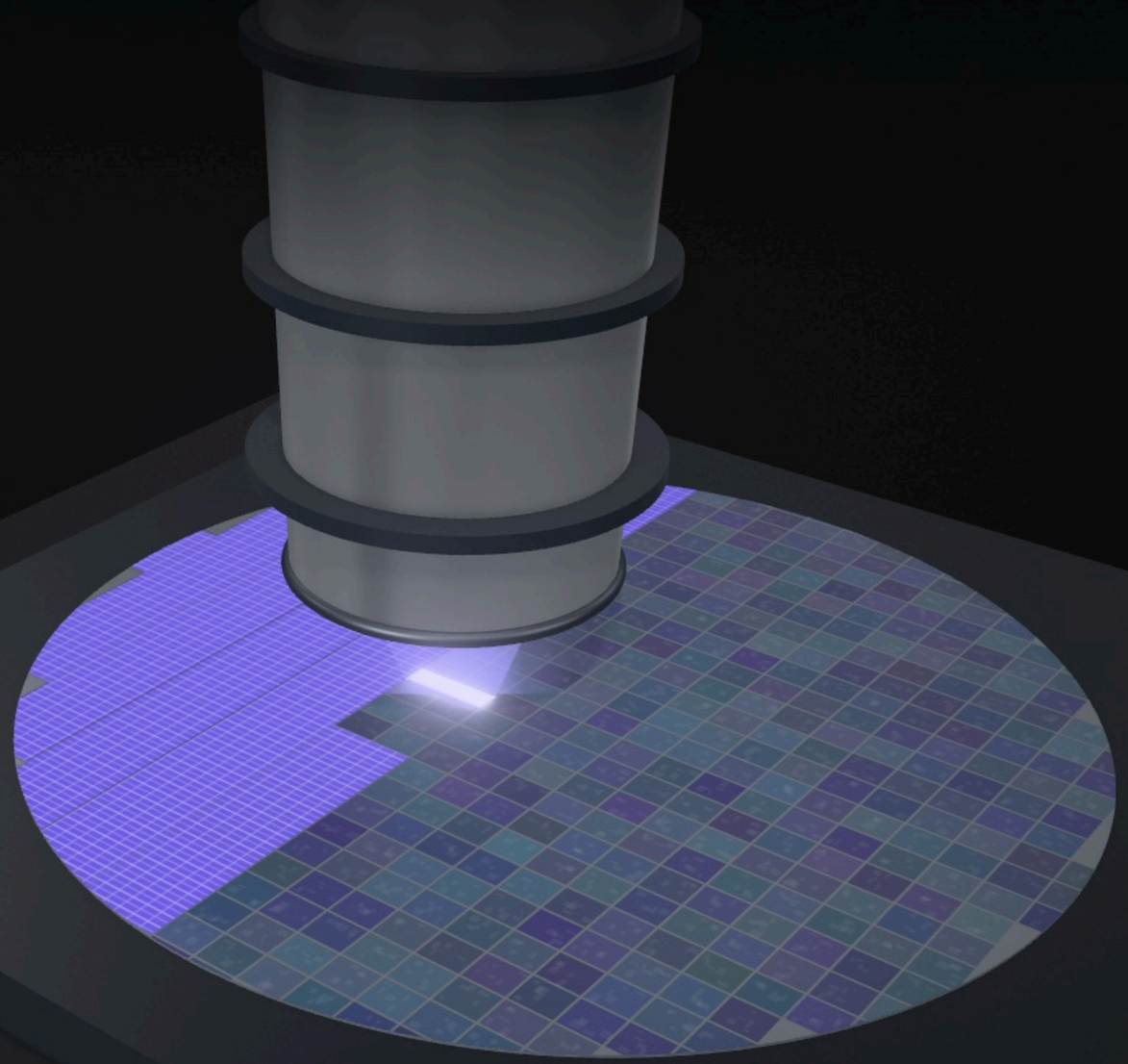
Writing with light

Lithos is Greek for stone. Today the stone is a 300 mm disc of silicon, and the finest pen is light with a wavelength of 13.5 nm: a virus is almost seven of those waves across.

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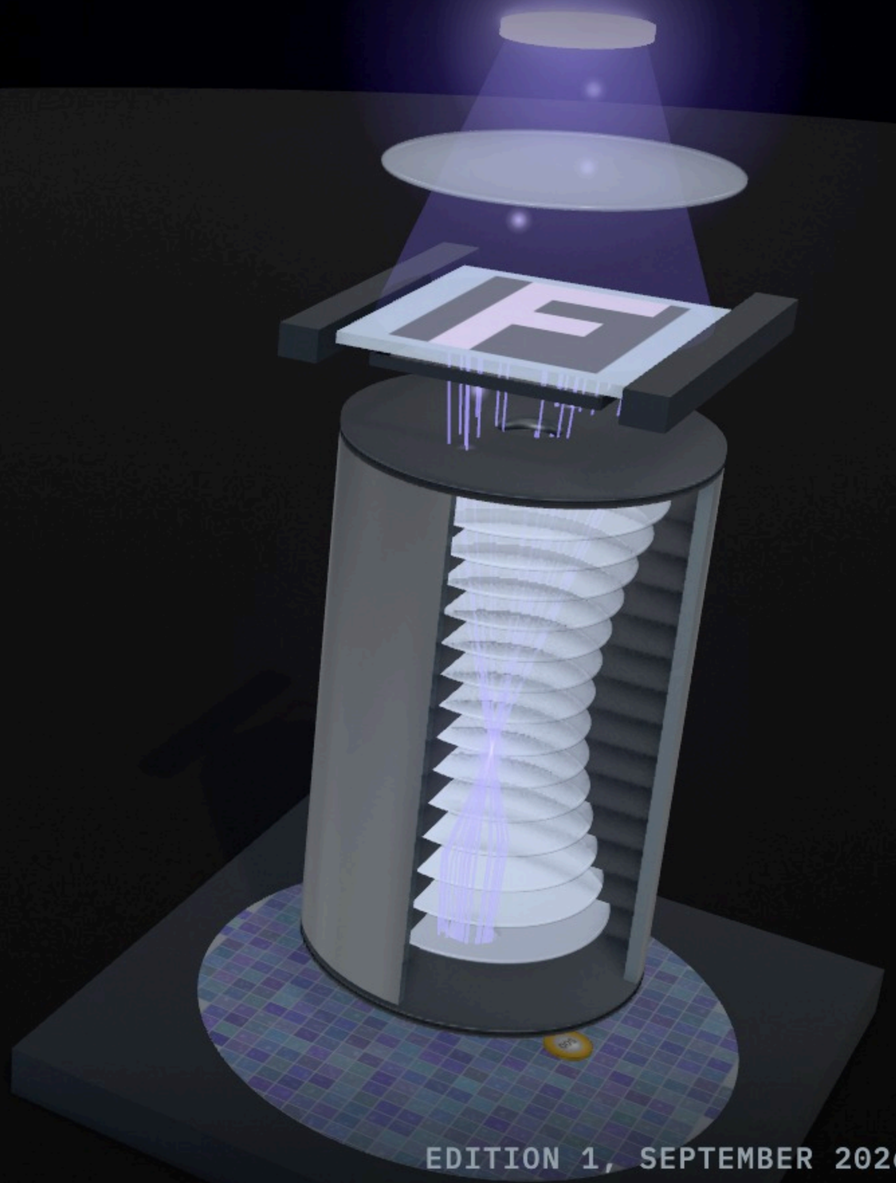
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01 · THE PRINCIPLE

A projector running backwards.

A cinema projector throws a small film frame large onto a screen. A lithography scanner does the opposite. It takes a mask, the reticle, and throws its image 4× smaller onto the wafer, through a projection lens of many elements.

Reduction: Berkeley Lab (Naulleau, 2012), and Nikon, which gives a quarter or a fifth. Reticle size: Canon; 6 × 25.4 mm is our arithmetic. Quartz and film: Shin-Etsu. Pellicle: Shin-Etsu and imec. Field: Nikon and Canon. Coins: the European Central Bank (€2, 25.75 mm) and the Japan Mint (500 yen, 26.5 mm). Lens elements: Canon and Nikon say many and give no count. The column is cut open and generic; the reticle, the wafer and the coins are drawn to one scale, the lens is not.



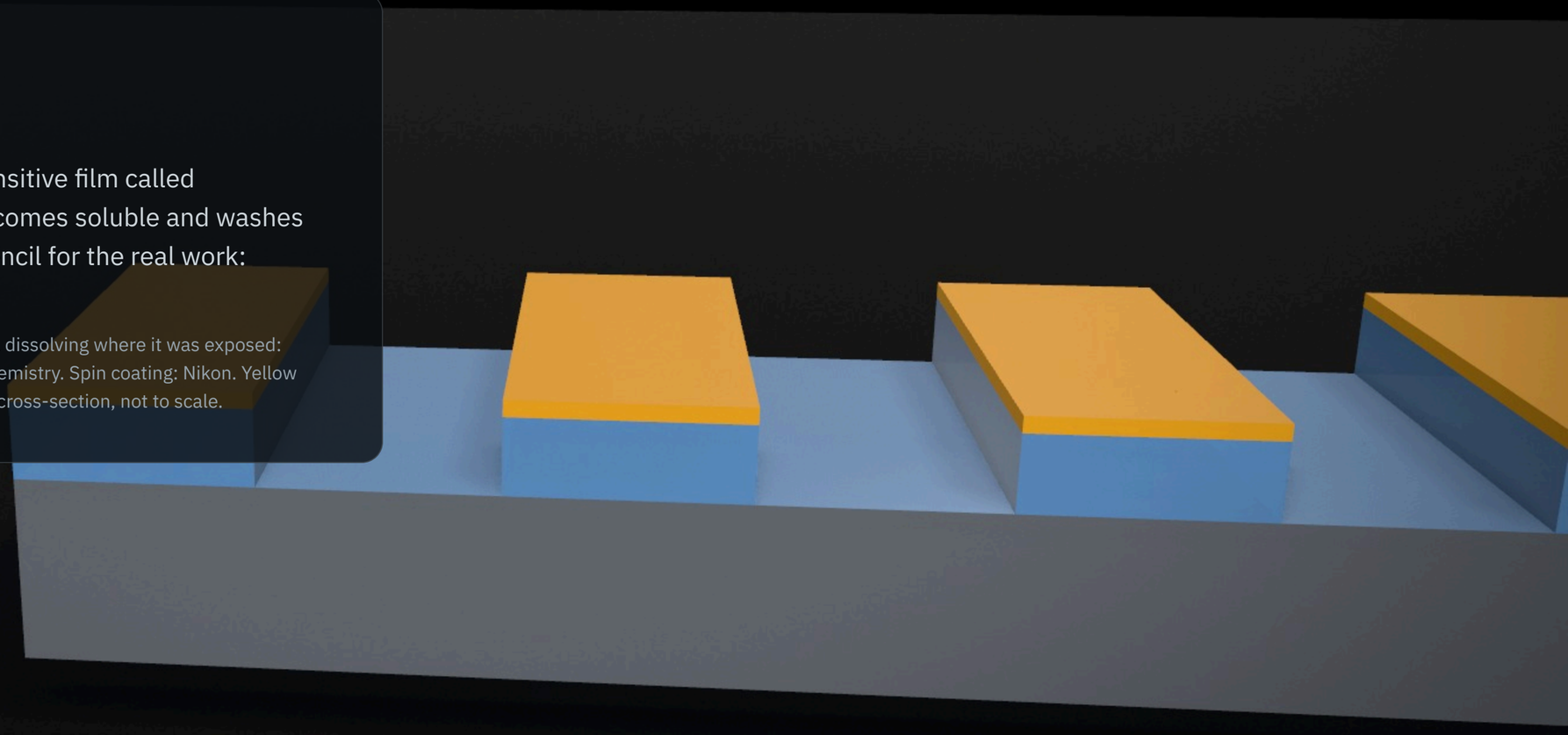
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02 · WHAT THE LIGHT ACTUALLY DOES

The print is a stencil.

Light deposits nothing. It changes a thin light-sensitive film called photoresist. Where light lands, positive resist becomes soluble and washes away in the developer. What stays behind is a stencil for the real work: etching, implanting, depositing metal.

The sequence and the stencil: Chris Mack and Nikon. Positive resist dissolving where it was exposed: Mack, for the classic i-line resist; DUV and EUV resists use other chemistry. Spin coating: Nikon. Yellow light: Kyungpook and Jeonbuk National Universities (May 2025). A cross-section, not to scale.



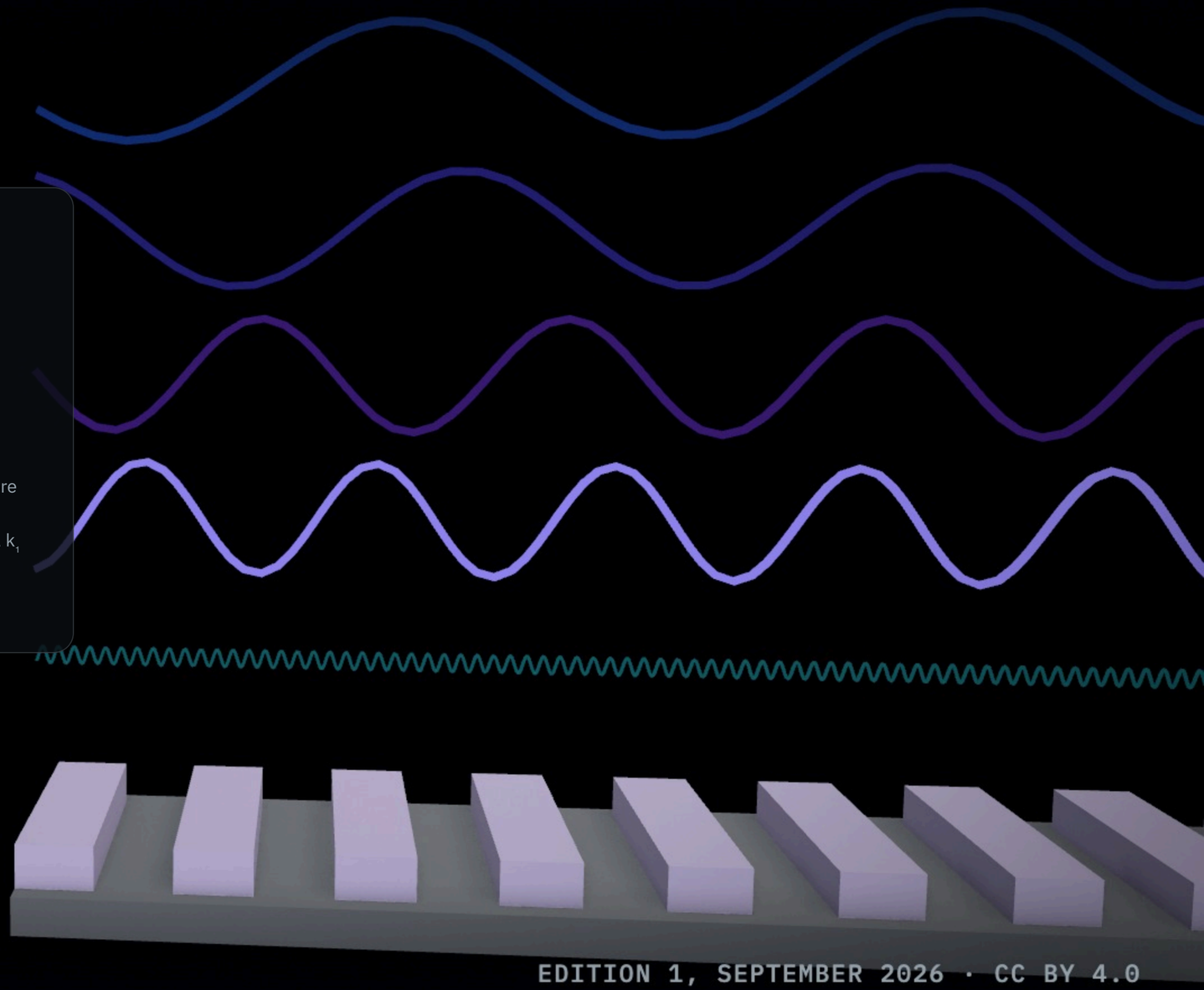
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03 · WAVELENGTH

Shorter waves draw finer lines.

You cannot draw a line thinner than your pen. For light, the pen is its wavelength. The industry has walked down the spectrum: mercury-lamp lines, then excimer lasers, then EUV.

Wavelengths and NA: Nikon and Canon for their own tools, Chris Mack for early tools, Lawrence Livermore and imec for EUV. Years: Nikon's corporate history and Kato's chronology, for Nikon's machines; 2019: Georgetown's Center for Security and Emerging Technology. High-NA: imec. Half-pitch is our arithmetic, k_1 × wavelength ÷ NA at k_1 = 0.3; Nikon gave 0.26 to 0.30 for its scanners in 2005. Fourteen: 193 ÷ 13.5, ours.



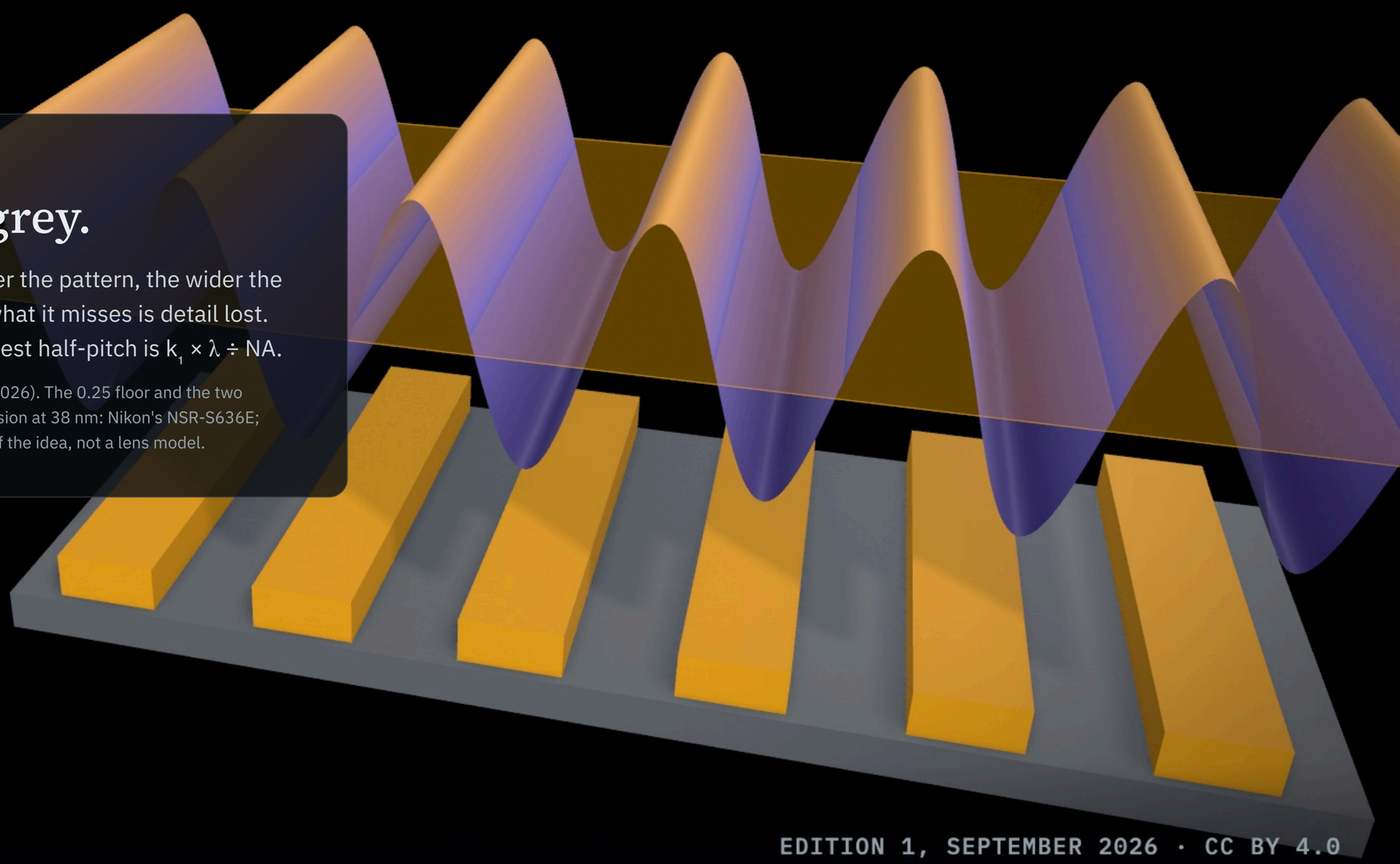
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04 · DIFFRACTION

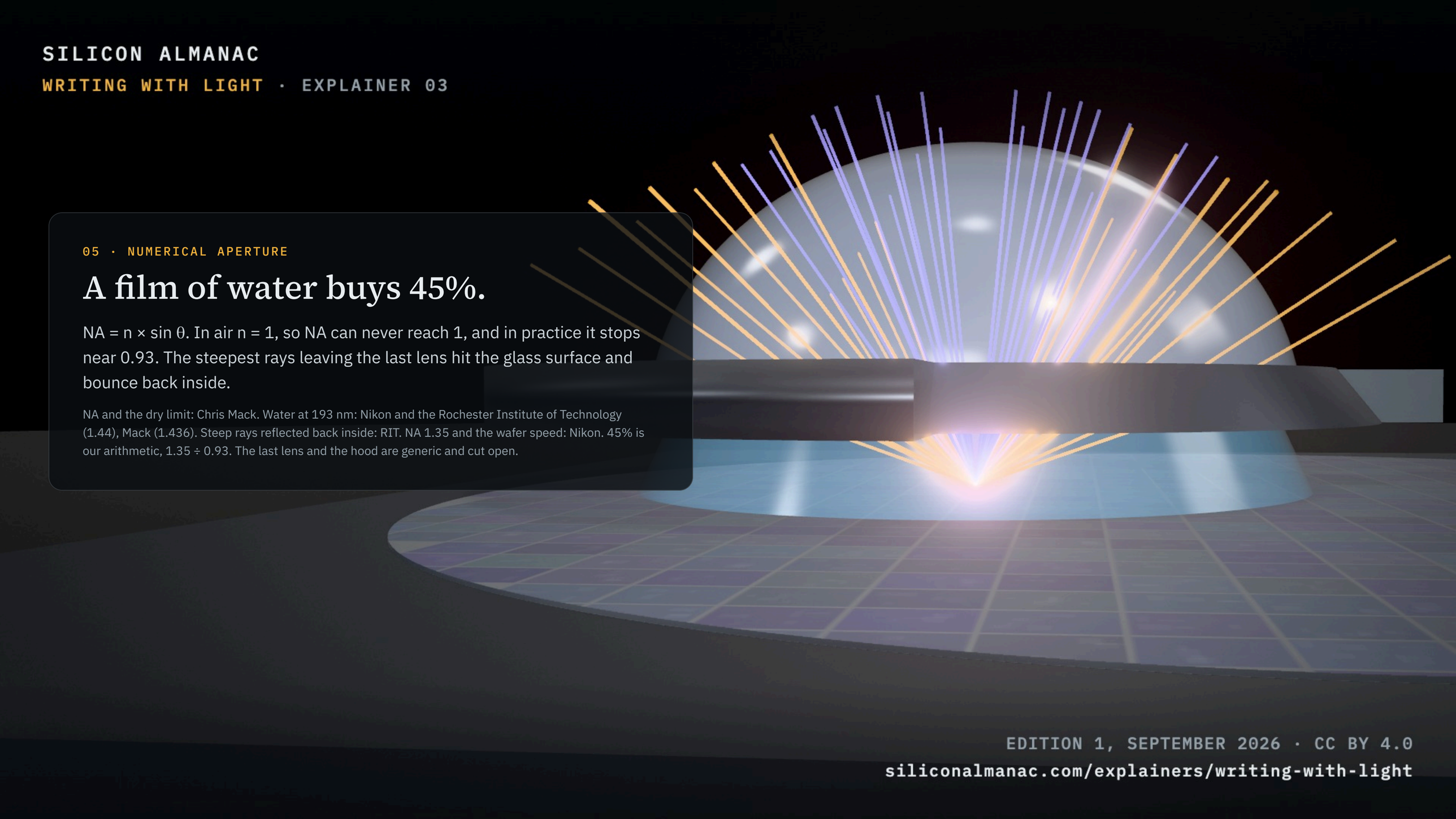
Where lines blur into grey.

Light passing a fine pattern spreads out. The finer the pattern, the wider the spread. The lens catches only a cone of it, and what it misses is detail lost. imec calls the rule the Rayleigh equation: the finest half-pitch is $k_1 \times \lambda \div NA$.

The equation: Nikon (Umatate and Matsuyama, 2005) and imec (2026). The 0.25 floor and the two beams: Chris Mack, in his lectures and a 2003 column. ArF immersion at 38 nm: Nikon's NSR-S636E; High-NA at 8 nm: the resolution imec says it promises. A picture of the idea, not a lens model.



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05 · NUMERICAL APERTURE

A film of water buys 45%.

NA = n × sin θ. In air n = 1, so NA can never reach 1, and in practice it stops near 0.93. The steepest rays leaving the last lens hit the glass surface and bounce back inside.

NA and the dry limit: Chris Mack. Water at 193 nm: Nikon and the Rochester Institute of Technology (1.44), Mack (1.436). Steep rays reflected back inside: RIT. NA 1.35 and the wafer speed: Nikon. 45% is our arithmetic, 1.35 ÷ 0.93. The last lens and the hood are generic and cut open.

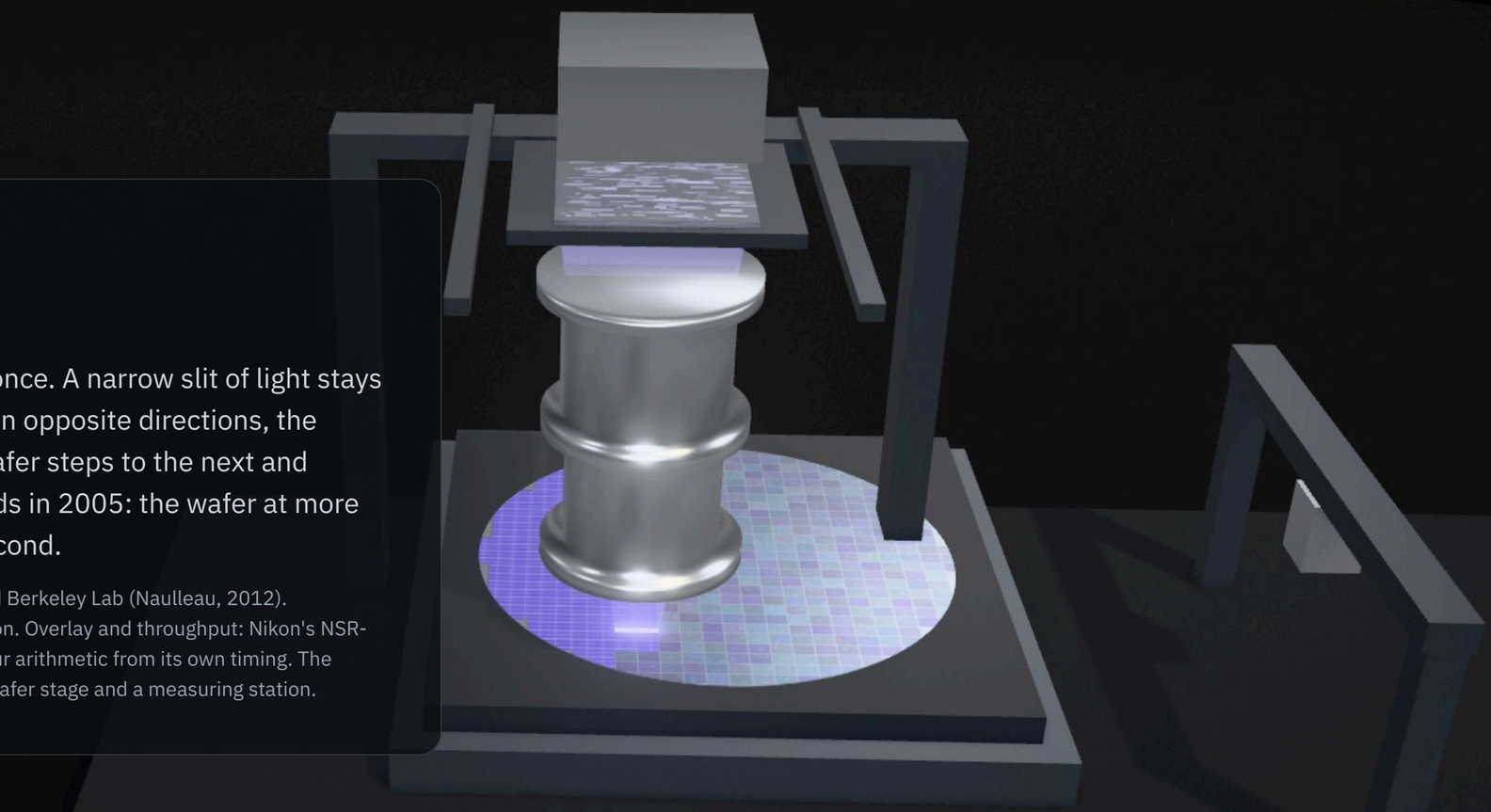
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06 · THE SCANNER

Step, scan, repeat.

The scanner does not flash the whole field at once. A narrow slit of light stays still. The reticle and the wafer slide through it in opposite directions, the reticle four times faster. One field done, the wafer steps to the next and scans back the other way. Nikon gave its speeds in 2005: the wafer at more than 500 mm a second, the reticle at 2 m a second.

Motion and speeds: Nikon (Umatate and Matsuyama, 2005) and Berkeley Lab (Naulleau, 2012). Measuring before exposure: Nikon. The parts of a scanner: Canon. Overlay and throughput: Nikon's NSR-S636E (December 2023) and NSR-S333F. The scene's rate is our arithmetic from its own timing. The machine is generic and shown without its enclosure, with one wafer stage and a measuring station.



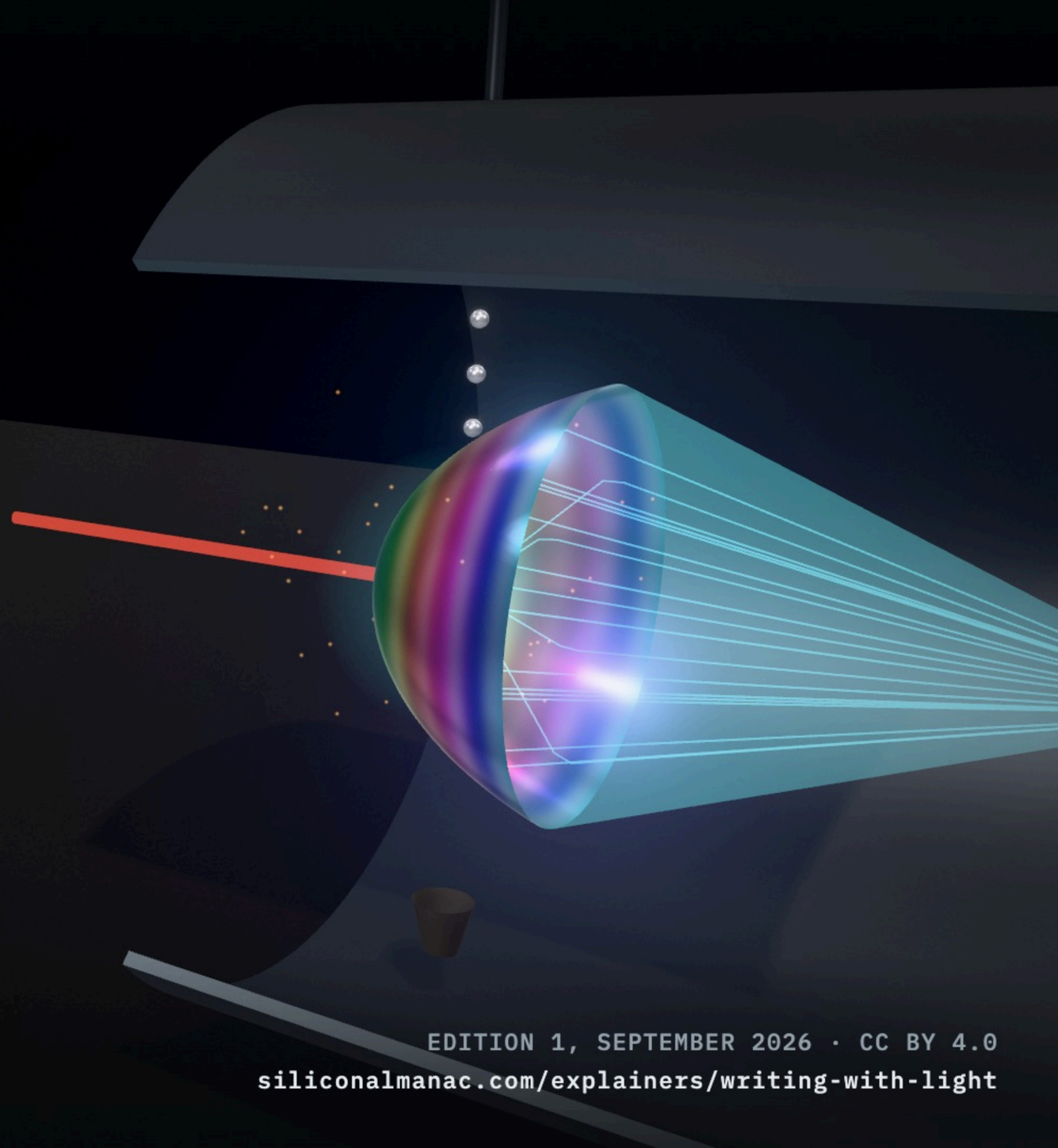
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07 · EXTREME ULTRAVIOLET

Making light that air swallows.

At 13.5 nm no lamp or ordinary laser will do, and air, glass and water all absorb it. So the machine makes its own light, in a vacuum, from tin.

Droplets, rate, pulses, collector and hydrogen: the University of Michigan with Samsung and Lam Research (December 2025); Lawrence Livermore gives about 30 µm (December 2024). Pre-pulse, then main pulse: Pacific Northwest National Laboratory and UC San Diego (2026). No lens and a vacuum: Lawrence Livermore and Berkeley Lab. Temperature: electron temperatures of 28.8 to 38.2 eV in simulations from Lanzhou and Dublin (2017), and 31 and 35 eV in calculations from Osaka and others (2026), turned into °C with NIST's CODATA value, our arithmetic; Lawrence Livermore rounds it to half a million degrees. The vessel is generic and cut open.



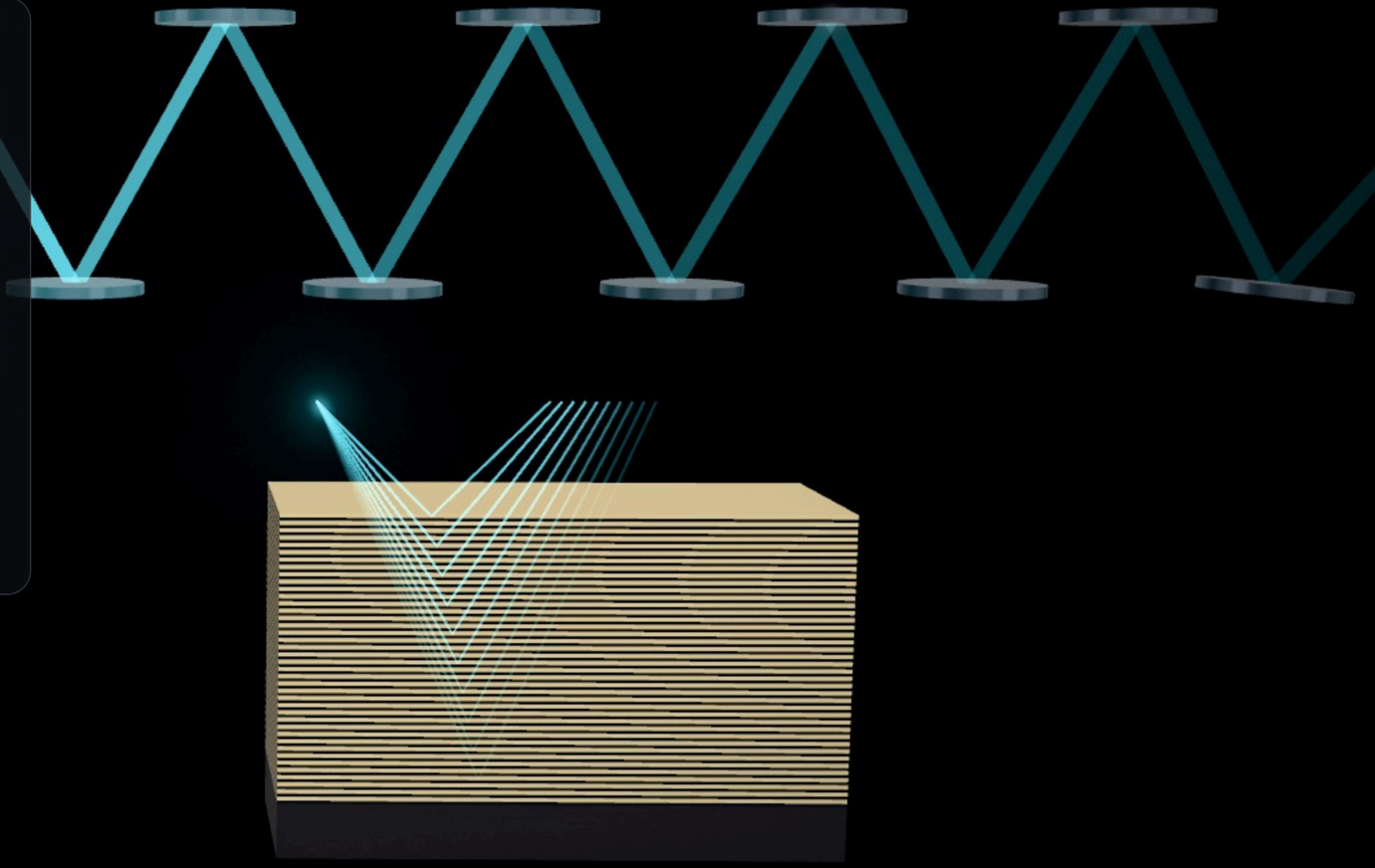
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08 · OPTICS WITHOUT GLASS

Mirrors all the way down.

No lens passes 13.5 nm, so every optic is a mirror, the mask included. One surface reflects almost nothing, so each mirror is a stack of about 40 pairs of molybdenum and silicon layers, each pair about 7 nm thick, and the tiny reflections add up in step. Even then, a mirror returns about 70% at best.

Layers, the 70% limit and the count of 11: Berkeley Lab (Naulleau, 2012). Measured: Lawrence Livermore, 6.89 nm pairs at 67.5% (1998) and 70% with 50 pairs (2001). The mask's own stack: HOYA (2003) and imec (2021). 0.1 nm: Patrick Naulleau, director of Berkeley Lab's Center for X-Ray Optics, in Lawrence Livermore's magazine (2022); the silicon spacing is Princeton's. The light left is our arithmetic: the reflectivity to the power N.



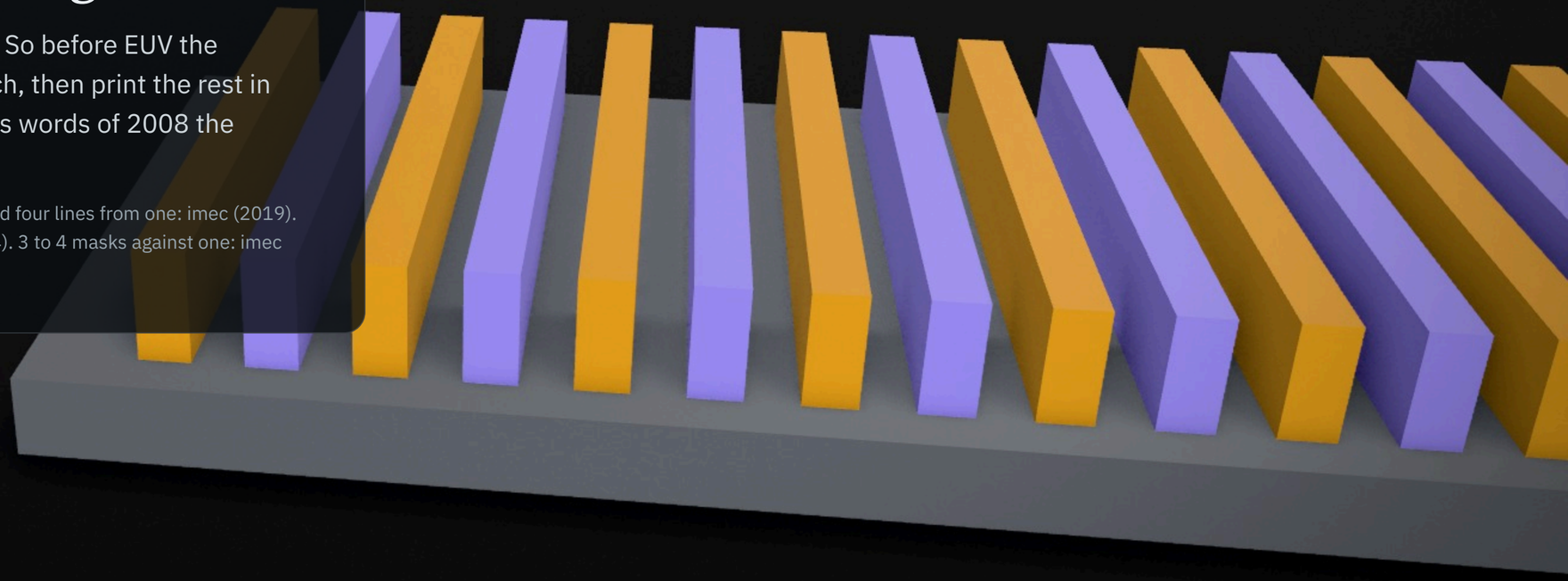
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09 · BEYOND ONE EXPOSURE

When one pass is not enough.

Below k_1 = 0.25 the lens cannot separate the lines. So before EUV the industry split the pattern: print every other line, etch, then print the rest in the gaps. Two masks, two exposures, and in Nikon's words of 2008 the second must land within 3 to 4 nm of the first.

Double patterning and its overlay: Nikon (February 2008). Spacers, and four lines from one: imec (2019). EUV and fewer steps: imec (2021) and the IEEE roadmap (IRDS, 2024). 3 to 4 masks against one: imec (2026). A cross-section, not to scale.



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10 · PUTTING IT TOGETHER

From disc to atom.

Slide from the wafer down to the spacing between two silicon atoms. Everything in between is what one scanner pass has to control.

Sizes: the field, Nikon and Canon; the €2 coin, the European Central Bank; a hair (80 to 100 µm) and DNA (2.5 nm), the US National Nanotechnology Coordination Office; the tin droplet, Michigan; a red blood cell (7 to 8 µm) and E. coli (about 1 µm across, 2 µm long), Milo and Phillips, Cell Biology by the Numbers; SARS-CoV-2, Klein and others (2020); the metal pitch, imec (28 nm for a 5 nm node); silicon, Princeton and NIST's CODATA lattice parameter. Each thing is drawn at its size relative to the others, a range at one value inside it; the row and its spacing are ours.



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Sources

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- Shin-Etsu: photomask blanks · Shin-Etsu: pellicles · imec: High-NA EUV, the next step (2021) · European Central Bank: euro banknotes and coins · Japan Mint: coins presently minted
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