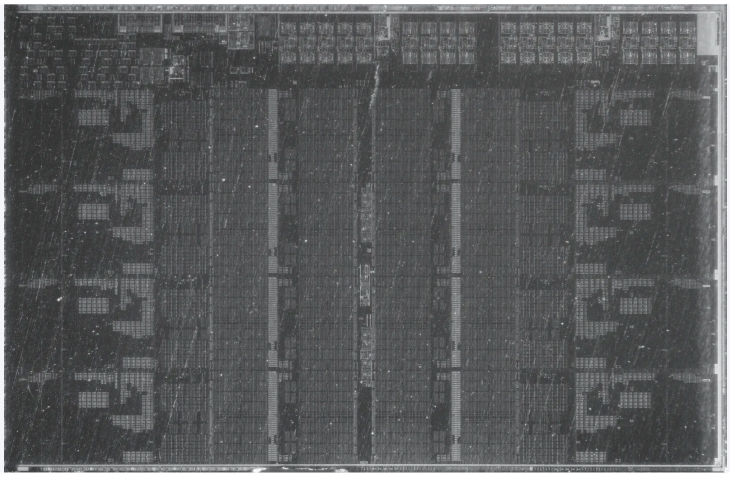
- **Export controls include supporting technologies**

ASML's June 2023 statement described EUV system sales as already restricted [45]. Japan's cited ministerial ordinance also lists specified EUV pellicles and production equipment, coater/developers, mask-blank inspection equipment and mask blanks among controlled items [44]. Reported

The rules apply to defined goods and technologies under their full terms; a component's name alone does not determine every shipment's treatment. Their breadth also shows why access to EUV capability involves an ecosystem of equipment and materials. Explanation



The Atmospheric Imaging Assembly on NASA's Solar Dynamics Observatory during pre-launch testing. EUV astronomy also uses multilayer reflective optics. Description follows the Commons record.
Image: NASA/Jack Pfaller / Wikimedia Commons / Public domain. Resized and converted to WebP.



The CPU die of an AMD Ryzen 5 7600, photographed in short-wave infrared. The Commons record gives dimensions of about 10.4 mm × 6.7 mm; its filename identifies the 5 nm process attribution. The photograph provides application context rather than a direct view of an EUV exposure step.
Image: FritzchensFritz / Wikimedia Commons / CC0. Resized and converted to WebP.

12. What still needs to improve

- **High-NA integration:** smaller fields, shallow focus depth and thin resists require coordinated changes in design, exposure and pattern transfer. Stitching and larger-mask approaches address different parts of the field-size problem [1].
- **Stochastic control:** stronger sources, better absorption and controlled reactions must improve defect performance without making exposure prohibitively slow [1][20].
- **Mask behaviour:** absorber materials and modelling must manage 3D effects at the required imaging conditions [1][6].
- **Energy efficiency:** ASML's 2025 report sets a target of **4.7 kWh per wafer exposure in 2027**, compared with the reported 5.5 kWh value [27]. Outlook

Where materials expertise makes a difference

EUV requires control across several material systems: multilayer interfaces, mask absorbers, resist chemistry, heat-resistant transmitting membranes, tin droplets and hydrogen-based cleaning. The examples connect nanometre-scale film formation to the performance of a factory-scale machine [3][4][14][21][30].

The development history links pioneering Japanese experiments, US laboratories and companies, European equipment and optics, and international materials research and chip production. No single part of that chain would have delivered a practical scanner on its own. Explanation

13. Recap and the next lesson

Topic	Key idea
Wavelength	13.5 nm matched useful tin emission with multilayer-mirror performance.
Vacuum and optics	Strong absorption rules out an ordinary air path and glass lenses; multilayer mirrors provide useful reflection.
Optical losses	Ten reflections at 67% leave about 2% relative to the starting point in that example, not 2% electrical efficiency.
Mask	A patterned reflector; oblique illumination and absorber thickness introduce 3D effects.
Source	Prepared tin droplets become plasma under laser pulses, about 50,000 times per second in the described system.
History	NTT reduction-imaging experiments, US laboratory/industry programmes, system development and production adoption over more than thirty years.
High-NA	NA 0.55 and 8 nm specified resolution, with half-sized fields and tighter focus margin.
Stochastics	Higher-energy photons mean fewer counts at equal dose; absorption, electrons and chemistry also vary.
Production ecosystem	Scanners, optics, lasers, masks, resists, tracks, inspection and pellicles all need to work together.

Next: Part 3-8, Etching and Plasma Physics. Lithography leaves a patterned resist mask. Etching uses it to remove selected parts of the layer beneath. Plasma, introduced in the PECVD discussion, now becomes a tool for removal rather than deposition.

14. Check your understanding

1. Why does EUV need a vacuum light path and mirrors rather than glass lenses?

▼ **Show answer**

Air and a lens-sized thickness of glass absorb too much 13.5 nm light. Vacuum reduces gas absorption and multilayer mirrors provide useful reflection. Very thin membranes can still transmit part of the light, so absorption does not mean zero transmission at every thickness.

2. How does a Mo/Si multilayer produce a stronger reflected beam?

▼ **Show answer**

Weak contributions from successive interfaces reinforce through interference. A normal-incidence geometric approximation gives $2d \approx \lambda$, but real design also accounts for material optical properties, angle, absorption and interface quality.

3. What remains after ten reflections with 67% reflectivity each?

▼ **Show answer**

0.67 to the tenth power is about 0.018, or 1.8%. For the source paper's example the starting point is the intermediate focus. This is not the electrical efficiency of the complete scanner.

4. Why use a weaker pulse before the main pulse hits the tin?

▼ **Show answer**

It reshapes the droplet into a better target. The stronger pulse then creates the hot plasma that emits EUV. The exposure light is emitted by the plasma, not the CO_2 laser itself.

5. How do photon energies compare at 13.5 nm and 193 nm?

▼ **Show answer**

$E = hc/\lambda$ gives about 92 eV for EUV and 6.4 eV for ArF. The EUV photon carries roughly fourteen times as much energy.

6. Why can equal-dose EUV exposure have larger relative photon-count variation?

▼ **Show answer**

The higher energy per photon means fewer photons for the same incident energy. For independent arrivals, relative standard deviation is $1/\sqrt{N}$. This is one contribution to pattern variation, alongside absorption, electron transport and chemistry; it is not directly a defect percentage.

7. What is the cost of increasing exposure dose at fixed source power?

▼ **Show answer**

It generally takes longer to expose each wafer, reducing throughput. More dose may reduce stochastic failures, but the useful balance depends on the resist, pattern and operating conditions.

8. Why does High-NA use unequal reduction factors, and what is the field-size consequence?

▼ **Show answer**

The anamorphic optics reduce the mask-angle problem while retaining the established reticle format. Reduction is fourfold in one direction and eightfold in the other, giving a 26 mm × 16.5 mm field, half the conventional area.

9. Which early imaging milestones are associated with Hiroo Kinoshita at NTT?

▼ **Show answer**

His account records line-space patterning in 1985 and presentation at the Japan Society of Applied Physics in autumn 1986. Those research milestones preceded the international development and industrialisation programme by many years.

10. Name three capabilities, beyond assembling the scanner, that EUV production needs.

▼ **Show answer**

Examples include ZEISS optics, TRUMPF laser technology, low-defect mask blanks from AGC/HOYA, mask inspection from Lasertec, Tokyo Electron tracks, resist platforms from several suppliers, and pellicles from Mitsui Chemicals. The lesson's cited claims concern specific products, dates and market categories.

15. Glossary

EUV
Extreme ultraviolet. Semiconductor exposure systems use a wavelength of 13.5 nm.

Multilayer mirror
Alternating thin films engineered so that reflected contributions reinforce at the required wavelength and angles.

Bragg condition
A condition for reinforcing reflections from a periodic structure. $2d \approx \lambda$ is a simplified normal-incidence form, not a full EUV mirror design equation.

Reflective mask
A patterned absorber above a multilayer reflector, used to form an image from reflected light.

Mask blank
The unpatterned substrate, reflective multilayer and associated coating stack from which a photomask is made.

Mask 3D effects
Imaging effects caused by finite absorber thickness, oblique illumination and the mask's multilayer optical response.

LPP source
Laser-produced plasma source. A laser heats prepared tin droplets to generate EUV-emitting plasma.

Conversion efficiency
The fraction of input energy converted into a defined output. Laser-to-EUV efficiency differs from whole-system electrical efficiency.

Intermediate focus
The source output location where collected EUV is delivered towards the illumination system; a reference point for useful source power.

Collector
A multilayer-coated mirror that gathers part of the radiation emitted by the plasma.

Debris
Ions and material fragments emitted from the source, potentially contaminating or damaging components.

High-NA
The EUV platform with NA 0.55, compared with conventional NA 0.33.

Anamorphic optics
Imaging with different reduction factors in the two directions; fourfold and eightfold in the described High-NA system.

Stitching
Joining exposed fields to form a pattern larger than a single field.

Photon shot noise
Random variation in photon counts. For a Poisson model with mean N, standard deviation is $\sqrt{N}$ and relative standard deviation is $1/\sqrt{N}$.

Stochastic defects
Random printing failures arising from photon, material and reaction variations, including bridges, breaks and missing features.

Metal-oxide resist
A resist platform containing metal-oxide species, investigated for strong EUV absorption and suitable patterning performance.

Dry resist
A resist film deposited from vapour rather than applied by conventional liquid spin coating.

EUV pellicle
A thin protective membrane spaced from the mask; light crosses it before and after mask reflection.

CNT pellicle
A pellicle membrane based on carbon nanotubes, developed for high transmission and resistance to demanding exposure conditions.

16. Sources and further reading

The reference numbers match the Japanese edition. English descriptions identify the documents even where the original is in Japanese or German. Corporate archive links retain the named publication and date; they are not substitutes for a claim about a different product or period.

1. **IRDS** — 2023 Update: Lithography (PDF pp. 5–10) — Read source
2. **IRDS** — 2022 Edition: Lithography (PDF pp. 9, 12) — Read source
3. **C. Montcalm, S. Bajt et al. (Lawrence Livermore National Laboratory)** — Multilayer reflective coatings for extreme-ultraviolet lithography, UCRL-JC-128289 (1998; pp. 3–4) — Read source
4. **I. Fomenkov et al. (ASML / Cymer)** — Light sources for high-volume manufacturing EUV lithography: technology, performance, and power scaling, Advanced Optical Technologies 6(3–4), 173–186 (2017; PDF pp. 2–4, 8, 10) — Read source
5. **H. Mizoguchi et al. (Gigaphoton)** — Performance of 100-W HVM LPP-EUV source, Advanced Optical Technologies 4(4), 297–309 (2015; pp. 1–2) — Read source
6. **A. Erdmann et al. (Fraunhofer IISB / imec)** — Characterization and mitigation of 3D mask effects in extreme ultraviolet lithography, Advanced Optical Technologies 6, 187–201 (2017; pp. 1, 3) — Read source
7. **Hiroo Kinoshita** — Editorial on processing and metrology in the nano-to-pico era, Kogaku 34(3) (Japanese; author's retrospective) — Read source
8. **Tsuneyuki Haga (NTT-AT)** — The Early Days of R&D on EUV Lithography and Future Expectations, Journal of Photopolymer Science and Technology 31(2), 193 (2018; pp. 3–4) — Read source
9. **ASML** — Making EUV: from lab to fab (30 March 2022) — Read source
10. **ASML** — EUV lithography systems — Read source
11. **ASML** — Product specifications: TWINSCAN NXE:3400B, 3400C, 3600D, 3800E, EXE:5000 and 5200B (individual links below) — Read source
12. **ASML** — 5 things you should know about High NA EUV lithography (25 January 2024) — Read source
13. **ASML** — Leibinger award recognizes EUV innovations (22 October 2021) — Read source
14. **ASML** — Indistinguishable from magic: the EUV pellicle (14 September 2022) — Read source
15. **ASML** — Lithography principles: Light and lasers — Read source
16. **ASML** — Lithography principles: Lenses and mirrors — Read source
17. **Lawrence Berkeley National Laboratory** — Superchips Partnership Teams Intel and Three National Labs (19 September 1997) — Read source
18. **Samsung** — Samsung Electronics Starts Production of EUV-based 7nm LPP Process (18 October 2018) — Read source
19. **TSMC** — TSMC's N7+ Technology is First EUV Process Delivering Customer Products to Market in High Volume (7 October 2019) — Read source
20. **imec** — Imec pushes the limits of EUV lithography single exposure for future logic and memory applications (imec Magazine, March 2018) — Read source
21. **imec** — Imec and Mitsui Chemicals sign strategic partnership agreement to commercialize CNT pellicle technology for EUV lithography (14 December 2023) — Read source
22. **JSR** — JSR Agrees to Acquire EUV Pioneer Inpria Corporation (September 2021) — Read source
23. **Lam Research** — Breakthrough EUV Dry Photoresist Technology from Lam Research Adopted by Leading Memory Manufacturer (29 January 2025) — Read source
24. **ZEISS SMT** — High-NA-EUV lithography (30 January 2024) — Read source
25. **ZEISS SMT** — EUV lithography — Read source
26. **NIST** — CODATA Recommended Values of the Fundamental Physical Constants (h, c and e) — Read source
27. **ASML** — Annual Report 2025 (printed pp. 16–17, 20, 41, 68, 168–169, 174, 176, 286) — Read source

28. **ASML** — Forms 20-F for 2017–2024: net system sales per technology (SEC filings) — Read source
29. **TRUMPF** — Annual Report 2024/25, Geschäftsbericht (PDF pp. 2, 40–41; German; corporate report portal) — Read source
30. **AGC** — Expansion of production capacity for EUV lithography photomask blanks (27 July 2020; Japanese release, corporate news archive) — Read source
31. **HOYA** — Integrated Report 2025 (PDF pp. 4, 87–88; Japanese) — Read source
32. **Lasertec** — Corporate profile (March 2026; pp. 4, 6; corporate publications portal) — Read source
33. **Ushio** — First production acceptance of an EUV light source for mask inspection (17 July 2019; Japanese) — Read source
34. **Gigaphoton** — LPP-EUV source for inspection applications (28 August 2026) — Read source
35. **Tokyo Electron** — Integrated Report 2026 (pp. 15, 48; Japanese) — Read source
36. **Tokyo Ohka Kogyo** — Integrated Report 2026 (PDF p. 12; Japanese) — Read source
37. **Japan, Ministry of Economy, Trade and Industry** — Future direction of semiconductor and digital industry strategy (23 December 2025; p. 5; Japanese) — Read source
38. **Fujifilm** — Sales launch of negative-tone EUV resist and developer (29 October 2024; Japanese) — Read source
39. **Mitsui Chemicals** — CNT pellicle production equipment announcement (28 May 2024); FY2026 first-quarter results Q&A (14 August 2026; additional publication identified in the text) — Read source
40. **SK hynix** — SK hynix Starts Mass Production of 1anm DRAM Using EUV Equipment (12 July 2021) — Read source
41. **Micron** — Micron to Bring EUV Technology to Japan, Advancing Next-Generation Memory Manufacturing (17 May 2023) — Read source
42. **Intel** — Intel Foundry Achieves Major Milestone with High NA EUV (18 April 2024) — Read source
43. **Rapidus** — EUV equipment installation announcement (18 December 2024); Rapidus achieves significant milestone with prototyping of 2nm GAA transistors (18 July 2025) — Read source
44. **Japan, e-Gov Laws** — Ministerial ordinance specifying goods and technology under the Export Trade Control Order and Foreign Exchange Order, Article 6(17) and related provisions, as cited on 7 November 2026 (Japanese) — Read source
45. **ASML** — Statement regarding Dutch government's export control regulations announcement (30 June 2023) — Read source

Individual product pages supporting reference 11: NXE:3400B, NXE:3400C, NXE:3600D, NXE:3800E, EXE:5000 and EXE:5200B.

17. Claims and evidence

Claim or group of claims	Supporting source	Treatment
Wavelength selection, source-power milestones, thin High-NA resists, field size, stitching, stochastics, dose trends and resist outlook	IRDS 2023 [1]	Dated roadmap analysis; forecasts distinguished
Pattern/dose examples and energy comparison with multiple patterning	IRDS 2022 [2]	Dated examples and analysis
Mo/Si 40 pairs, 6.89 nm period, constituent thicknesses and 67.5% reflectivity	LLNL [3]	1998 research example
Tin spectrum, laser wavelength, laser-to-EUV conversion, intermediate-focus power, optical loss and collector cleaning	Fomenkov et al. [4]	Source-development paper
Magnetic debris control and 140 W burst output	Gigaphoton researchers [5]	Research result under stated conditions
Oblique illumination, absorber thickness, multilayer penetration and mask 3D effects	Erdmann et al. [6]	Mask-imaging research
Early NTT experiments, 1985 result, 1986 presentation and 1993 meeting	Kinoshita [7]	Author's retrospective
Start of NTT programme and first pattern-transfer report	Haga [8]	Historical research account
Early wavelength exploration, source milestones and early commercial product context	ASML [9]	Supplier historical account
Reflective reticle, reduction optics, demonstration shipments, NXE:3300 and development investment	ASML [10]	Supplier system/history account
System NA, resolution, throughput and associated dose	ASML products [11]	Product specifications; conditions retained
High-NA scaling comparison, anamorphic reduction and stage acceleration	ASML [12]	Supplier explanation
Early source output and the 80 W barrier	ASML [13]	Historical account
Pellicle role, 13 nm membrane and 500°C capability	ASML [14]	2022 description of then-leading membrane
Tin droplet size, speed, two-pulse preparation and 50 kHz repetition	ASML [15]	Source principle
Mirror-based vacuum optics and more than 100 material layers	ASML [16]	General optics explanation
EUV LLC and US national laboratories, 1997 agreement and US$250 million programme	LBNL [17]	Contemporary institutional announcement
2018 7LPP production, up to four ArF masks replaced by one, mask-count reduction	Samsung [18]	Process-specific company announcement
N7+ commercial EUV production	TSMC [19]	Company announcement and first-use wording
Stochastic failures and the dose/productivity problem	imec [20]	2018 research discussion
CNT pellicle partnership, ≥94% transmission and >1 kW capability	imec / Mitsui Chemicals [21]	2023 development announcement
Inpria acquisition and US$514 million value	JSR [22]	2021 acquisition announcement
Dry resist, DRAM adoption and chemical-use comparison	Lam Research [23]	Supplier announcement and estimates
High-NA optics: more than 40,000 parts and approximately 12 tonnes	ZEISS [24]	Supplier description
Surface-quality analogy, conventional optics assembly and >300 optical systems	ZEISS [25]	Supplier description and deliveries
Photon-energy calculation inputs	NIST [26]	Physical constants

Claim or group of claims	Supporting source	Treatment
ASML market-position statement, 2025 sales, supplier relationships, energy metrics and High-NA/energy targets	ASML Annual Report 2025 [27]	Company figures; outlook separated from results
Historical EUV system units and revenue	ASML Forms 20-F [28]	Year-specific filings; restatement noted
TRUMPF EUV business revenue	TRUMPF [29]	Fiscal-year business figures
AGC capability, development milestones and 2025 targets	AGC [30]	Company description; historical targets not treated as results
Mask-blank position and possible customer multisourcing	HOYA [31]	Company market assessment
EUV mask-blank and mask inspection	Lasertec [32]	Company description; no numeric share inferred
Production acceptance of inspection EUV source	Ushio [33]	2019 announcement
Inspection-source applications	Gigaphoton [34]	Company announcement
EUV coater/developer share	Tokyo Electron [35]	Supplier estimate for the specified category
EUV resist share of 29.3% in 2025	TOK [36]	Company report citing Fuji Chimera data
ASML 91% of broader lithography-equipment revenue	METI / Global Net [37]	Defined market figure, separate from EUV-only supply
Negative-tone EUV resist and developer launch	Fujifilm [38]	2024 announcement
Pellicle commercial production and CNT equipment/customer-evaluation update	Mitsui Chemicals [39]	Company milestones with dates
1a DRAM volume production using EUV	SK hynix [40]	2021 announcement
Planned introduction of EUV memory production in Hiroshima	Micron [41]	2023 plan; first-use scope retained
EXE:5000 assembly and reported machine mass	Intel [42]	2024 development-tool announcement
Chitose equipment delivery and first exposure/development	Rapidus [43]	Company milestones, distinct from volume production
Specified EUV-related controlled goods and technologies	e-Gov [44]	Cited ordinance under its full terms
EUV system restrictions already in place in 2023	ASML [45]	Dated regulatory statement
Wavelength ratio, implied k1, approximate period, reflection powers, pulse energy, elapsed years, focus ratio, photon counts and Poisson variation, average revenue/unit, power ratio and T^2	Stated inputs and equations in the text	This article's calculations
Atomic-scale thickness comparison and connections between optical, materials and production constraints	Source dimensions and explanatory reasoning	Approximate interpretation, not a new measurement

Updated 7 November 2026. Technical sources include research papers, national laboratories, IRDS roadmaps, imec and supplier publications. Historical milestones and business figures retain their source dates; first-use and market-position claims are attributed. Forecasts are distinguished from achieved results. The six Image Gen diagrams are educational schematics, not equipment drawings or scaled optical designs. Photographs retain the credits and licences in their captions.

© 2026 Troy Technical. Original text and illustrations: all rights reserved, subject to applicable legal exceptions. The credited photographs retain their stated licences. Links to this article are welcome.