OPTICAL LITHOGRAPHY FOR NANOTECHNOLOGY

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ABSTRACT

Optical lithography is continually evolving to meet the ever demanding requirements of the micro – and nano-technology communities. Since the optical exposure systems used in lithography are some of the most advanced and complex optical instruments ever built, they involve ever more complex illuminator designs, nearly aberration free lenses, and hyper numerical apertures approaching unity and beyond. Fortunately, the lithography community has risen to the challenge by devising many inventive optical systems and various methods to use and optimize exposure systems. The recent advancement of water immersion technology into lithography for 193nm wavelengths has allowed the numerical aperture (NA) of lithographic lenses to exceed 1.0 or a hyper-NA region. This allows resolution limits to extend to the 45nm node and beyond with NA>1.3. At these extreme NAs, the imaging within the photoresist is accomplished by not only using water immersion but also using polarized light lithography.

This paper will review the current state-of-the-art in immersion, hyper-NA lithography. We show the latest results and discuss the various phenomena that may arise using these systems. Furthermore, we show some of the advanced image optimization techniques that allow lithographic printing at the physical limits of resolution. In addition, we show that the future of optical lithography is likely to go well beyond the 30nm regime using advancements in 193nm double-patterning technology and/or the use of extreme ultra-violet (EUV) optical systems.

Keywords: High NA, polarization, imaging, immersion, 193nm

1.   INTRODUCTION

An optical step and scan system is a highly complex opto-mechanical tool which combines the finest resolution optical lenses and illumination systems with the highest precision mechanical scanning stages and metrology systems.   The end-goal is to provide a high productivity, profitable means for making microcircuits on silicon wafers. By using higher and higher numerical apertures (NA), lower wavelengths, and resolution enhancement techniques (RETs), we have been able to push the limits of the optics well beyond would have been expected just a few years ago. The result of this relentless technical advancement is that optical lithography continues to be the engine that drives Moore's Law. Figure 1 shows the resolution needed by various world-wide chip manufacturers as a function of time. The population is divided into Logic, DRAM, and Flash makers. Traditionally, DRAM has been the driver for resolution; however, in recent years, the extensive use of Flash memory has driven this technology to surpass DRAM such that the projected resolution for high volume production will be ~30nm in 2011.

Recent extensions of 193nm lithography have used resolution enhancement technology (RET) and hyper-NA immersion optics to obtain resolutions less than 45nm half pitch. This has enabled the production of higher density DRAM and flash memories, as well as new generations of multi-core processors. The chief technology improvements have come due to the development of water immersion optics with NA>1, the use of polarized illumination, and the maturation of several low k_1 technologies such as model-based optical proximity correction, source-mask optimization, and various forms of double exposure lithography.

To help in the understanding of how this plethora of technology can achieve such resolution improvement, it is worthwhile to examine the fundamental equation that relates lithography and optics to resolution. Typically, the industry has used a modification of the Rayleigh criterion to define the industry progress of diminishing linewidth by change of

optical parameters. In its most general form, for lines and spaces with a 1:1 ratio, the linewidth (or resolution) is given as,

$$LW = k_1 \frac{\lambda}{n \sin \theta} = k_1 \frac{\lambda}{NA} \quad , \tag{1}$$

where λ is the wavelength and θ is the limiting angle of the lens, as defined by the marginal ray in a medium (immersion) with an the index of refraction, n, NA is the numerical aperture, and k_1 is related to the difficulty of the process and has a lower limit of 0.25 with partial coherent imaging using a single exposure.   This simple equation with 3 parameters governs optical lithography. We note that the complimentary equation for depth of focus (DOF) is given by,

$$DOF = \frac{\lambda}{n(1-\cos\theta)} = \frac{\lambda}{n\left(1-\sqrt{1-\dfrac{NA^2}{n^2}}\right)} \quad , \tag{2}$$

which will result in an increase in DOF, when comparing immersion systems to dry systems assuming a constant NA.
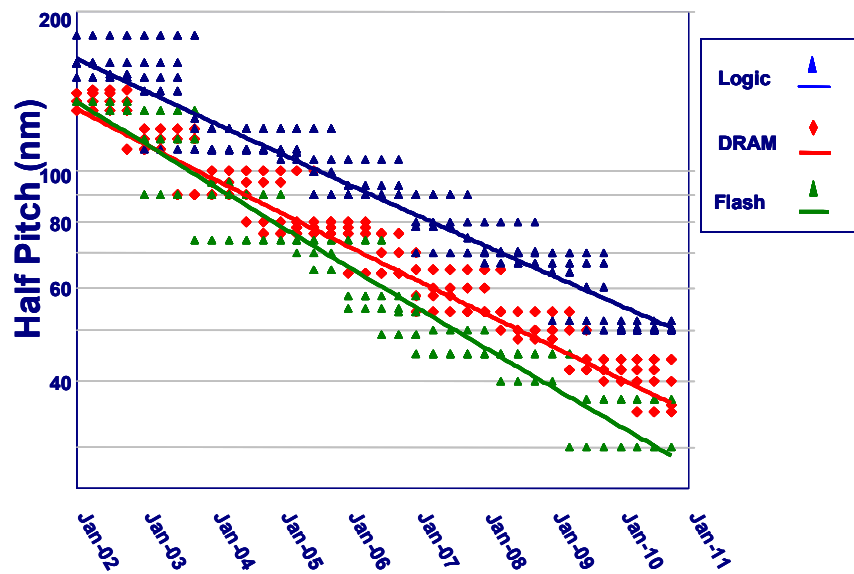

Fig. 1. Feature size reduction needed for development and manufacturing of ICs.

Current resolution improvements have been facilitated by the use of immersion technology to increase the NA limit beyond 1. If one assumes that the maximum angle in the fluid medium should not extend beyond $\sin\theta=0.95$ using $\lambda=193$nm, then NAs up to ~1.35 can be contemplated when water is used as the immersion medium (n_{water} =1.437). However, if we also assume that higher index fluids (n≥1.6) may be available, then the maximum NA could easily approach 1.5.

The use of these NAs to extend imaging to sub-50nm levels will also require using polarization imaging to increase the overall contrast. This enables the use of single processing k_1's approaching 0.25 when combined with a multitude of resolution enhancement techniques (RETs). One of these RETs that will likely be needed is source-mask optimization[1]. This technique simultaneously optimizes the shape of the source and the reticle features to effectively solve the inverse imaging problem. In addition, the use of double processing techniques effectively negates any lower limit is k_1 factor. For example, a process that enables interleaving of gratings will half the k1 factor, such that the lower theoretical limit becomes k_1=0.125.

Figure 2 highlights the possible ranges of resolutions by use of equation (10) with λ= 193 nm and λ =13.5 nm (EUV). For λ=193 nm, the use of immersion technology is clearly required to go to resolutions beyond 50nm. Extension much beyond 35 nm will require the use of multiple processing schemes to push the k1<0.25. The situation is different for EUV wavelengths. Here, the current system NA is 0.25, but for even modest k1=0.5, the resolution approaches 30nm. Furthermore, the theoretical potential exists to go close to 10nm using single processing techniques as the NA is increased to 0.35. However, achieving this will involve substantial lens development and technology infrastructure.
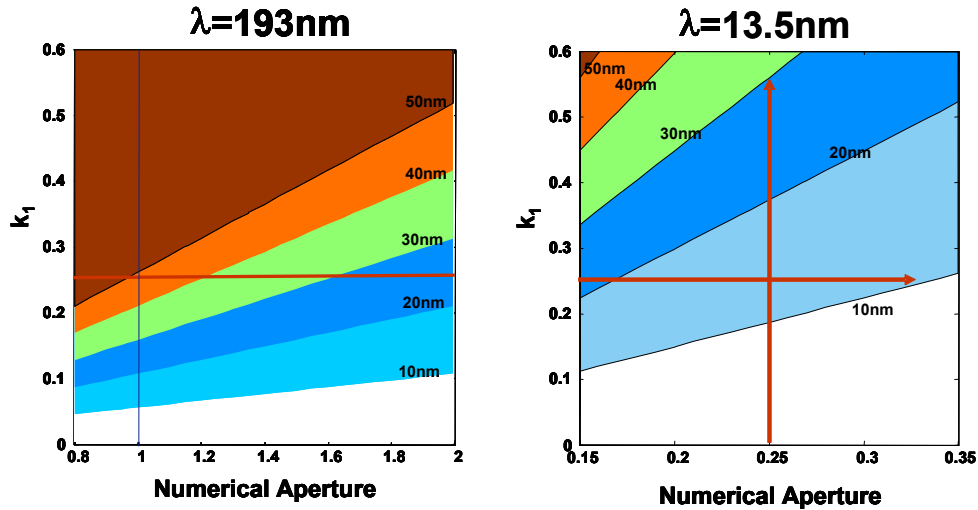

Fig. 2. Resolution space for 193nm and EUV (13.5 nm) technologies

This paper will first show, in section 2, the general status of the state-of-the-art in immersion technology and the use of polarization imaging with hyper-NA lenses. Section 3 will explore a few of the methods used to lower k_1 in single processing, while section 4 will discuss the current EUV system and results. Finally the last section shows recent advances in double processing techniques that will allow for resolutions well into the 10nm regimes.

2. IMMERSION LITHOGRAPHY AND HYPER-NA

The use of immersion fluids in optics has been known for well over 150 years. In the late 1840's, Giovanni Battista Amici[2] filled the space between the microscope objective and the cover glass with oil to enhance the image quality and brightness. Since the oil matched the index of refraction of both the objective and the cover glass better than air, there was a reduction in spurious reflections that enhanced contrast. Amici also experimented with other fluids including water as the medium. However, it was not until 1880 that Ernst Abbe[3] used a more carefully defined optical theory to specifically design microscopic objectives for immersion fluids.

Immersion for use in lithography first appeared about 100 years later in the patent by Taberrelli[4] where a fluid that is indexed matched to the photoresist fills the area between the lens and the wafer. In 1987 Kawata[5] presented an optical projection system that used an oil immersion fluid at an exposing wavelength of 453nm. They were able to attain 160nm isolated line features in Novalak photoresist using a research system based on an inverted microscope.

The use of interferometric systems for detailed exploration in lithography is well known[6,7]. Hoffnagle[8] in 1999 extended this technique for immersion to increase the working resolution. He demonstrated line/space imaging in DUV photoresist. Subsequently, Switkes and Rothchild[9] demonstrated interferometric immersion imaging at 157nm.

In more recent history, interference lithography coupled with immersion techniques has become a major method to achieve extremely high resolutions for periodic structures needed in some nanotechnology areas. This method is also extremely useful to explore various fluid materials needed for future generations of immersion tools. Figure 3 shows the results of an imaging test at ASML with a 2nd-generation fluid (1st generation being water) using an immersion interferometer setup. Aggressive 32nm L/S imaging from this test setup is shown and some line edge roughness (LER) is

observable, which is a property of the chemically amplified resists that is used. No adverse immersion fluid effects were observed in the resist profiles.
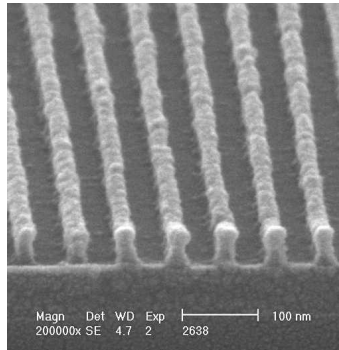

Fig. 3. Images of 32nm line and space (L/S) patterns in resist using an immersion fluid with n=1.65. Two beam interference was used at λ=193nm and the sine of the half angle within the fluid was sinθ=0.915.

In order to explore the issues with water immersion lithography with a high volume full field system, in 2003 ASML and Zeiss modified the lens and wafer stage of an existing ArF (λ=193nm) system (XT 1150, NA =0.75) to produce the world's first scanned images using water immersion[10]. By introducing water between the last lens element and the wafer, we were able to demonstrate a substantial improvement in depth of focus over imaging in air. However, since the same lens design was used, there was no improvement in numerical aperture, hence no improvement in limiting resolution. In 2004 ASML introduced a second generation system, the XT 1250i (NA=0.85), and in 2005 we introduced the third generation system, the XT 1400i (ArF, NA=0.93). These immersion tools have been shipped to different customer locations around the world to facilitate early learning and process development.

The latest generation immersion system is the first hyper-NA system, i.e., NA>1. The TWINSCAN™ XT:1700i, as depicted in Fig. 4 combines the immersion technology of the dual stage TWINSCAN™ platform[11] with the new hyper-NA projection system and new illumination system. The Starlith™ 1700i is the fourth generation of 193 nm immersion lenses and the first catadioptric lens from Carl Zeiss SMT. This lens operates in a NA range of 0.75 to 1.2 and supports a field size of 26x33 mm^2. The Aerial™ XP illuminator supports a wide range of illumination settings, in different polarization modes and improved pupil parameters as ellipticity and telecentricity. For both polarized and un-polarized usage, the system has maximum efficiency for all supported illumination modes. The immersion hood is designed to support both hydrophobic and hydrophilic processing at 550 mm/s scan speed. Table I gives the specifications of this tool.

Fig. 4. ASML TWINSCAN XT:1700i 1.2 NA with 26x33mm2 field

Table I. Specifications of ASML Twinscan XT 1700i

Lens	Spec		Illumination	Spec
Max NA	1.2		Laser	6 kHz, >50W
Field Size	26 x 33 mm		Uniformity	<0.3%
Max RMS Aberration	1.4 nm			
Astigmatism	20 nm		**Overlay**	
Focal Plane Deviation	30 nm		Stage Repeatability	4 nm
Resolution, Annular	50 nm		System Overlay	7 nm
Resolution, Dipole	45 nm		Matched Overlay	11 nm
CDU 3σ	3.0 nm			
Distortion	5 nm		**Throughput**	
			125 shots, 30mJ/cm2	> 122 WPH

With 1.2 NA ArF optics, it is possible to manufacture 45nm design rule memories such as NAND flash devices with acceptable depth of focus and exposure latitude. Figure 5 shows 3 sets of images from this tool using 3 different illumination shapes (1st column) to successively lower the k_1 factor and increasing resolution.
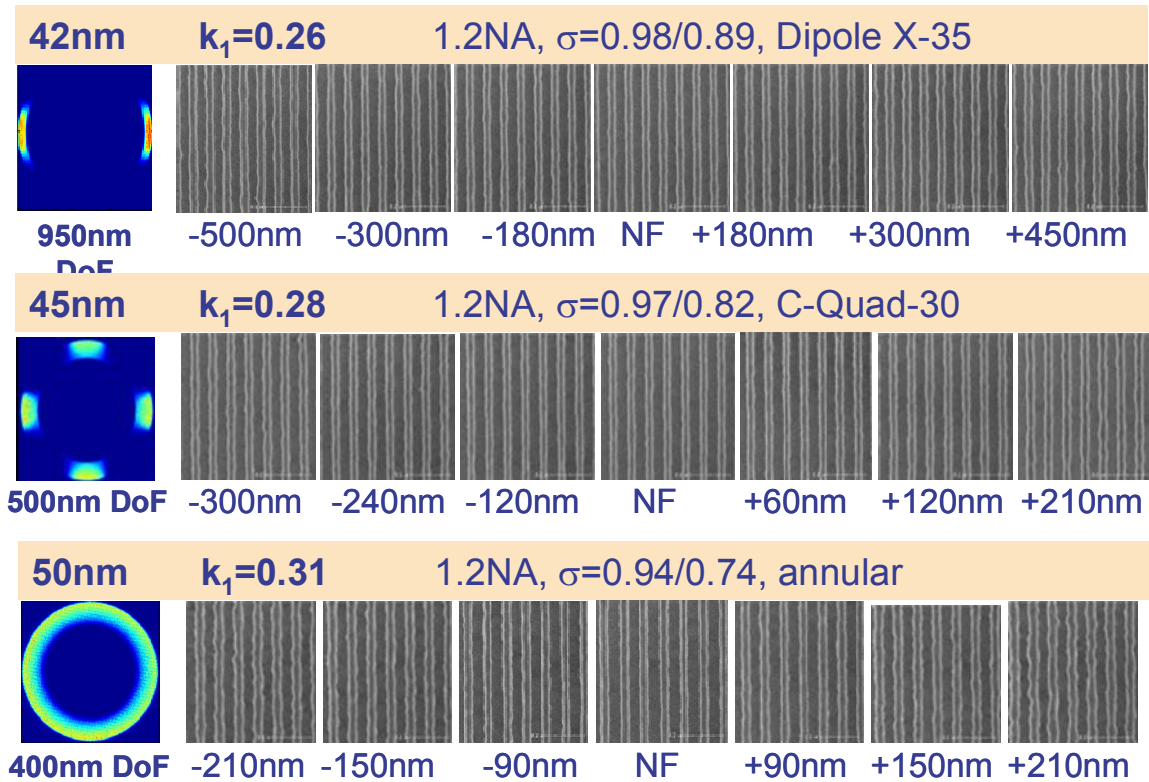

Fig. 5 Depth of Focus versus resolution for ArF lithography at NAs varying from 0.93 to 1.20

Development of hyper numerical aperture optics (NA>1) has stressed the size and weight of optics. To date, most scanner optics from ASML and it's competitors have been dioptric designs, in which only refractive elements of either fused silica or calcium fluoride have been used. In order to control the complexity and cost of the projection optics, Zeiss has designed the 1.2 NA lens to be an in-line catadioptric lens, using both mirrors and refractive elements. A cross-sectional view of an example of this design is shown in Fig.6. This design has allowed a large aperture to be built within the maximum length and diameter of previous lenses. ASML and Zeiss chose the in-line catadioptric design over further

extension of dioptric form because it offered 15% more NA while saving 40% in glass material. Compared to other catadioptric forms, the in-line design allows easy extendibility to NA > 1.35, offers a rectangular scan field which supports maximum productivity, retains the same image orientation as refractive lenses, and has high mechanical stability.

Imaging at very high NA values will require that polarization effects need to be taken into account as well. This is graphically illustrated in figure 7 for 3 polarization conditions: transverse electric (TE), transverse magnetic (TM), and the unpolarized condition. The contrast is calculated inside a photoresist of index n_{resist}=1.7 as function of NA using a 2-beam interference assumption. This approximates imaging dense lines with an alternating phase mask using a small partial coherent illumination. Although the TE case will have maximum interference resulting in a contrast of 100%, the TM case will have a contrast that decreases by the cosine of the angle between the beams. The contrast within the resist will drop to 0 at NA=1.2 and increasing the NA further will result in image reversal for TM. Since the unpolarized condition is the average of the TE and TM polarization, the unpolarized case will also suffer from an image degradation that increases with NA.

The illumination system of the ASML TWINSCAN™ XT:1700i supports polarized illumination modes in order to get to full benefit of the 1.2NA. The AERIAL™ XP illuminator of system supports both polarized and un-polarized illumination with the same efficiency. All future systems at these extreme NAs will require some amount of polarizability to restore lost contrast. Figure 8 shows polarized illumination achieving an improvement of 30% exposure latitude (EL) and almost 60% improvement in maximum DOF.
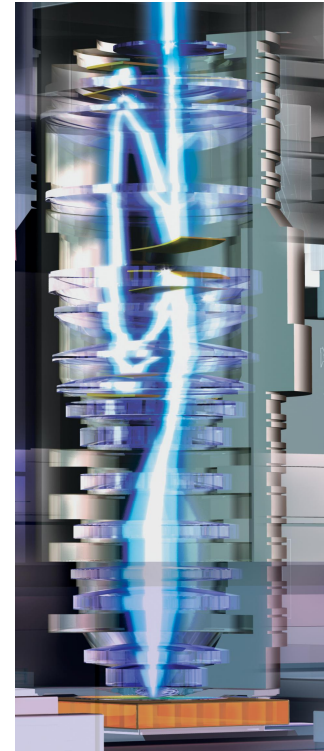

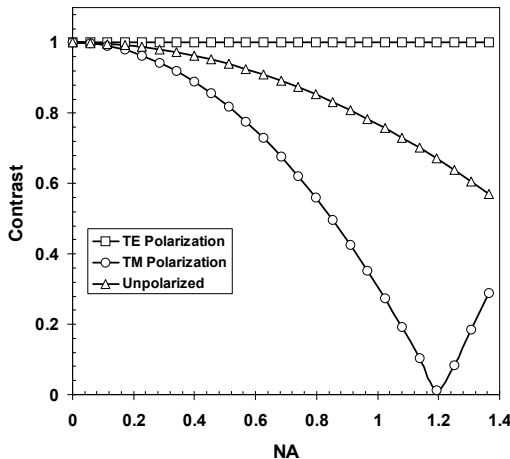Fig. 6. Starlith™ 1700i In-Line Catadioptric Lens, maximum NA=1.2.

Figure 7. Contrast of 2 beams interfering within photoresist film of index 1.7. The half angle between the beams is given as the NA.
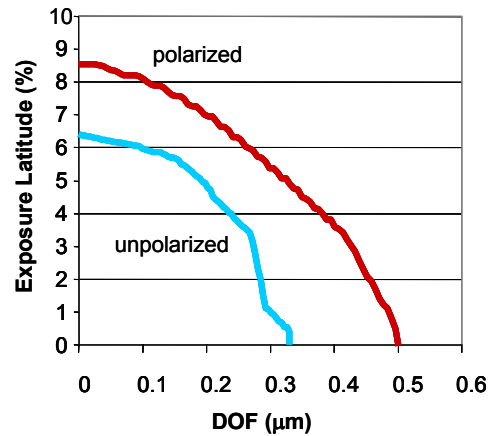

Fig. 8. 45nm dense H &V lines using TE polarized C-Quad illumination 1.2NA, s=0.94/0.87 .

3. LOWERING k_1 BY RESOLUTION ENHANCEMENT TECHNIQUES

As a consequence of pushing the technology to lower and lower resolutions using lower k_1 values, the image contrast degrades, as well as, the size and shape of the final image. Short of going to the next NA or wavelength (equivalent to increasing k_1), one has two main choices how to improve the image: change the shape and size of features on the mask and / or optimize the illumination. The first choice is known as optical proximity correction (OPC) in which the edges of mask features are purposely moved with respect to the CAD layout in order to achieve a better final wafer result.

One of the more recent approaches for periodic structure involves optimization of the illumination shape. For memory devices, pattern density is paramount, putting significant restrictions on available options for OPC. For these cases, illumination optimization is very attractive. Figure 9 shows how the lithography process window for a typical DRAM isolation layer can be improved by using an optimized illuminator customized for that layer compared to more standard illumination types such as annular.
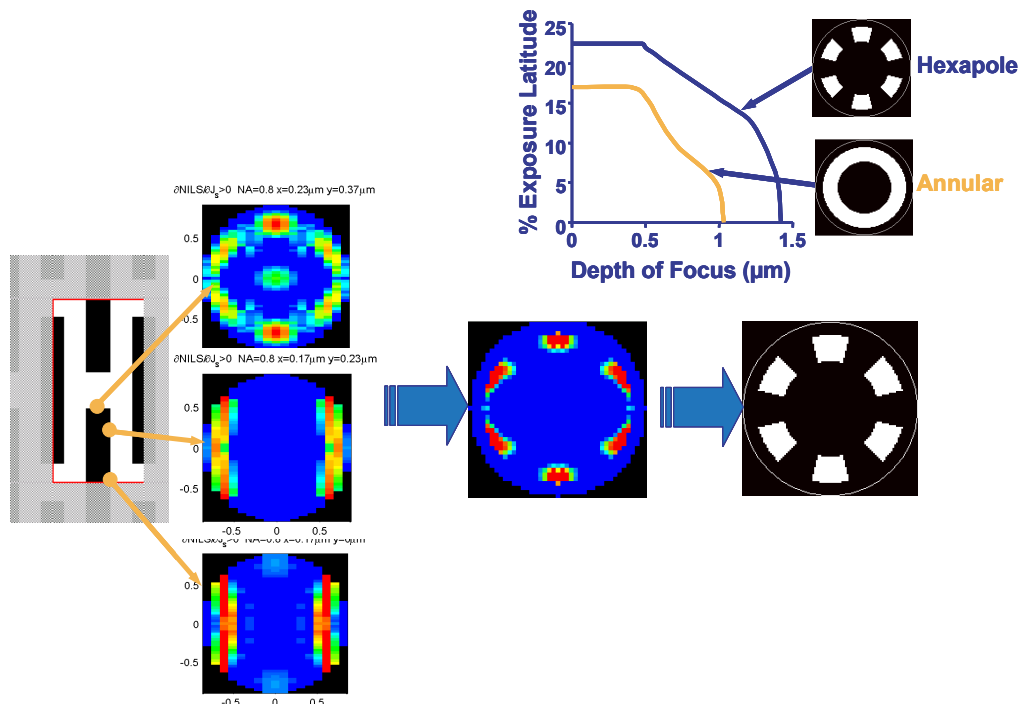

Fig. 9. The illuminator shape is designed by finding the optimum illuminator for each critical edge point, then doing a weighted sum to come up with a total illuminator shape. In this example a hexapole shape was optimum as compared to an annular shape.

At a further level of sophistication, it is possible to vary both mask layout and optimize illumination simultaneously, i.e., *source-mask* optimization[1] (SMO). This technique is based on solving the inverse imaging equation by simultaneously deriving an optimized illumination and reticle for a given optical system. An example of this approach for a sub-50nm brick-wall feature using annular illumination is shown in figure 10a. This feature has a critical line width at 45nm with a 90nm pitch. The line length is 288nm with an end gap of 72nm. In best focus, at the nominal exposure, the annular illumination shows bulging line ends with a gap of 91.6nm or a 27.2% increase of the desired gap. Using an internal ASML algorithm, the optimum mask and illumination design can be calculated and are shown in figure 16b. The shape of the brick wall with the optimization routine is much closer to the desired shape. The gap now is 82.2nm or an increase in the gap of 14.2%. This is approximately a 2x improvement in the end-of-line.
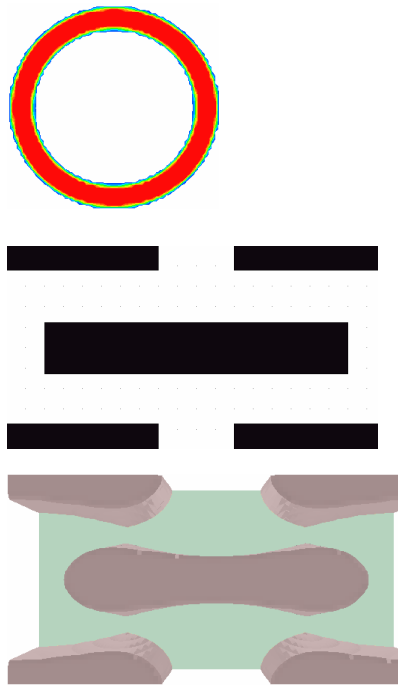
Fig. 10a. (Top) annular illumination source with souter=0.95 and sinner=0.75; (middle) traditional brick wall pattern; (bottom) resultant top-down photoresist pattern.
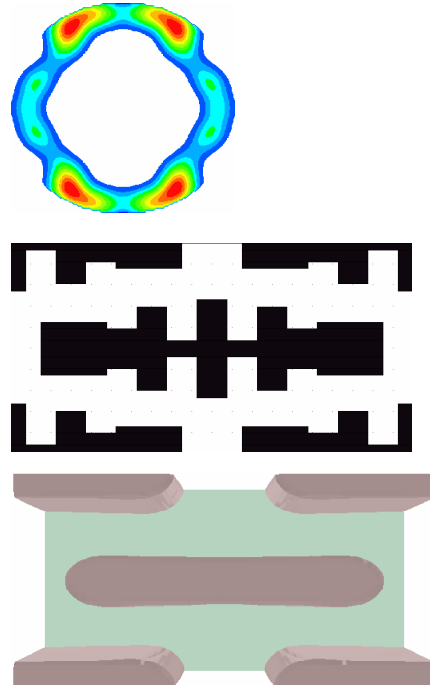

Fig. 10b. (Top) optimized illumination source; (middle) optimized brick wall pattern; (bottom) resultant top-down photoresist pattern.

In logic devices, as in many practical cases, the device is not laid out on the densest pitch possible and the critical features are often relatively isolated from neighboring features in an optical sense. The process window for printing small isolated features is usually worse than that for dense features due to small depth of focus. A very successful approach to improving process window for logic structures as might be found at, for example, gate level of a system on chip (SoC) device is to add scatter bars[12] to the mask. Scatter bars are sub-resolution mask features which improve the printing fidelity of isolated features by making them "look dense". Combined with off-axis illumination, scatter bars can increase the size of a lithography process window substantially. Automated software is available to place and size scatter bars on a given CAD layout, as well as to recommend optimized NA and illumination parameters for scanner settings (ASML Masktools product LithoCruiser™).

4. EUV TECHNOLOGY

Tremendous progress has been realized in the past year in all key areas of EUVL development. EUV systems operate at λ=13.5nm and must be in vacuum. The reticle technology, as well as the lens and illuminator technologies, uses all reflective components due to the lack of any exiting materials with acceptable transmission at this wavelength. As previously seen in figure 2, the potential gain in resolution with EUV is large, but, the realization of large scale use of this technology is not trivial. However, several small-field exposure tools are now operational around the world, and ASML has built the world's first 0.25 NA large field EUV system that is capable of use in a high volume production facility. This is an alpha demo (AD) tool and is now in the final phase of imaging qualification. The main objectives for building this tool are to provide a means to utilize this new lithographic wavelength such that risks associated with changing to a new technology can be minimized. Thus, this tool is designed to support the global development of needed infrastructure of reticles, illumination sources, and photoresists.

The alpha demo tool is fully assembled and shown in figure 11. All modules required for lithography have been integrated, and the system's metrology sensors, wafer- and reticle stages, and material handling modules have been qualified. The complete optical train comprising the illuminator and projection optics is integrated and is currently being qualified.
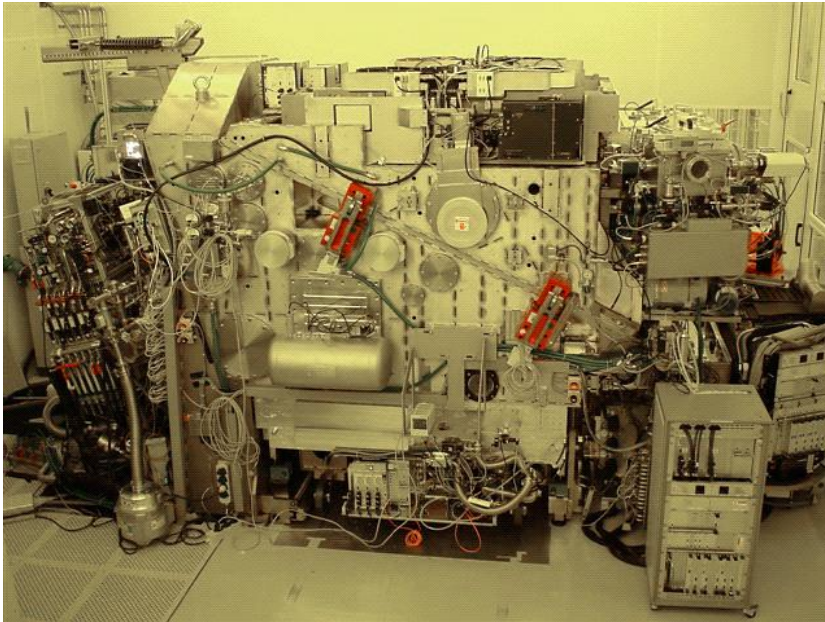
	AD-tool
λ	13.5 nm
NA range	0.15 – 0.25
Field size	26 x 33 mm^2
Wafer size	300 mm
Magnification	4x
Flare	16%
Dense L/S	40 nm
Isolated lines	30 nm
Iso/dense contact	55 nm
Overlay	12 nm
Throughput	~10 wph

Figure 11. Picture of the ASML EUV alpha demo tool and a summary of characteristic tool parameters. All modules needed for lithography have been integrated, and testing to system specifications is in process.

The ASML EUV alpha demo tool builds on TWINSCAN™ technology, adding in new modules and capabilities that are unique to EUVL. In some cases, sensors, such as used for alignment and registration, must be made vacuum compatible. In other areas, like reticle handling, an entire new module design has been developed to address particle-free transfer of reticles from atmosphere to vacuum. Key architectures such as software, electrical, and temperature control are based on TWINSCAN™, but modified to address the additional components for EUV. The vacuum system architecture is completely new. By building on the previous architecture and modules, we have been able to focus on the development of EUV-unique areas, while taking advantage of hardware that has been proven on existing ASML products. The AD-tool has been targeted for early learning of EUVL, hence it is a low throughput tool with a single stage. Still, both the reticle stage and wafer stage design concepts are extensible for high throughput EUVL.

Initial imaging results are presented in figure 12. These are 40 nm periodic lines demonstrating more than 20 nm DOF., through a focus series. Figure 13 shows these lines at best focus, but through the extent of the image field. Finally, figure 14 shows perhaps one of the greatest strengths of EUV, the ability to print dense and isolated contacts, simultaneously at the same exposure dose and focus resulting in the same dimension without the need for OPC. This is a direct consequence of imaging at high k_1.
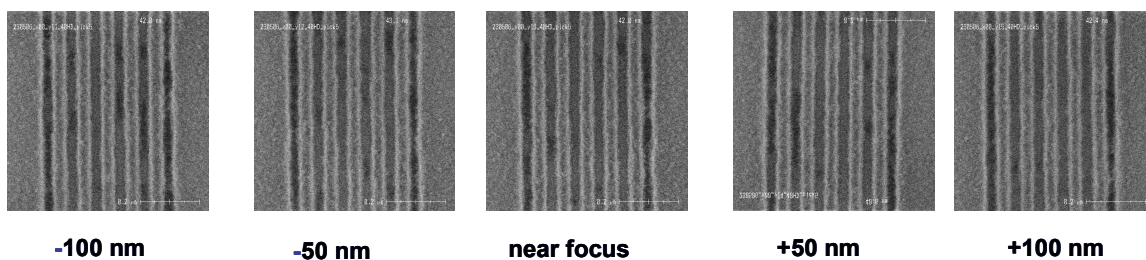

| -100 nm | -50 nm | near focus | +50 nm | +100 nm |

Fig 12. SEM pictures showing >200 nm depth-of-focus for 40 nm lines. (MET-2D resist, NA=0.25; σ=0.5 conventional illumination).

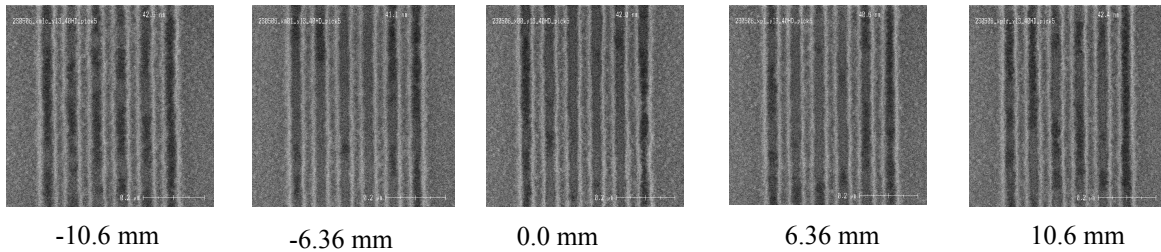| -10.6 mm | -6.36 mm | 0.0 mm | 6.36 mm | 10.6 mm |

Fig. 13. SEM pictures showing full field coverage for 40 nm lines. (MET-2D resist, NA=0.25; σ=0.5 conventional illumination).

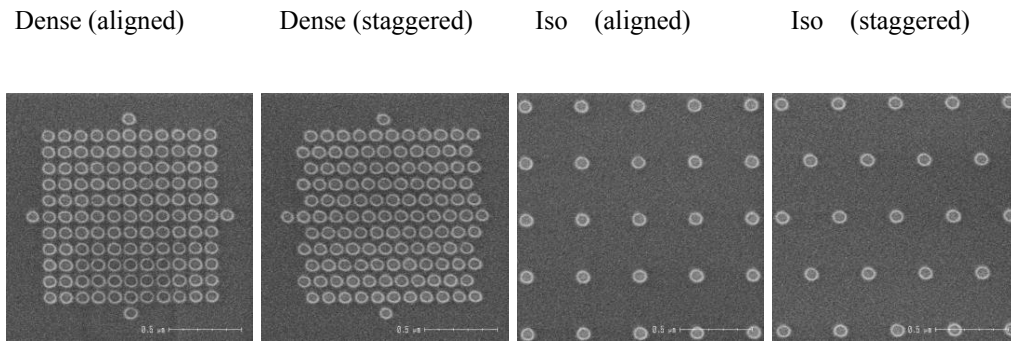Dense (aligned)   Dense (staggered)   Iso   (aligned)   Iso   (staggered)

Fig. 14. 55nm dense and isolated contact holes print simultaneously – same dose & focus.

5.   THE PROMISE OF DOUBLE PROCESSING TECHNOLOGY

Over the next few years, 193nm lithography buttressed by the twin pillars of hyper NA immersion optics and low k_1 technology, will continue the reduction shrink required by leading volume producers of integrated circuits.   In 2007, ASML will introduce a tool with NA= 1.35 which will allow mass production of memory devices at 40nm design rule. However, the refractive index (n) of water establishes the upper limit of NA which can be achieved in water immersion lithography at approximately 1.4. An aperture of at least 1.6 is required to image 32nm half-pitch resolution with $k_1 \sim$ 0.28, the current benchmark for mass production with good yields. Higher apertures will require the introduction of new fluids and possibly new glasses with higher refractive index.

 Some progress has been made in identifying a class of fluids with n ~ 1.64. However, an immersion fluid also has to satisfy a number of other physical and economic requirements as well. For example, it must have low absorption, it must have low dn/dT (small change of n with temperature), it must have viscosity and wetting characteristics suitable for high speed scanning, and it must be readily available for relatively low cost. When one considers the set of stringent requirements which must be met, one is struck with what a miracle fluid is water!

Likewise, it is difficult to find new high index glasses which could replace fused silica for the bottom lens element. Current focus is on materials such as garnets (e.g., LuAG) which have n > 2, but have very high intrinsic birefringence (IBR), a material property that makes light polarized along one axis travel slower through the material than light polarized along an orthogonal axis. Such high IBR leads to unacceptable imaging degradation. It is not currently clear if the lens designers can find ways to compensate for these effects.

If no new fluids or glasses are found and NA is limited to ~1.4, then what are some other ideas which may allow further extension of 193nm lithography? One idea which has attracted attention in the last couple of years is the use of double exposure (DE) and double patterning technologies (DPTs). Although the use of two exposures can enable a smaller k_1 to be achieved, it is not possible to resolve features at k_1 less than 0.25 even if two exposures are used in a single resist step since the combined image has zero contrast.

The DPTs that go beyond the k_1=0.25 barrier usually rely on splitting the frequencies of the pattern, and then treating each split frequency as separate lithographic images. Intermediate steps that contain developed photoresist are etched to transfer the 1st intermediate image. The result is an interleaving of the patterns that doubles the pitch. An example of this process and experimental results indicating resolution of grating patterns down to k_1= 0.19 have been demonstrated at ASML (shown in figure 15), IMEC[13], and by Ebihara[14]. Alternatively, each exposure can be done with 1 photoresist develop step, but this requires a fixation step to stabilize and threshold the 1st image such that it does not interact with the 2nd exposure.
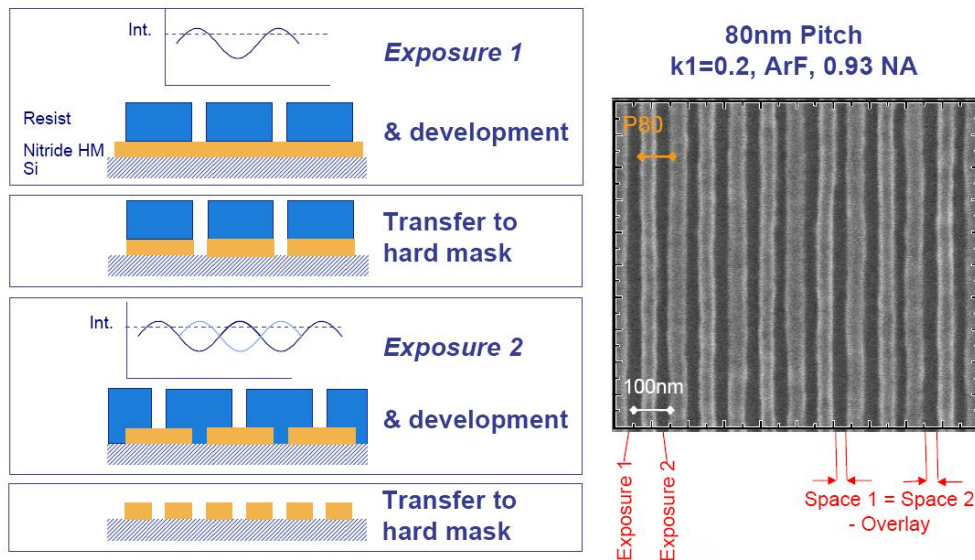

Fig. 15. Principle of Double Patterning: a method to break the effective 0.25 k_1 barrier

The advantage of DPT is that it is a relatively straightforward extension of existing technology – no new fluids, glasses, reticles, exposure sources, resists, etc. are needed to make it work. However, there are several disadvantages, a few we list here: two (or more) reticles are needed for each critical layer, and twice the number of exposures must be done effectively cutting scanner productivity by half. Thus it is clear that cost of ownership of advanced lithography will be challenged. In addition, double patterning brings with it very tight overlay requirements as overlay errors are now directly part of the critical dimension budget. A further critical issue is the availability of sophisticated design splitting software which can deconstruct a complicated pattern into two complementary patterns which can be recombined through double imaging without errors.

The technology is not limited to 193 nm wavelengths. Indeed, one can envision the use DPT to proceed down the resolution evolutionary ladder towards sub-10 nm using a future EUV lens with NA=0.35 and k_1=0.5 !

6. CONCLUSION

Optical lithography continues to provide means and methods to produce nanoscale devices on a grand scale. Recent developments in immersion, hyper-NA, EUV, and multiple patterning lithography continue to open new avenues for development and manufacturing. There are considerable challenges for further extension of 193nm lithography in both the development of high index materials to drive apertures beyond 1.4, and in further extension of low k_1 technology through double exposure (DE) / double patterning (DPT). Momentum of recent developments makes it likely these further extensions will be attempted – at what point we have to give up and say we need to move to the next wavelength (13.5 nm or EUV), will be the next great debate in the lithography community.

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