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Review paper

Continued dimensional scaling through projection lithography

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A R T I C L E I N F O

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Resist
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A B S T R A C T

This article discusses the important role that optical lithography has played in realizing Moore's Law. With the introduction of Artificial Intelligence, Machine Learning, and the Internet of Things, the demand for computing power and data storage capacity has never been as large as today. Optical lithography has been able to keep up with the resolution demand by increasing the Numerical Aperture of the projection Lens, decreasing the wavelength and innovative resist schemes. After the introduction of Immersion lithography and Double patterning, EUV was introduced by the industry. Although the transition from 193 nm lithography to EUV lithography was very difficult, EUV follows the same scaling laws as Optical Lithography. The conclusion is that the scaling laws of Optical Lithography continue to support Moore's Law, through the development of high NA EUV Lithography.

1. Introduction

The semiconductor industry has been driven by Moore's Law in the past decades. Moore's law predicts doubling of the number of transistors per chip every 2 years. With the increased use of Artificial Intelligence (AI) and the data generation by Internet of Things the demand for computing power and data storage has never been as large as today. Therefor it is crucial to continue Moore's Law in the next decades. In the past, this duplication was fully enabled by lithography scaling (Fig. 1). At some point, lithography scaling needed the collaboration with designers to make the layouts more lithography friendly. This is commonly known as Design-Technology Co-Optimization (DTCO). More recently, lithography scaling and DTCO were not enough and required to stack different technologies (e.g. logic versus memory) with a large number of interconnects in order to provide the required bandwidth for communication between logic and memory. This is commonly known as System-Technology Co-Optimization (STCO). The role of 3D packaging and 3D integration becomes crucial here.

By combining dimensional scaling, DTCO and STCO, the logic technology roadmap has been predicted at the SPIE Advanced Lithography Conference, as shown in Fig. 2 [1]. It is clear that dimensional scaling is continuing, but also new device concepts, new materials and new interconnect schemes are necessary.

The projection lithography resolution has scaled over the years by increasing the numerical aperture (NA) of the projection lens, decreasing the wavelength (λ) and reducing the k_1. The k1 factor is used for every technique that improves the resolution without changing the wavelength or numerical aperture. It is typically used when a resist/process is replaced by a new resist/process with better resolution. The use of optical techniques such as phase shifting masks [2,3], or off axis illumination [4] are impacting the k_1 factor as well. These are techniques reducing the k_1 and hence improve the resolution, as predicted in Abbe's law defining the minimum resolution (R), shown in the following equation:

$$R = k_1 \lambda / NA$$

This increase in numerical aperture and decrease in wavelength is clearly shown in Fig. 3 [5].

In the next paragraphs, the main lithographic innovations from the past, and outlook to the future will be illustrated.

2. From 436 nm to 193 nm: dry optical lithography

The initial projection lithography tools used 436 nm wavelength and had very low numerical aperture lenses. Mercury bulbs were used as light source, where the g-line peak was selected in the mercury spectrum. The step towards sub-100 nm dimensions was made between 1980 and 1990 when 365 nm lithography was introduced, also known as i-line lithography. Mercury bulbs were used as light sources where the i-line peak was selected. Numerical apertures increased up to 0.6. The most common photoresists were novolacs[1].

A big innovation came with 248 nm (Deep-UV or KrF). Here the

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[1] The team of Prof Hatzakis developed an epoxy novolac resist for direct electron-beam patterning of 30 nm patterns [6,7]

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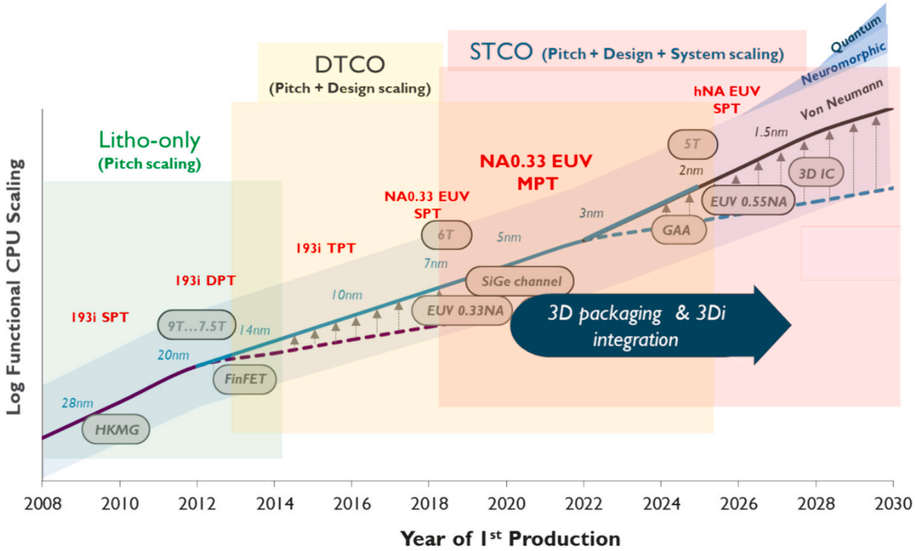
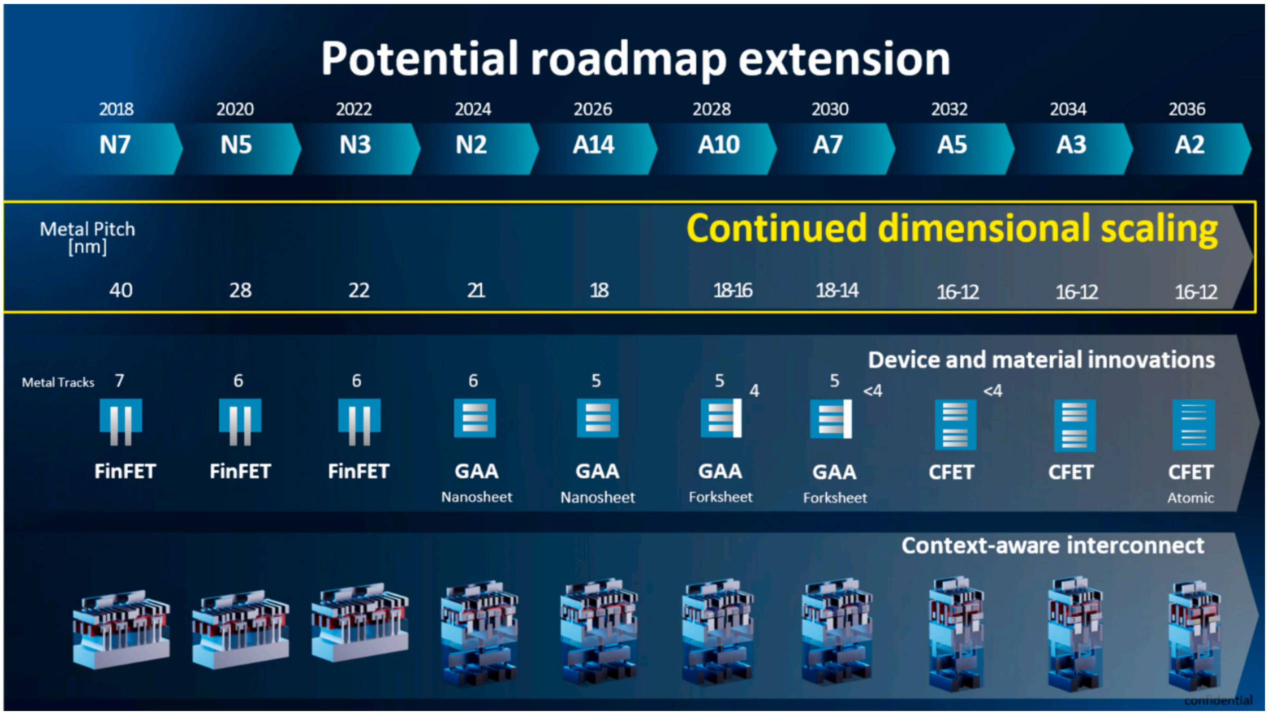


Fig. 1. The role of lithography, DTCO and STCO in chip scaling following Moore's Law.


Potential roadmap extension

Continued dimensional scaling

Device and material innovations

Context-aware interconnect

	2018	2020	2022	2024	2026	2028	2030	2032	2034	2036
	N7	N5	N3	N2	A14	A10	A7	A5	A3	A2
Metal Pitch [nm]	40	28	22	21	18	18-16	18-14	16-12	16-12	16-12
Metal Tracks	7	6	6	6	5	5 4	5 <4	<4		
	FinFET	FinFET	FinFET	GAA Nanosheet	GAA Nanosheet	GAA Forksheet	GAA Forksheet	CFET	CFET	CFET Atomic

Fig. 2. Logic Technology roadmap from 2018 to 2021.

mercury bulb was not strong enough so that excimer lasers had to be introduced (using KrF gas). Lenses with numerical apertures up to 0.93 were developed. Even with the KrF lasers, the photoresists had to become very sensitive to enable enough throughput. In optical lithography, throughput is expressed in number-of-wafers-per-hour that can be exposed, and every increase of that number has a direct impact on the lithography cost. Throughput numbers started at 25 wafers per hour and are currently over 200 wafers per hour and still increasing. In deep UV lithography, this led to the introduction of the very transparent chemically amplified resists. This new resist concept came with quite some problems, like T-topping and footing, which were initially not understood [8]. This led to ammonia filtration [9] of the litho-cells to avoid interaction with the acids formed in the resists. Also, the materials under the resists need to have the right amount of acidity [10].

The next wavelength was 193 nm (Deep-UV or ArF), powered again by Excimer lasers but now with ArF gas. Also, here the lens NA went up to 0.93. The chemically amplified resists had to be improved in terms of transparency by introducing new polymers.

3. Innovation: 193 nm immersion lithography and multiple patterning

For a while, research was done at 157 nm as the next wavelength (F2 excimer lasers). However, there were quite a few challenges. All quartz in the lens had to be replaced by CaF_2 for transparency. An issue surfaced quite late: the birefringence characteristics of CaF_2 which required a redesign of all lenses [11].

In parallel some research groups were looking at water immersion

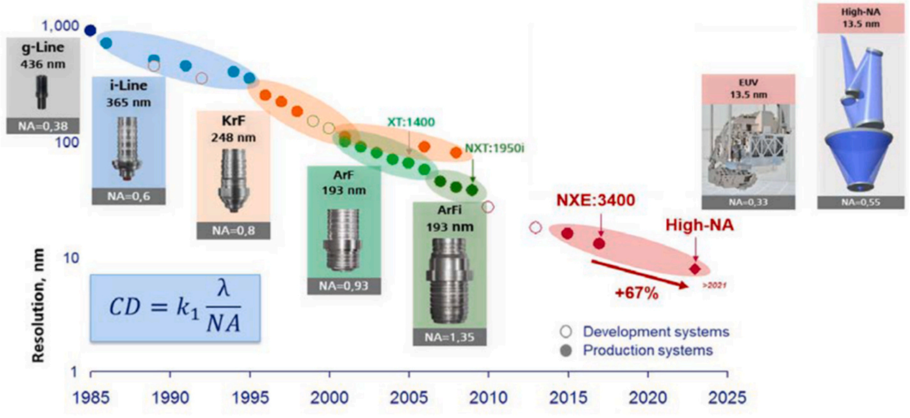


Fig. 3. Projection lithography resolution scaling, from g-line to EUV.

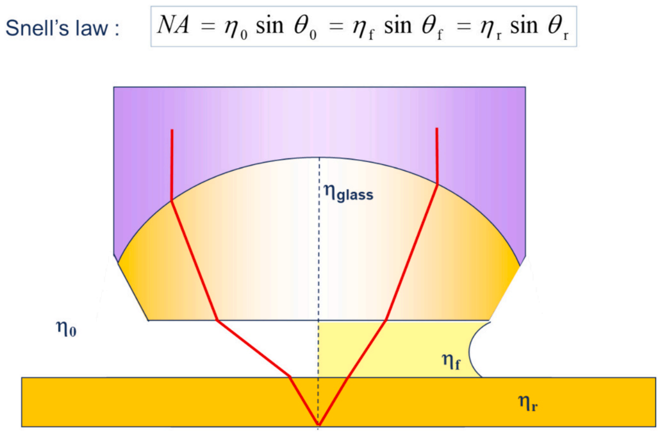


Fig. 4. Comparison dry ArF versus wet ArF lithography.

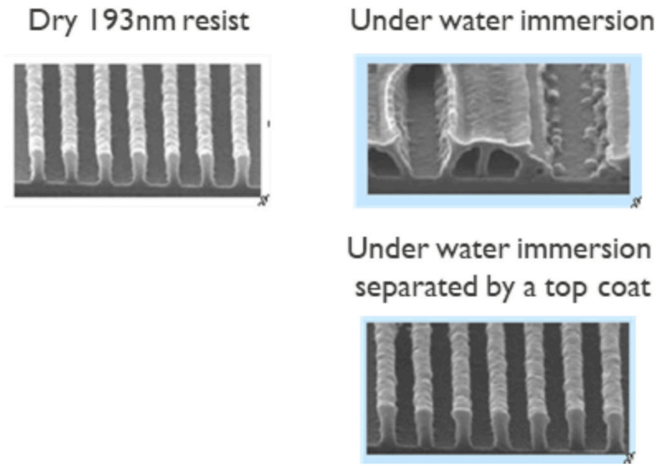


Fig. 5. Dry ArF resists (90 nm lines and spaces) in direct contact with water, and separated by a topcoat.

tests of 193 nm which seemed to be feasible [12]. The refractive index of water of about 1.45 would increase the numerical aperture of the 0.93NA dry lenses to 1.35, according to Snell's law (Fig. 4). The resolution gain from 193 nm dry to 193 nm wet (45%) was larger than the step from 193 nm dry to 157 nm dry lithography (23%). In ArF immersion, many modules could stay the same, like the lens materials. Only the immersion hood needed to be developed. The belief was that also the ArF resists could continue, but many dry ArF resists formed defects in contact with water (Fig. 5). This led (temporarily) to the reintroduction of top coatings to protect the resist from the water, although later resist chemistries did not suffer from that anymore [13].

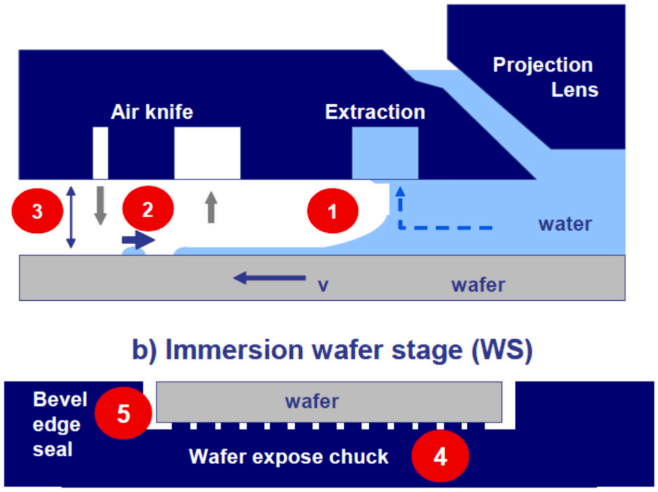


Fig. 6. Immersion hood design [14].

The biggest innovation came from the immersion hood (Fig. 6). The immersion hood, attached to the bottom element of the lens, needed to scan with high speed and acceleration over the surface of the resist, even exceeding the edge of the wafers and make sure no water droplets were leaking and no air bubbles would be absorbed. Several redesigns lead to defect free immersion lithography [14].

Due to the delays in EUV lithography development, 193 nm immersion has been extended by double patterning techniques. Various schemes have been developed as can be seen in Fig. 7. In theory these techniques could double the resolution. However, after implementing triple and even quadruple patterning it became clear that edge placement errors (EPE) were limiting the further extension. Moreover, the technology became very expensive, had a high turn-around time and suffered from reduced yield. Clearly the industry wanted to go back to a single exposure lithography technology.

4. Innovation: 13.5 nm extreme ultraviolet lithography (EUVL)

Extreme UV lithography was the answer to go back to single exposure. Although the development of EUV Lithography started before 1990 [15], it took many years to overcome the various hurdles, such as

- Low EUV source power

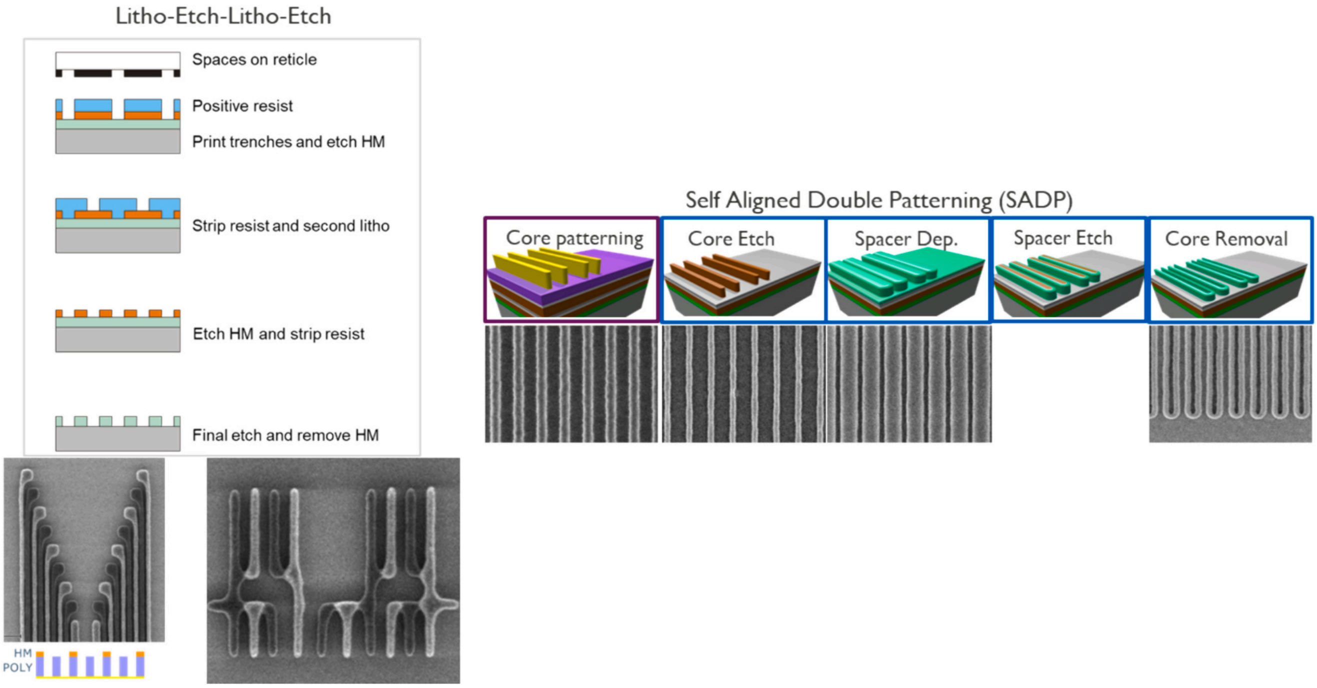


Fig. 7. Two different double patterning flavors.

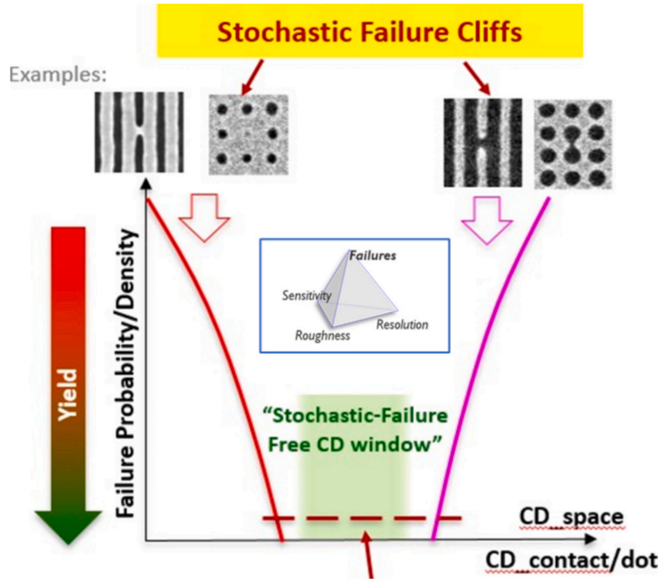


Fig. 8. Stochastic failures: nanobridges and nanobreaks for lines/spaces and missing holes or merging holes for contact holes.

- Very high energy photons, leading to shot noise [16].
- The low wavelength is absorbed by most materials. Transmissive optics had to be replaced by reflective mirrors, consisting of 40 pairs of Mo and Si, which reflect about 70% of the light.
- Transmissive masks also had to become reflective. Blanks had to be defect free as small pits or bumps could easily turn into printing phase defects.
- Complete system under vacuum, except from some gases like hydrogen at very low partial pressure
- The resist needs to be very sensitive to compensate for the low power reaching the wafer. Since every mirror (the complete optical train contains at least 7 mirrors, including the reticle) only reflects about 70% of the EUV light generated by the source, only 10% of the light reaches the wafer. Typically, EUV users expect 35-50 mJ/cm^2 resist dose today. The challenge for the resist manufactureres is to reach such a low dose while keeping a good resolution and small line edge roughness.

It took many years to achieve a reasonable source power and good reliability. The other aspects were improved step-by-step.

An unexpected new phenomenon was observed in the resists. Stochastic failures (nanobridges and nanobreaks for lines/spaces and missing holes or merging holes for contact holes) became visible after development of the resist [17]. Fig. 8 shows the failures in line/space and contact hole layout. Low defectivity is reached between the failure cliffs. This indicates that the resolution for EUV is no longer defined by Abbe's Law but rather by the low defectivity zone. This phenomenon is partly caused by shot noise, but there are many other contributors like the resist material chemistry, the underlayer interaction with the resist, the image contrast, mask imperfections, track processing, and finally the etch process. Also here, gradual improvements were achieved. As a result, EUV lithography was introduced in high volume manufacturing by a few logic foundries in 2019, for the 7 nm logic technology node. Nevertheless, mitigating stochastic failures remains a very important activity for the next technology nodes, where the dimensions keep shrinking.

Today, the source power keeps increasing [18], masks are defect free, but the main attention point is the further reduction of stochastic failures.

5. High NA EUV lithography

As can be seen in Fig. 9, EUV double patterning becomes a necessity as of the next technology node beyond the 7 nm node. This will improve the resolution of the 0.33NA EUV system. It has been applied for a long time in 193 nm immersion lithography, waiting for EUV to become mature. But 193 nm immersion multiple patterning has also learned that multiple patterning is expensive, risks reduce the yield and requires long turn-around times. Although EUV double patterning has already reached high volume manufacturing, the industry did not want to go as far as they did in 193 nm immersion. Higher NA EUV also increases the

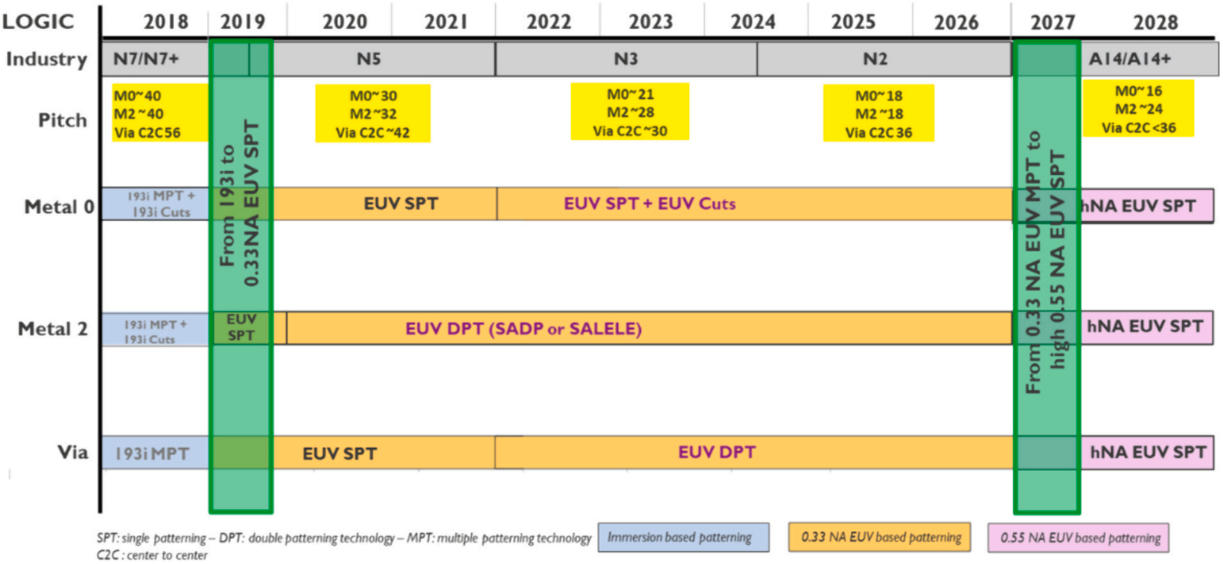


Fig. 9. Transition from 0.33NA single patterning to double patterning.

Fig. 10. Step by step assembly (Top picture: wafer stage, bottom picture: reticle stage) of a High NA EUV tool in joint imec-ASML High-NA lab at ASML's headquarters in Veldhoven (NL). Credit: ASML.

resolution and can delay the need for double patterning. Today all EUV scanners in high volume manufacturing have projection lenses with an NA of 0.33. The first high NA scanners are being shipped to the foundries and have an NA of 0.55.

Again, several new challenges came up. A lot of learning was done at 0.33NA already and the BMET5 at Berkeley was instrumental for the resist community to test their resists at higher NA [19,20].

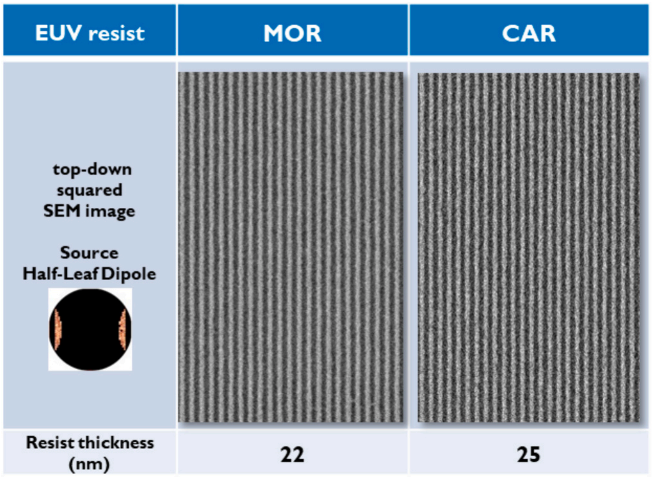


Fig. 11. 24 nm pitch lines and spaces in MOR and CAR resist resolved with aggressive 0.33NA source.

- High NA is significantly reducing the depth-of-focus (DOF), defined in Abbe's second law:

$$DOF = k_2\,\lambda/NA^2$$

- Anamorphic imaging (8× magnification in the scan direction, 4× magnification orthogonal to the scan direction) resulting in half field stitching [21].
- The need for EUV materials and patterning techniques with less stochastics
- Masks needed for improved imaging performance, primarily changing the absorber material from the conventional Ta-based absorbers [22].
- Thinning the resist to cope with the focus budget but keep the etch resistance.
- Metrology and inspection for thin resist and underlayer films
- The biggest challenge is the short time to enable all these.

In order to accelerate the readiness of high NA EUV, a high NA lab is opened by imec and ASML where a prototype high NA scanner is installed (Fig. 10). In this lab, with the help of imec and ASML,

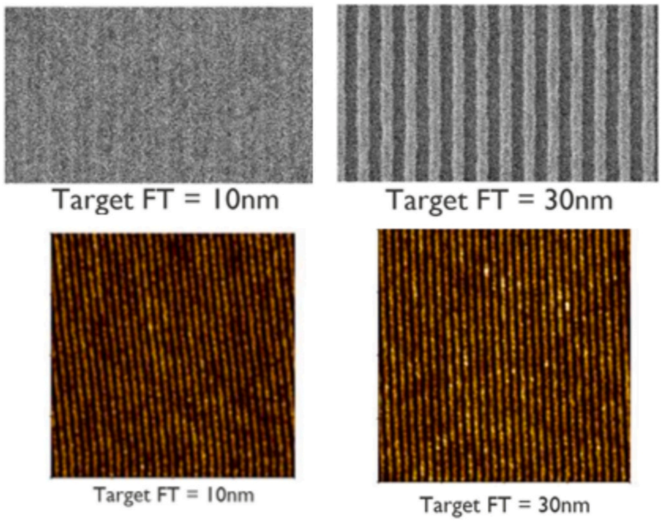


Fig. 12. SEM image contrast loss by thinning the film (bottom images are taken by AFM proving that the lines do really exist).

interested companies can step up the learning curve of high NA EUV lithography in an early phase.

On top of that, many challenges can already be investigated before a high NA scanner is built. By inserting aggressive dipole source into a 0.33NA scanner, 24 nm pitch lines and spaces can be resolved. 24 nm pitch is considered a relevant pitch for the insertion of high NA single exposure (Fig. 11). This allows the investigation of the effect of resist thickness reduction and simultaneously develop the etch technology.

Here the Metal-Oxide Resists (MOR) are shown to be a good candidate to take over from the chemically amplified resists (CAR) for metal lines [23,24]. They are typically thinner and offer a large etch resistance.

One of the findings is also that the SEM and optical contrast of images of thin films is degrading significantly for CD, roughness, overlay and defect inspection (Fig. 12). This is useful input for the metrology and dry-etch equipment suppliers, paying attention to the high NA challenges like thin films. Denoising by machine learning [25] is heavily investigated to facilitate metrology.

Also, half field stitching (8) and investigation of novel mask absorbers can be studied at 0.33NA [26].

6. Summary and outlook

Optical (EUV) projection lithography has been and will remain the workhorse for High Volume Manufacturing of advanced logic and memory chips.

Due to smart choices in wavelength, NA and the co-development of the required infrastructure (resists, masks…), the dimensional scaling is continuing.

The current development focus is to accelerate the insertion of 0.55NA EUV lithography into HVM. A lot of learning has been done based on 0.33NA EUV and as of Q2 2024 the learning will be accelerated in the high NA Lab based on the high NA EUV prototype.

The next step in optical projection printing is not decided. Studies are on-going on so-called hyper NA EUV, i.e. lenses with NA of 0.75 or even 0.85 [27,28]. Several items need to be addressed here. The very high angles of incidence of these high NA make polarization needs to be taken into account. Current EUV sources are un-polarized and using only one polarization direction may reduce the power by a factor more than two. Resists will have to become even smaller. New multi-layer mirrors will need to be developed. Given the time it took for bringing 0.33NA into HVM, the question is if hyper NA will come in time and will be affordable. Double patterning with 0.55NA may be more economical this time. The future will tell.

Reducing the wavelength to 6.5 nm has been studied for a while but does not seem to be an option to improve resolution, since it would reduce the potential NA.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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