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Ultimate lithography/Lithographie ultime

Optical lithography—a historical perspective

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Abstract

Optical lithography (also called photolithography) has been the key enabler for scaling feature sizes of integrated circuits, allowing the exponential growth of the semiconductor industry. Often in the past the end of optical lithography has been predicted but this technology is, and is expected to stay, mainstream for the next several years. This article will describe the breakthroughs which allowed photolithography fulfilling all the requirements of advanced volume manufacturing. Based on few principles of optics, this technology went through significant evolutions in the exposure tool and in the photoresist, in reducing the exposure wavelength and more recently by taking advantage of the light coherence and correcting proximity effects, esp. through advanced mask design and optimized illumination techniques. Finally this article will discuss some recent trends in photolithography. ***To cite this article: K. Ronse, C. R. Physique 7 (2006).***

Résumé

Lithographie optique—une vue historique. La lithographie optique (aussi appelée photolithographie) a été le facteur clé pour réduire les tailles de motifs des circuits intégrés, ce qui a permis une croissance exponentielle de l'industrie du semiconducteur. Souvent par le passé on a prédit la fin de la lithographie optique, mais cette technologie est et devrait rester pour les quelques années qui viennent la voie privilégiée. Cet article décrit les percées qui ont permis à la photolithographie de satisfaire toutes les exigences d'une production avancée de volume. Basée sur quelques principes d'optique, cette technologie a fait évoluer de manière significative l'outil d'exposition et la résine photosensible, en réduisant la longueur d'onde d'exposition et plus récemment en tirant parti de la cohérence de la lumière et en corrigeant les effets de proximité, en particulier par une conception de masques avancée et des techniques d'illumination optimisées. Enfin cet article discutera de quelques tendances récentes en photolithographie. ***Pour citer cet article : K. Ronse, C. R. Physique 7 (2006).***

Keywords: Optical lithography; Photoresist; Phase shifting mask; Optical proximity correction; 157 nm lithography; Immersion lithography; EUV lithography

Mots-clés : Lithographie optique ; Résine photosensible ; Masque à décalage de phase ; Correction d'effets de proximité ; Lithographie 157 nm ; Lithographie en immersion ; Lithographie extrême UV

1. Introduction

Optical lithography, also well known as 'photolithography', has always been the workhorse for volume manufacturing in the semiconductor industry. Many times, the end of optical lithography has been predicted, but still today

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in 2006, optical lithography is the workhorse and is expected to remain so for several years to come. In this article, it will be explained how optical lithography has managed to keep fulfilling all requirements for critical layer patterning in the subsequent technology nodes that have been taken to volume production.

Typically, lithography requirements for volume manufacturing can be classified under 3 main topics:

(1) *Resolution*: the lithography has to be able to keep up with the basic resolution requirements for critical dimension (CD);
(2) *Overlay*: the lithography also has to be able to meet the typical overlay requirements, which were traditionally corresponding to 1/3 of the CD as a general rule of thumb. More recently, memory applications tend to require tighter overlay as has been adapted in the 2005 ITRS roadmap update;[1]
(3) *Economics*: last but not least, the lithography has to remain cost-effective, which typically means it has to have sufficient throughput in order to keep the overall costs under control. It is clear the optical lithography has kept the overall semiconductor manufacturing costs under control, otherwise one would never have seen the integrated circuits appearing everywhere in the daily life of almost every individual (personal computers, cell phones, cars, personal digital assistants, MP3 players, TV and hifi equipment for home entertainment, ...).

2. Exposure tool evolution

The evolution of the exposure systems in optical lithography over the past 20 years played a key role in keeping improving the resolution requirements and keeping the overall economics under control.

2.1. Contact and proximity printers

The early days (1970–1980) of photolithography were dominated by contact and proximity printers/aligners (Fig. 1(a)). In the case of contact aligners, the mask, which is a replicate of the pattern that is desired in the pho-

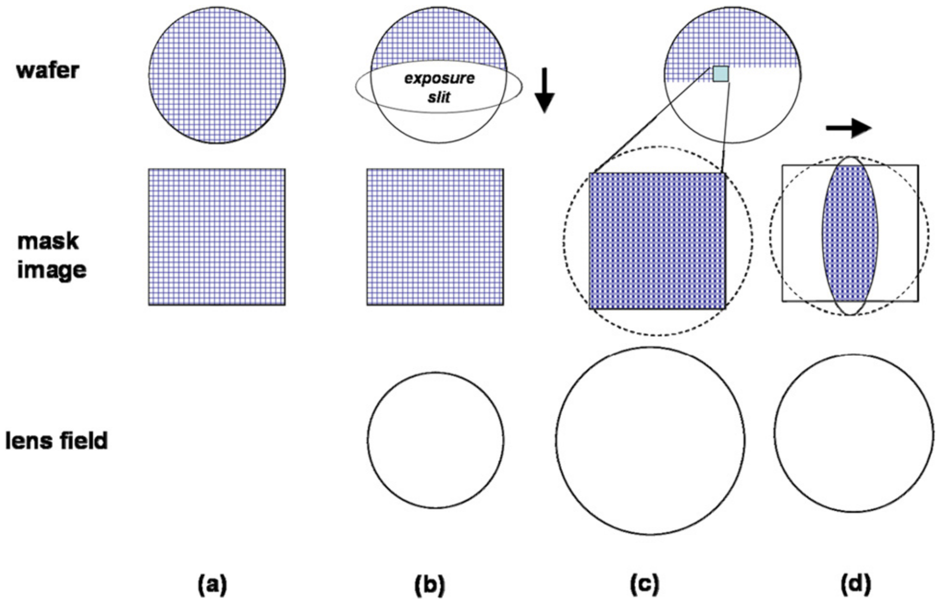

Fig. 1. Evolution of the lithography exposure tool. (a) Contact or proximity printing: the pattern is printed on the whole wafer at 1x magnification. (b) 1x projection aligner: the 1x pattern is projected through a collimated light ('exposure slit') scanned over the wafer. (c) Step and repeat system ('stepper'): the mask pattern is projected through a demagnifying optics on a part of the wafer and by 'stepping' the mask pattern over the wafer. (d) Step and scan system ('scanner'): part of the mask pattern is projected using a scanned collimated light on a part of the wafer. The mask pattern is then stepped over the whole wafer.

[1] The International Technology Roadmap for Semiconductors (ITRS) roadmap can be found on http://www.itrs.net.

tosensitive layer, is brought in direct physical contact with the photoresist and the light passing this 1x mask will selectively expose the areas in the resist where the light is transmitted.

The main issue with this type of technology is the fact that the mask will be contaminated by the photoresist due to the physical contact and needs to be cleaned after a certain number of wafers exposed, in order to avoid repeating defects being formed on every subsequent wafer. Contact aligners were typically used for dimensions between 10 to 5 μm.

In proximity printers/aligners, a small gap is kept between mask and photoresist to avoid physical contact and thus contamination. The issue was to keep this gap under control as an increasing gap size resulted in a degraded resolution. Proximity aligners were typically used for dimensions between 5 to 3 μm.

2.2. 1x projection aligners

Later on (1980–1990), projection systems were introduced, in which the image of a mask is projected by an optical system onto the wafer. At that moment, the distance between mask and wafer was becoming extremely large and contamination problems due to physical contact were no longer a concern.

Initially the masks remained 1x and contained the complete image to be projected onto the wafer, although only part of the image was exposed simultaneously (the 'exposure slit') to keep the complexity of the optics under control (Fig. 1(b)). Obviously the synchronization between the wafer and mask scanning had to be very accurate. 1x projection aligners have been used for critical dimensions between 3 and 0.7 μm.

2.3. Step and repeat systems ('steppers')

In the late 1980s, step and repeat systems with reduction projection optics were introduced, also commonly known as 'steppers'. The reason for that was that making the masks containing the pattern of a complete wafer was becoming increasingly difficult and time consuming, and with the increasing wafer sizes, the optics were growing out of proportion.

From that moment onwards, it was decided that a mask would only contain the pattern of one or a couple of dies to be printed simultaneously. This also allowed the masks to become magnified with a factor of 4 or 5 compared to the image required on the wafer, and the optical system became a reduction projection system, reducing the mask image with this same 'magnification factor'. The wafer was filled with dies by 'stepping' the masks (also called reticles from that moment onwards) with a fixed distance over the wafer after each exposure step (Fig. 1(c)). By this demagnification of the mask pattern on the wafer, also the size of the defects on the mask which were detrimental for yield became bigger allowing better and easier mask inspection and repair.

This evolution was another step in obtaining a better resolution at a manageable lens cost. Steppers have been introduced for feature sizes around 0.7 μm and were typically used for feature sizes down to 0.25 μm.

2.4. Step and scan systems ('scanners')

The last evolution in optical exposure systems was the transition to step and scan systems (also commonly called 'scanners') [1]. Here the complexity of the optics was further reduced by only projecting one slit of the mask onto the wafer and scanning wafer and reticle in a synchronized way to complete the total mask image. After that, the wafer is stepped on the next position where a new scanning operation can start.

This allows some further improvements in the optics opening the path to printing smaller dimensions with better control. Besides the effectively reduced field size of the lens (Fig. 1(d)), also some averaging of the aberrations is taking place while scanning and a more accurate focus/leveling control between the projected image and the wafer is realized on-the-fly during scanning.

Step and scan systems are being used today for manufacturing of integrated circuits of the 65 nm technology node and are expected to continue to be used down to at least the 32 nm technology node critical layer lithography.

3. Principles of optical projection lithography

As soon as optical lithography started to be based on projection systems, using an optical "lens" between the mask and the wafer, the principle of today's optical lithography has been established and may still remain unchanged for many years (Fig. 2) [2,3].

3.1. Definitions

The key input parameters in optical lithography are the exposure wavelength (λ in nm), the numerical aperture of the projection lens (NA), and the coherence factor (σ). In optical lithography, the numerical aperture of a lens is defined as the sine of the maximum outcoupling angle of light exiting a lens, measured at the wafer side, multiplied by the refractive index of the material in which the image is formed.

For traditional lithography in air, this refractive index has always been approximately 1.0, but for water immersion lithography, this refractive index increases to approximately 1.45 for 193 nm lithography.

The coherence of fill factor is defined by the numerical aperture of the condenser lens, determining the angles of light illuminating the reticle and filling part of the capture range of the projection lens. Instead of defining the absolute NA of the condenser lens, one typically uses the fill factor σ, expressing the relative capture range of the condenser lens with respect to the projection lens, both seen at the wafer plane.

3.2. Image formation in a projection system

The condenser lens has the task to illuminate the reticle in a uniform way, both in terms of light intensity and range of incident light angles (Fig. 3).

At the reticle plane, the light is diffracted in a series of diffraction orders, indicating the principal directions in which the light is traveling further with respect to the optical axis and defined by the Bragg law:

$$\sin \alpha_n = n\lambda / P$$

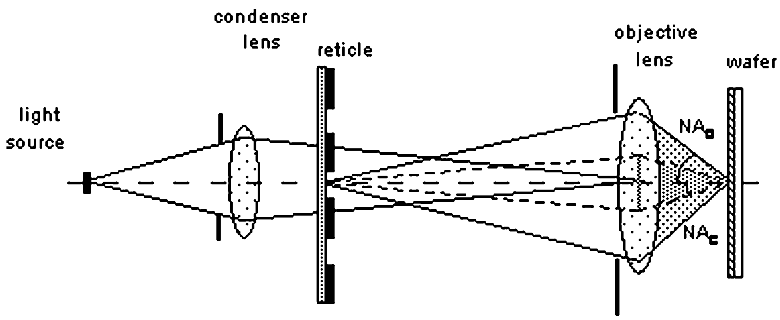

Fig. 2. Basic scheme of the optical projection lithography, where a light source projects the mask pattern through a projection optics onto the wafer.

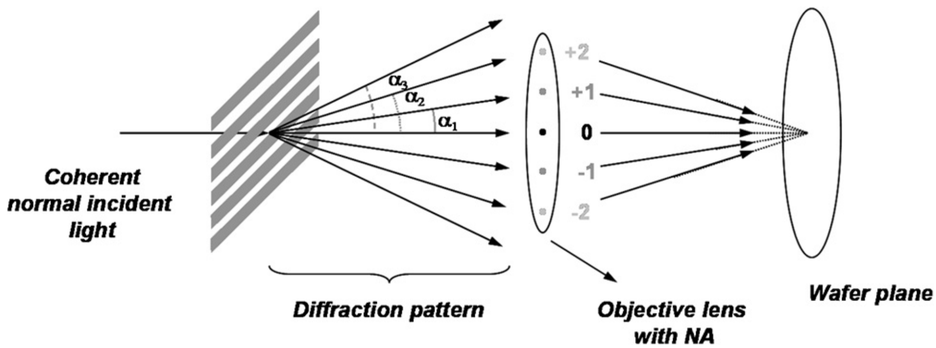

Fig. 3. The image formed through a projection lithography system uses the lower diffraction orders, the information of the high orders being lost.

with

- n: the diffraction order,
- λ: the exposure wavelength,
- α_n: the corresponding diffraction angle, and
- P: the period or pitch between the reticle apertures.

The projection lens is then going to capture the lower diffraction orders that fall within the capture range of the lens (or numerical aperture). As such, the image will be reconstructed at the wafer level as an approximation of the original mask object, since only the lower order information can be taken into account and the high order information is lost and does not contribute to image reconstruction.

Using this simple theory, the Rayleigh equation for resolution in optical lithography can be easily derived:

$$R = k_1\lambda/\mathrm{NA} \quad \text{with } k_1 > 0.5$$

This equation expresses resolution as a function of 3 main lithography parameters for coherent illumination:

- Resolution improves with smaller exposure wavelength λ;
- Resolution improves with larger numerical aperture NA in the projection lens;
- Resolution improves with smaller k_1. This k_1 factor was originally introduced to represent the quality of the resist process, but is also commonly used to represent resolution enhancement techniques like phase shift masks, off-axis illumination, OPC, etc.

4. Trends in lithographic lens design and manufacturing

One of the key drivers for improving resolution in optical lithography has recently been the increase of the numerical aperture of the projection lens. As a result, projection lenses have been steadily growing to accommodate the increased angle of light incidence as well as the increasing exposure field size [4].

The projection lens has become a considerable portion of the total price of an exposure tool. This is related to the number and size of the optical lens elements forming the projection lens. As can be seen in the Fig. 4, an exponential trend with NA is observed in the amount of optical material needed to meet the NA of the next generation projection lenses (tangens scaling trend). This would lead to an exponential trend in the lens price, which cannot be justified. Clever lens design tricks (like the introduction of non-spherical lens elements) have allowed the reduction of the amount of fused silica needed in the next generation lens, and, as such, also the lens price (Fig. 4).

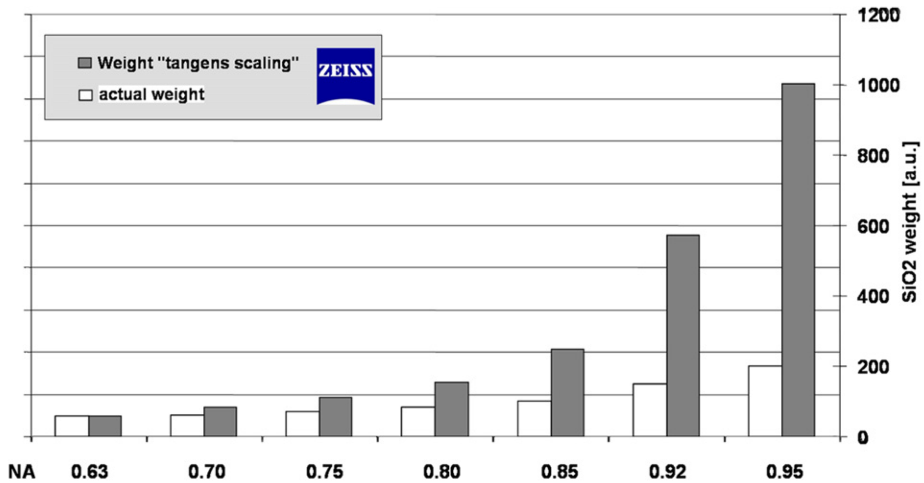

Fig. 4. Clever lens design allows keeping the lens price under control while increasing its numerical aperture.

Besides the amount of fused silica, also the polishing requirements are becoming increasingly severe, in order to control the aberration levels in the lens. With lower exposure wavelengths, higher numerical apertures and lower k_1 factors, smaller and smaller polishing deviations can be tolerated. Manual lens polishing is being replaced by computer controlled polishing machines, with nanometer accuracy.

5. Photoresist evolution

5.1. i-line (novolac) photoresists

Most commercially available i-line resists (365 nm exposure wavelength) today are positive tone and consist of a novolac polymer structure, sensitized by a diazonaftoquinone (DNQ) derivative as the photoactive compound [5].

The chemical structure of novolac polymer and DNQ is shown in Fig. 5.

The quality of the photoresist is determined by the difference in dissolution rate between the unexposed and exposed photoresist polymer. Adding DNQ to the novolac polymer typically inhibits the dissolution if the resist is not exposed, while the exposure reaction increases the dissolution rates with 2 to 3 orders of magnitude (Fig. 6)

5.2. Deep-UV (chemically amplified) resists

For deep-UV (248 nm, 193 nm), novolac resists could not longer be used because of the high absorption of the novolac polymer at 248 nm and below. To get a decent transparency, poly-hydroxy-styrene (PHS) is generally used as the resist polymer at 248 nm. In order to reduce the dissolution rate of the unexposed PHS, the PHS polymers are 'protected' by adding several types of groups to the PHS backbone. No generic sensitizer like DNQ can be named for 248 nm resists as a series of several different kind of molecules is being used.

Second, early 248 nm light sources (Mercury light bulb and KrF excimer lasers) had an order of magnitude less power than the Mercury light bulb at the i-line wavelength, and hence more sensitive resists were required for a cost effective lithography process with decent throughput.

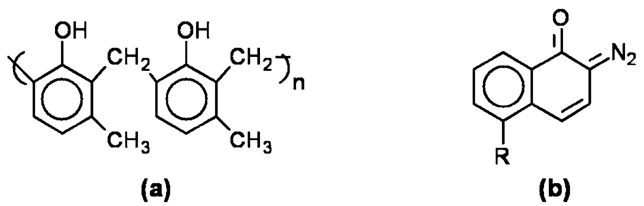

Fig. 5. Chemical structure of: (a) the novolac polymer; and (b) the diazonaftoquinone photoactive compound used in most commercial i-line resists.

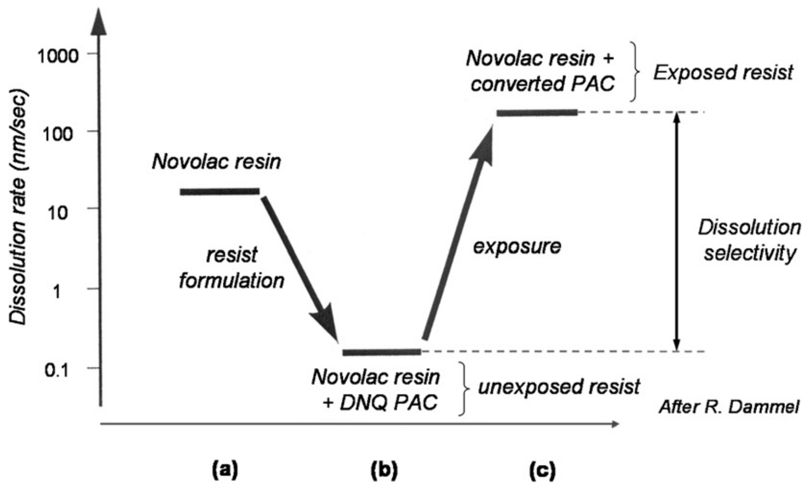

Fig. 6. Dissolution rate of: (a) novolac resin; (b) unexposed; and (c) exposed i-line resist.

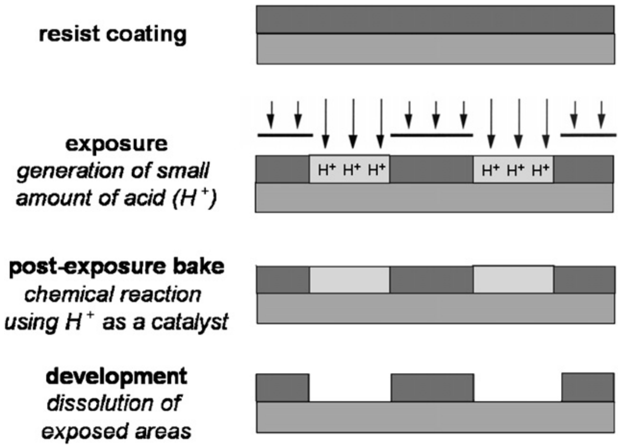

Fig. 7. In chemically amplified resists the light exposure generates protons which will 'deprotect' the poly-hydroxyl-styrene (PHS) resin in a catalytic reaction, enhancing the dissolution of the resist in the exposed areas.

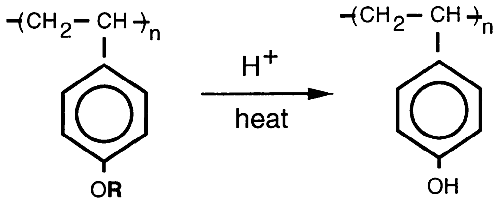

Fig. 8. Deprotection reaction in a chemically amplified resist.

Because of these reasons, the principle of chemical amplification was introduced. The exposure reaction now consists of two steps as shown in Fig. 7 (instead of one step in the case if i-line resists described above):

- During the first step, the sensitizer is forming an H^+ proton. This will, however, not change the solubility of the resist in the developer. A second step is needed;
- The second step generally consists of a bake step (post-exposure bake), in which the protons will 'deprotect' the PHS (Fig. 8). This deprotection reaction is a catalytic reaction, meaning that no protons are being consumed. One proton can deprotect thousands of PHS monomers. This is the key to increase the sensitivity of 248 nm resists by an order of magnitude. This principle is known as 'chemical amplification'.

5.3. Delay and stability problems with chemically amplified resists

The transition to chemically amplified resists did not go very smoothly initially, due to effects that were not well understood [6]:

- Line widths after resist development were not always reproducible;
- The printed lines suffered from an undevelopable resist skin on top of the resist or by T-top shapes;
- Also at the bottom of the resist lines, sometimes a large foot or undercut could be observed.

All three effects were understood after a few years of research to be caused by acid diffusion and acid neutralization that takes place after the exposure reaction, before the deprotection reaction was completed (Fig. 9):

- The observed line width variation had to do with diffusion of the acid during the delay time between exposure and post-exposure bake, resulting in smaller or larger line widths after development, depending on the duration and reproducibility of that delay.
  Solutions implemented in the resist chemistry were the use of a higher soft bake to densify the polymer structure before light exposure and as such reduce the diffusivity of acid. Also quencher was added to neutralize the acid between the exposed and unexposed resist areas, reducing diffusion as well. The most important measure against this is to keep the delay time between exposure and PEB as constant and short as possible, by linking the exposure tool with the resist coat and development tracks.
- The resist skin was caused by airborne contamination (amine, ammonia, ...) from the air that has a basic character and that neutralized the generated acid at the resist-air interface before the deprotection reaction was started or

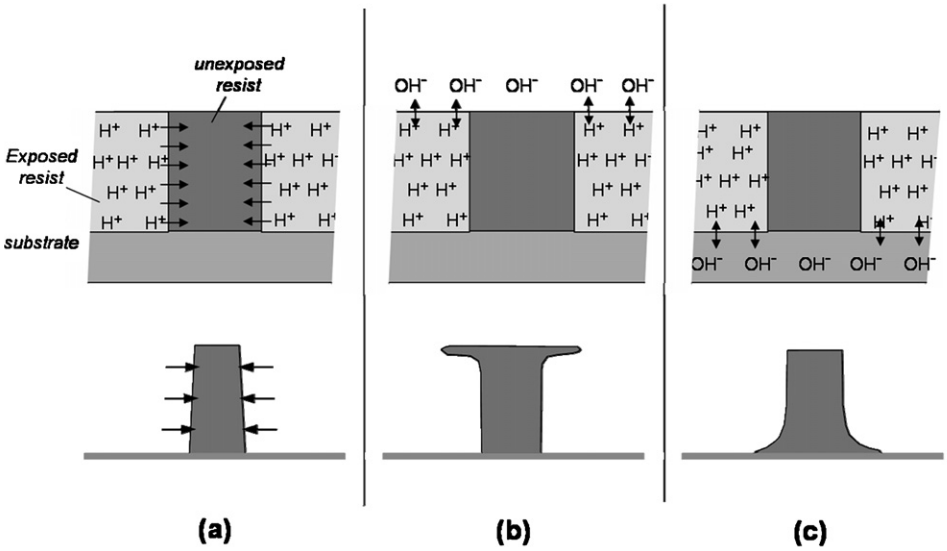

Fig. 9. Issues initially observed in Chemically Amplified Resists. (a) Diffusion of the photo-generated acid during the delay time between exposure and post-exposure bake could result in variation in CD. (b) Airborne basic contamination (esp. amine-based) results in a surface resist skin called T-top. (c) Undercut or foot at the bottom of the feature is caused by the chemical reaction between the photo-generated acid and the substrate.

completed. As a result, the top of the resist became a non-deprotected region, not soluble in the developer and gave the impression of a resist skin.
These effects were effectively solved by installing chemical filters at the top of the exposure tool and resist track. These 'charcoal' filters capture and neutralize the basic contaminants in the air, which then no longer get into contact with the resist skin. Environmental ammonia detection tools are used quite commonly in litho areas of wafer fabs to detect possible breakthrough of the filters and excessive spill peaks which can no longer be removed by the filters.

- Footing or undercut at the resist bottom has a very similar cause as T-topping, but is caused by the basic or acidic character of the material on which the resist is coated. Acidic substrate materials (like SiO_xN_y) result very often in undercuts, basic substrate materials result in foot formation.
  Solutions are the use of very thin neutral films on top of the SiO_xN_y or to bake the organic bottom ARCs to higher temperatures to reduce their basic character.

6. Low-k_1 optical lithography

Improving the resolution of optical lithography by reducing the wavelength is the last solution the industry will choose. This has impact on the complete lithography food chain. In most cases, new resist chemistries are required, new light sources, new optical materials for the projection lenses, etc. Such a transition takes easily 5 to 10 years before it is mature enough for manufacturing.

Increasing the numerical aperture of the projection lens does not need a novel resist chemistry, a new light source, but requires a new exposure tool with a new lens. This is not a cheap solution either but can generally be implemented in a more easy way and in a shorter time frame. The main issue is that the higher numerical aperture will also reduce the focus depth of the image, which may require better planarization of the wafer process. This is the one but last option the industry will choose.

The first option for the industry is to keep the same exposure tool, and try to improve its resolution by improving the resist process or by implementing some resolution enhancement tricks (also called optical extension techniques). Here the k_1-factor of the process will be scaled down.

Several low-k_1 techniques have been developed, such as phase shifting masks, off-axis illumination, optical proximity correction, etc.

6.1. Phase shifting masks

The research into phase shifting masks (PSM) really started booming in the early 1990s. Several types of phase shifting masks have been proposed then, all of which can be divided into two major classes: frequency doubling type PSM and edge contrast enhancement PSM.

All types of phase shifting masks are characterized by a phase shift layer with a phase shift as close as possible to 180°. This phase shifting material will shift the light with half a wavelength, which is ideal to interfere with a light ray that has not traveled through a phase shift layer. Both waves will have an opposite phase and cancel out each other very effectively.

6.1.1. Frequency doubling type PSM

The principle of this type of PSM [7–10] is based on applying a phase shifting layer on every second aperture of a photo-mask structure. This is illustrated in Fig. 10. By doing so, the light between adjacent apertures will have an opposite phase and will effectively be cancelled out, improving the contrast of the formed aerial image.

Although the frequency doubling PSM have enormous potential to improve resolution, focus depth and process window, their implementation in manufacturing has always been hampered by two major shortcomings: (i) applicability to random layouts; and (ii) complexity to manufacture defect free masks.

6.1.1.1. Design limitations. The attractive frequency doubling character of this type of PSM is ideal for regular structures like word- and bit-lines in memory arrays but is not so easy to apply to random logic designs. Design conflicts are very likely to occur. In that case, double exposure techniques or intermediate phase steps have to be foreseen. The first solution is detrimental for throughput of the exposure tool (although a very elegant complementary phase shift mask approach has been presented for printing the gate level of a microprocessor with heavily scaled gate lengths. In this approach, the fine lines of the gate level which run over active area are printed using the alternating PSM while the interconnecting poly lines over the field area are printed using the binary mask during the second exposure [11]), the second complicates the mask making even more.

6.1.1.2. Mask manufacturability limitations. The biggest change for mask making was that two layers have to be printed on one mask plate, in an aligned manner. Each level can give rise to defects formed, resulting in a lower yield. The biggest problem for manufacturing alternating PSM had to do with defect inspection and repair. Phase defects can be very hard to find with the existing inspection infrastructure, and even when they are found, it is hard to determine whether it is missing phase or extra phase. Mask repair for phase defects is not straightforward either. The result of all this is that alternating phase shifting masks, even if they can be made, are not guaranteed to be defect free by the merchant mask shops and as such not attractive for the industry to take into production.

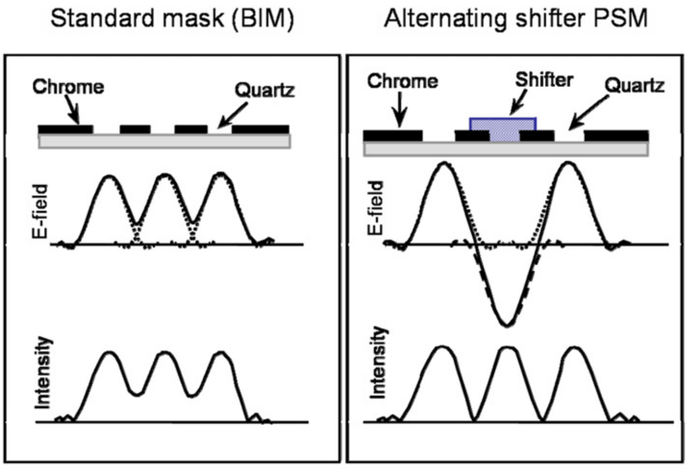

Fig. 10. Frequency doubling phase shifting mask. By inducing through a phase shifting pattern an opposite phase for adjacent apertures in a mask, the contrast of the aerial image is improved.

6.1.2. *Edge contrast enhancement type PSM*

Edge contrast enhancement type PSM [12,10] typically overcome the layout restrictions of the frequency doubling types, and also the mask manufacturing and defect inspection/repair is less complex. As a result, these types of PSM have been implemented much more widely by the industry. The drawback is that the improvements to be expected from these techniques are less pronounced, but still valuable.

A typical case of edge contrast enhancement PSM is the so-called 'outrigger' PSM (Fig. 11). Now phase shift layers are added on top of sub-resolution apertures located around each main feature. The net result of this phase shifted sub-resolution feature is an increased image contrast compared to a conventional mask.

This type of PSM has been further simplified over a 'rim' mask to an embedded attenuated PSM (or simply embedded PSM). Design limitations are no longer present, and also the mask making process has come very close to the process of conventional binary masks. The main issue of this type of PSM is that the absorber transmission must be under control: a too large transmission gives rise to ghost images (so-called side lobes), while a too low transmission does not give the expected improvements.

This type of PSM has been implemented in the most advanced contact and via layers (dark field masks) and starts to become mainstream in many advanced gate levels as well (bright field masks). The main cost increase from these masks comes from the higher mask blank cost.

6.2. *Off-axis illumination*

A completely different type of low-k_1 technique is the use of off-axis illumination. This is a technique that is not implemented at mask level but at the illuminator level [13,14].

Like frequency doubling phase shifting masks, off-axis also allows an increase in the resolution of the optical system (with a given exposure wavelength and lens NA). This is done by modifying the illumination shape so that the majority of the light is falling off-axis onto the reticle. Practical implementations of off-axis illumination are annular or quadrupole illumination (Fig. 12).

The advantage of this approach is that mask technology does not have to change, which is attractive especially for companies where the number of wafers exposed per reticle set is quite low, resulting in mask costs dominating the lithography costs.

Early limitations to implement this type of optical extensions was the fact that a large portion of the light (the central part) was blocked in the illuminator, causing low intensity at wafer level and as such low throughput. Very soon

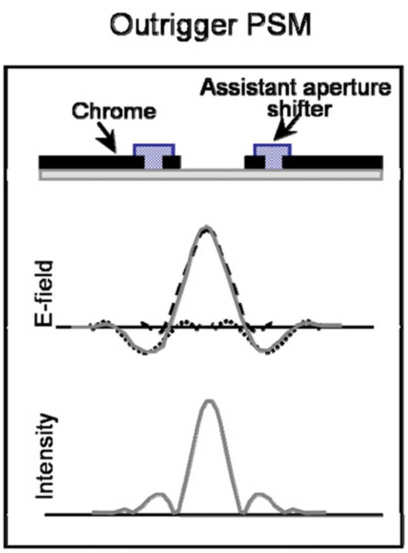

Fig. 11. Outrigger phase shifting mask. A phase shift layer is added on top of sub-resolution apertures located around each main feature resulting in an increased image contrast compared to a conventional mask.

Fig. 12. Off-axis illumination allows to increase the resolution of the optical system for a given exposure wavelength and lens NA. Shown from left to right are a standard illumination, an annular one and a quadrupole illumination.

however, exposure tool manufacturers came up with clever optical solutions to avoid that 'loss of light power'. From that moment onwards, these techniques have been widely adapted in many critical level applications.

6.2.1. Design limitations

The more generic limitations of these techniques are that they are typically only improving the imaging characteristics of specific feature types, especially high resolution dense lines. Isolated lines and also larger feature sizes benefit much less or can even be degraded by applying off-axis illumination (especially intermediate or so-called 'forbidden' pitches). Quadrupole illumination has the intrinsic property to only enhance horizontal or vertical lines, and degrades 45°orientations, requiring Manhattan type of designs. This means that one has to be very much aware of all the critical patterns that are present on the design before one can decide to use this type of illumination. As a result, this technique is particularly useful in regular patterns like memories, and much less in random logic designs where features can be completely irregular.

6.3. Optical proximity correction

The closer the resolution limits of the exposure tool are approached by reducing the k_1-factor, the larger the difference in pattern information between grouped and isolated features that will be captured by the projection lens (which essentially is a low-pass filter for diffraction orders) and used to reconstruct the image.

This statement is the fundamental explanation why optical proximity effects are occurring. In optical lithography, the trend is to correct for these effects by predistorting the mask patterns, to compensate [15–17].

Various types of optical proximity effects can be distinguished. Size differences between dense and isolated lines or contacts are the most obvious (commonly referred to as iso-dense bias). However, also line end shortening and corner rounding are seen as typical proximity effects.

Also non-optical effects such as resist development or dry etch loading effects are usually taken into account, so that the final result after litho and etch (often also referred to as 'patterning'), suffers as little as possible from residual proximity effects.

Various solutions have been proposed for predistorting the masks. The most obvious are local linewidth changes on certain segments of the mask pattern. A more elegant way is to apply sub-resolution assist features (SRAF) around the main isolated features to make all features appear as grouped features and in that way reduce the proximity effects (see Fig. 13(a)).

Line end shortening can be compensated by extending the lines, applying serifs or hammerheads (see Fig. 13(b)).

Finally, corner rounding is typically compensated by outer and inner serifs (see Fig. 13(c)).

The key for optical proximity correction (OPC) is to be able to automate the whole conversion process and reduce the turn around time as much as possible (typically one night conversion time or less is pursued). Globally two routes have been explored to implement this automation.

6.3.1. Rules based OPC

The first approach that was chosen was rules based OPC. In this case, the necessary corrections are stored upfront in a massive look-up table. Filling out the look-up table is a very time consuming job that has to be done by evaluating a specific test structure for the proximity effects observed.

During the OPC conversion process itself, the software is trying to identify each location in the layout to a specific case in the look-up table and gives the indicated correction. Rules based OPC is a single step approach and therefore very fast.

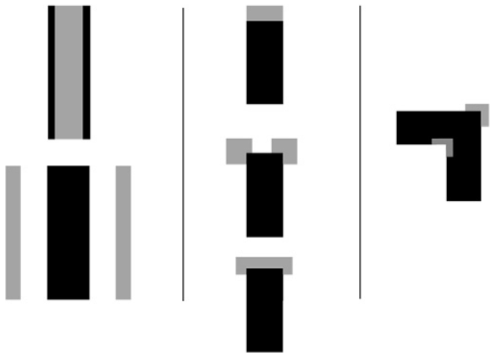

Fig. 13. By approaching the resolution limit of the exposure tool the difference between the designed pattern and the image on the wafer increases. Optical Proximity Correction (OPC) is a way to mitigate this issue by predistorting the mask patterns. (a) Addition of sub-resolution assist features (SRAF) around the main isolated features to reduce the proximity effect. (b) Reduction of line end shortening by applying serifs or hammerheads. (c) Corner rounding is compensated by outer and inner serifs.

The weakness of this approach is however that certain layout situations may not appear in the look-up table, hence no or a wrong correction will be applied. There is no way to guarantee that a look-up table is complete enough to represent any layout situation. For that reason, the trend has been shifting to model based OPC.

6.3.2. Model based OPC

In a model based OPC approach, a model will be constructed (instead of a look-up table). The model has to represent the experimental process as accurately as possible. In order to generate the model, test structures will again be used to experimentally quantify the proximity effects, and the model will be fitted to the experimental data as close as possible.

In that way, the OPC conversion process becomes an iterative process, where any layout situation will be simulated first using the calibrated model, and based on the size of the deviation of the simulated layout with the desired layout, a correction will be applied. Then the corrected layout will be simulated again, to apply a second order correction, until the layout converges to certain accuracy. A number of iterations will typically be needed, making this approach intrinsically slower. Moreover, the simulation process of a two dimensional layout is typically quite calculation intensive and needs to be implemented as efficiently as possible.

6.3.3. Hybrid OPC

Although computer power is increasing all the time, also the size of designs is increasing. As a result, there is never enough computing time to do all OPC using model based approaches only. Typically OPC conversion times should not last longer than one night. Therefore, many OPC software developers have chosen for hybrid approaches, in which first a fast and rough rules based OPC is done, after which the parts where the layout is very critical is fine-tuned using model based OPC.

7. Lithography roadmap and state-of-the-art today

193 nm lithography has been introduced in production mainly at the 90 nm technology node. Lens numerical apertures go up to 0.93 (before immersion lithography has to be used) and all critical layers utilize one or more low-k_1 techniques such as PSM or OPC. In this way, also the 65 nm technology node becomes feasible for 193 nm lithography.

7.1. 157 nm lithography

The next step to further improve the resolution of optical lithography was considered to reduce the wavelength from 193 nm down to 157 nm lithography. This development was started in the late 1990s and was initially targeting to the 65 nm technology node and beyond. In 2004, it was decided to stop all 157 nm work again.

Quite a number of challenges had to be overcome to make 157 nm a feasible wavelength:

- On the photoresist side, new polymers were needed again offering sufficient transparency at 157 nm. This was done by trying to incorporate F in the polymer structure;
- In terms of optical materials, all lens components between laser and wafer required CaF_2 for sufficient transparency (avoiding lens heating). In 193 nm lithography only a small fraction of the lens elements requires CaF_2 while most lens elements can still use high quality fused silica. The development of high quality CaF_2 in high volume and for large lens elements turned out to be a very difficult process, requiring very long and tedious cooling and annealing steps. Nevertheless steady progress was made during several years. A CaF_2 material property that has been overlooked initially was its 'intrinsic' birefringence. The discovery of that effect in 2002 required all lens designs to be modified and caused quite some delay in the development of 157 nm early exposure tools. Nevertheless, also that problem was ultimately proven to be overcome by clever lens design, alternating CaF_2 grown in different crystal orientations ($\langle 100 \rangle$ and $\langle 111 \rangle$). In order to achieve the numerical apertures required, given the laser bandwidths that could be obtained, catadioptric lens designs (instead of the traditional refractive lens designs) needed to be introduced. Catadioptric lens designs contain a limited number of reflective surfaces allowing color correction for the non-zero bandwidth of the laser;
- The complete optical path was also N_2 purged, as both oxygen and water are absorbing 157 nm light;
- Many changes were also needed at the mask level. The mask substrates needed to be doped with F as well in order not to absorb the 157 nm light. The biggest challenge was to design a 157 nm pellicle to keep defects away from the reticle patterns. During 5 years of research, no organic pellicle materials were found to have the required transparency at 157 nm wavelength along with a sufficient lifetime under typical 157 nm fluence. A parallel route to introduce a so-called 'hard' or 'thick' pellicle was started. In this case, a 300 μm parallel plate of modified fused silica had to be mounted very accurately on a frame attached to the reticle. As the hard pellicle must be regarded as an additional optical element, it has to be manufactured and mounted very accurately and the projection lens has to be redesigned to take it into account.

7.2. 193 nm immersion lithography

All the challenges mentioned above were not the main reason to remove 157 nm from the roadmap again in 2004. In fact 157 nm was really killed by the early R&D on 193 nm immersion lithography, showing good progress and looking very attractive compared to 157 nm:

- 193 nm immersion lithography allows the lens NA to be increased with a factor as large as the refractive index of the liquid, in this case water ($n = 1.44$), leading to a larger potential gain in resolution than by reducing the wavelength to 157 nm;
- Since one keeps using 193 nm light, the complete lens does not have to consist out of CaF_2, one can keep using our typical 193 nm reticle materials (substrate and pellicle), and one can start the resist optimization from a semi-mature resist platform.

Many more details on status and challenges of immersion lithograph follow in a subsequent paper in this special issue. Immersion lithography is expected to take over from 193 nm dry lithography beyond the 65 nm half pitch node, so, basically, used in the 45 nm half pitch node. Whether also the 32 nm half pitch node can be exposed using 193 nm immersion lithography is a topic of debate today. High index materials are being investigated to further enhance the capabilities of 193 nm water immersion litho, by using liquids and optical materials with higher refractive index. However, the timeliness of these materials and economic feasibility is not proven today.

Looking back at 157 nm lithography, it turns out the exploration of this wavelength has not been useless. For hyper NA immersion lithography, catadioptric lenses are being introduced. The first designs of catadioptric lenses were made for 157 nm lithography. Also the drive towards a continued improvement of CaF_2 quality for 157 nm is currently paying off in hyper NA 193 nm immersion lithography. Even some approaches in 157 nm resist development have been continued to end up with hydrophobic 193 nm immersion resists. In the quest for a high index optical lens material, the properties of stress induced and intrinsic birefringence are taken very seriously, in order not to make the same mistake as in 157 nm lithography. Looking at all these aspects, the development of 157 nm has not been a complete waste of time in view of 193 nm immersion lithography development.

7.3. *Extreme UV lithography*

From the 32 nm half pitch node onwards, Extreme Ultra Violet lithography is becoming the prime candidate on the ITRS roadmap (www.itrs.net). EUV lithography can be regarded as a kind of natural extension of optical lithography, using a very low wavelength: 13.5 nm, which improves the intrinsic resolution compared to 193 nm with a factor of 15.

On the other hand, EUV lithography is very different from optical lithography as it can only operate in vacuum using reflective optics (including reflective masks). As a result, the projection lens NA typical for EUV fall down to 0.25–0.35 which is a factor of 4 less than what is possible with immersion lithography. Overall, the intrinsic resolution gain of EUV over 193 nm immersion is a factor of 3 or more, offering a window of opportunity beyond 32 nm half pitch as well.

Many challenges remain for EUVL, such as optics, masks, light source and resists. They are explained in detail in a following paper of this special issue.

8. Conclusion

Though optical lithography was expected for many decades to reach its ultimate limit, the cleverness of disruptive approaches tends to prove that this technology will dominate the semiconductor volume manufacturing for the next decade. 193 nm immersion lithography will most likely meet the requirements of 45 nm and probably 32 nm half pitch nodes. The next big step may be EUV lithography. However, besides a purely optical performance issue in terms of resolution, overlay, ... where technical solutions are in sight, there is a growing concern for the increasing complexity and cost of obtaining an exact pattern transfer putting the burden on a more elaborated mask technology and on a costly adaptation of design data: this may be a serious obstacle for the future of the optical lithography.

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