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Technology backgrounder: Immersion Lithography

1.0. Introduction

The growth of the semiconductor industry is driven by Moore's law: "The complexity for minimum component cost has increased at a rate of roughly a factor of two per year" [1]. Notice that Moore observed that not only was the number of components doubling yearly, but was doing so at minimum cost. One of the main factors driving the improvements in complexity and cost of ICs, is improvements in photolithography and the resulting ability to print ever smaller features. Recently optical lithography, the backbone of the industry for 45 years has been pushing up against a number of physical barriers that have led to massive investments in development of alternate techniques such as Scalpel, Extreme Ultraviolet and others.

Since the mid eighties, the demise of optical lithography has been predicted as being only a few years away, but each time optical lithography approaches a limit, some new technique pushes out the useful life of the technology. The recent interest in immersion lithography offers the potential for optical lithography to be given a reprieve to beyond the end of the decade.

2.0. Resolution limits for optical lithography

The minimum feature that may be printed with an optical lithography system is determined by the Rayleigh equation:

$$W = \frac{k_1 \lambda}{NA} \qquad (1)$$

where, k_1 is the resolution factor, λ is the wavelength of the exposing radiation and NA is the numerical aperture.

As minimum linewidths have shrunk, the exposing wavelength has also periodically shrunk. Table 1 lists the year, minimum linewidth generation and exposure wavelength for state-of-the-art ICs since the mid eighties. At 1.2μm and larger linewidths, the G-line output of mercury lamps (λ = 436nm) was used, at the 0.8μm (800nm) generation the I-line output of mercury lamps (λ = 365nm) was introduced for critical layers and I-line use continued to the 350nm linewidth where early adopters began to use Krypton Fluoride (KrF) Excimer Lasers (λ = 248nm) as the exposure source. KrF use has surprised many observers by persisting through the 130nm linewidth generation. With 90nm linewidths now entering production, KrF is finally running out of stream and Argon Fluoride (ArF) Excimer lasers are being introduced (λ = 193nm). Beyond ArF there are Fluorine Excimer lasers (F_2) with λ = 157nm, but there are still a number of technical challenges to overcome. Below the 157nm wavelength, the optical exposure systems must change to all reflecting optics due to high levels of absorption in refractive lens at shorter wavelengths. The introduction of an all reflective lens exposure system introduces a number of technical challenges.

At the same time that exposure wavelengths have been reduced, improvements in lens design has led to improvements in the NA of exposure systems lens, see figure 1. In the mid eighties an NA value of approximately 0.4 was typical, today 248nm exposure systems are available with an NA greater than 0.8. The physical limit to NA for exposure systems using air as a medium between the lens and the wafer is 1, the practical limit is somewhere around 0.9, with recent reports suggesting that an *NA* as high as 0.93 may be possible for ArF systems in the future [2].

Table 1. Minimum linewidth and exposure wavelength versus year.

Year	Linewidth (nm)	Wavelength (nm)
1986	1,200	436
1988	800	436/365
1991	500	365
1994	350	365/248
1997	250	248
1999	180	248
2001	130	248
2003	90	248/193
2005 (fcst)	65	193
2007 (fcst)	45	193

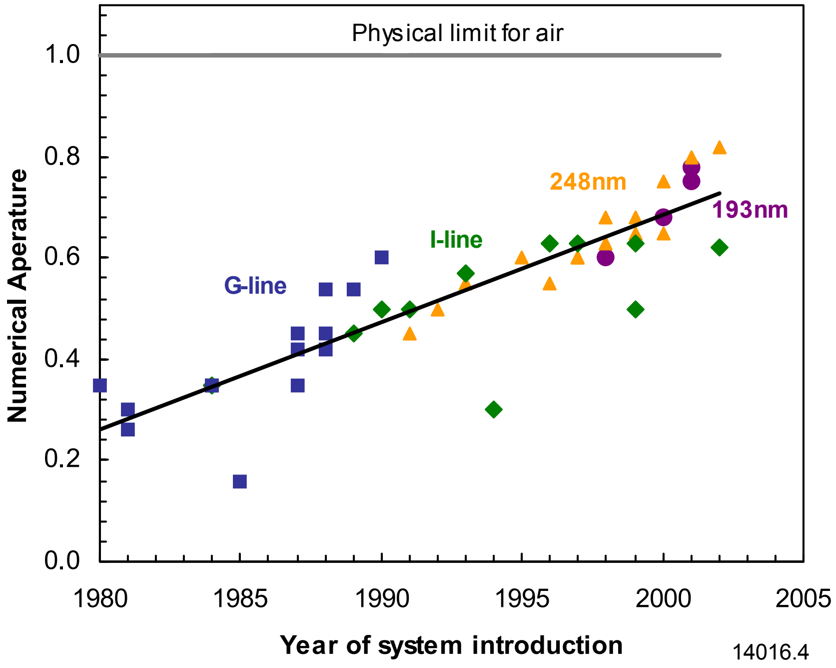

Figure 1. Numerical Aperture trend for commercial exposure systems.

The third element in the Rayleigh equation is k_1. k_1 is a complex factor of several variables in the photolithography process such as the quality of the photoresist and the use of resolution enhancement techniques such as phase shift masks, off-axis illumination and optical proximity correction. While exposure wavelengths have been falling and *NA* rising, k_1 has been falling as well, see figure 2. The practical lower limit for k_1 is thought to be >0.25.

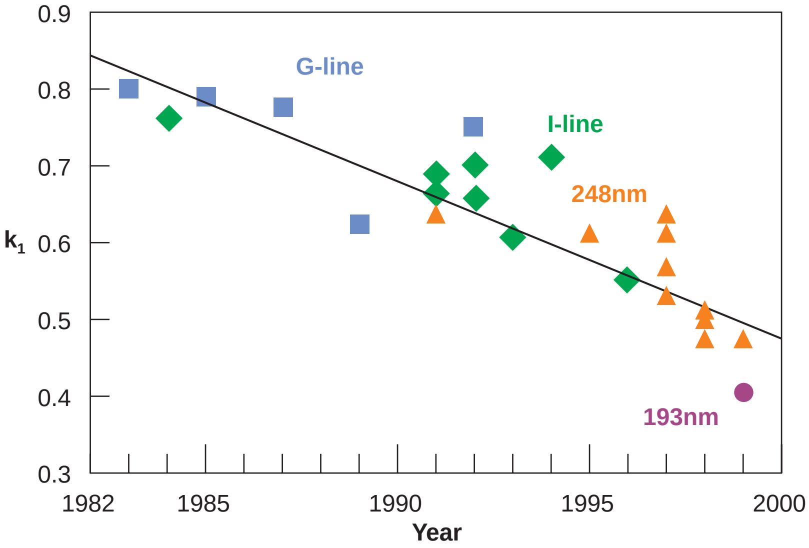

Figure 2. K_1 trend [5].

From the discussion to this point, the resolution limit for 193nm exposure systems may be calculated using the Rayleigh equation with, λ = 193nm, *NA* = 0.93 and k_1 = 0.25, see equation (2).

$$W = \frac{0.25 \times 193}{0.93} = 52nm \tag{2}$$

From equation (2), a highly optimized ArF exposure system has an absolute maximum resolution of 52nm, sufficient for 65nm linewidths forecast in 2005, but not capable of meeting the 45nm linewidths forecast in 2007.

The technical challenges with 157nm and shorter wavelength exposure systems make any technique that can improve the resolution of the 193nm exposure systems and delay the need to move to shorter wavelengths an important development.

3.0. Immersion lithography

In section 2 we noted "The physical limit to *NA* for exposure systems using air as a medium between the lens and the wafer is 1". The use of "air" in the statement was quite deliberate. NA is actually determined by the acceptance angle of the lens and the index of refraction of the medium surrounding the lens and is given by

$$NA = n \sin\alpha = d/(2f) \tag{3}$$

where, *n* is the index of refraction of the medium surrounding the lens and α is the acceptance angle of the lens, see figure 3.

Since the sine of any angle is always ≤ 1 and *n* = 1 for air, the physical limit for an air based system is clear, but what if a medium with a higher index of refraction is substituted for air? Microscopy has for years used oil the lens and the sample being viewed for resolution enhancement and it is somewhat surprising that the semiconductor industry has taken this long to seriously consider the merits of replacing air with an alternative.

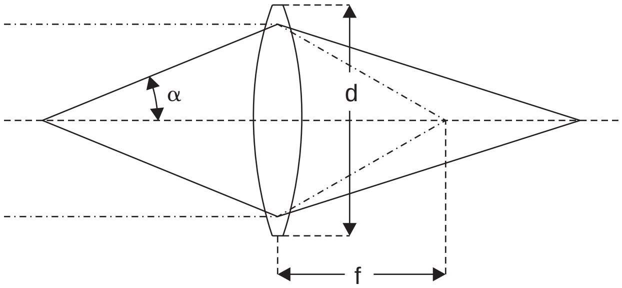

Figure 3. Numerical aperture.

The medium between the lens and the wafer being exposed needs to have an index of refraction >1, have low optical absorption at 193nm, be compatible with photoresist and the lens material, be uniform and non-contaminating. Surprisingly, ultrapure water may meet all of these requirements. Water has an index of refraction $n \cong 1.47$ [3], absorption of <5% at working distances of up to 6mm [4], is compatible with photoresist and lens and in it's ultrapure form is non-contaminating. There have been observations of significant variations in absorption between ultrapure water samples [4], but this is probably due to contaminants or dissolved gases. Plugging in $n = 1.47$ into equation 3 and assuming $\sin\alpha$ can reach 0.93, then the resolution limits for 193nm immersion lithography are

$$W = \frac{k_1\lambda}{n\sin\alpha} = \frac{0.25 \times 193}{1.47 \times 0.93} = 35nm \tag{4}$$

35nm theoretical resolution carries 193nm exposure beyond 2007. Similar techniques applied to 157nm exposure could carry optical lithography even further, although it should be noted that water is not a usable medium at 157nm and suitable mediums are still being researched.

4.0. Immersion lithography systems issues

There are a number of practical issues to implementing immersion lithography that still need to be resolved. The stage on a 193nm exposure tool steps from location to location across the wafer scanning the reticle image for each field. In order to achieve high throughput the stage must accelerate rapidly, move accurately to the next field location, settle, scan the image and then step to the next location all in a short period of time. Maintaining a consistent bubble free liquid between the lens and the wafer is very difficult. There are basically three approaches to the problem.

The first approach is to submerge the whole chuck, wafer and lens in a pool of water. The issue with the pool approach is that a complex system of servo motors and laser interferometers are required to accurately move the chuck, see figure 4, and submerging this whole system would require significant engineering.

The second approach is to limit the pool size to the top of the chuck. This technique would keep all of the chuck control mechanisms out of the water but would add considerable mass to the chuck that must rapidly accelerate.

The third technique and most likely to be used [4], is too dispense the water between the lens and the wafer with a nozzle and rely on surface tension to maintain a “puddle”. Figure 5 illustrates the puddle approach. Note how the wafer is recessed into the chuck in figure 5. The lip around the chuck is to allow edge the puddle to extend off the edge of the wafer during edge die exposure.

One issue that is likely to be significant for immersion lithography is temperature control. Variations in temperature cause variations in n and therefore image distortion. Maintaining temperature uniformity with a rapidly moving stage and a pulsed laser passing through the fluid will likely be a significant challenge.

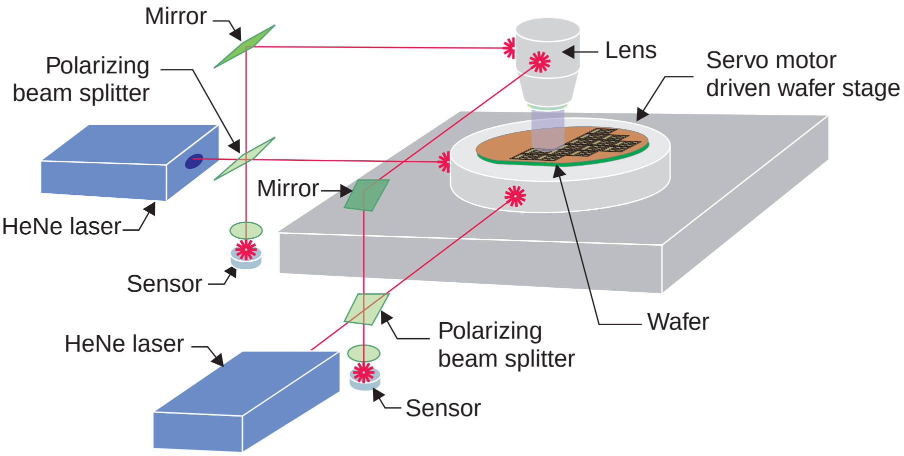

Figure 4. Stepping exposure system stage control

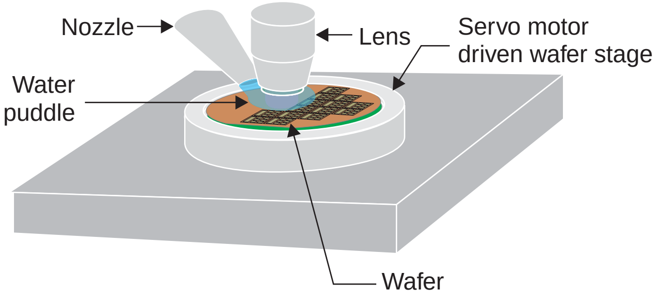

Figure 5. Immersion lithography. Stage control omitted for clarity.

5.0. Conclusion

Immersion lithography has the potential to extend 193nm - ArF exposure systems to 45nm linewidths, and 157nm - F_2 systems to <30nm. Considering the significant issues still to be resolved with all of the post optical "Next Generation Lithography" tools, immersion lithography may prove to be an essential tool for extending optical lithography through the end of the decade.

Reference

[1] Gordon E. Moore, "*Cramming more components onto integrated circuits*," Electronics, Vol. 38, N. 8, Apr. (1965).

[2] "*Intel's 157nm litho decision prompts varied reactions*," http:www.silicon strategies.com/prinatbleArticle?doc_id=OEG20030523s0057

[3] E.D. Palik, Academic Press, Boston, Vol. 2 (1991).

[4] M. Switkes, M. Rothschild, R.R. Kunz, S-Y. Baek, D. Coles and M. Yeung, "*Immersion lithography: Beyond the 65nm node with optics*," Microlithography World, p.4, May (2003).

[5] International SEMATECH.