Chapter 2

UEEP2613

Microelectronic Fabrication

Lithography

Prepared by
Dr. Lim Soo King
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Chapter 2

Lithography

2.0 Introduction

The fabrication of integrated circuit IC both MOS and bipolar devices involves a numbers of repeated major process steps. The processes can be broadly classified into wafer cleaning process, lithography (imaging, resist-bleaching and resist development), oxidation process, etching, diffusion/ion implantation, chemical vapor deposition CVD of thin film deposition, epitaxial silicon and polycrystalline process, physical vapor deposition/metal deposition or evaporation/sputtering, thin film such as silicon nitride Si_3N_4, titanium nitride TiN, Ti-W alloy, titanium silicide $TiSi_2$, tungsten silicide WSi_2 processes, and sintering/rapid thermal annealing RTA.

Lithography is a process encompasses all the steps involved in transferring a design pattern from a mask or reticle to the photoresist coated surface of silicon wafer. This is also a process to create precise dimensioned open area on silicon dioxide/silicon nitride or metallic surface. Opening on surface of silicon dioxide will allow diffusion or ion implantation of impurities into the silicon. The open area can be the opening for bond pad etc.

The process steps of lithography are cleaning wafer, deposit barrier layer of silicon dioxide SiO_2, silicon nitride Si_3N_4, metal, coating with photoresist, soft bake, align mask, expose pattern, hard bake, develop photoresist, inspection. In brief, lithography has three steps i.e. imaging, resist bleaching, and resist-development.

In the modern era of VLSI/ULSI integration, lithography can be done in several ways. Among the methods are direct writing and using mask. After the pattern generator generated the circuit pattern, the pattern can be directly written on the photoresist material film deposited on the surface of the wafer either by light source, electron beam, ion beam, X-ray sources etc.

For the case of using mask, the mask is made from pattern generator and uses light sources like ultraviolet light, ion beam, and X-ray as the exposure source to impinge pattern on the photoresist. The mask is made by mask making machine that transfer either an electron beam or laser pattern generator. It is

usually made of fused silica plate covered with a thin layer ~ 80nm of chromium.

2.1 Requirements of Lithography

Lithography process requires high resolution, high sensitivity, precise alignment, and low defect density. As the integration level is decreased, high resolution and precise alignment are required. There is little room for alignment error since the maximum tolerance is 10% of the critical dimension. Thus, for advanced and sub-micron device lithography, it needs automatic alignment system. This is a very challenging process step because one degree Celsius difference in temperature for a wafer of diameter 200mm, it can cause a difference of 0.5μm in diameter due to thermal expansion of silicon that is $2.5x10^{-6}/^{0}C$.

Lithography process needs to minimize defect density since the defect introduces in this process can be transferred to device and circuit via each successive etch or ion implantation steps, and it affects the yield and reliability of the device.

Since lithography is a high resolution process, it requires shorter wavelength photon. Modern exposure system produces diffraction limited image and diffraction effect is strongly related to wavelength of the exposing radiation.

2.2 Photoresist

Photoresists are photosensitive materials used to temporarily coat on the surface wafer and to transfer the optical image of circuit design on the mask or reticle to surface of wafer. Unlike the photosensitive material coat on the plastic of photographic film, the material is not sensitive to normal visible light, not sensitive to change of color or gray levels of the light. Photoresist material is sensitive to ultraviolet UV light. Thus, in lithography process, it does not require a dark room. It is usually done in yellow light room, whereby the photoresist material is not sensitive to yellow light.

There are two types of photoresist, which are positive and negative types. For a negative type, the exposed part of the photoresist becomes cross-linked, polymerized, and harden due to photochemical reaction. The polymerized part remains hard and not soluble to aqueous developer solution. The unexposed part remains not cross-linked and becomes soluble in aqueous developer solution.

The positive photoresist is mainly resin, which is a cross-linked polymer before exposure to light. After exposing to UV light, the exposed part becomes soften due to photochemical reaction called *photosolubilization* and it will be dissolved in developer solution. Figure 2.1 shows the lithography pattern process using negative and positive photoresists.

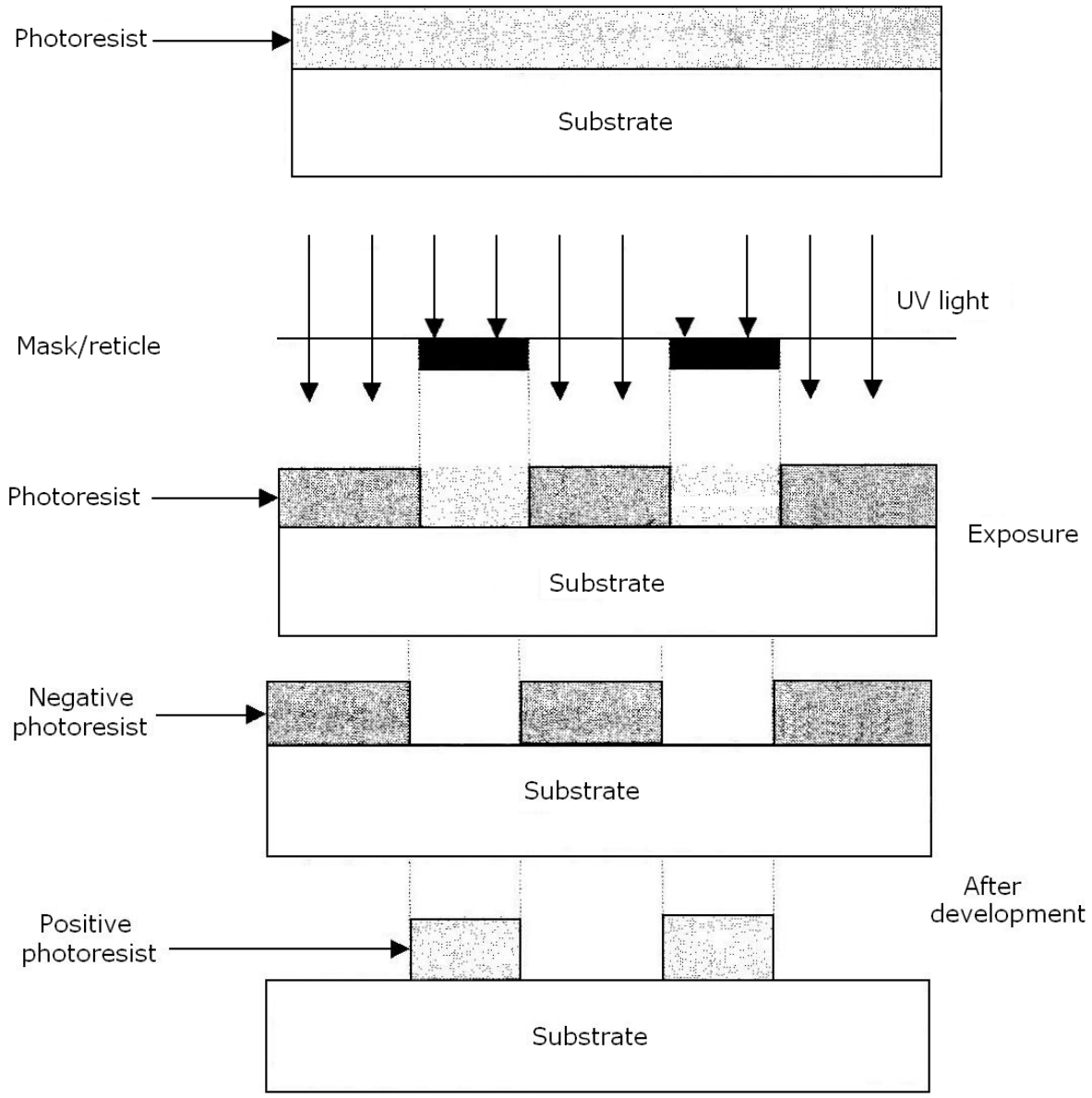


Figure 2.1: Pattern process with negative and positive photoresists

In the advanced semiconductor fabrication, positive photoresist is usually used for lithography process due to high resolution requirement for sub-micron feature size. Negative photoresist is widely used in semiconductor industry before 1980 because the feature size of the device is larger than 3.0μm.

Photoresist material has four components. They are polymer, sensitizer, solvent, and additives. Let's discuss one by one and emphasize on the importance of each component.

2.2.1 Polymer

Polymer is an organic solid material that sticks on the surface of wafer and it can withstand etching process and ion implantation. The polymer is an organic compound, which is hydro-carbon C_xH_y with complicated chain and ring structure. The most commonly used positive photoresist polymer is phenol-formaldehyde or novolac resin. The most commonly used negative photoresist polymer is polyisoprene rubber.

2.2.2 Sensitizer

The sensitizer is an organic compound with very high photosensitivity that controls and modifies the photochemical reaction of photoresist during exposure. The sensitizer of positive photoresist is a dissolution inhibitor, which is cross-linked with resin. During exposure, the energy of the light dissociates the sensitizer and breaks the cross-link of the resin and makes it soluble in aqueous developer solution.

The sensitizer of negative photoresist is an organic molecule containing N_3 group. Exposure to light will liberate nitrogen N_2 gas forming free radical that helps to cross-link the rubber molecule. The chain reaction of the cross-link polymerizes the exposed area, which has greater bonding strength and higher chemical resistance.

2.2.3 Solvent

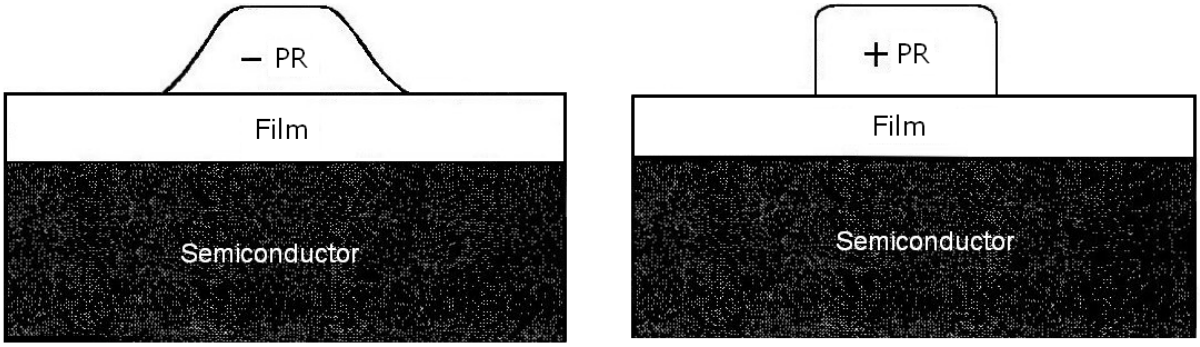
Solvent is the liquid that dissolves the polymer and sensitizer and suspends them in the liquid photoresist. It makes photoresist easy to apply on the surface of wafer that has thickness ranges from 0.5 to 3.0μm. The solvent thins the photoresist to allow the application of thin layer by spinning. Before spin coating, about 75% of photoresist is solvent. Solvent for positive photoresist is commonly acetate-type solvent, while negative photoresist is xylene C_8H_{10}.

2.2.4 Additive

Additive control and modify the photochemical reaction of photoresist during exposure to achieve optimized resolution. Dye is the common additive for both

positive and negative photoresist that reduces reflection from the surface of wafer that improves the resolution of the exposure.

The developer solution of negative photoresist is mainly xylene. It dissolves the unexposed uncross-linked photoresist. It causes photoresist to swell to about three times the thickness of photoresist that affects resolution. Positive photoresist does not absorb the developer solution. Thus, it can achieve higher resolution. Figure 2.2 illustrates the resolution of negative and positive photoresists.



(a) (b)

Figure 2.2: Resolution of negative and positive photoresists

To pattern small feature, short wavelength exposure light is required. Lithography process uses deep ultra violet light with wavelength either 193nm or 248nm. However, different wavelength requires different photoresist.

2.3 Lithography Process

The process of lithography has three basic steps, which are photoresist coating, exposure, and developing. To achieve high resolution, lithography process also has a number of baking process and chilling process. The process steps of lithography are basically consisting of eight steps. They are wafer cleaning, pre-bake and primer vapor coating, photoresist spin coating, soft bake, alignment, exposure, post exposure bake PEB and development, hard bake, and pattern inspection. The flowchart of the lithography process is shown in Fig. 2.3.

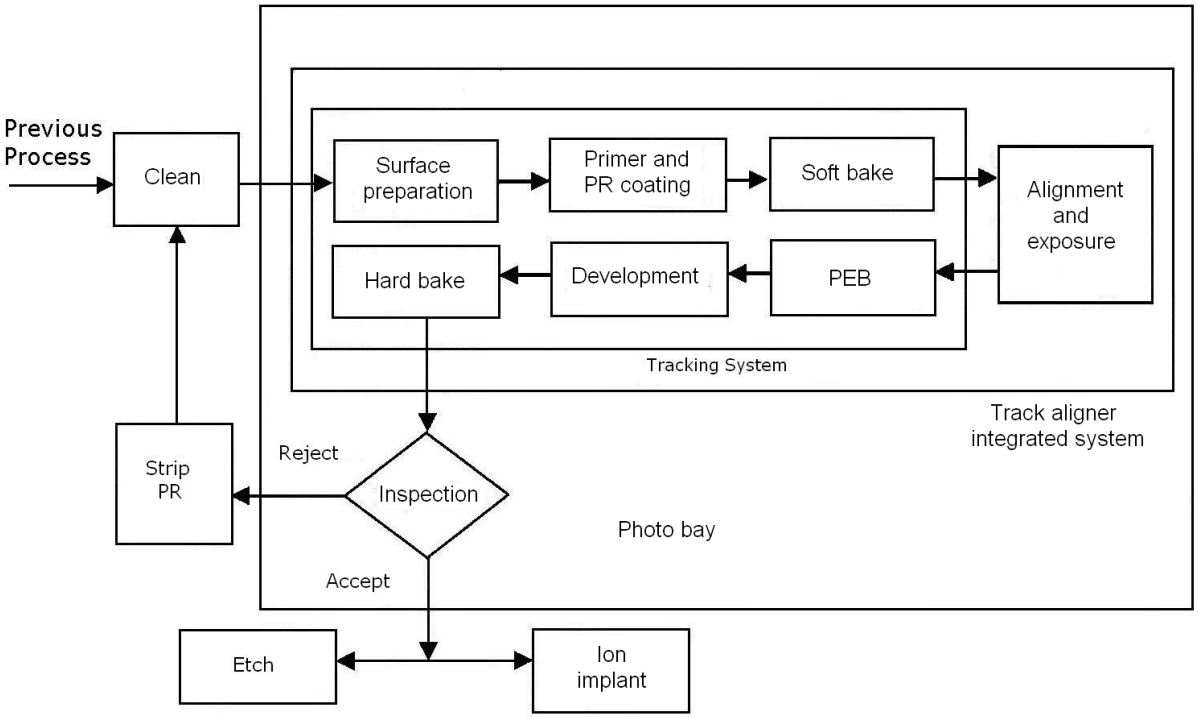


Figure 2.3: Flowchart of lithography processes

2.3.1 Surface Preparation

Surface preparation step is a two-step process, which consists of cleaning the surface of wafer and primer coating step.

It is necessary to keep away organic and inorganic contaminants, bacteria, debris of human skin, and dust particles such as residue from container etc from previous process steps such as etching, ion implantation and annealing, oxidation, chemical vapor deposition CVD, physical vapor deposition PVD, chemical mechanical polishing CMP etc before lithography process. Thus, it is necessary to clean the wafer before beginning of lithography process. The wafer can be cleaned using RCA clean 1 and clean 2 solutions to remove organic and inorganic contaminants respectively. It is then followed by final DI water rinsing before being spinned dry.

Other methods of cleaning are dry air or nitrogen blow, high pressure steam blow, oxygen plasma ashing, and mechanical brushing. These methods work well for device having long length channel. As the device shrinks to sub-micron dimension, these methods are not suitable to get rid of smaller dust particle.

After cleaning, the next process of wafer surface preparation is primer coating before photoresist coating. It is done in preparation chamber. The first

step is the dehydrate bake or pre-bake process. This step is used to remove water moisture from the surface of the wafer. This step is necessary to ensure the surface of wafer is dry to provide good adhesion of photoresist on the surface. Poor adhesion can lead to failure of photoresist patterning and cause undercut during subsequent etch process. In most case, the wafer is pre-baked for one to two minutes using a hot plate with temperature ranged from 150^0C to 200^0C. If the temperature and duration of pre-bake are not sufficient, dehydrated surface may not be able to achieve optimize adhesion.

Priming process step is a process step that depositing a thin layer primer on the surface of wafer. The purpose is to wet the surface for good adhesion of organic photoresist with silicon surface, metallic surface, or silicon dioxide etc. Hexamethyldisilazane HMD or $(CH_3)_3SiNSi(CH_3)_3$ is the most commonly used primer. In sub-micron process, HMD is vaporized in the preparation chamber and deposited on the surface of wafer in situ with pre-bake process. After the process, it is important to apply photoresist coating immediately to prevent surface dehydration. However, photoresist coating cannot be applied while the wafer is still hot. This is because the solvent in photoresist will cool down the hot wafer and at the same time lose due to vaporization. This makes it not desirable for the photoresist process because there are change of viscosity of the photoresist, the thickness of photoresist, and uniformity of the photoresist. The hot wafer is normally chilled to ambient temperature on chilled plate, which is a water cooled process by heat exchange on the same track system.

Primer step can be coated by spin on process in situ with photoresist coating. But this method is not as popular as the vaporized method due to the fact that vaporized priming will introduce less contaminant and less HMD is used. Unlike the spin type, contaminant can be carried in liquid chemical. Spin coating of primer is normally done by dispensing the liquid primer and spin at low rate and then ramping up to of 3,000 to 6,000rpm for 20 to 30s to dry the HMD.

2.3.2 Photoresist Coating

This is a process of depositing a layer of thin photoresist material on the surface of wafer. The wafer is placed on spindle with a vacuum chuck that can hold the wafer during the high speed rotation. Usually the thickness of photoresist coating is between 5,000 and 30,000 $\mathring{A}$. Photoresist has high viscosity and very high surface tension force. Thus, high spin rate is needed. The higher the spin rate, the thinner will be the thickness that would give better uniformity of the photoresist layer. Photoresist thickness is inversely proportional to square root

of spin rate. Figure 2.4 illustrates the thickness and its relationship with viscosity and spin rate of wafer. It is clearly shown that the higher the spin rate, the thinner is the thickness and also the higher the viscosity, the thicker will be the photoresist.

The photoresist is normally dispensed at the center of wafer while the wafer is spinned at rate of 500rpm. After photoresist is dispensed, the wafer is accelerated to a spin rate of 700rpm to spread the photoresist uniformly across the surface of wafer. The dynamic dispense method uses less photoresist material, whereas static dispensing can achieve better photoresist uniformity. Figure 2.5 shows the change of spin rate in a dynamic dispense photoresist coating.

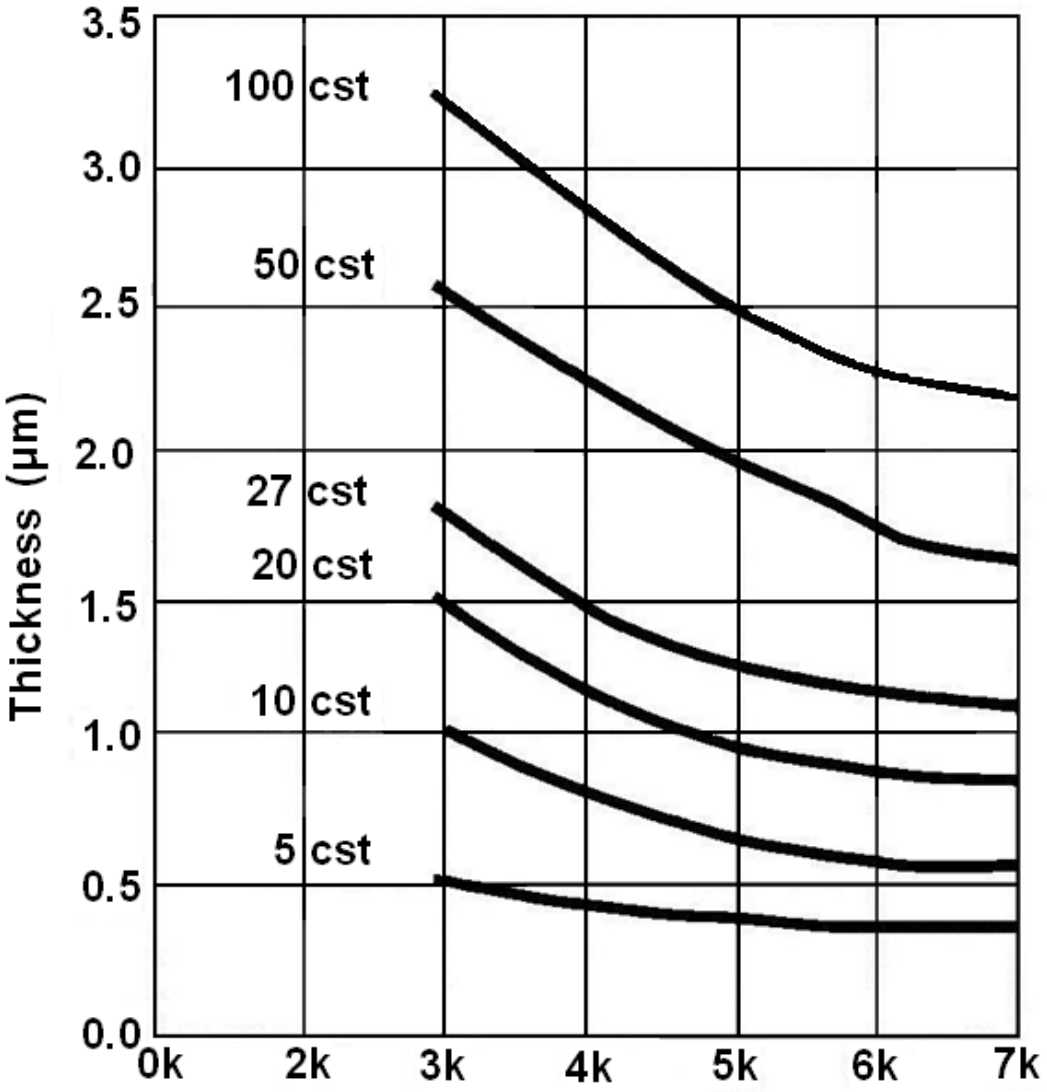


Figure 2.4: Thickness of photoresist and its relationship with spin rate and viscosity in centi-Stoke

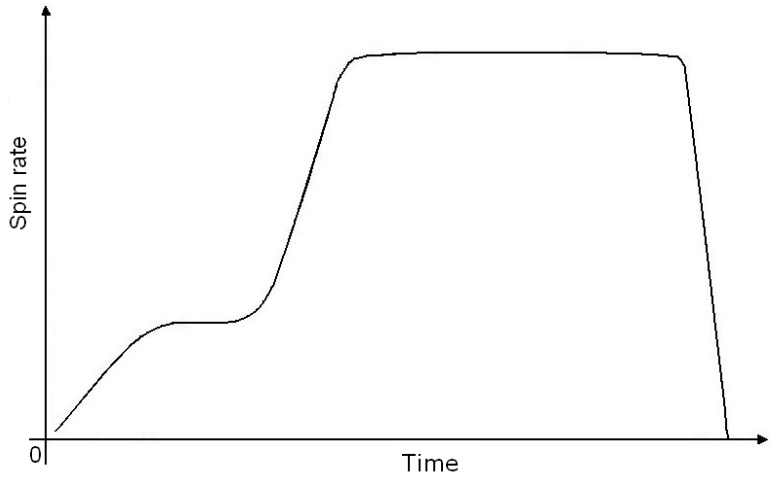


Figure 2.5: Spin rate of dynamic dispensing

It is important to know that once the photoresist is dispensed, it must be spinned as quickly as possible because the solvent in photoresist is evaporating very fast and photoresist will become viscous. In some processes, a thin layer of solvent is spinned on surface before photoresist is spinned on to provide better adhesion and uniformity. The dispenser also provides the feature of drawback of photoresist to prevent the dry droplet of photoresist accumulating at the nozzle of the dispenser due to evaporation of solvent.

Owing to centrifugal force and surface tension force, the thickness of photoresist coating at the edge of wafer will be thicker. It is necessary to remove it because thick edge causes focus problem during exposure, clamping by robotic arm causes crack, and causes contaminant to build up. There are two methods to remove the thick photoresist at the edge. The methods are chemical and optical methods. Chemical method uses edge-bead removal solution EBR as shown in Fig. 2.6. With the wafer spins on spindle, solvent sprayed at the edge of the wafer as shown in Fig. 2.6(a) dissolves the photoresist and drained away the photoresist as shown in Fig. 2.6(b). The optical method is done after patterning.

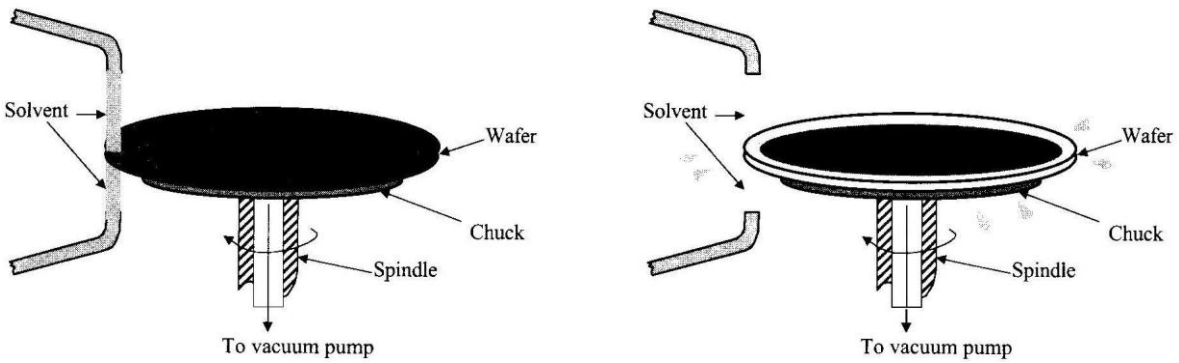
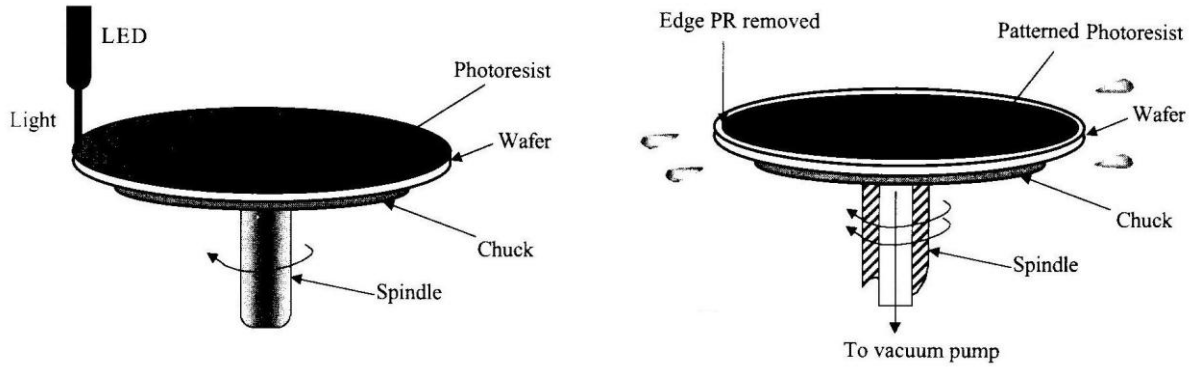


Figure 2.6: Chemical edge-based removal

As shown in Fig. 2.7, light from light emitting diode is shinned on the edge of spinned wafer as shown in Fig. 2.7(a). The light would dissociate the cross link of the polymer and it would subsequently dissolve in aqueous development solution as shown in Fig. 2.7(b).



(a) (b)

Figure 2.7: Optical edge-based removal

2.3.3 Soft Bake

Soft bake is necessary to further drive away the solvent in photoresist so that it turns the photoresist in liquid form to solid form. Soft bake also improves the adhesion of the photoresist to the surface of silicon wafer. After soft baking, the thickness of PR shrinks about 10% to 20% and the residue of solvent reduces to 5% to 20%. Depending on the type of photoresist used, the baking temperature and duration are typically from 90^0C to 120^0C for about 30 minutes.

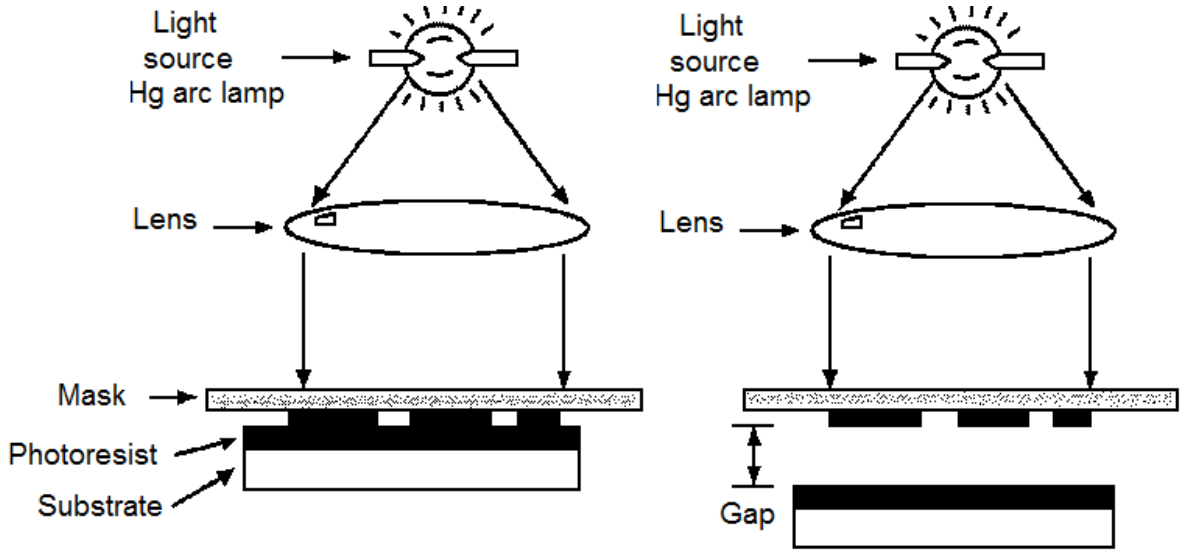
There are several methods for soft baking process. It can use convection oven, infrared oven, microwave oven, and hot plate. The convection oven uses convection flow of the heated nitrogen gas to heat the wafer at the required temperature, which is from 90^0C to 120^0C. The infrared oven can bake the wafer in a shorter time.

After soft bake, the wafer is placed on a chill plate to cool down to ambient temperature. It is very important to keep the temperature difference of about 1^0C between temperature of the wafer and ambient temperature because a degree Celsius difference can cause 0.5μm difference for a 200mm silicon wafer due to thermal expansion effect.

2.3.4 Alignment and Exposure

Alignment and exposure are the most critical steps of the lithography. Indeed, it is also the most critical process of the whole fabrication. An alignment system must have high resolution, high repeatability and reliability, and high throughput. The two main types of alignment and exposure process are the contact and proximity printer, and projection printer.

Contact and proximity printers as illustrated in Fig.2.8 were widely used in the earlier year where the dimension of the device is large. In contact printing process as shown in Fig. 2.8(a), the mask is made directly contact with photoresist on the surface of wafer so that the ultraviolet UV light can pass through the clear pattern from the mask and expose the photoresist underneath. This type of printing process can achieve very good resolution. However, due to curvature of the mask, there are a few points of the mask are actually in contact and most parts of the mask are about 1.0 to 2.0μm above the photoresist.



(a) (b)

Figure 2.8: (a) Contact and (b) proximity printing

For every contact printing alignment and exposure, the contact and detach between mask and photoresist will accumulate particle on the surface of mask and cause defect on the wafer from both particulate contamination particle image transfer. As the result, the lifetime of mask is seriously limited by particle contamination. To solve this problem, engineer adapted an approach by putting the mask about 10 to 20μm away from photoresist as shown in Fig. 2.8(b). This is called *proximity printer*. Since there is no direct contact, there is less contamination. The trade off of this method is resolution because of more

diffraction of light. However, the best resolution can be achieved is 2μm above the photoresist. Neither contact nor proximity printers are used in today's VLSI/ULSI chip fabrication.

Figure 2.9 shows the schematic of proximity printing. W is the width slit, while g is the distance between photoresist planes and mask. It is illuminated by a monochromatic light source of wavelength λ. If g and W are larger than the wavelength λ of the light source such that $\lambda << g < W^2/\lambda$, which is in the region of Fresnel diffraction, the diffraction formed the image of the slit is a function of wavelength λ, W, and g. It is called parameter Q, where Q is equal to defined by equation (2.1).

$$Q = W\sqrt{2/(g\lambda)} \tag{2.1}$$

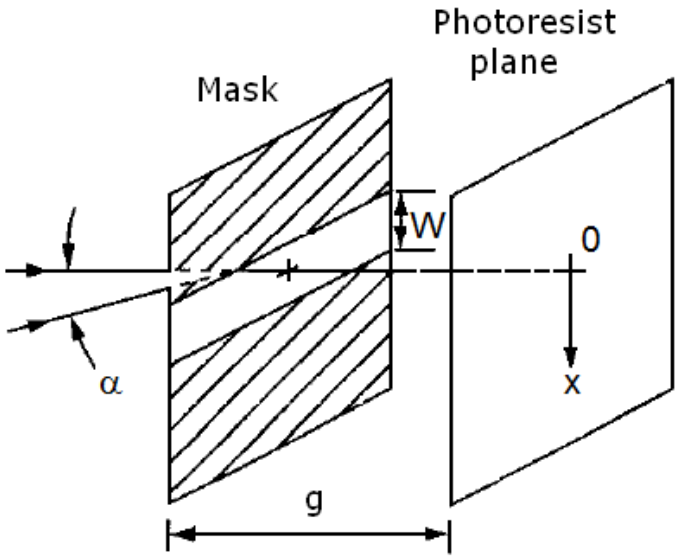


Figure 2.9: Schematic proximity printing

This parameter can be considered as a normalized slit width. The lower limit of the near field diffraction region is at $Q = \sqrt{2}$ or $g = (W^2/\lambda)(2/Q^2) < W^2/\lambda$. Thus, the resolution W becomes better at smaller gap and shorter wavelength and is also equal to minimum resolvable feature size as shown in equation (2.2). i.e. when $Q = \sqrt{2}$.

$$W = \sqrt{g\lambda} \tag{2.2}$$

The height of photoresist image, for practical purposes is converted to photoresist thickness and mask-wafer gap, has been measured as a function of line width, wavelength, and intensity tolerance. The optimum image heights of

0.25μm and 0.5μm patterns are 0.9μm and 3.2μm respectively in the case of a deep ultraviolet light DUV (wavelength less than about 200nm) light source with ±5% intensity tolerance.

Another parameter is the divergence of the illuminating beam as a result of the size of the light source. One effect is to smooth out the undulations in the image intensity profile, and the other is to produce a greater line width variation as the mask-to-wafer distance varies. The apparent source size of the illumination system must be large enough to give a value of λ that allows the smallest features to be printed. The mercury arc lamp used as the source is too small to yield the required wavelength λ. The illumination is telecentric or normally incident at the mask to prevent run-out (magnification) error similar to that in X-ray lithography. The optical system must also minimize non-uniformity of the intensity across the field. The illumination system needs to have a large enough α and normal incidence. With a mercury arc source, the strong lines at G-line 436nm, H-line 405nm, and I-line 365nm. It can provide the exposure sufficient flux. The same printer is available with a xenon mercury Xe-Hg source for enhanced output in the 200-300nm spectral regions.

Projection printing as shown in Fig. 2.10 improves the exposure resolution while maintaining low particle contamination level.

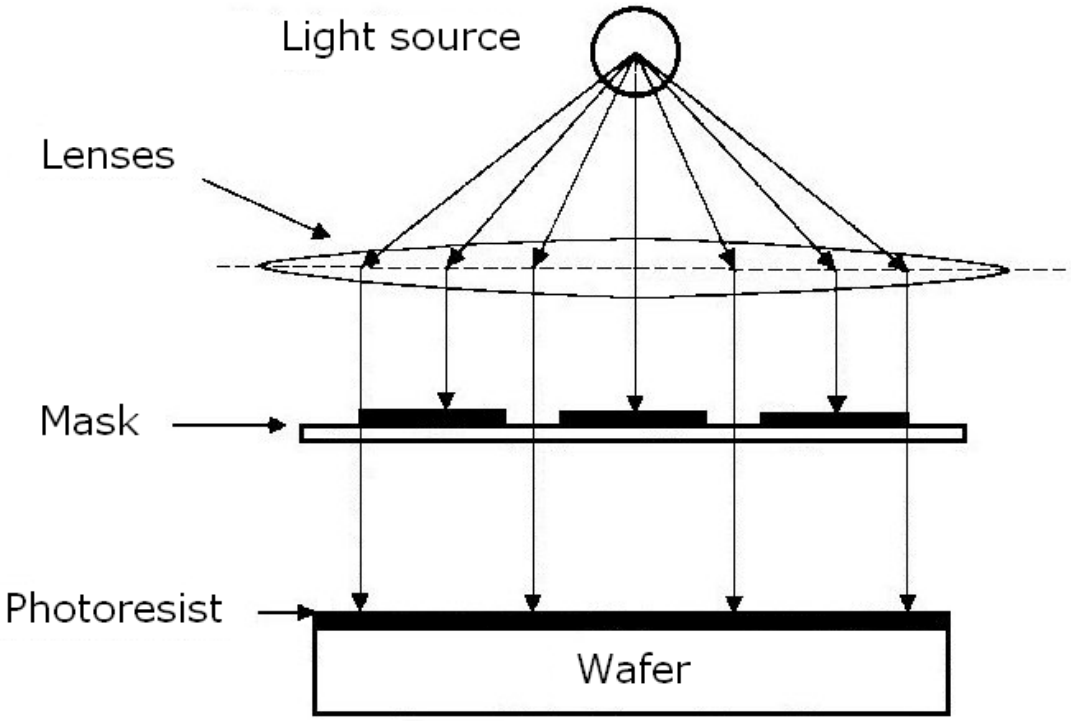


Figure 2.10: Projection printing

Projection exposure system was developed and became widely used in VLSI semiconductor device fabrication. It has a larger separation between the mask and the wafer because of its image formation system. According to Rayleigh's criterion, the resolution W of the optical system is given by in equation (2.3).

$$W = k_1 \lambda / NA \tag{2.3}$$

k_1 is equal to 0.6. It is used to account for process type and numerical aperture NA of the lens.

The depth of focus DOF as illustrated by Fig. 2.11 is given by equation (2.4).

$$DOF = \frac{\pm W/2}{\tan\alpha} \approx \frac{\pm W/2}{\sin\alpha} = k_2 \lambda / \left(2NA^2\right) \tag{2.4}$$

k_2 is known as Rayleigh's coefficient for DOF.

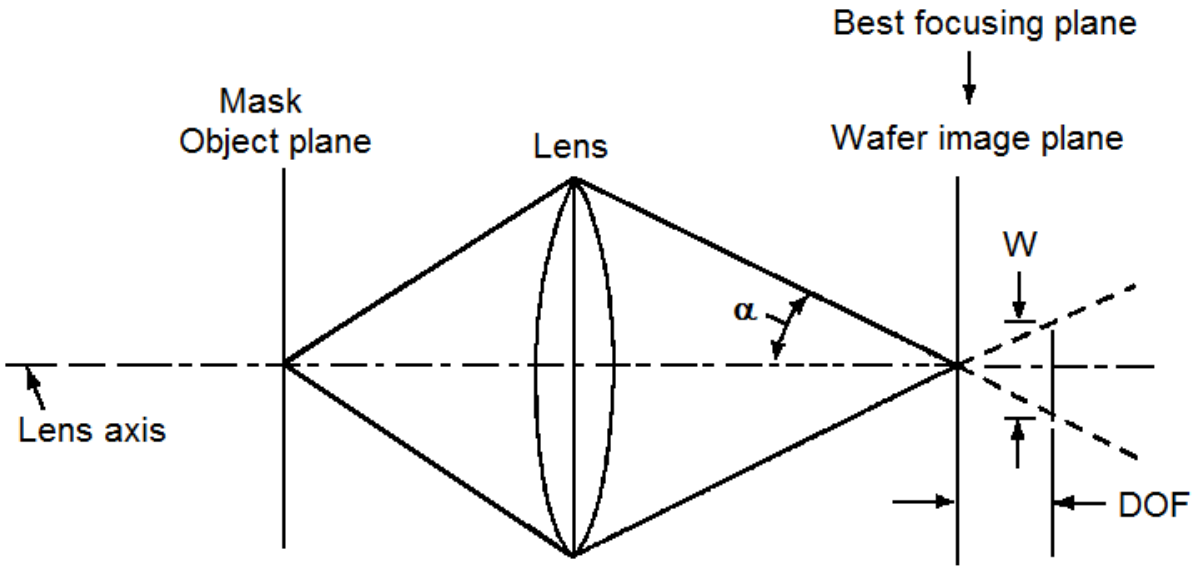


Figure 2.11: Illustration of depth of focus

NA is numerical aperture and is defined by equation (2.5).

$$NA = n\sin\alpha \tag{2.5}$$

n is the refractive index equals to 1 for air, 2α is the solid angle of the cone of light ray reaching a imaging point from the objective lens, and λ is the wavelength.

It is believed that high numerical aperture NA is always better. However, in the submicron region there is an optimum numerical aperture NA if a resolution requirement and imaging wavelength are given. If the numerical aperture is too low, the resolution cannot be achieved. If the numerical aperture is too high, the depth of focus DOF, which inversely proportional to $(NA)^2$, becomes unacceptable. The optimum NA at which DOF is at maximum. the normalization of the resolution W derived from equation (2.3) is given by

$$k_1 = W\frac{NA}{\lambda} \tag{2.6}$$

where k_1 is known as Rayleigh's coefficient for resolution but is now redefined as the normalized resolution. Thus, the normalized DOF is given by

$$k_2 = \Delta Z\frac{(NA)^2}{\lambda} \tag{2.7}$$

where ΔZ is the physical axial displacement from the focal plane and k_2 is known as Rayleigh's coefficient for DOF, is now defined as the normalized DOF.

Projection printing works like an overhead projector. The mask is like the transparency foil and the image is refocused on the surface in 1:1 ratio. This type of printing can achieve 1.0μm minimum feature size. This is because of the optical characteristics of lens and mirror. This type of system is widely used in the VLSI device fabrication.

Scanning projection exposure system as shown in Fig. 2.12 is commonly used in fabrication of integrated circuit. It uses a slit to block some light from the light source to reduce light scattering in order to improve exposure resolution. The light is focused on the mask by a lens and refocused on the wafer surface by a projection lens as a slit. The mask and wafer move synchronously allowing UV light to scanning across the mask to refocus on the surface of wafer and expose the photoresist across the wafer.

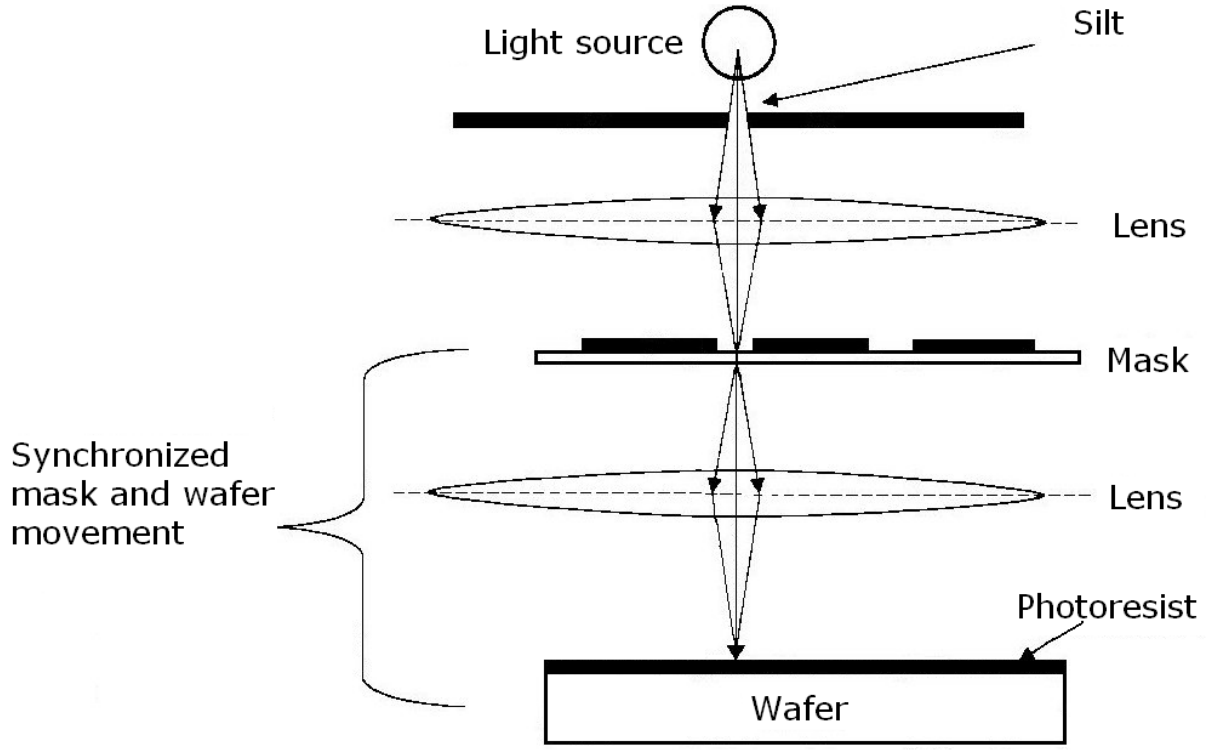
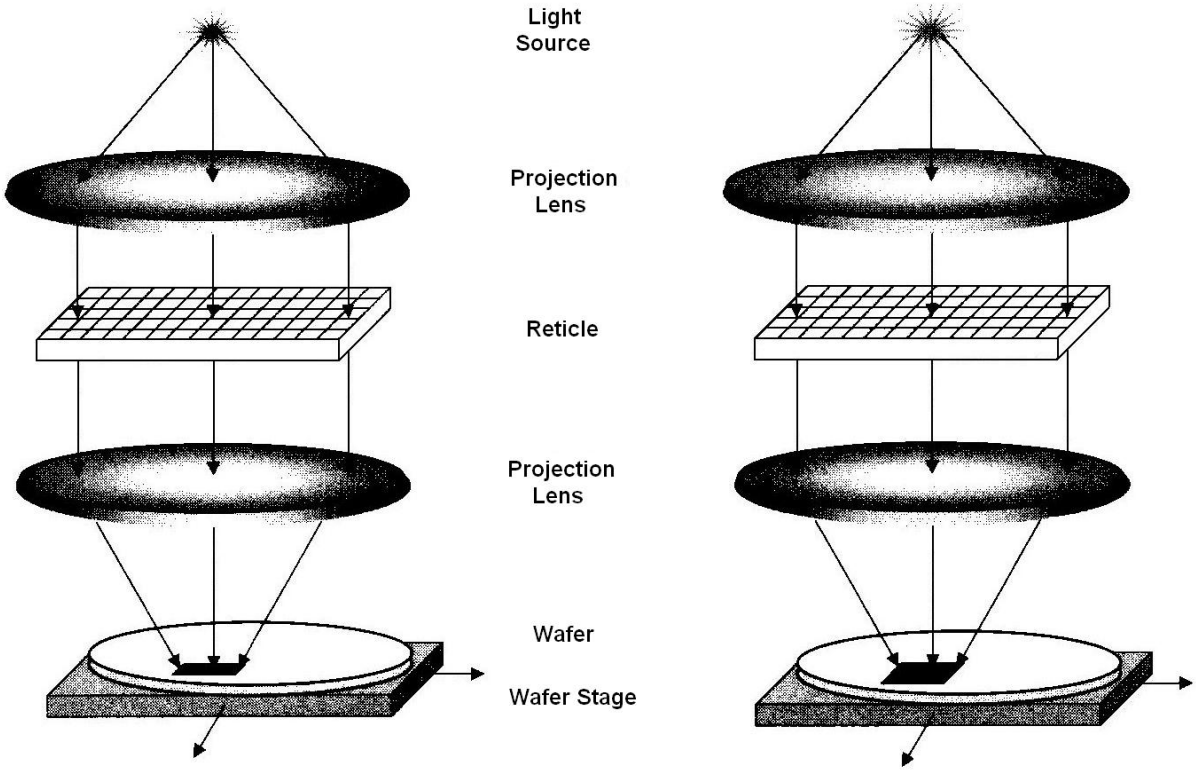


Figure 2.12: Scanning projection printing

When the feature size continues to shrink and approaches sub-micron level, the projection system no longer can meet the requirement of resolution. A different approach of exposure is needed. The step and repeat system as shown in Fig. 2.13 has to be used especially for VLSI/ULSI fabrication.

In the normal exposure system, the image transfer is 1:1 ratio and the wafer needs only one exposure for transferring the pattern from the mask to photoresist. The step and repeat system shrinks the image of mask/reticle and refocuses it on the photoresist at the ratio of 5:1 or 10:1. In this manner the resolution of pattern transfer can be improved. However, in this type of exposure system, it is not possible to expose the whole wafer in one exposure. The reason being, it is not possible to make a mask that is 5X or 10X of the size of wafer, it is not possible to get a high precise optical system that can shrink the pattern of such a large mask/reticle, and finally, there is no UV light intensity that is high enough to provide the exposure of whole wafer. Therefore, for this system type, the mask/reticle is made larger than the size of an integrated circuit and the exposure is not the whole wafer surface. The exposure is made on a particular part of the wafer that has image of reticle. Thus, one needs to repeat the step and exposure multiple times until the whole wafer is exposed. Thus, a step and repeat exposure system has xy table whereby it can precisely control the step and followed by exposure. The stepper system is a

complicated system. It needs alignment for every step. Each wafer requires 20 to 60 steps to complete the exposure.



(a) An example of 10:1 (b) An example of 5:1

Figure 2.13: Step and repeat exposure printing

For step and exposure system used in sub-micron device fabrication, there is no room for error. Also in order to meet the throughput requirement, each exposure step takes one to two seconds to complete. Thus, an automatic alignment system is required for the stepper system. An illustration of the system is shown in Fig. 2.14.

After mounting the wafer with photoresist layer on the xy table, it is first aligned with previous alignment mark by computer controlled reticle and lens mechanism. For first lithography step, the alignment is accomplished by using the notch or flat of the wafer to serve as the alignment mark. The stepper motor usually adjusts the alignment optically with the automatic laser interferometry positioning system. To further improve the resolution image patterning, technologist uses combined scanning projection system and stepper technology to develop step-and-scan system.

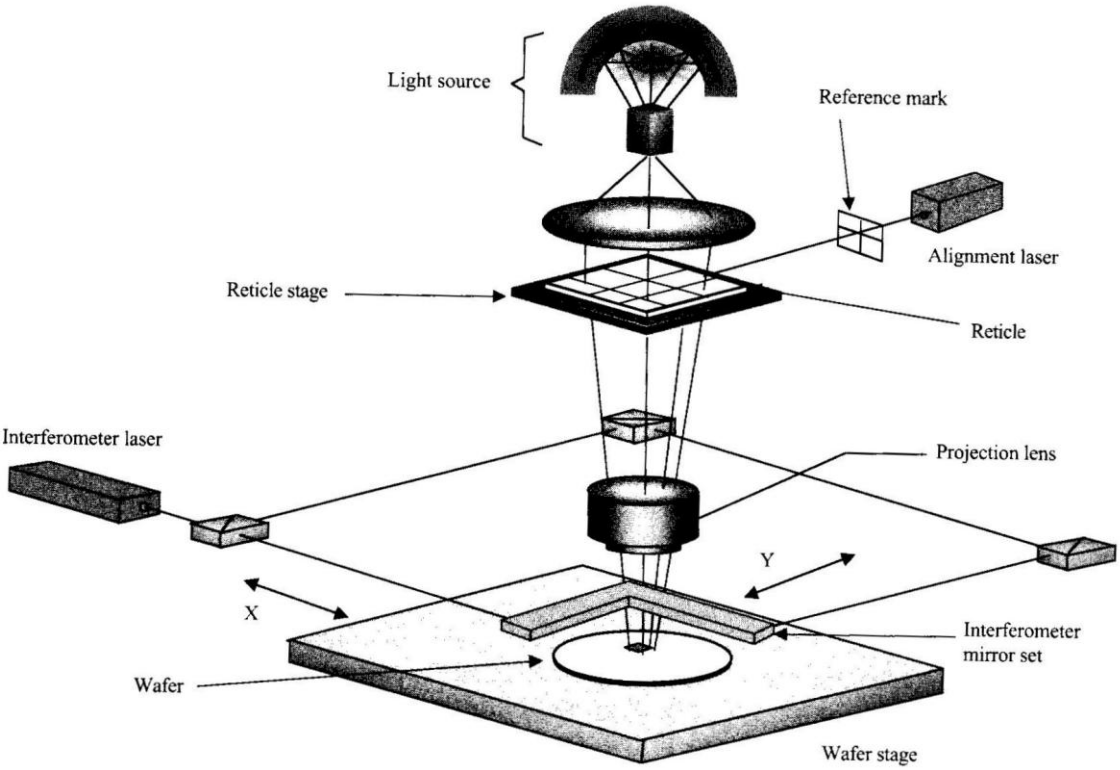


Figure 2.14: A step and repeat alignment and exposure automatic system

A photographer knows that he/she needs high light intensity in order he/she can capture high resolution picture. Besides, it would take longer exposure time in low light intensity environment than high light intensity environment. Thus, high intensity light is a key to have high resolution and high throughput. The ultra violet UV light source used in the exposure system is the key for a successful exposure. The wavelength of UV light is also a key factor because the sensitivity of photoresist is dependent on wavelength. Moreover, the feature size of the device is also dependent on wavelength of the light source. As the device shrinks down, the wavelength of the UV light has to be shorter to match the requirement of the pattern resolution.

There are two types of light source that are widely used for lithography process. They are mercury light and excimer laser. Exposure light source must be stable, reliable, and adjustable, with short wavelength, high intensity, and long lifetime. For feature size greater than 2.0μm, the broad band mercury lamp is used as light source for contact/proximity and projection printing. When the feature size shrinks, single wavelength light source is required to achieve the desired resolution. High pressure mercury arc lamp is the most commonly used light source to get ultraviolet UV for sub-micron lithography projection system and stepper system used in the 80's and 90's. The wavelength spectrum mercury ultraviolet light source is shown in Fig. 2.15. The G-line, H-line, I-line are the

most commonly used for lithography exposure processes of 436nm, 405nm, and 365nm features respectively.

For lithography processes with 0.25μm and 0.18μm minimum feature size, the light source with even shorter wavelength is required. Krypton fluoride KrF excimer laser with deep ultraviolet DUV wavelength at 248nm is the most commonly used as the light source for the stepper exposure system for processing 0.25μm feature size. This light source is also capable to process less than 0.13μm feature size. More advanced UV light source of wavelength 157nm from F_2 excimer laser will soon be used for feature size less than 0.10μm.

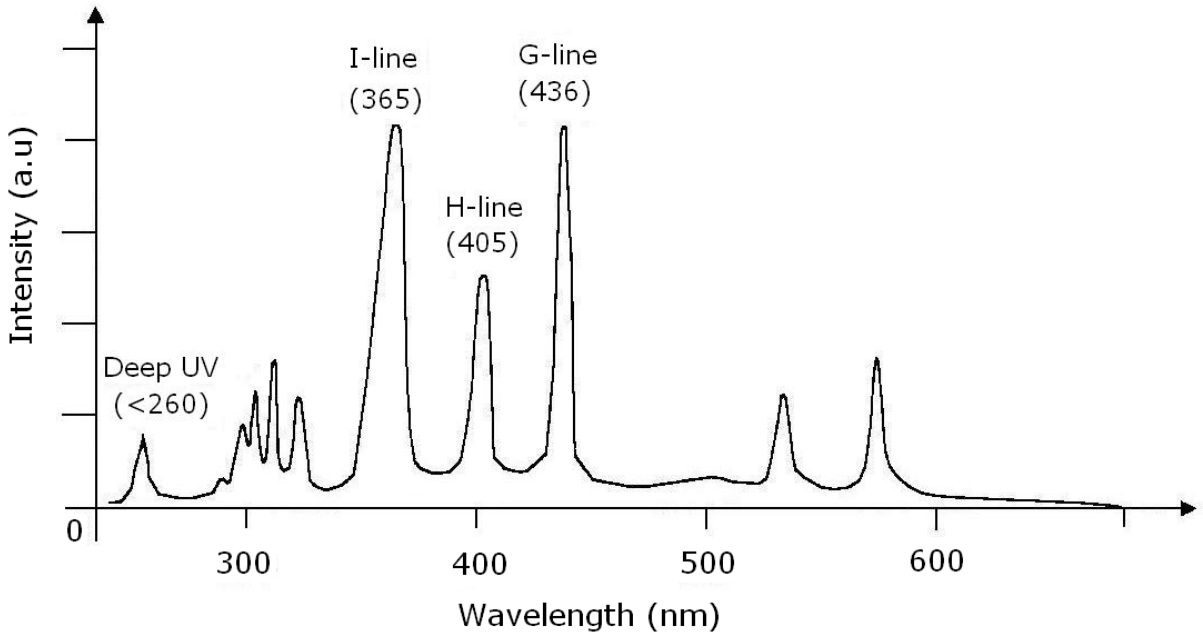


Figure 2.15: Wavelength spectrum of mercury UV light source

When exposure light reflects from photoresist-substrate interface, it can interfere with incoming light and cause the standing wave effect due to constructive and destructive interference at different depth. The standing wave pattern is illustrated in Fig. 2.16.

When feature is large, standing wave effect is not much concern. As feature getting smaller, the effect is significant. Several methods are being employed to overcome this issue. Dye, additive, can be added to the photoresist to reduce the intensity of reflection. Metallic and dielectric layer can be deposited on the surface of the wafer as anti-reflection coat ARC to reduce and minimize the reflection from the surface of the wafer. An organic anti-reflective coating can be applied on the surface of wafer spin coating photoresist. Post exposure bake PEB can also help to reduce the effect of standing wave.

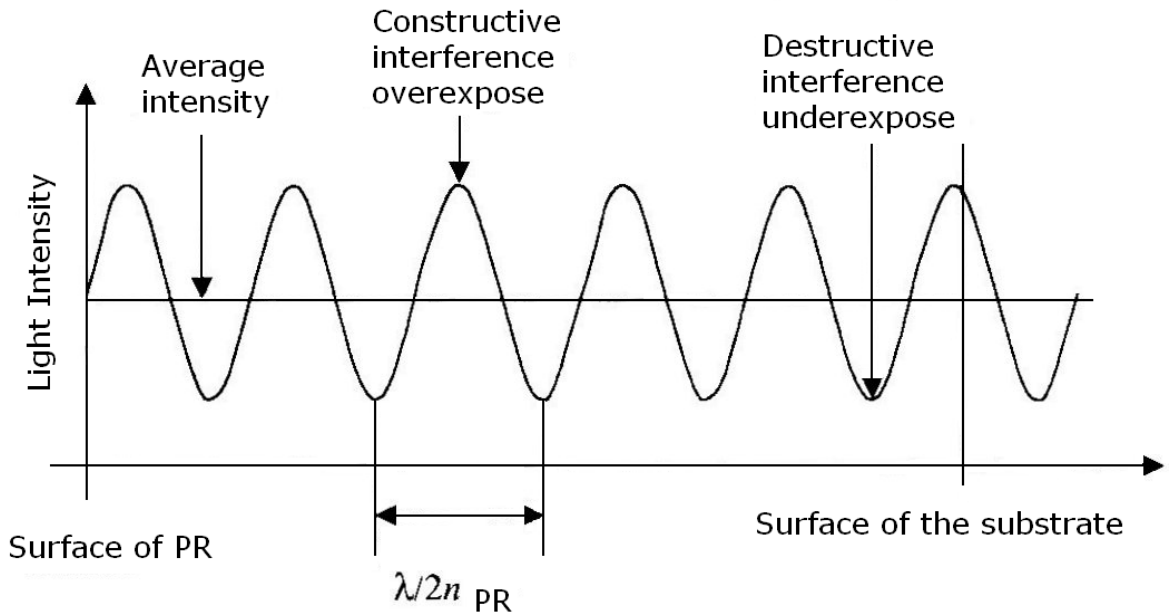


Figure 2.16: Standing wave effect induced intensity change

The standing wave effect causes striation of over exposed and under exposed area through the photoresist as shown in Fig. 2.17.

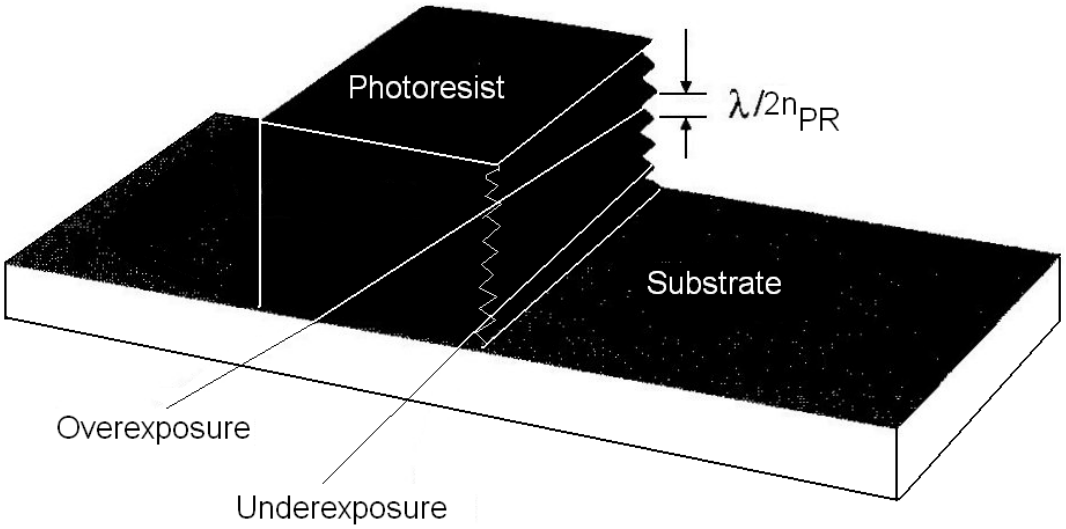


Figure 2.17: Standing wave effect on photoresist

2.3.5 Post Exposure Bake

The post exposure bake process is normally done with hot plate set at temperature between 110^0C and 130^0C for about one minute. Insufficient bake will not completely eliminate standing wave effect. Over bake will cause polymerization of photoresist that affects the development process. After post exposure bake, the wafer is chilled to ambient temperature using chilled plate.

2.3.6 Development

After the post exposure bake, the photoresist is subjected to development. There are three stages to be done, which are developing, rinse, and dry. The development process removes unwanted photoresist and forms the desire pattern defined by the mask or reticle. For positive photoresist coating, the exposed part is dissolved in development solution, while for negative photoresist, the unexposed part is removed.

The developer solution for photoresist is a weak base, which is alkaline-water base solution like sodium hydroxide NaOH and potassium hydroxide KOH. However, these types of solution are not desired because they introduce Na^+ and K^+ ions which are contaminants and would change the characteristic of device. Thus, in most semiconductor fabrication facility uses non ionic base solution like tetramethyl ammonium hydroxide TMAH or $(CH_3)_4NOH$.

The most commonly use developer solution for negative photoresist is xylene and usually *n*-butylacetate is used for rinse. Mixture of alcohol and trichloethylene TCE or CH_3CCl and milder-acting Stoddart solvent may be used for the negative phototoresist.

Spinner development is normally used, whereby it can run developing, rinsing, and drying sequentially. Figure 2.18 shows a schematic of a spinner developer system.

Developer solution is sprayed at the center and spread across the wafer by the centrifugal force of the spinner. DI water is sprayed after development for rinsing. After rinsing, the rate of spin is increased to spin dry the wafer.

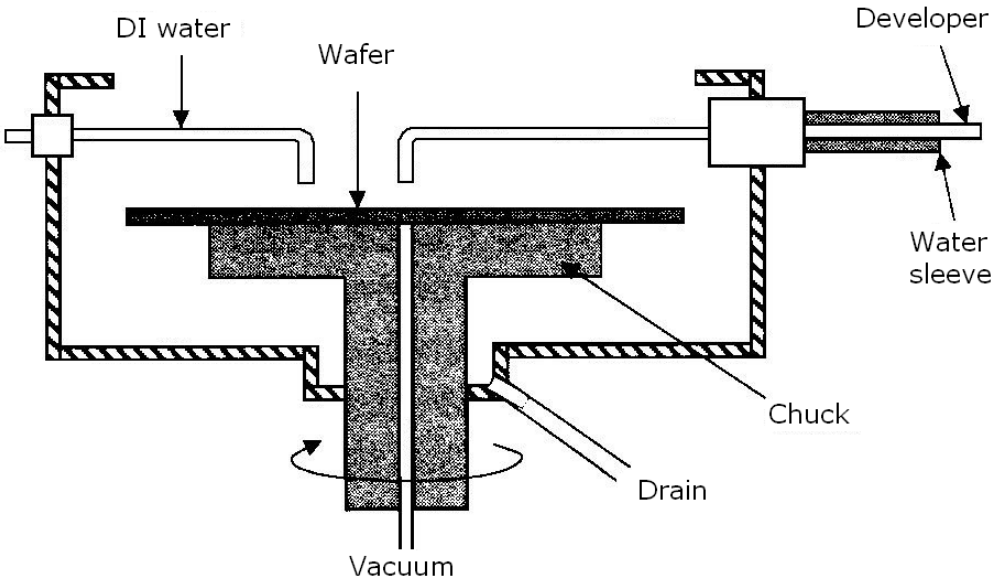
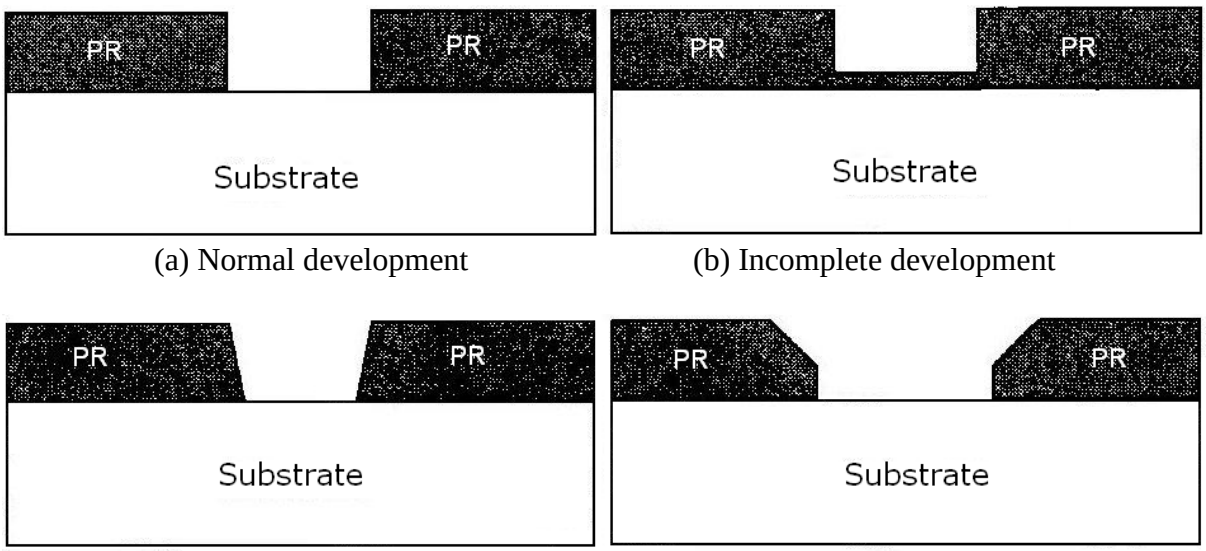


Figure 2.18: Schematic of a spinner developer system

Development is a chemical reaction that is sensitive to temperature and duration. Thus, the temperature of wafer and photoresist has to be kept constant. Otherwise, problem of under development, over development, incomplete development will be the results. The illustrations of these problems are shown in Fig. 2.19.



(a) Normal development (b) Incomplete development

(c) Under development (d) Overdevelopment

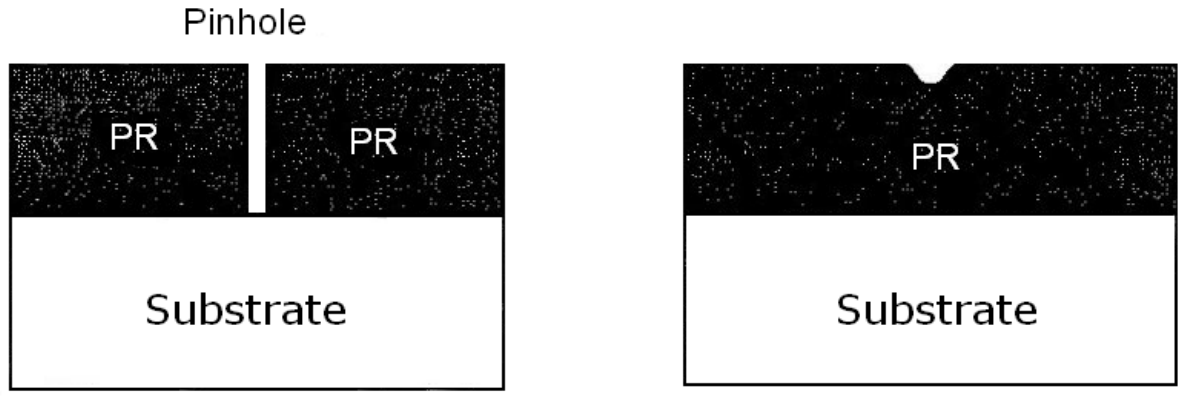
Figure 2.19: Profile of photoresist caused by temperature and duration

2.3.7 Hard Bake

Hard bake is process after development. Hard bake drives out the remaining solvent in photoresist. Photoresist without solvent helps to improve etching,

adhesion to surface of wafer, and resistance to ion implantation due to more polymerization.

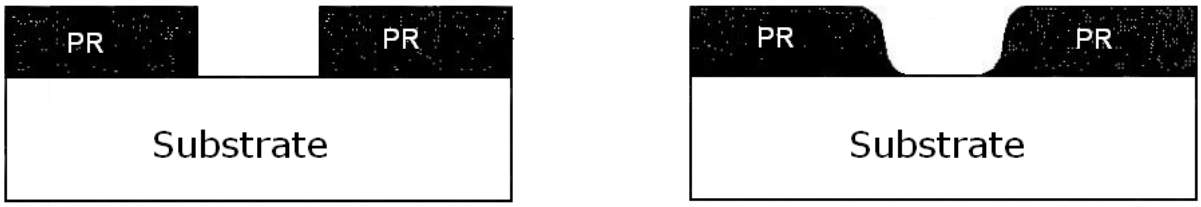
The time and temperature of hard bake are important. It can affect adhesion and causing high photoresist etch rate if it is under bake. It affects the resolution if it is over bake. Normally the temperature of baking is set slightly higher than the transition temperature of photoresist material so that the photoresist can flow to refill the pinhole as illustrated in Fig. 2.20.



(a) Pinhole before reflow (b) Pinhole after reflow

Figure 2.20: Pinhole reflow by thermal flow of photoresist

Over bake such as either too high temperature or too long duration, the photoresist can reflow resulting resolution problem as illustrated in Fig. 2.21.



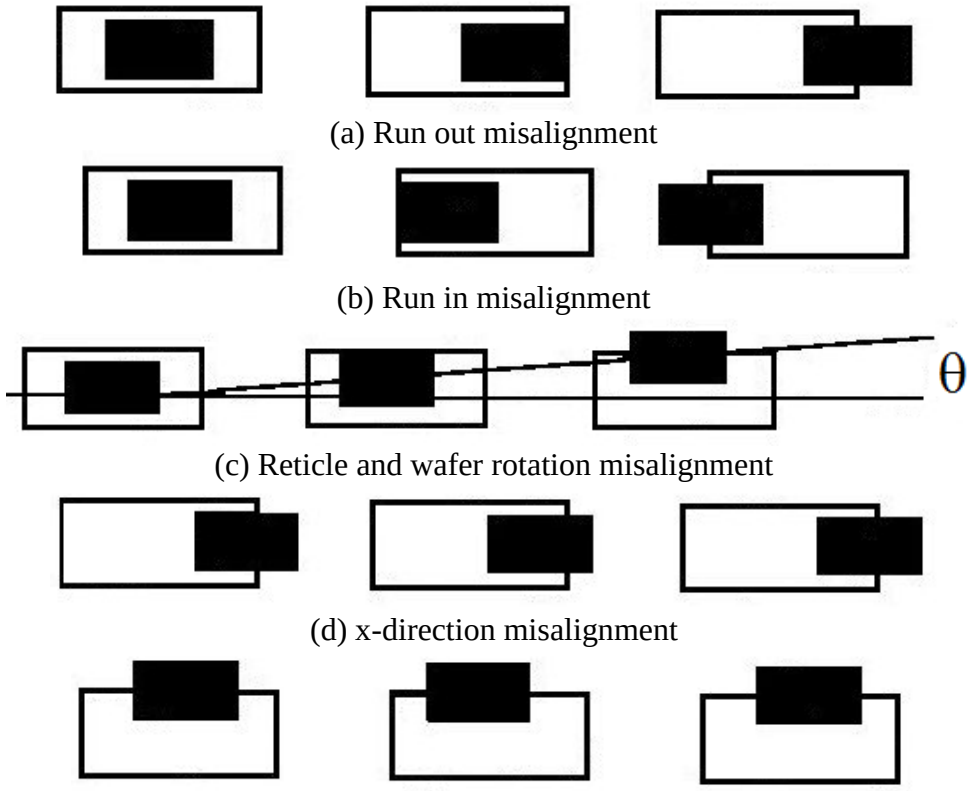
(a) Normal baking (b) Over baking

Figure 2.21: Photoresist reflow due to over bake

2.3.8 Pattern Inspection

The last step of lithography is pattern inspection. If the wafer fails pattern inspection, the photoresist has to be stripped and sent back to re-start the lithography process. Anything wrong with the photoresist can be re-worked but not if wafer has been etched or ion implanted with impurity. The purpose of inspection is to ensure the pattern on the photoresist is not distorted or misaligned, free from surface irregularity, stain, contaminant etc. There several types of misalignment, which are shown in Fig. 2.22. The misaligned problem can be grouped into run out, run in, reticle rotation or wafer rotation issues, and

xy table misplacement issues. Run-out and run-in issues are basically due to stepper misalignment problem between stepper. Reticle rotation and wafer rotation is due xy guides misaligned issue, and xy misplacement is due xy stepper initial stepper and alignment issue with flat and notch of wafer.



(a) Run out misalignment

(b) Run in misalignment

(c) Reticle and wafer rotation misalignment

(d) x-direction misalignment

(e) y-direction misalignment

Figure 2.22: Various types of misalignment

Inspection using optical microscope can be done if the feature size is larger than the wavelength of normal light, which ranges from 390nm (violet) to 750nm (red). For small feature size of 0.25μm, an electron microscope is needed. The electron beam of the electron microscope hits the photoresist pattern can excite secondary electron. By mapping the detected electric field from the secondary electron emission, the image of the sub-micron feature can be viewed. Sharp edge of the pattern has higher rate of secondary electron emission and therefore shown as high electric field resulting higher detection and brighter image.

In advanced integrated circuit, critical dimension CD loss or line width loss as shown in Fig. 2.23 causes the most lithography rework mainly due to overexposure or over development. Certainly rework would lose in throughput and yield.

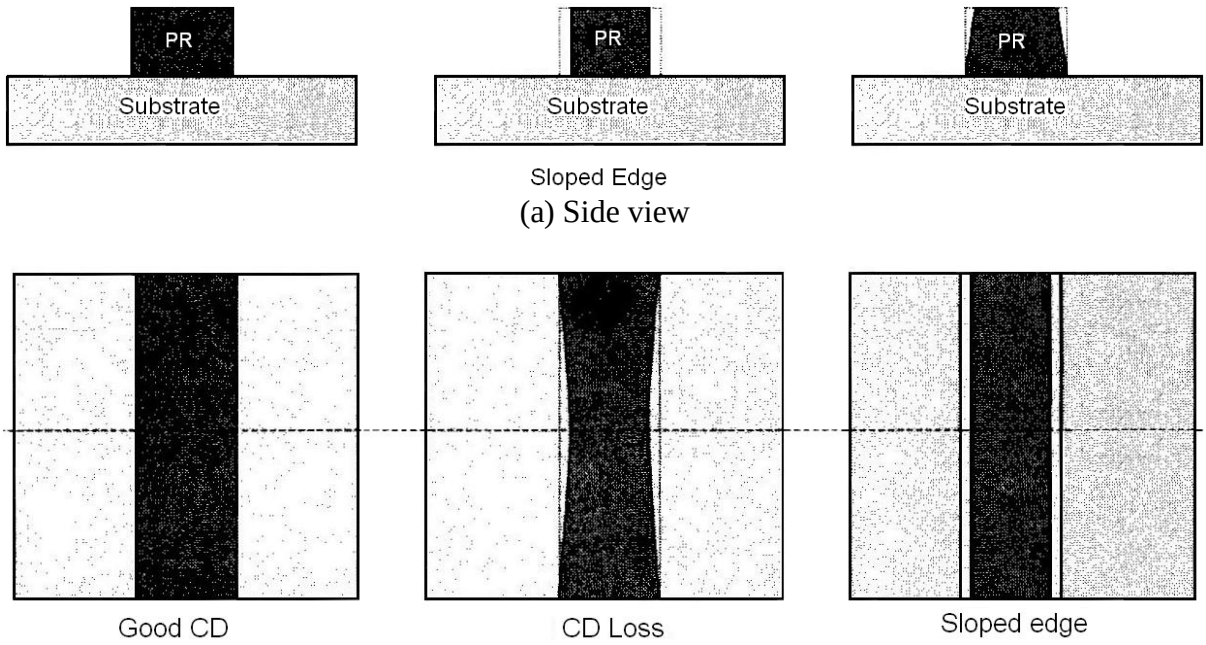


Figure 2.23: Good critical dimension and bad critical dimension

2.4 Electron Lithography

Electron lithography has higher resolution than optical lithography because of the small wavelength (less than 1 Armstrong) of the 10-50keV electrons. Resolution in electron lithography system is not limited by diffraction but by electron scattering in the target materials including the photoresist and by the various aberrations of the electron optics. Scanning electron beam pattern generators have been under development for more than 20 years and were derived from the scanning electron microscope.

Figure 2.24 shows the schematic of an e-beam lithography system. The electron gun generates a beam of electron with suitable current density. A tungsten thermionic emission cathode or single-crystal lanthanum hexaboride LaB_6 is used for electron gun. Condeser lenses are used to focus the electron beam to spot size 10-25nm in diameter. Beam banking plates are used to turn the electron beam on or off. Beam deflection coils are computer controlled and operated in MHz or higher rates to direct the focused electron beam to any location in the scan field on the substrate. Owing to the scan field typically is 1.0cm, it is much smaller than the substrate diameter. A precision mechanical stage is used to position the substrate to be patterned.

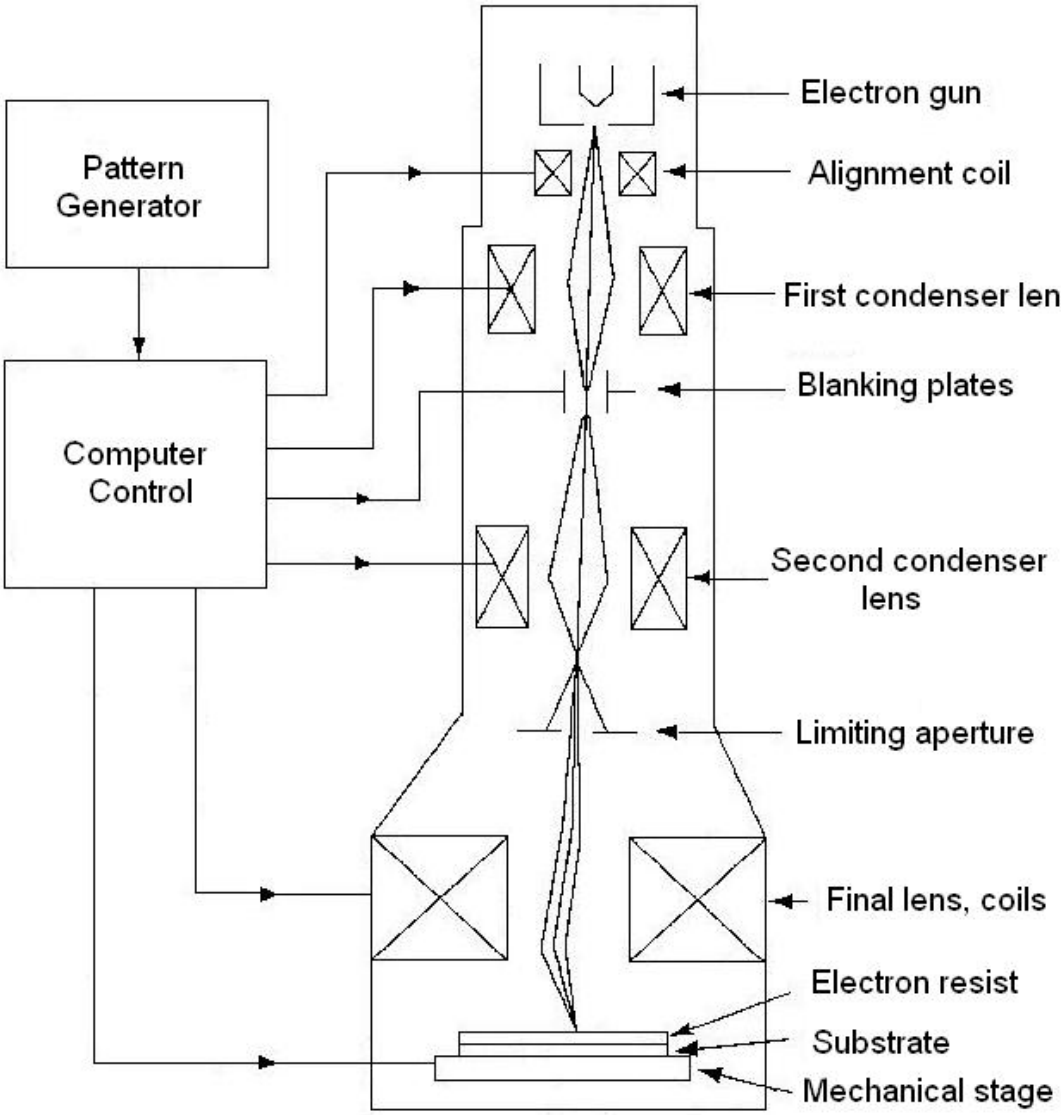


Figure 2.24: e-beam lithography system

Owing to the serial nature of the pattern writing, throughput is much lower than optical systems. However, a wide variety of applications is available in the pattern-generating function for electron lithography. They are mask fabrication for optical or X-ray lithography, direct writing on the wafers, and direct reaction with some materials on the substrate. Electron lithography is classified into two types that are scanning and projection and the scanning type. It can be either raster or vector scanning type.

The exposure scheme is illustrated in Fig. 2.25. The ULSI pattern is composed by a computer-aided design CAD system. The output format from the CAD system is converted into the internal format of the individual exposure systems. The electron exposure machine decomposes the data into simple elements like trapezoids or rectangles, depending on the machines to control the

electron beam irradiation. Electron beam exposure machines are bigger and more complicated than the optical printers because of their data-handling function.

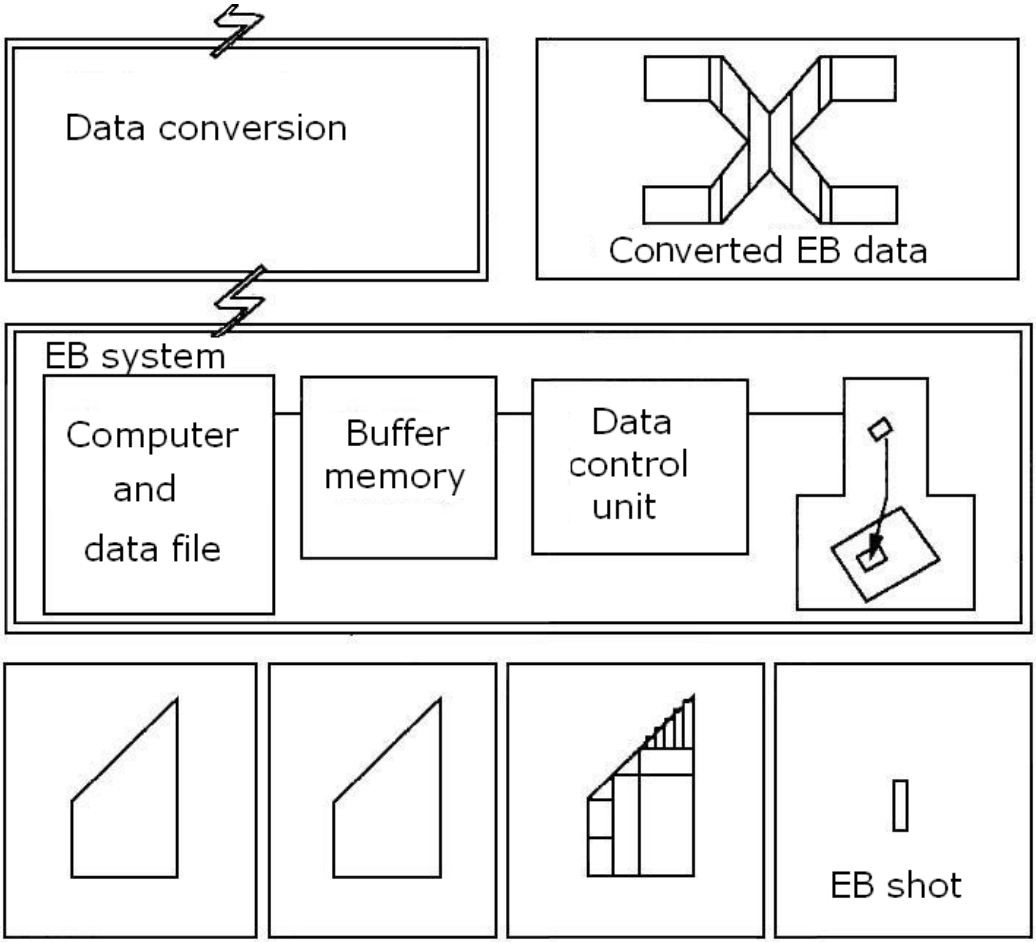


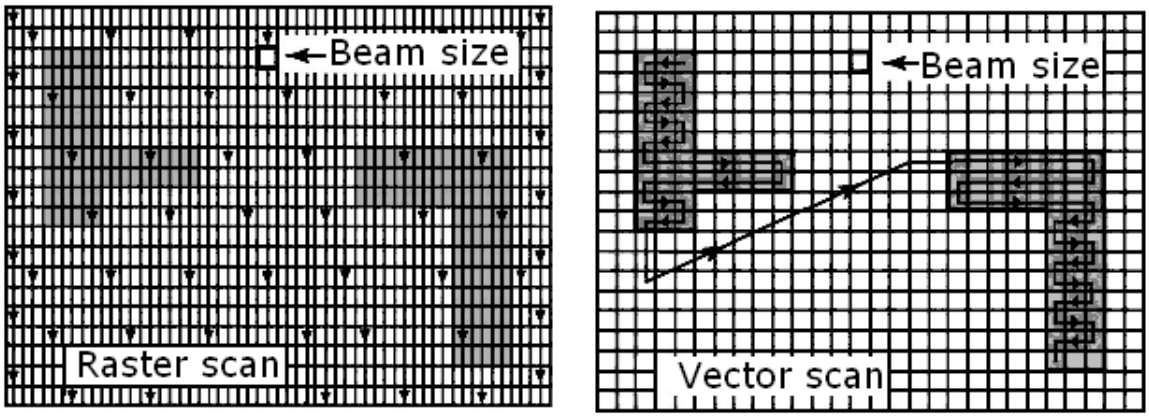
Figure 2.25: Flow of data in electron beam exposure systems

2.4.1 Raster and Vector Scans

The raster and scan writing schemes of the pattern are shown in Fig. 2.26. For the raster scan, the electron beam is deflected repetitively over the exposure area like the raster scan of television. The beam is turned on at various points in the scan to expose the desired pattern. As shown in Fig. 2.25(a), the stage moves continuously in a direction perpendicular to the beam scanning direction. The pattern data are decomposed into a number of stripes parallel to the stage movement, and one stripe is written on all chips of the same type before the next stripe is begun.

The stripe is 2,048 addresses wide, an address corresponding to a width from 0.1 to 1.0μm. The diameter of beam can be varied from 0.1 to 1.0μm. The pattern information comes to the blanking plates from a shift register at a 40 to

80MHz rate. Since the total time to write the 2,048 scan is 31.6μs to 12.5ns per spot plus 6.0μs for fly back, the writing rate is approximately 8cm^2/min with a 0.5μm address and 2.4cm^2/min with 0.25μm address. The electron beam is irradiated on the substrate by controlling the blanker that turns the beam on at the exposure starting points and turns off at the end point during rastering.



(a) (b)

Figure 2.26: The principles of raster and vector scan, (a) Raster scan and (b) Vector scan

In vector scan, the beam is directed sequentially to the parts of the chip pattern to be exposed. The pattern is decomposed into a number of elements like rectangles, triangles etc and each is exposed by the writing beam. Many vector scan machines expose in a step-and-repeat fashion. Figure 2.26(b) shows an exposure field of dimensions FxF, which is the electron beam deflection area. The dotted lines indicate where the beam is turned off deflected by the blanking plates, similar to blanking in a raster scan. After all elements in one field are exposed, the stage is stepped to the next field and the exposure process is repeated. The stage does not require to provide highly precise positioning. Stage position is monitored by a laser interferometer, and small differences from the desired stage location are compensated by small offsets of the beam. If a chip is larger than an exposure field as shown in Fig. 2.26(b), several fields can be used to expose the chip. The scan field must be as large as allowed by deflection.

2.5 X-Ray Lithography

X-ray lithography was proposed in 1972. One knows that diffraction effects and resolution improve by reducing the wavelength. If the wavelength is reduced further than DUV, all optical materials become opaque because of fundamental absorption but transmission increases again in the X-ray region. There are several advantages in X-ray lithography in addition to short wavelength. Some contaminants, such as light organic materials, do not print as a defect; and the

depth of focus is larger than the optical printers. The essential technology components of this process are (1) a mask consisting of a device pattern made of X-ray absorbing materials on transmitting material, (2) an X-ray source, and (3) an X-ray resist.

The X-ray absorption of several materials is shown in Fig. 2.27. The absorption coefficient of an elemental material of density ρ and atomic number Z is proportional to $\rho Z^4 \lambda^3$ over a wide range of wavelengths. The proportionality constant decreases in a step-function fashion at the absorption edge. It is a wavelength that corresponds to the ionization energies of inner electrons of the K, L, and other shells. Notice that in Fig. 2.27 the big differences in absorption coefficients for different materials are observed at the same wavelengths that are utilized for absorbing materials to make patterns and the transmitting substrate of the X-ray mask.

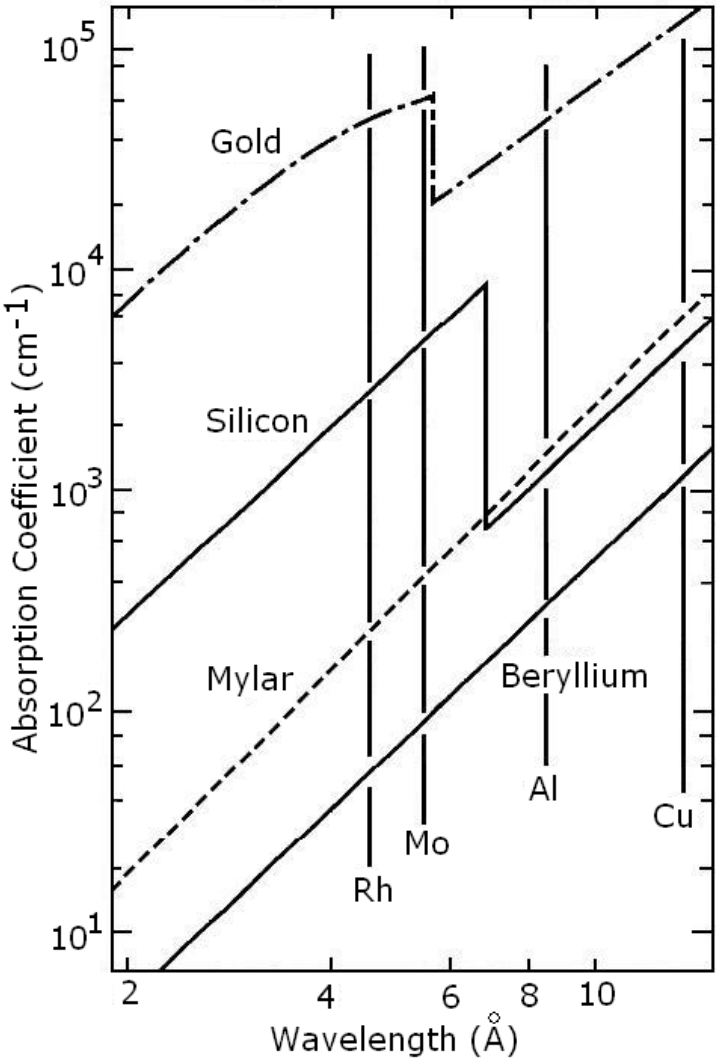


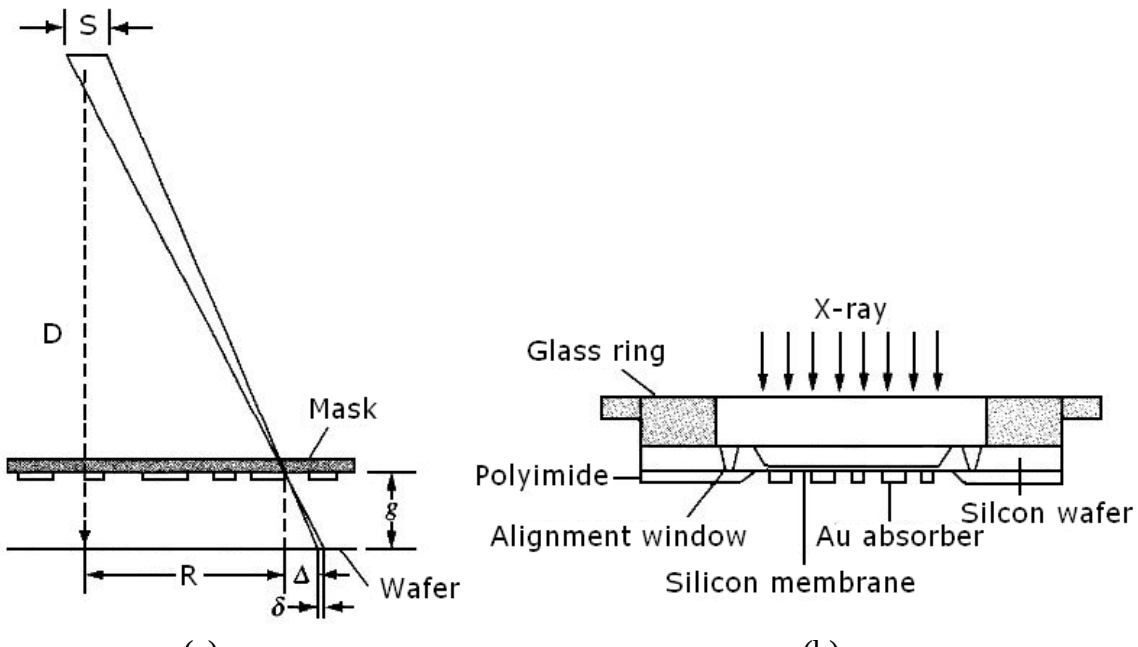
Figure 2.27: Typical X-ray absorption coefficients with some lines characteristic of commonly used materials

The performance required of X-ray lithography, as the alternative to optical lithography, has become more exacting as optical technology has continued to improve. The resolution and placement accuracy should surpass 0.2μm and 0.03μm respectively.

2.5.1 Proximity Printing

Owing to the wavelength of X-ray is short, simple geometrical considerations can be used to relate the image formation and the wafer without having to consider diffraction as shown in Fig. 2.28(a). The opaque parts of the mask cast shadows onto the wafer below. The edge of the shadow is not absolutely sharp because of the finite extent of the X-ray source at distance D from the mask. If the gap between mask and wafer is g, this blur δ is given by

$$\delta = Sg / D \tag{2.8}$$



(a) (b)

Figure 2.28: X-ray shadowing errors and X-ray mask structure. (a) X-ray proximity printing consideration, (b) X-ray mask structure

The angle of incidence of the X-ray on the wafer varies from 90 °at the center of the wafer to $\tan^{-1}(D/R)$ at the edge of the exposure field of radius R. The shadows are slightly longer at the edge by the amount Δ specified by equation (2.9).

$$\Delta = g(R/D) \tag{2.9}$$

This small magnification is generally of no concern. In the special case where it may be undesirable but it can be compensated for when the mask is patterned. For multi-level devices the magnification must have the same value for each level or at least its variation must be within the registration tolerance. This implies stringent control of the gap g. Wafer warping in processing can be nearly eliminated with a proper vacuum chuck. It is not necessary that the gaps have the same value at all points on the wafer, only that the spatial variations be the same, within close tolerance, for all levels. The step-and-repeat motion is indispensable to the narrow beam line of X-ray lithography.

2.5.2 X-Ray Mask

The role of an X-ray mask is to select where the impinging radiation is allowed to reach the resist and where it is not allowed. An example of a typical mask structure is shown in Fig. 2.28(b). An X-ray mask consists of a transmissive membrane substrate, which is usually made of low atomic number material like beryllium, carbon (amorphous or glassy graphite) and a patterned absorber layer, in which it is usually made of heavy metal such as gold. The ratio of metal thickness to substrate thickness is greater than for a photo mask because no material is available that is fully transparent or fully absorbent, unlike the combination of glass and chromium in optical lithography. This thickness is determined by the transmission of the materials for the X-ray wavelength of interest. X-ray masks are made by electron lithography and use the technologies of mask making and direct writing. The pattern on the X-ray mask must be as perfect as a photo mask, but the dimension is the same as on the wafer because of proximity printing. For features down to 0.1 to 0.2μm geometry it is harder to check the pattern integrity and to repair defects in X-ray than in optical lithography.

Of the heavy metals with large ρZ^4 values, gold was once widely used, because it is relatively easily patterned by liftoff or electroplating. Tungsten and tantalum are used now, because they are easily etched by dry etching. The thicknesses of gold necessary for absorption of 90% of the incident X-ray flux are 0.7μm, 0.5μm, 0.2μm, and 0.08μm for X-ray wavelengths 4.4 $\mathring{A}$ (Pd_L), 8.3 $\mathring{A}$ ($A1_K$), 13.3 $\mathring{A}$ (Cu_L), or 44.8 $\mathring{A}$ (C_K) respectively. In general, the metal is considerably thicker than the chromium layer (0.1μm) on a photo mask. Methods for high resolution patterning of the gold include electroplating and ion milling. Electroplating produces excellent definition with vertical walls but requires a vertical wall primary pattern in a resist that has a thickness equal to that of the metal to be plated. More often, a subtractive process has been

employed in which a thinner resist layer is used to pattern a thin layer of a refractive metal; the refractive metal serves as a mask for ion-milling the underlying gold. With this method, walls that depart from the vertical by 20 ° or less can be formed. The minimum line width attainable by ion milling 0.5μm thick gold is approximately 0.4μm For higher resolution, and where gold thickness can be reduced, longer wavelengths such as the 12 Å Cu_L radiation may be used. Line as small as 0.16μm, has been replicated with this type of radiation.

The membrane forming the mask substrate should be as transparent as possible to the X-rays, smooth, flat, dimensionally stable, reasonably rugged, and transparent to visible light if an optical registration scheme is used. Materials that have been used include polymers such as polyimide and polyethylene terephthalate, silicon, silicon carbide SiC, silicon nitride Si_3N_4, Al_2O_3, and a Si_3N_4-SiO_2-Si_3N_4 sandwich structure. Although different mask substrates are appropriate for different portions of the soft X-ray spectrum, there is not yet general agreement on the best material for any particular wavelength.

The major questions remaining about X-ray masks concern their dimensional stability, minimum attainable defect densities, and ease of handling. The stress applied on the thin membrane during processing and formation of the absorber structure causes distortions. Absorber-induced distortion is not noticeable because it is evaluated by comparing the measured fiducial marks before and after electroplating. Resist films on the membrane produce tensile stress on the membrane. In the case of a multilayer process, RIE heating can cause membrane distortion with a maximum error of 0.1μm. Dimensional stability can be degraded by radiation damage produced by x-ray flux, which also makes the mask substrate optically opaque. Pattern placement and critical dimension CD accuracies are reported as 0.06μm (3σ) and are repeatable.

2.6 Ion Lithography

Ion beam used to expose a resist has possible higher resolution than with an electron beam because of less scattering. In addition, resists are more sensitive to ions than to electrons. There is also the possibility of a resistless wafer process. However, the most important application of ion lithography is the repair of masks for optical or X-ray lithography, which is available commercial systems.

The sputtering yield increases with beam energy if the beam energy is larger than some small threshold value. However, there is an energy limit beyond which the yield decreases because the ions penetrate more deeply and fewer surface atoms receive enough energy to leave the surface. For example, the peak in the sputtering curve for Ar^+ ions incident on copper Cu occurs at 23.0keV. For ion implantation, energies from 30.0keV to 500.0keV are used, and the dose ranges up to 10^{15}ions/cm^2 (or $1.6x10^{-4}$C/cm^2 for monovalent ions). This represents a much larger dose than that used for resist exposure.

The sensitivity of polymethyl methacrylate PMMA resist has been measured for 30.0keV, 60.0keV, and 200.0keV He^+ ions and for 100.0keV and 150.0keV Ar^+ ions. The required dose is nearly two orders of magnitude less than with 20.0keV electrons. The perpendicular straggle of the penetrating ion path and the range of low-energy secondary electrons produced are less than the range of backscattered electrons in electron lithography. The ion energies for exposing a resist depend on the ion species. If the ion must penetrate 2,500 Å of resist, then a proton would need 14.0keV; and a gold Au ion, 600.0keV for the projected range to be 3,000 Å.

Two types of ion lithography systems are available, which are scanning focused-beam system and a mask-beam system. The problems of ion optics for scanning ion systems are more serious than for electron optics. The problems are the ion source and the beam-forming system.

The performance of various lithography methods based on throughput and resolution are summarized in Fig. 2.29. The borderline of each technology is very fuzzy. It will be difficult for another technology to replace optical lithography until 0.2 μm resolution is required. However, other key issues are the pattern-width uniformity and the overlay accuracy. If the tolerances of these items are defined as 10% of the feature size, they should be less than 0.02 μm. It is very difficult to guarantee these accuracies because the accuracy of present measurement tools cannot meet this requirement. Pattern-geometry accuracy is degraded in each step of the device manufacturing process.

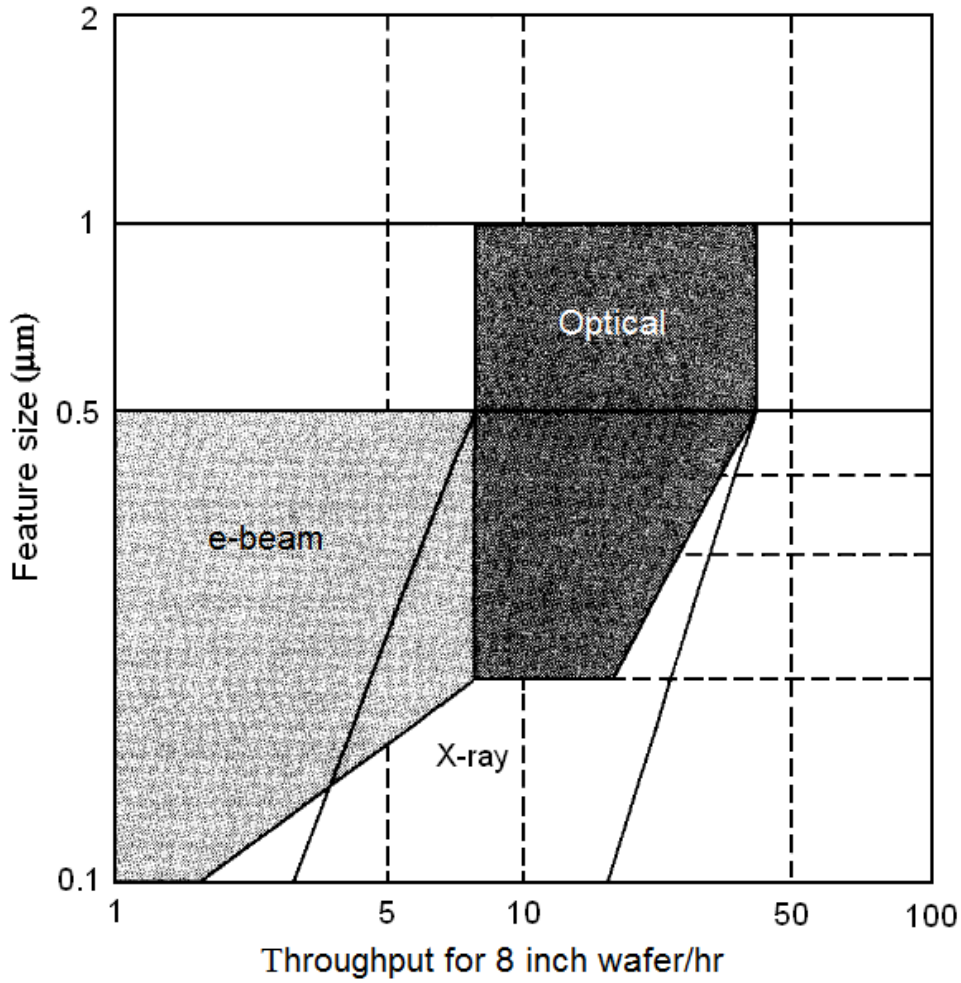


Figure 2.29: Resolution and throughput in submicron region

Exercises

2.1. What is photolithography?

2.2. What is the difference between positive and negative photoresist?

2.3. List four components of photoresist and explain their functions.

2.4. What is the purpose cleaning the wafer before photoresist coating?

2.5. A proximity printer with a 10µm mask-wafer gap and wavelength of 430nm. Another printer uses a 40µm gap with wavelength 250nm. Which printer offers higher resolution?

2.6. Why must the reticle used in a wafer stepper be completely free of defect? Why some defects can be tolerated in system exposing the entire wafer at once?

2.7. What is the purpose of post exposure baking?

2.8. List the consequences of overbaking and underbaking.

2.9. Explain the purpose of post exposure bake. What can go wrong from overbaking and underbaking of PEB?

2.10. Why does the wafer need inspection before next process step after lithography?

2.11. Most likely optical lithography cannot be used for nano-device that minimum feature size less than 50nm patterning process. State the reason.

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