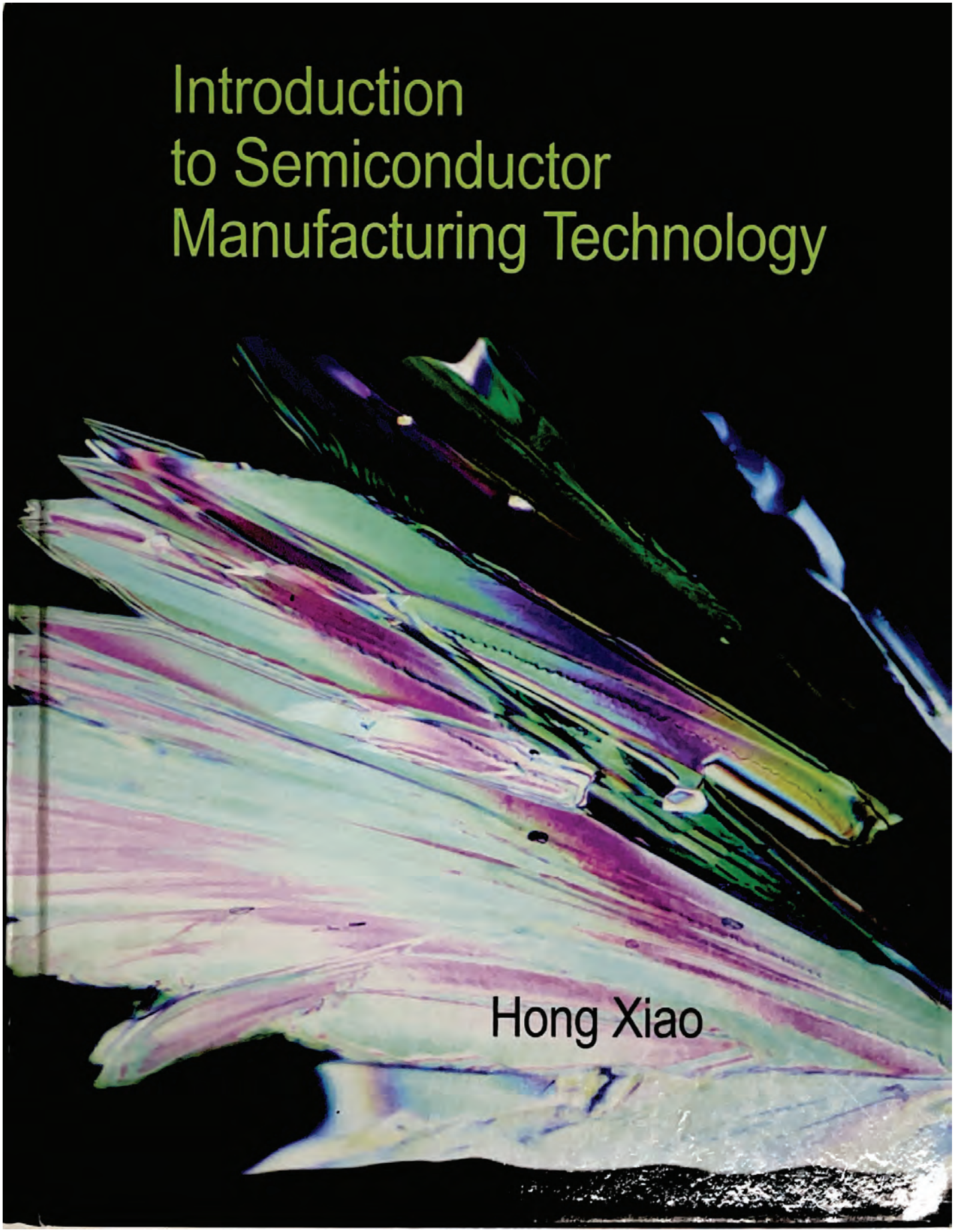
Introduction to Semiconductor Manufacturing Technology



Hong Xiao

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To my wife, Liu Huang
and my son, Jarry Xiao

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CONTENTS

CHAPTER 1 INTRODUCTION 1

1.1 Brief History 2
1.2 Brief Overview 10
Summary 17
Review Questions 18
References 18

CHAPTER 2 INTRODUCTION TO IC FABRICATION 19

2.1 Introduction 19
2.2 Yield 20
2.3 Cleanroom Basics 24
2.4 Basic Structure of an IC Fab 32
2.5 Testing and Packaging 43
2.6 Future Trends 50
Summary 51
Review Questions 52
References 52

CHAPTER 3 SEMICONDUCTOR BASICS 53

3.1 What Is a Semiconductor? 53
3.2 Basic Devices 60
3.3 IC Chips 73
3.4 Basic IC Processes 77
3.5 CMOS 85
3.6 Technology Trends After 1990 88
Summary 90
Review Questions 92
References 92

CHAPTER 4 WAFER MANUFACTURING 93

4.1 Introduction 93
4.2 Why Silicon? 94
4.3 Crystal Structure and Defects 95
4.4 From Sand to Wafer 99
4.5 Epitaxial Deposition 110
Summary 119

Review Questions 119
References 120

CHAPTER 5 THERMAL PROCESSES 121
5.1 Introduction 121
5.2 Thermal Process Hardware 122
5.3 Oxidation 127
5.4 Diffusion 150
5.5 Annealing 157
5.6 High-Temperature CVD 161
5.7 Rapid Thermal Process (RTP) System 170
5.8 Future Trends 176
Summary 179
Review Questions 180
References 180

CHAPTER 6 PHOTOLITHOGRAPHY 181
6.1 Introduction 181
6.2 Photoresist 183
6.3 Photolithography Process 187
6.4 Lithography Technology Trends 214
6.5 Safety 224
Summary 226
Review Questions 227
References 228

CHAPTER 7 PLASMA BASICS 229
7.1 Introduction 229
7.2 Definition of Plasma 229
7.3 Collisions in Plasma 232
7.4 Plasma Parameters 236
7.5 Ion Bombardment 243
7.6 DC Bias 244
7.7 Advantages of Plasma Processes 248
7.8 PECVD and Plasma Etch Chambers 252
7.9 Remote Plasma Processes 255
7.10 High Density Plasma 258
Summary 261
Review Questions 262
References 262

CHAPTER 8 ION IMPLANTATION 263
8.1 Introduction 263
8.2 Ion Implantation Basics 272
8.3 Ion Implantation Hardware 282

8.4 Ion Implantation Processes 294
8.5 Safety 304
8.6 Technology Trends 306
Summary 310
Review Questions 311
References 312

CHAPTER 9 ETCH 313
9.1 Introduction 313
9.2 Etch Basics 316
9.3 Wet Etch Process 323
9.4 Plasma (Dry) Etch 328
9.5 Plasma Etch Processes 342
9.6 Process Trends 354
9.7 Future Trends 356
Summary 359
Review Questions 360
References 360

CHAPTER 10 CVD AND DIELECTRIC THIN FILM 361
10.1 Introduction 361
10.2 Chemical Vapor Deposition (CVD) 363
10.3 Applications of Dielectric Thin Film 383
10.4 Dielectric Thin-Film Characteristics 393
10.5 Dielectric CVD Processes 408
10.6 Spin-On Glass 423
10.7 High-Density Plasma CVD 425
10.8 Dielectric CVD Chamber Clean 429
10.9 Process Trends and Troubleshooting 433
10.10 Future Trends 440
Summary 444
Review Questions 445
References 446

CHAPTER 11 METALLIZATION 447
11.1 Introduction 447
11.2 Conducting Thin Films 450
11.3 Metal Thin-Film Characteristics 462
11.4 Metal CVD 471
11.5 Physical Vapor Deposition (PVD) 480
11.6 Copper Metallization 494
11.7 Safety 501
Summary 502
Review Questions 503
References 504

CHAPTER 12 CMP (Chemical Mechanical Polishing) 505
12.1 Introduction 505
12.2 CMP Hardware 517
12.3 CMP Slurries 523
12.4 CMP Basics 528
12.5 CMP Processes 533
12.6 Future Trends 542
Summary 543
Review Questions 544
References 544

CHAPTER 13 PROCESS INTEGRATION 545
13.1 Introduction 545
13.2 Wafer Preparation 545
13.3 Well Formation 547
13.4 Isolations 551
13.5 Transistor Making 557
13.6 Interconnections 566
13.7 Passivation 575
Summary 577
Review Questions 578
References 578

CHAPTER 14 CMOS PROCESSES 579
14.1 Introduction 579
14.2 CMOS Process Flow of the 1980s 579
14.3 Advanced CMOS Process Flow (1990s Technology) 583
14.4 State-of-the-Art CMOS IC Process Flow 601
Summary 629
Review Questions 630
References 630

CHAPTER 15 SUMMARY AND FUTURE TRENDS 631

INDEX 635

CHAPTER

6

Photolithography

OBJECTIVES

After reading this chapter, you should be able to

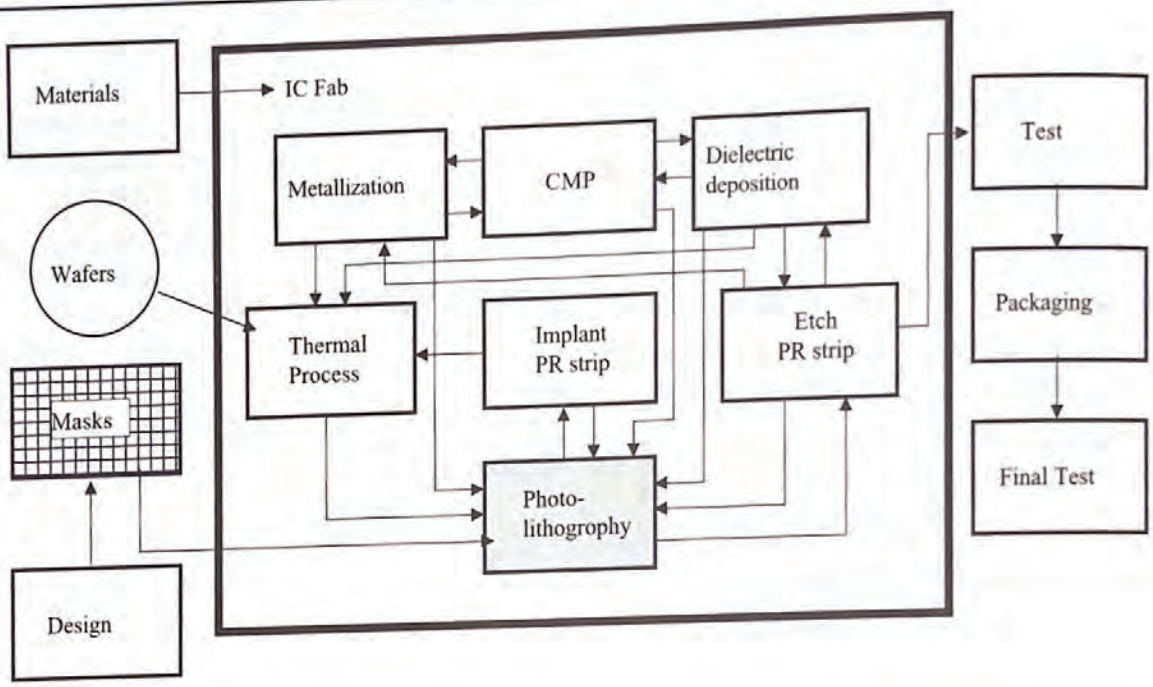
- List the four components of the photoresist
- Describe the difference between positive and negative photoresist
- Describe a photolithography process sequence
- List four alignment and exposure systems, and identify the one with the highest resolution and widest use in IC production
- Describe the wafer movement in a track-stepper integrated system
- Explain the relation of resolution and depth of focus to the wavelength and numerical aperture

6.1 INTRODUCTION

Photolithography is the patterning process that transfers the designed pattern from the mask or reticle to the photoresist on the wafer surface. Photolithography was first used in the printing industry and has long been used to make printed circuit boards. It was adapted in the semiconductor industry for transistor and integrated circuit manufacture in the 1950s. It is the most crucial process step in IC fabrication, since the device and circuit designs are transferred to the wafer by either etch or ion implantation through the pattern defined on the photoresist on the wafer surface by the photolithography process.

Photolithography is the core of the IC manufacturing process flow, as shown in Figure 6.1. From the bare wafer to the bonding pad etch and photoresist strip, the simplest MOS-based IC chip needs five photolithography process or mask steps, and an advanced IC chip may take more than 30 mask steps. The IC processing is very time consuming: even with a 24-hour-a-day, nonstop work schedule, it takes six to eight weeks from bare wafers to finished wafers. The photolithography process takes about 40% to 50% of the total wafer-processing time.

Figure 6.1
IC fabrication process flow.



The requirements of photolithography are high resolution, high sensitivity, precise alignment, and low defect density. The development of IC process technology is measured by the shrinking of the minimum feature size on the production wafer, which was 0.18 μm in 2000. The smaller the minimum feature size, the more chips can be made on a wafer. The 0.18 μm technology in 2000 was limited by the photolithography resolution. By improving this resolution, the minimum feature size can be further reduced to 0.10 μm and beyond. The photoresist must be very sensitive to the exposure light to achieve reasonable throughput. The higher the PR sensitivity, the shorter the exposure time, and the higher the throughput. However, if the sensitivity is too high, other photoresist characteristics can be affected, including the resolution. Thus, a careful balance between resolution and sensitivity is required. An advanced IC chip needs more than 30 patterning process steps; each one must precisely align with the previous one to achieve successful pattern transfer for the whole chip

design. There is very little room for alignment error, since the maximum tolerance is 10% of the critical dimension. For 0.18 μm technology, misalignment must be controlled within 0.018 μm, or 18 nm. Therefore, advanced photolithography needs automatic alignment systems. This is very challenging, since every aspect must be precisely controlled. For example, 1 °C difference on a 200-mm wafer can cause 0.5-μm difference in the wafer diameter due to silicon thermal expansion (or contraction, when temperature is lower) with the $2.5 \times 10^{-6}/^{\circ}C$ expansion (or contraction) rate. The photolithography process needs to minimize defect density, since defects introduced in this process will be transferred to devices and circuits via each succeeding etch or ion implantation process and affect the yield and reliability of the products.

The photolithography process can be subdivided into three main operations: photoresist coating, alignment and exposure, and photoresist developing.

First the wafer is coated with a thin layer of photosensitive material, called *photoresist* (PR), which is exposed by ultraviolet light through a mask or reticle with the pattern of clear and dark areas generated by the plotter, based on IC design. The chemistry of the exposed photoresist will be changed by the photochemical reactions under the clear areas where the UV light can pass through. For the positive photoresist, which is commonly used in advanced semiconductor fabs, the exposed area is dissolved in the developer solution, leaving the unexposed PR on the wafer surface, which reproduces the dark pattern on the mask/reticle.

6.2 PHOTORESIST

Photoresists are the photosensitive materials used to temporarily coat the wafer and to transfer the optical image of the chip design on the mask or reticle to the wafer surface. It is similar to the photosensitive material on the plastic of photo films, which can transfer the optical images focused by the lens of a camera on the plastic film surface. But unlike these photosensitive coatings on film, the photoresists are not very sensitive to the visible light, nor are they required to be sensitive to the changes of color, or *gray levels*, of the light. Since it is mainly sensitive to ultraviolet (UV) light and insensitive to visible light, the photolithography process does not need a darkroom, as is required for film development. Since photoresists are insensitive to yellow light, all semiconductor fabs use yellow lights to illuminate photolithography areas, commonly called *photo bays*.

There are two kinds of photoresists, positive and negative. For the negative PR, the exposed parts become cross-linked and polymerized due to the photochemical reaction, which hardens and remains on the wafer surface after development, whereas the unexposed parts are dissolved by the developer solution. For the positive photoresist, the main component is novolac resin, which is a cross-linked polymer before the exposure. After the exposure process, the exposed part's cross-links break down and become "softened" due

to the photochemical reaction called *photosolubilization*, and will be dissolved by the developer while the unexposed parts remain on the wafer surface.

Figure 6.2 illustrates the two different kinds of photoresists and their pattern-transfer processes. The image of positive photoresist is the same as the image on the mask or reticle, and the image of negative photoresist is the reversed image. The roll of photo film one purchases is usually a negative film; the images on a negative film after developing are the reversed images the camera has taken, which need exposure and developing again on the negative photo papers to print the normal images. At a higher price, one can buy a roll of positive film, which gives the same images the camera has taken after development. Positive films are normally used to make slides.

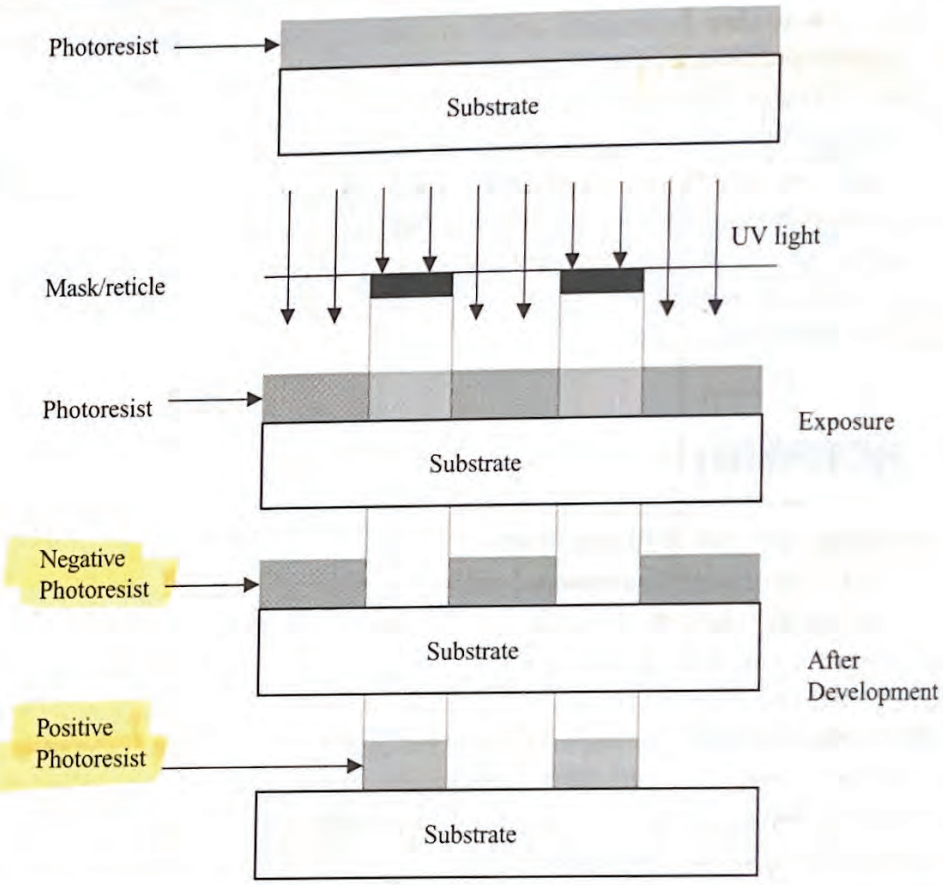


Figure 6.2
Patterning process with negative and positive photoresists.

Presently, most advanced semiconductor fabs use positive photoresist because it achieves the high resolution required for the submicron feature size. Photoresist has four basic components: polymer, sensitizer, solvent, and additives.

Polymer is the organic solid material that sticks on the wafer surface and withstands etch and ion-implantation processes for the masking of the pattern transfer process. It is formed by organic compounds, which are carbon-hydrogen molecules (C_xH_y) with complicated chain and ring structures. The

most commonly used positive photoresist polymer is phenol-formaldehyde or novolac resin. The most commonly used negative photoresist polymer is polyisoprene rubber.

The *sensitizer* is an organic compound with very high photoactivity, which controls and modifies the photochemical reaction of the photoresist during exposure. The sensitizer for the positive photoresist is a dissolution inhibitor, which is cross-linked within the resin. During the exposure process, the energy from the light dissociates the sensitizer and breaks down the cross-links, which makes the exposed resin become soluble in an aqueous developer solution. The sensitizer for the negative photoresist is an organic molecule containing the N_3 group. Exposure to UV light liberates N_2 gas, forming the free radicals that help to cross-link the rubber molecules. The chain reaction of the cross-links polymerizes the exposed areas, which have greater bonding strength and higher chemical resistance.

Solvent is the liquid that dissolves the polymer and sensitizer, and suspends them in the liquid photoresist. It makes photoresist easy to apply on a wafer surface as a thin film of 0.5-μm to 3-μm thickness. The solvent thins the PR to allow the application of thin layers by spinning, analogous to paint. Before the spin coating process, about 75% of photoresist is the solvent. Positive photoresists commonly use acetate-type solvents, and negative photoresists normally use xylene (C_8H_{10}).

Additives control and modify the photochemical reaction of photoresist during exposure to achieve the optimized lithography resolution. Dye is a commonly used additive for both positive and negative photoresist.

For negative photoresist, the developer solution is mainly xylene. It dissolves the unexposed photoresist while some developer solvents can be absorbed in the exposed, cross-linked photoresist. It causes the PR "swelling" effect, which distorts the pattern features and limits the resolution to about 2 to 3 times the thickness of the photoresist. Negative photoresist was widely used in the semiconductor industry before the 1980s, when the minimum feature size was larger than 3 μm. It is no longer used in advanced semiconductor fabs because of its poor resolution. Positive photoresists do not absorb the developer solvents. They can achieve much higher resolution, and are widely used for the photolithography processes. Figure 6.3 illustrates the resolution of the negative and positive photoresist.

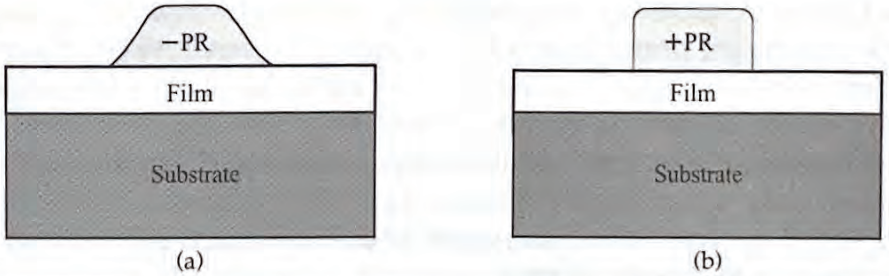


Figure 6.3
(a) Negative and (b) positive photoresists.

Question

Positive photoresist can achieve much higher resolution than negative photoresist. Why didn't people use it before the 1980s?

Answer

Positive photoresist is much more expensive than negative photoresist, therefore manufacturers used negative photoresist until it had to be replaced, when the minimum feature size shrank to smaller than 3 μm. Photoresist is the most important material used in the photolithography process. Unless it is absolutely necessary, engineers are reluctant to switch from one photoresist to another.

To pattern a small feature, shorter-wavelength exposure light is required. Photolithography processes using deep UV light (248 nm or 193 nm) require different photoresists from processes that use mercury g-line (436 nm) and I-line (365 nm). This is because the intensity of DUV light sources, usually excimer lasers, is much lower than that of mercury lamps. Chemically amplified photoresists have been developed for the DUV photolithography processes in 0.25-μm or smaller feature patterning applications. Catalysis effect is used to increase the effective sensitivity of the photoresist in this kind of process. A photoacid is created in the photoresist when it is exposed to the DUV light. In the postexposure bake (PEB) process, the wafer is heated, and heat drives acid diffusion and amplification in a catalytic reaction, as shown in Figure 6.4.

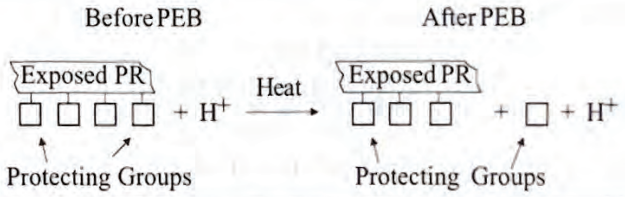


Figure 6.4 Chemically amplified photoresist.

To achieve completed pattern transfer, the photoresist needs to have good resolution, high etch resistance, and good adhesion. High resolution is the key to achieve successful pattern transfer. Without high etch resistance and good adhesion of the PR, the next etch or ion implantation processes will most likely fail to meet process requirements and will cause intolerable error. Normally, the thinner the photoresist film, the higher the resolution. However, the thinner the photoresist film, the lower the etching and ion-implantation resistance. It is always a trade-off between these two conflicting requirements.

The PR process latitude consists of tolerance of the PR to the varying spin rate, baking temperature, and exposure flux. The wider the process latitude, the more stable the process. This is one of the important factors when engineers choose the photoresist for the process.

6.3 PHOTOLITHOGRAPHY PROCESS

The photolithography process includes three major steps: PR coating, exposure, and developing. To achieve high resolution, photolithography also has lots of baking and chilling steps. For the older, all-manual process technology, the photolithography process flow had eight steps: wafer clean, prebake, spin-coating primer and PR, soft bake, alignment and exposure, developing, pattern inspection, and hard bake. If a wafer failed to pass the inspection, it bypassed the hard bake step, the PR stripped, and the whole process repeated until it passed the inspection.

For the advanced photolithography process, the three basic steps are the same. Detailed steps are added to achieve high photolithography resolution. Integrated track-aligner systems are widely used to improve the process yield and throughput. Because all the coating, baking/cooling, exposure, and developing process steps are performed in a track-aligner system, the pattern inspection is performed after the hard bake. Figure 6.5 shows a flowchart of the photolithography process, and Figure 6.6 gives an advanced photolithography process sequence on the wafer surface.

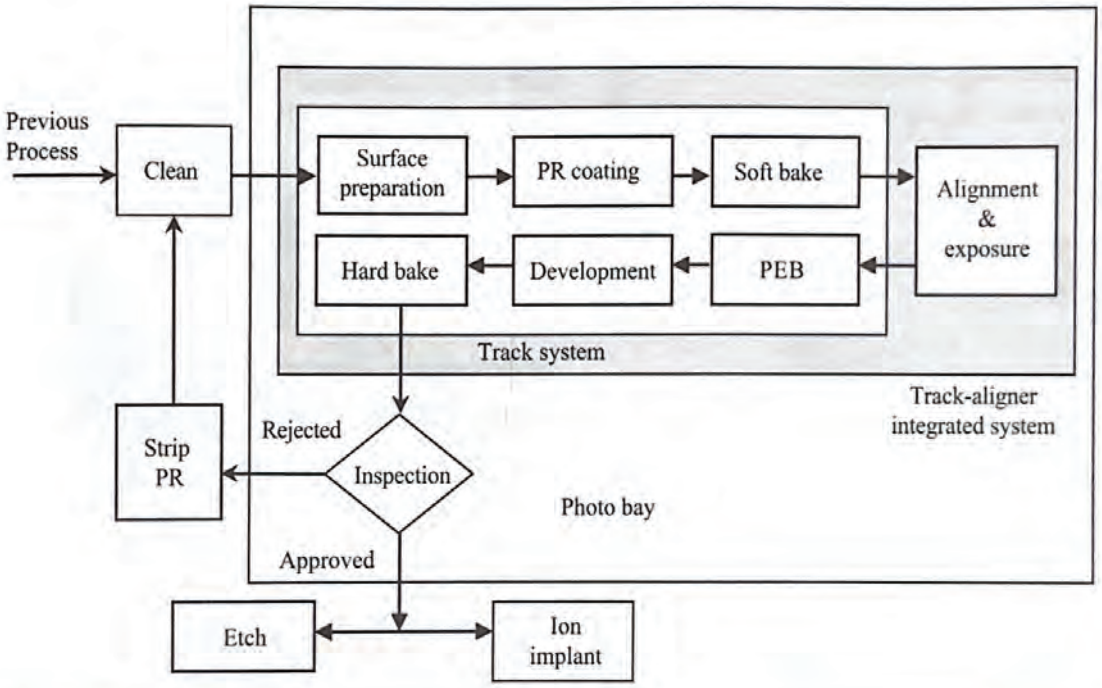
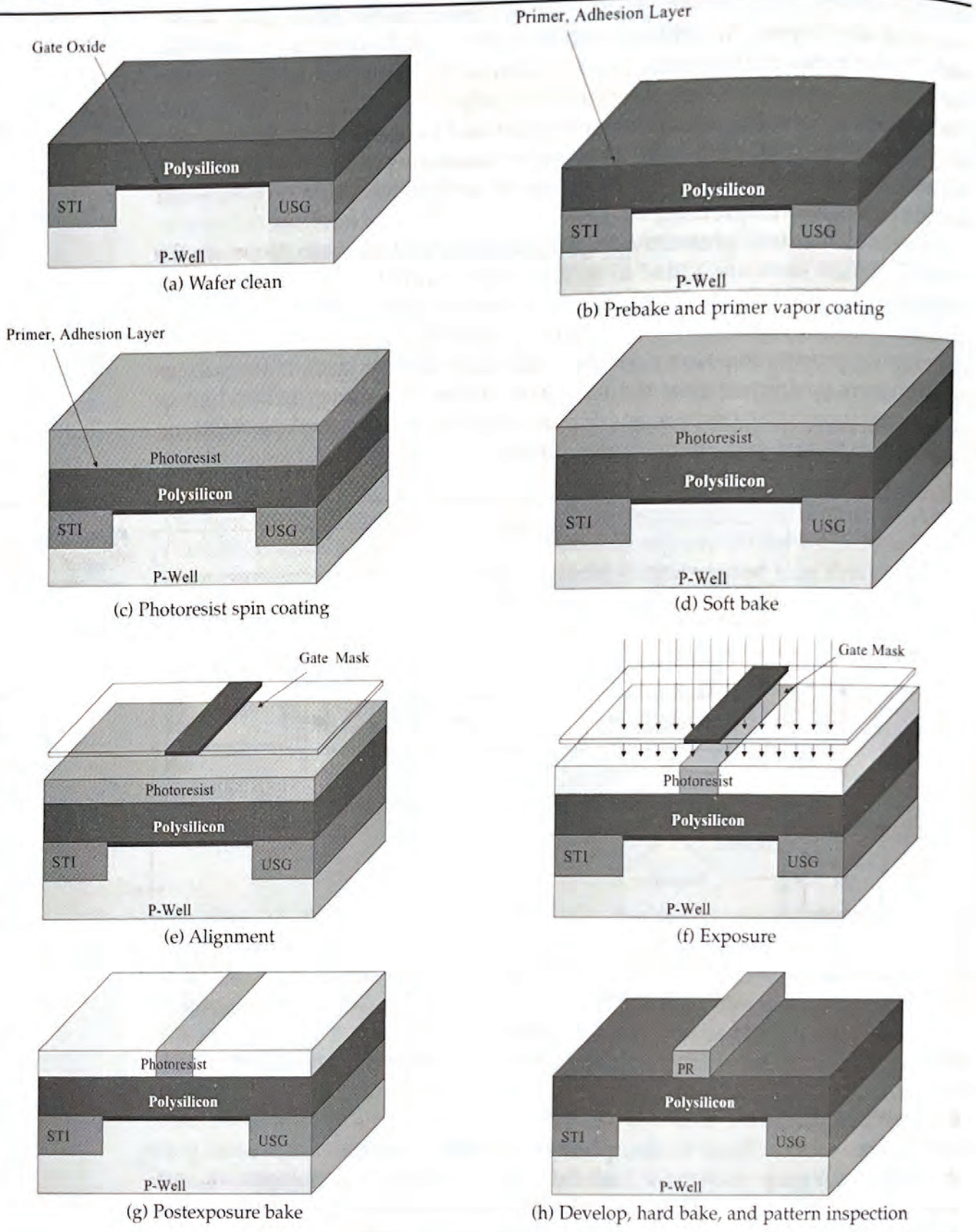


Figure 6.5 Flowchart of the photolithography processes.

6.3.1 Wafer Clean

Before the wafers come to the photolithography process, they have gone through previous processes such as etch, ion implantation and annealing, oxidation, CVD, PVD, and CMP. The wafer might have some organic contaminates (from the photoresist, the etch byproducts, bacteria, and debris of

Figure 6.6
Photolithography process.



human skin) and inorganic contaminates such as particles and residues from storage containers, improper wafer handling, environmental materials (e.g., dust and mobile ions). The wafers need to be cleaned to get rid of these contaminates before they are ready for the photolithography process. Even if the wafers are contamination-free, further cleaning is desirable for better adhesion of photoresist on the wafer surface.

Chemical cleaning is standard for the wafer clean, using solvents and acids to remove organic and inorganic contaminant residues, respectively. It is usually followed by deionized (DI) water rinse and spin dry processes, as illustrated in Figure 6.7.

Other methods such as dry air or nitrogen blow, high-pressure steam blow, oxygen plasma ashing, and mechanical brushing had been used before and may still be used in some fabs. When the feature size shrinks, the killer particle size also shrinks. These methods worked well in getting rid of larger particles, but not only do they fail to remove smaller particles on the wafer surface, they can even add more killer particles than they are able to remove.

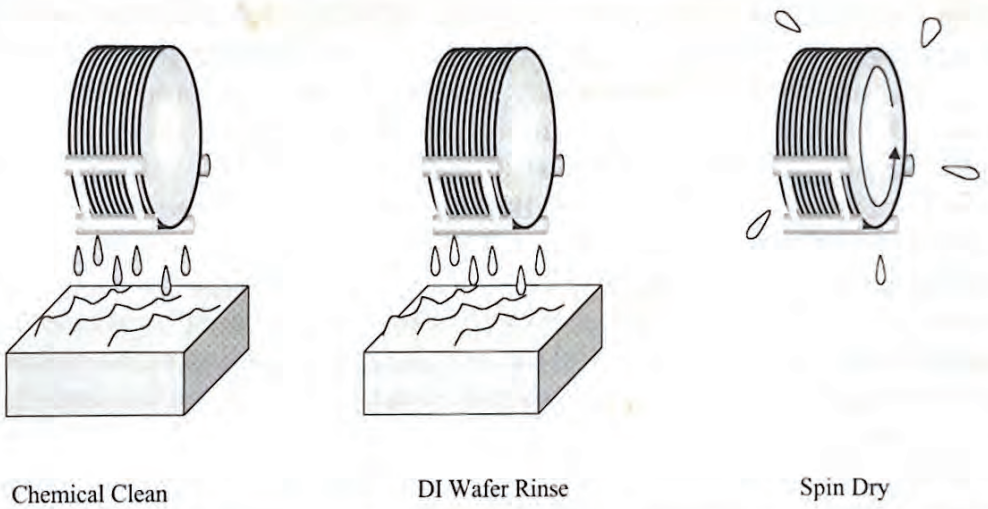


Figure 6.7
Wafer clean process.

Particles on the wafer surface can cause pinholes in the photoresist; the organic and inorganic contamination may cause PR adhesion problems and device and circuit defects. It is very important to minimize or eliminate these contaminants before the photolithography process to ensure the process yield.

In advanced IC fab, wet clean is usually performed in wet bay, or wet hoods, in other process areas, before the wafers are brought to the photo bay. Wet hoods are usually placed in a class 1000 cleanrom. In photo bay, however, all photolithography equipment is installed in the highest grade cleanroom, which differs from other process bays, which usually place process tools in a class 1000 cleanroom.

6.3.2 Preparation

PR preparation is a two-step process performed in a sealed chamber commonly called the prep chamber.

The first step is a heating process for removing the moisture adsorbed on the wafer surface, called the *dehydrate bake* or *prebake*. A clean, dehydrated wafer surface is essential for adhesion of the photoresist on the wafer surface. Poor adhesion can lead to failures of the photoresist patterning and can cause undercut during the subsequent etch processes. In most cases, the wafer is baked for one or two minutes on a hot plate, with the temperature from 150 to 200 °C. The baking temperature and time are critical to achieve the optimal process results. If the baking temperature is too low or the time too short, insufficient surface dehydration can cause photoresist adhesion problems. If the baking temperature is too high, it may cause primer dissociation, which can cause contamination and affect the photoresist adhesion.

The second step is a deposition process called *priming*. In this process a thin layer of primer, which can "wet" the wafer surface and promote adhesion between the organic photoresist and the inorganic silicon or silicon compound wafer surface, is coated on the wafer surface before the photoresist coating. Hexamethyldisilazane (HMDS, $(CH_3)_3SiNHSi(CH_3)_3$) is the most commonly used primer in IC photolithography processes. In advanced photolithography processes, the HMDS is vaporized, introduced into the prep chamber, and deposited on the wafer surface in situ with the prebake process. It is very important to apply the photoresist immediately after the primer coating to prevent surface rehydration. Thus, the prep chamber is always in line with PR coater on a track system. Primer can also be coated by a spin-on process in situ with photoresist coating, but this is not as popular as vapor primer coating in advanced IC fabs. Vapor primer coating is preferred over spin primer coating because it minimizes the potential for surface contamination by the particulate carried in liquid chemicals. Figure 6.8 illustrates the in situ prebake and primer coating processes.

If the photoresist is still hot during spin coating, the solvents in the photoresist will evaporate rapidly and cool down the wafer at the same time. This makes a very undesirable process condition, since both solvent loss and temperature change can affect the PR viscosity, which will affect the thickness and thickness uniformity during the PR spin coating. Therefore, after the preparation process, the wafer needs to be cooled to the ambient temperature before applying photoresist. Normally the wafer is cooled on a chill plate, which is water cooled by a heat exchanger, on the same track system.

6.3.3 Photoresist Coating

The photoresist coating is a deposition process in which a thin layer of photoresist is applied on the wafer surface. The wafer is placed on a spindle with a vacuum chuck that can hold the wafer during the high-speed rotation. Liquid

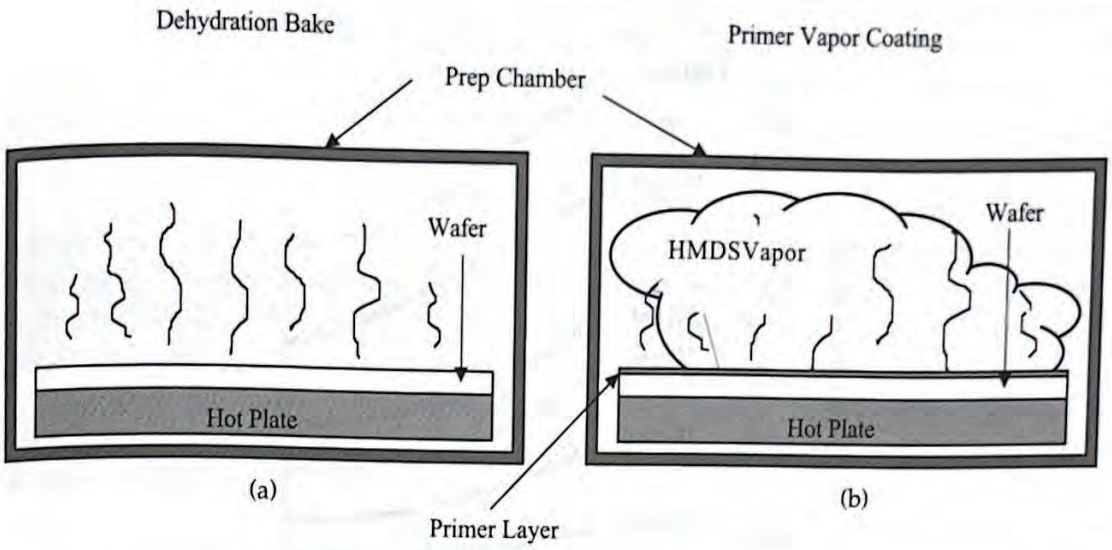


Figure 6.8
In situ prebake (a) and (b) primer coating process.

photoresist is applied on the wafer surface, and the centrifugal force from the wafer rotation spreads the liquid over the whole wafer. After the solvents in the PR have evaporated, the wafer is coated with a thin layer of PR. The PR thickness is related to both PR viscosity and the wafer spin rate, as illustrated in Figure 6.9. The higher the spin rate, the thinner the PR layer, and the better the PR thickness uniformity. The PR thickness is inversely proportional to the square root of the spin rate. Since photoresists have high viscosity and very high surface tension, very high spin rate is required for uniform PR spin coating. The higher the viscosity, the thicker the PR films at the fixed spin rate. Viscosity of the photoresist can be controlled by the solid content of the photoresist solution. The typical photoresist thickness in photolithography is between 5000 and 30,000 Å.

The photoresist can be dispensed with either a static or dynamic method. For the static method, the photoresist is dispensed onto a stationary wafer surface, and is allowed to spread over part of the wafer surface. When the PR puddle spreads to a certain diameter, the wafer is spun rapidly, with spin rate up to 7000 rpm, to distribute the photoresist evenly across the entire wafer surface. The thickness of the photoresist is related to the PR viscosity, surface tension, PR drying characteristics, the spin rate, the acceleration rate, and the spin time. PR thickness and thickness uniformity are especially sensitive to the acceleration rate.

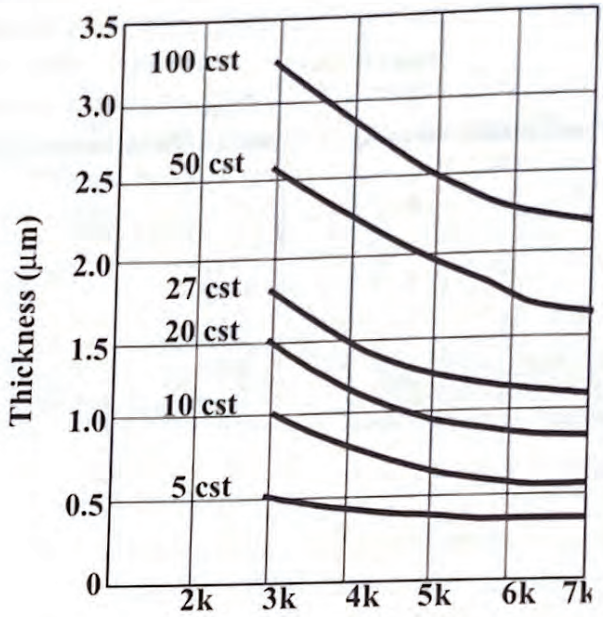


Figure 6.9
Relationship of PR thickness and spin rate at different viscosities. *Source:* Integrated Circuit Engineering Corporation

For the dynamic dispense, the photoresist is applied at the center of the wafer while it is rotating at a low spin rate, around 500 rpm. After the PR is dispensed, the wafer is accelerated to a high spin rate, up to 7000 rpm, to spread the PR uniformly across the wafer surface. The dynamic dispense method uses less photoresist, whereas static dispense can achieve better PR coating uniformity. Figure 6.10 shows the change of spin rate in a dynamic dispense spin coating process.

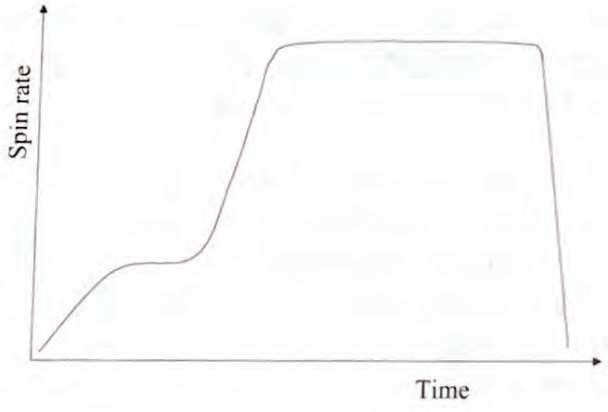


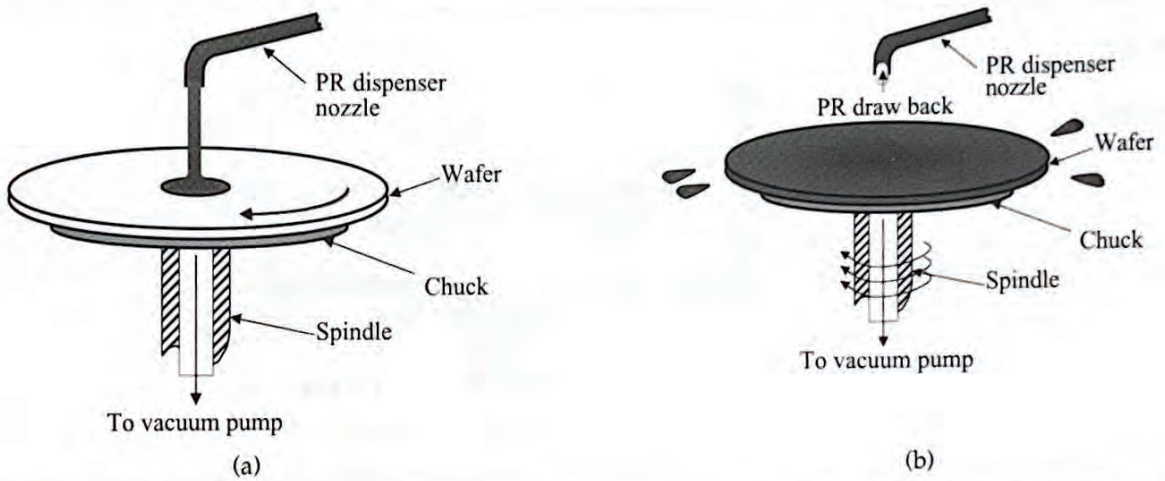
Figure 6.10
Spin rate change for spin coating processes.

The solvents in the photoresist evaporate rapidly during the spin spreading processes, changing the PR viscosity. Therefore, it is very important to

increase the spin rate as quickly as possible after the PR is applied on the wafer surface to reduce the effects of the PR viscosity change due to the solvent evaporation. In some processes, a thin layer of solvent is spin coated on the wafer surface before the photoresist coating to improve the photoresist adhesion and uniformity.

The photoresist spin coating process is illustrated in Figure 6.11. The PR "draw back" feature is designed to prevent a dry PR droplet from forming at the end of the dispenser nozzle due to solvent evaporation. Without this feature, the dried PR droplet can cause defects on the photoresist layer in the next PR coating process.

Figure 6.11
Photoresist applying (a) and (b) spin coating.



The spin coating was also used for the primer (HMDS) deposition just prior to the PR coating. First, liquid HMDS was applied on the wafer surface at a low spin rate to coat the wafer, then the spin rate ramped up to 3000–6000 rpm to dry the HMDS in 20–30 seconds. The advantage of the primer spin coating is the in situ process with the PR coating, which can effectively prevent the rehydration of the wafer surface before PR coating. However, most people prefer the vapor primer coating now due to less primer usage (HMDS is very expensive), better coating uniformity, less risk of particulate contamination, and PR dissolving by the wet HMDS, associated to the liquid applications.

A schematic of a PR spin coater is illustrated in Figure 6.12. The photoresist is brought into the dispense nozzle from a tube with a water sleeve, in which water from a heat exchanger is used to maintain a constant temperature of the photoresist since the viscosity is related to the PR temperature. The spin rate and spin rate ramp are precisely controlled; so are the air flow temperature and air flow rate in the coater, since they can affect the drying

characteristics of the PR. The spindle is either nitrogen- or water-cooled to avoid wafer temperature nonuniformity caused by the center heating, since the spindle can become very hot during the high-speed spin if not properly cooled. The excess PR and edge-bead removal (EBR) solution are collected and drained out of the station from the bottom, and the vaporized solvent is evacuated from the exhaust. The photoresist thickness and uniformity are also related to the exhaust gas temperature and gas flow rate, since they can affect the photoresist-drying characteristic. In fact, the best PR thickness uniformity can be achieved without exhaust flow. However, without exhaust, the accumulation of the solvent vapor fumes can endanger health and safety. Usually, increasing exhaust flow rate causes edge-thick PR thickness profile, because of the faster drying of PR near the edge, increasing the viscosity of PR and its thickness there.

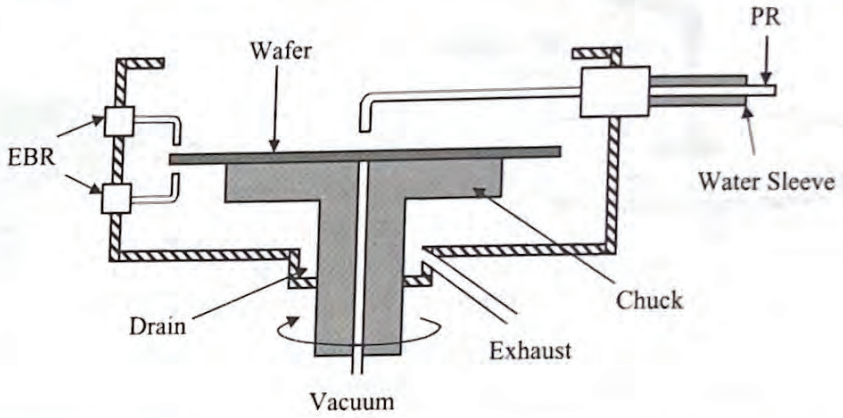


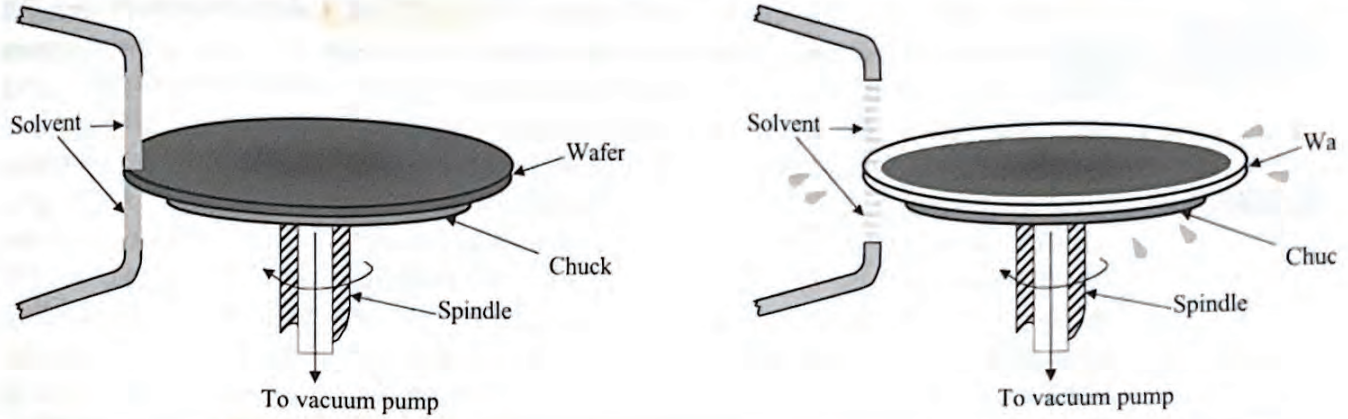
Figure 6.12 Schematic of a photoresist spin coater.

After the PR spin coating, both sides of the wafer near the edge are covered by the photoresist. It is necessary to do edge-bead removal (EBR) to get rid of the PR buildup on the edge; because in the following etch or ion implantation process, mechanical wafer handlers such as robot fingers or wafer clamps can crack the photoresist buildup at the edge of the wafer and cause particulate contamination. The thick edge bead may also cause focus problems during the exposure process at the edge of the wafer. Both chemical and optical methods are used to remove edge bead.

The chemical EBR normally is performed in the spin coater, after the PR spin coating. In this process, solvents are injected onto the edge of both sides of the wafer while the wafer is rotating; they dissolve the photoresist at the edge and wash it away, as shown in Figure 6.13.

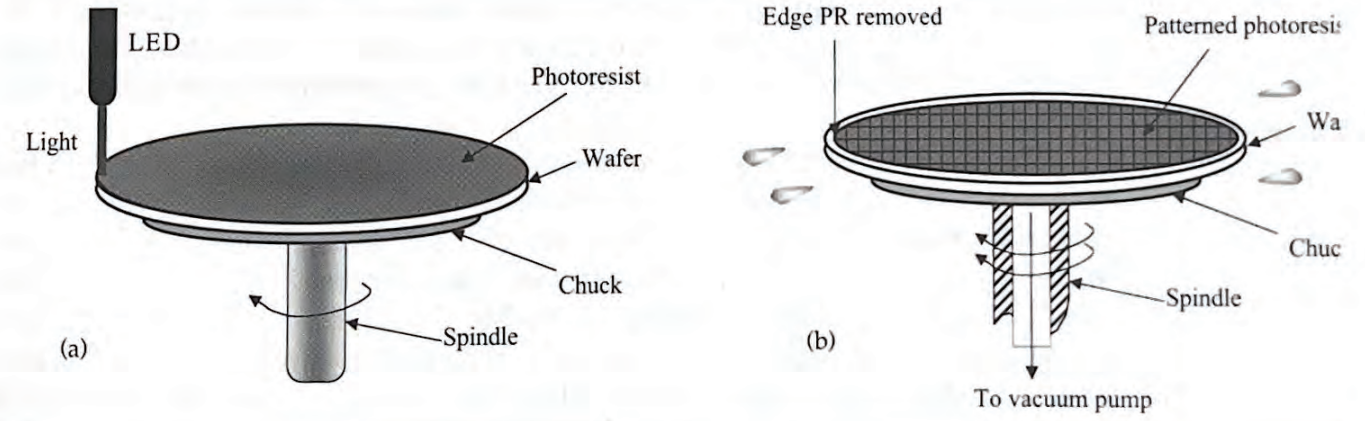
Optical edge-bead removal is normally performed after the exposure process in a specially designed optical EBR station on a track system before the wafer is sent to the developer. It uses a light source such as a light-emitting diode (LED) to expose the top side of the wafer edge while the wafer

Figure 6.13
Chemical edge-bead removal (EBR).



is rotating. The center of the wafer could move at the same time according to the image of the clamp of the next process tool. The exposed PR will be removed during the develop process, which ensures no particle contamination during the wafer clamping, particularly for some etch processes. The optical EBR processes are illustrated in Figure 6.14.

Figure 6.14
Optical EBR, (a) edge exposure and (b) after develop.



Other photoresist coating methods, such as moving arm dispensers and roller coaters, may still be used in some less-advanced IC fabs; however, they are not as popular as spin coating.

6.3.4 Soft Bake

After the photoresist coating, the wafer is put into a thermal process again to drive out the majority of solvent inside the photoresist and transform the PR from the liquid state to the solid state. This *soft bake* also improves the PR adhesion to the wafer surface; in some fabs this process is called pre-exposure bake. After soft bake the photoresist thickness shrinks about 10% to 20%, and the PR consists of about 5% to 20% solvent residue.

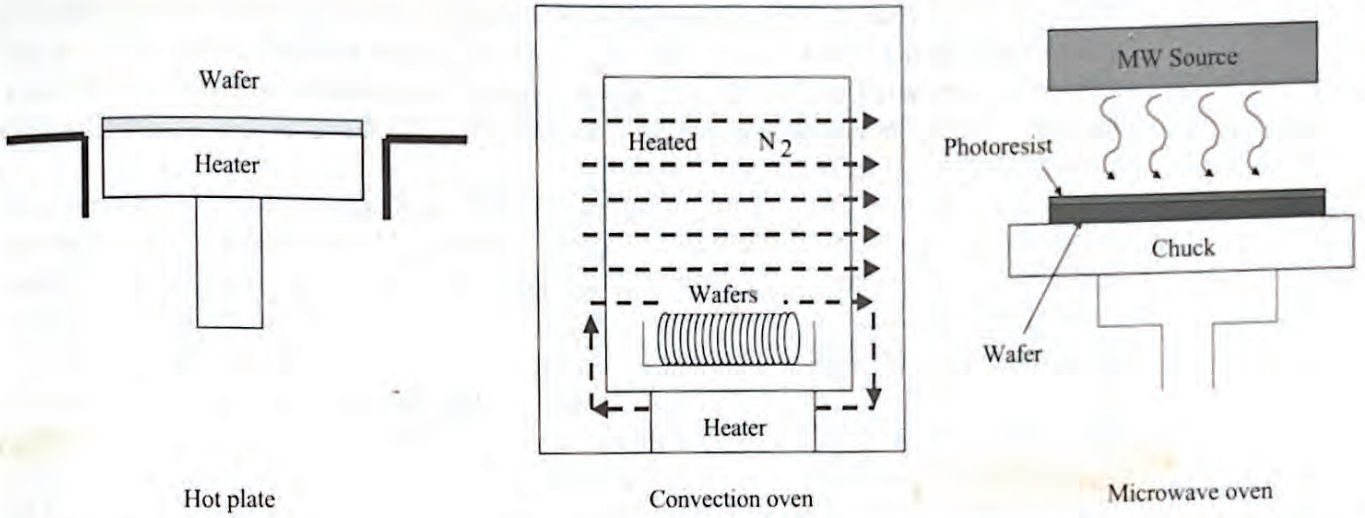
The soft bake temperature and time depend on the type of photoresist (negative or positive) and vary with the specific process. Etch of PR has its own optimized baking time and temperature. If the PR is underbaked, either because the baking temperature is too low or because the baking time is too short, the PR might peel off from the wafer surface during subsequent processes due to adhesion failure. It also can affect the pattern resolution, first because excessive solvents in the PR cause insensitivity to the exposure light and second because of the microscopic shaking of the photoresist. Underbaking causes insufficient hardening, and jellylike PR can shake in the microscopic scale during the wafer stepping, enough to create a blurred image on the PR, (think of shooting a picture with a shaky camera). Overbaking in the soft bake step can cause premature polymerization of the photoresist, making it insensitive to the exposure light. For chemical-amplified photoresists used in DUV lithography processes, some residue solvent in photoresist is needed for acid diffusion and amplification during the postexposure bake (PEB) step. Overbake can cause insufficient catalysis chemical reaction, with resulting image underdevelopment.

There are several methods used for soft-baking processes: convection oven, infrared oven, microwave oven, and hot plate (see Figure 6.15). The convection oven uses convection flow of the heated nitrogen gas to heat the wafer at the required temperature, from 90 to 120 °C for about 30 minutes. The infrared oven can bake the wafer in a shorter time period, but can also heat the wafer bottom up, since infrared radiation can pass through the photoresist layer to heat the wafer first, then heat the PR. The microwave oven is another method used for the baking process.

The hot plate can also heat and dry the photoresist on the wafer from the bottom up, since it heats the wafer first through heat transfer between the plate and the wafer. Thus it can avoid the PR crust problem from surface heating and drying associated with the convection oven baking processes. Unlike the convection oven batch system, hot plate is a single-wafer system, which can achieve uniform heating within the wafer and, more important, stable process results from wafer to wafer. Hot plates can be easily integrated into a track system for in-line coating, baking, and developing. Although it is possible that some less advanced IC fabs may still use one of the other methods, hot plate is the most common method for all the baking processes. It can be found in almost all photo-track systems in an advanced IC fab.

After the soft bake, the wafer is put on a chill plate to cool down to ambient temperature. It is very important to keep the wafer temperature constant during the alignment and exposure, because 1 °C difference in temperature

Figure 6.15
Different baking methods.



can cause 0.5 μm difference in a 200-mm silicon wafer due to the thermal expansion effect.

6.3.5 Alignment and Exposure

Alignment and exposure are the most critical steps of the photolithography process, and indeed for the whole IC processing. This process determines the success of transferring the IC design pattern on the mask or reticle to the photoresist on the wafer surface.

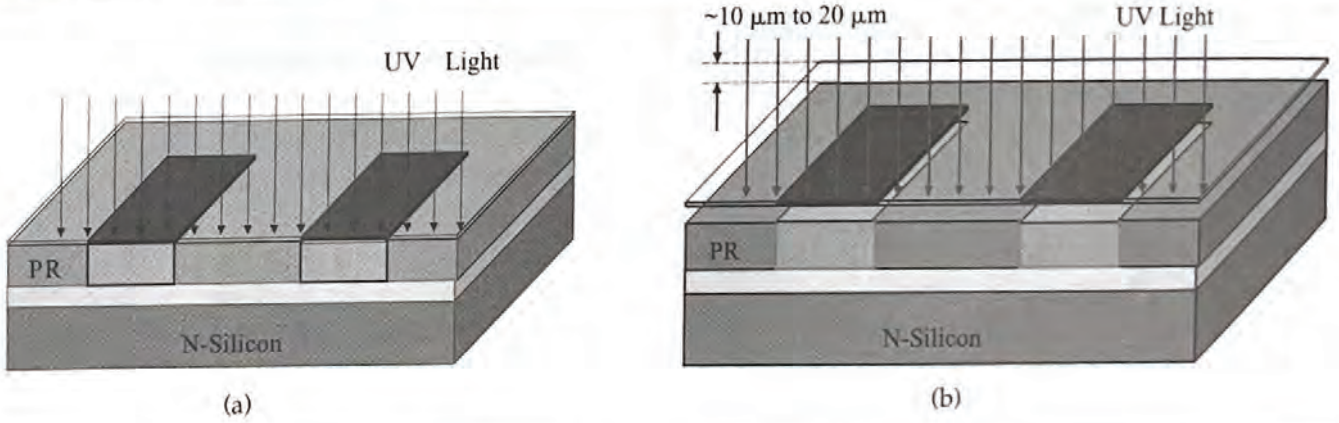
The exposure process is very similar to taking a photo with a camera: the patterned image on the mask or reticle is exposed to the photoresist on the wafer, just as the image is exposed on the film inside the camera. The resolution of the IC photo exposure system is much higher than a camera's, which is why the IC photo exposure tool, called the aligner or stepper, is much more expensive than the finest photo camera. One advanced alignment and exposure tool, a 200-mm wafer deep UV (DUV) stepper, costs more than $5 million each, and a 300-mm wafer tool will be predictably more expensive. In addition to the resolution requirement, precise alignment is also vital. Advanced IC chips have more than 30 mask steps, and each mask or reticle needs to be precisely aligned with the original alignment mark. Otherwise it can't successfully transfer the designed pattern to the wafer surface, causing device and circuit failures. Other requirements are high repeatability and reliability, high throughput, and low cost of ownership.

Contact and Proximity Printers In the early years of the semiconductor industry, contact and proximity printers were widely used for the alignment and exposure process. The *contact printer* was the earliest and simplest tool. In the contact

printing process, the mask makes direct contact with the photoresist on the wafer, and the UV light passes through the clear pattern from the mask and exposes the PR underneath. The contact printer can achieve very good resolution, close to what can be achieved on the mask. However, due to the different curvatures of the mask and wafer, only a few points on the wafer really make direct contact with the mask, and most areas on the wafer surface have about 1 to 2 μm air gap between the mask and the PR. Still, the highest resolution of the contact printer is in submicron range.

For every contact printing alignment and exposure, the touch and detach between the mask and PR can generate particles on both the wafer and the mask surface. Particles quickly accumulate on the mask surface and cause defects on the wafer from both particulate contamination and the particle image transfer. The mask lifetime is seriously limited by the particle contamination. To solve this problem, engineers adapted another approach by putting the mask about 10 to 20 μm away from the photoresist. This is called a *proximity printer*. Since there is no direct contact, it has much less particle contamination and much longer mask lifetime than that of the contact printer. The tradeoff is worse resolution, because of more light diffraction in the larger gap. The highest resolution a proximity printer can achieve is about 2 μm. Neither contact nor proximity printers are used in very large scale IC (VLSI) and ultra large scale IC (ULSI) chip fabrications. Figure 6.16 illustrates the exposure processes with contact and proximity printing systems.

Figure 6.16
(a) Contact printing and (b) proximity printing.



Projection Printer To further improve the exposure resolution while maintaining the low particle contamination level, the *projection exposure system* was developed and became widely used in the VLSI semiconductor fabs (see Figure 6.17).

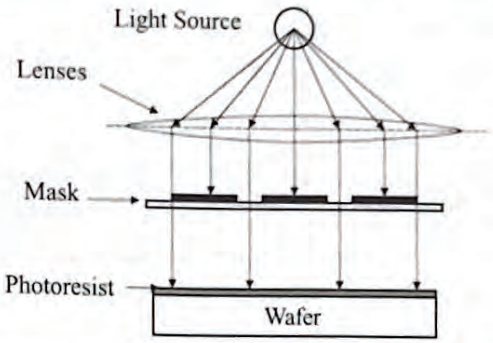


Figure 6.17
Schematic of a projection exposure system.

The projection system works like an overhead projector. The mask is like the transparency foil, and the image is refocused on the wafer surface in 1:1 ratio. In comparison, an overhead projector refocuses the image on the transparency foil to the screen in about 1:10 ratio. In a projection exposure system, the mask and wafer are far apart, which eliminates the possibility of particle generation from the mask–wafer contact. By taking advantage of the optical characteristics of the lenses and mirrors, projection exposure systems can achieve 1-μm minimum feature sizes. They are widely used for the VLSI device fabrications.

The most commonly used projection system is the *scanning projection exposure system* (see Figure 6.18) which uses a slit to block some light from the light source to reduce light scattering and improve the 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 the UV light scanning across the mask to refocus on the wafer surface and expose the photoresist across the wafer.

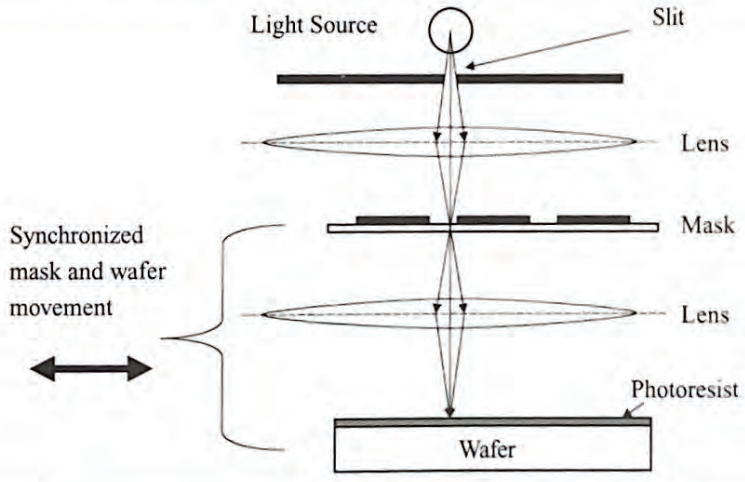


Figure 6.18
Schematic of a scanning projection exposure system.

Steppers When the feature size continues to shrink and approach to the submicron level, the projection system can no longer meet the resolution requirement. Step and repeat systems have been developed for VLSI and ULSI chip manufacturing.

In a projection system, the image transfer from mask to wafer is 1:1, and a wafer needs only one exposure for the pattern transfer process. By shrinking and refocusing the image of the mask/reticle to the wafer surface at the ratio of 5:1 or 10:1, the patterning transfer resolution can be improved. However, the exposure system must be totally redesigned, because it is impractical to make a mask and a high-precision optical system with dimension more than five to ten times the wafer diameter, which is 1000 to 2000 mm for a 200-mm wafer, to expose the whole wafer in one exposure. It is also very difficult to find an UV light source intense enough to do this kind of exposure. Therefore, the designed pattern is made of a piece of chromium glass, called a reticle, which is used to expose only part of the wafer. In comparison, the masks used in projection, contact, and proximity printers expose the whole wafer. Since a stepper shrinks the image from the reticle, the feature size on the reticle is much larger than that on the wafer surface. For instance, if the minimum feature size is 0.25 μm on the wafer surface, the minimum feature size on the reticle is 1.25 μm, for a 5:1 shrink ratio. This is much easier to make than the 1:1 ratio photo mask.

Question

Why is the 5:1 shrink ratio more popular in the semiconductor industry than the 10:1 shrink ratio?

Answer

Choosing between the 5:1 and the 10:1 shrink ratio involves a tradeoff between resolution and throughput. Obviously, 10:1 image shrink will have better photolithography resolution than 5:1 image shrink; however, it exposes only a quarter of the area exposed by 5:1 shrink ratio for a reticle. This means that total exposure time will be quadrupled. Keep in mind that area changes in the power of the square of the dimension change, $A \propto d^2$.

Because the stepper exposes only a small portion of the wafer at one exposure, one needs to repeat the step and exposure multiple times until the whole wafer is exposed. Figure 6.19 shows the basic structure of the stepper system and two steps of the exposure processes. The stepper system is much more complicated than other optical exposure systems. For instance, the stepper needs to align in every step, and each wafer needs 20 to 60 steps, determined by the process and the product specification, to cover the whole wafer. In comparison, the projection and contact/proximity printers need only one alignment per wafer. For the submicron photolithography process, there is little

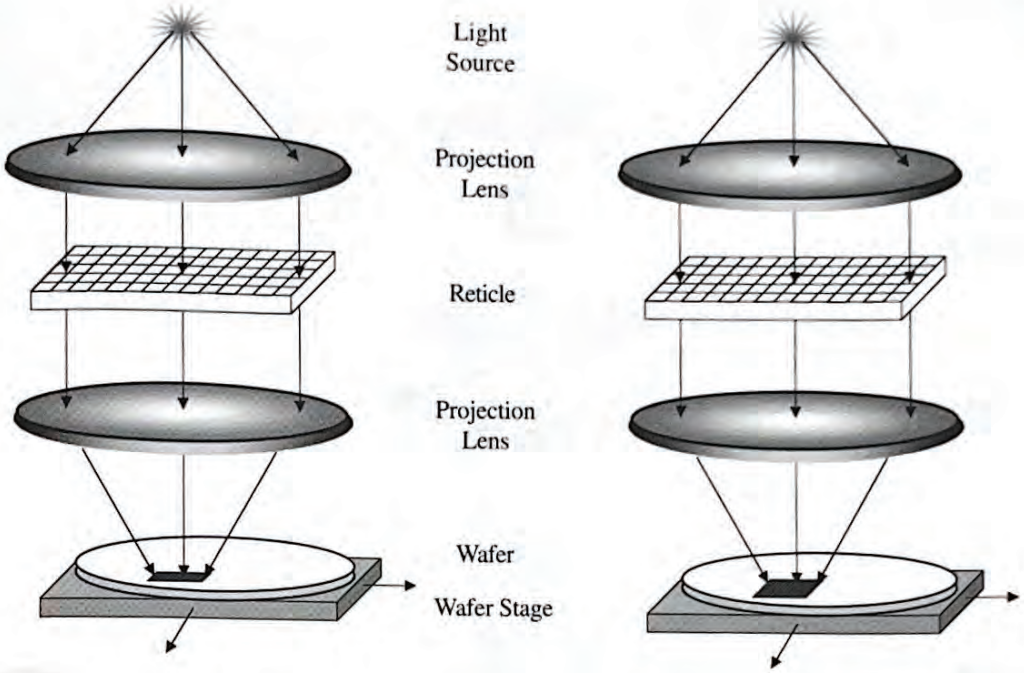


Figure 6.19
Step and repeat exposure system.

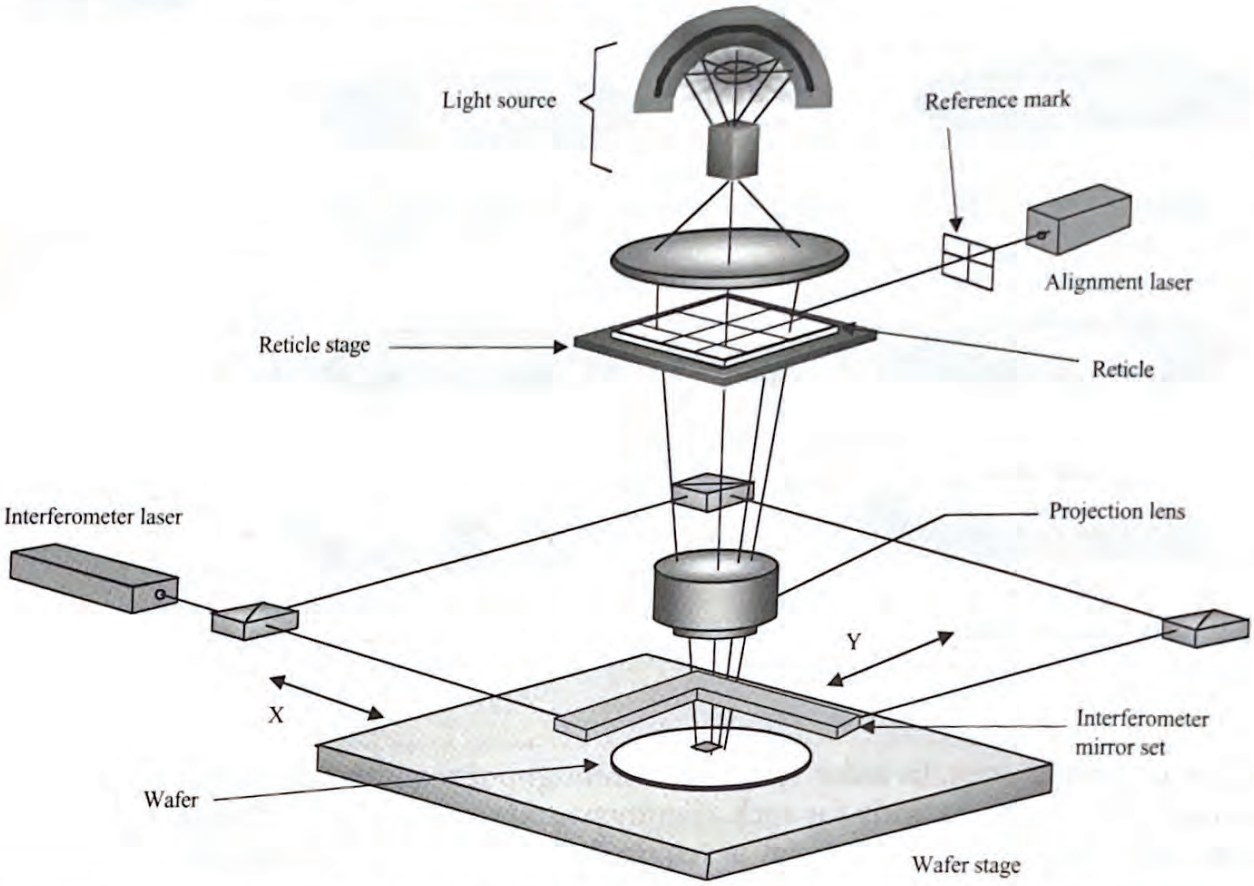
room for alignment error. In order to meet the throughput requirement, it can allow only one or two seconds for each alignment and exposure step. Therefore, an automatic alignment system is required for the stepper systems. A schematic of a stepper system is illustrated in Figure 6.20.

After the wafer finishes photoresist coating and soft baking, it is sent into a stepper and put on the wafer stage. It is first aligned with a previous alignment mark by a computer-controlled reticle and lens mechanism. For the very first photolithography step of the process, the alignment is accomplished by using the notch or flat on the wafer, which is designed to indicate the wafer crystal orientation and also serves as the alignment mark. The stepper usually adjusts the alignment optically with the automatic laser interferometry positioning system.

To further improve resolution of the image transfer, engineers combined the scanning projection printer and stepper technology to develop the step-and-scan system, which is currently widely used in deep submicron IC fabrication.

Because of the high-precision requirements for the optical, mechanical, and electric systems, the stepper normally is the most expensive stand-alone process tool in the semiconductor fab. Many photoresists used for submicron semiconductor fabrication need to be exposed as soon as they have finished the soft bake; otherwise, the exposure resolution could be affected due to sensitizer decay in the photoresists. Therefore, in most fabs, the steppers are integrated with the coater-developer track systems.

Figure 6.20
Schematic of a step and repeat alignment and exposure system.



Exposure Light Sources The exposure process of photolithography is similar to the exposure of photo film with a camera. A picture taken under bright sunlight requires less exposure time than one taken under candlelight and can normally achieve higher resolution. Therefore, high-intensity light sources are important to achieve high resolution and high throughput. The wavelength of the UV light source used to expose the photoresist is a key factor in photolithography. Since curtain photoresist is sensitive to only a narrow range of wavelength of UV light, people normally choose the exposure light wavelength according to the photoresist sensitivity and the feature size of the circuit. The shorter the wavelength, the better the patterning resolution. When the feature size shrinks, the wavelength of the exposure light also needs to be shorter to match the patterning resolution requirement. There are two kinds of light sources widely used for photolithography processes: mercury lamp and excimer laser. Exposure light sources must be stable, reliable, and adjustable, with short wavelength, high intensity, and long lifetime.

For feature size larger than 2 μm, the broadband (multiwavelength) mercury lamp is used as the light source for contact/proximity and projection printers. When the feature size shrinks, single-wavelength light sources are required to achieve the desired resolution. High-pressure mercury lamps were the most commonly used UV light sources for submicron photolithography processes in projection systems and steppers in the 1980s and 1990s. The mercury UV lamp wavelength spectrum is given in Figure 6.21. The G-line and I-line are the most commonly used for photolithography exposure processes of 0.50-μm and 0.35-μm features, respectively.

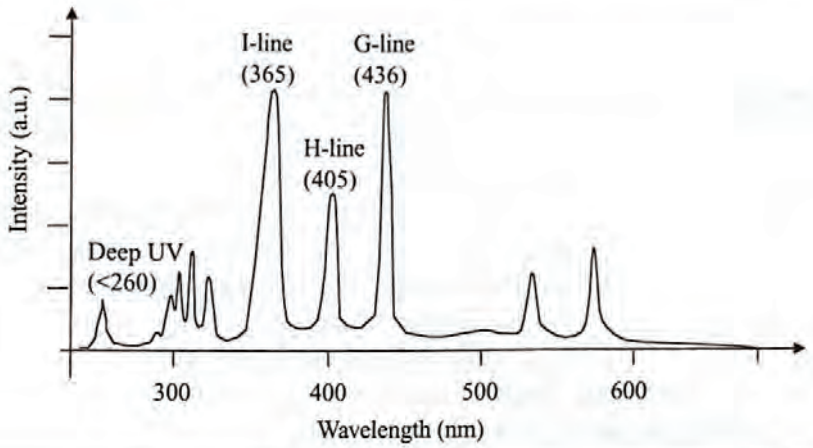


Figure 6.21
The light spectrum of the mercury lamp.

For photolithography processes with 0.25- and 0.18-μm minimum feature size, light sources with even shorter wavelengths are needed. The KrF excimer laser with deep ultraviolet (DUV) wavelength at 248 nm is most commonly employed as the light source for the steppers used in the 0.25-μm processes, and it is capable of patterning feature sizes as small as 0.13 μm. Steppers using the ArF excimer laser, with wavelength of 193 nm, have already been used in IC production to pattern 0.18- to 0.13-μm features. More advanced steppers with 157-nm F_2 excimer lasers are still in research and development. They will be used for IC production in the near future for less than 0.13-μm feature size IC chip manufacturing. The light sources commonly used for semiconductor photolithography are summarized in Table 6.1.

Table 6.1 Light sources for photolithography in fabrication and R&D

	Name	Wavelength (nm)	Application feature size (μm)
Mercury lamp	G-line	436	0.50
	H-line	405	
	I-line	365	0.35 to 0.25
Excimer laser	XeF	351	
	XeCl	308	
	KrF (DUV)	248	0.25 to 0.13
	ArF	193	0.15 to 0.07
Fluorine laser	F_2	157	0.10 and smaller

Exposure Control The exposure depends on light intensity and exposure time. The total exposure light flux is the product of the intensity and the exposure time. It is very similar to the exposure of a camera.

The light intensity is mainly controlled by electric power on the lamp or laser. By increasing applied power, one can increase output light intensity; however, it may affect the reliability and the lifetime of the lamp or laser.

An aligner needs to expose wafers differently with different photoresists and reticles, so fab technicians need to be able to adjust its light intensity with precision. Even when the aligner runs the same process for a certain time period, the light intensity may shift and cause patterning problems. Frequent light-intensity calibration is required to maintain a stable photolithography process. The illuminator intensity, I, is normally measured in mW/cm^2 by a photodetector. The amount of exposure is the light intensity times the exposure time, measured in mJ/cm^2.

Question

A technician performed a routine illuminator-intensity calibration with a reticle still on the reticle stage. What kind of problem will it induce?

Answer

Since the reticle blocks some of the light from the illuminator, the photodetector on the wafer stage will receive fewer photons than it would without the reticle. Therefore, it will read a lower intensity than it should. To calibrate the light source to the required level, the applied power will be increased, and the light intensity will be higher than it should be. During the exposure process, the wrongly calibrated illuminator will overexpose the photoresist. As with overexposure of photo film, it will cause bad resolution. For the positive photoresist, overexposure can induce critical dimension (CD) loss. Sometimes it is very hard to find the source of this kind of problem; however, correct recalibration will solve the problem.

6.3.6 Postexposure Bake

When the exposure light reflects from the photoresist-substrate interface, it can interfere with incoming exposure light and cause the standing wave effect due to the constructive and destructive interference at the different depth. The standing wave pattern is illustrated in Figure 6.22.

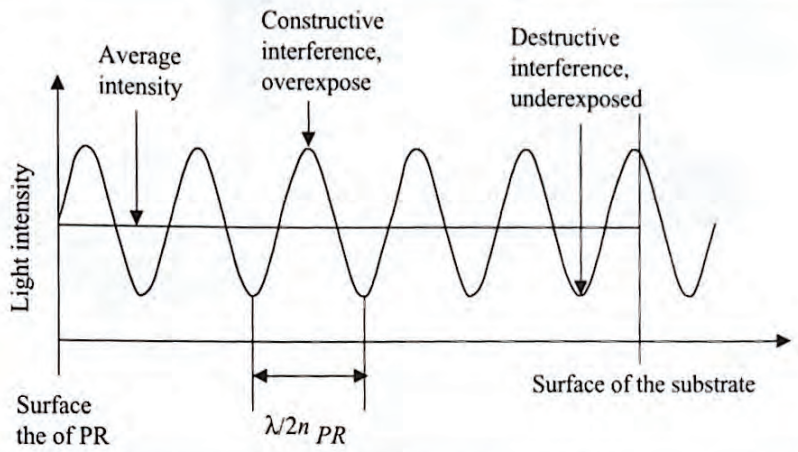


Figure 6.22 Standing wave effect-induced light-intensity change.

The standing wave effect causes striations of overexposed and underexposed areas through the photoresist, as shown in Figure 6.23. The distance between two peaks is the wavelength of the exposure light (λ) divided by 2 × the refractive index of the photoresist ($2n_{PR}$).

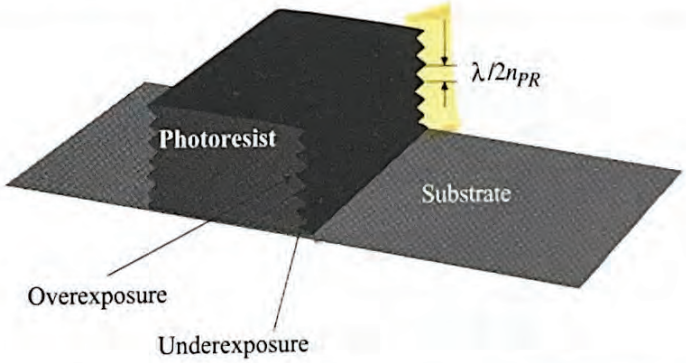


Figure 6.23 Standing wave effect on the photoresist.

When the feature size is large, the standing wave effect is not a big concern. As the minimum feature size shrinks, several methods are used to reduce the reflection-induced standing wave effect. Dye has been added in the photoresist to reduce the reflection intensity. Metallic and dielectric layers have been deposited on the wafer surface as antireflection coatings (ARC) to reduce and minimize the reflection from the surface of the wafer. An

organic anti-reflective coating is also used, which may be applied by the photoresist spin coater prior to photoresist spin-on. A baking process called *post-exposure bake* (PEB) between the exposure and develop processes also can help to minimize the standing wave effect (see Figure 6.24).

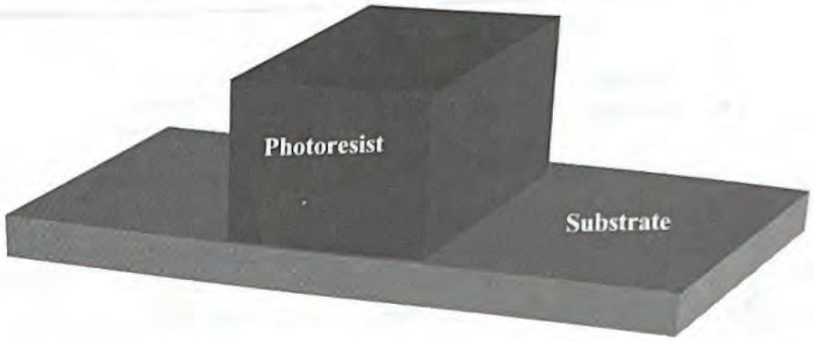


Figure 6.24
PEB minimizes the standing wave effect.

The photoresists have a special property called *glass transition*. When temperature is above the glass transition temperature T_g, photoresist molecules become more mobile. The baking process with temperature higher than T_g provides the heat needed for sufficient thermal movement of the molecules of the photoresist. The thermal motion rearranges the overexposed and underexposed molecules, which averages and smoothes the standing wave effect, and improves the photolithography resolution.

For chemical-amplified photoresists used for DUV processes, the PEB provides the heat needed for acid diffusion and amplification. After the PEB process, the images of the exposed areas appear on the photoresist, due to the significant chemical change from acid amplification.

The postexposure bake processes normally use a hot plate at 110 to 130 °C for about 1 minute. For the same kind of photoresist, the PEB usually requires a higher baking temperature than the soft bake. Insufficient PEB will not completely eliminate the standing wave pattern, which affects the resolution. On the other hand, overbaking will cause polymerization of the photoresist and affects the development process, which could result in the failure of the pattern transfer. After PEB the wafer is put on a chill plate to cool down to the ambient temperature before continuing the development process.

6.3.7 Development

After the photoresist-coated wafer goes through the exposure, PEB, and, occasionally, optical EBR, it will be sent to a developer station. There are three steps in the development process: develop, rinse, and dry, as illustrated in Figure 6.25. The development process removes the unwanted photoresist and forms the desired pattern defined by the mask or reticle. For commonly used positive photoresist, the exposed portions are dissolved in the developer solution.

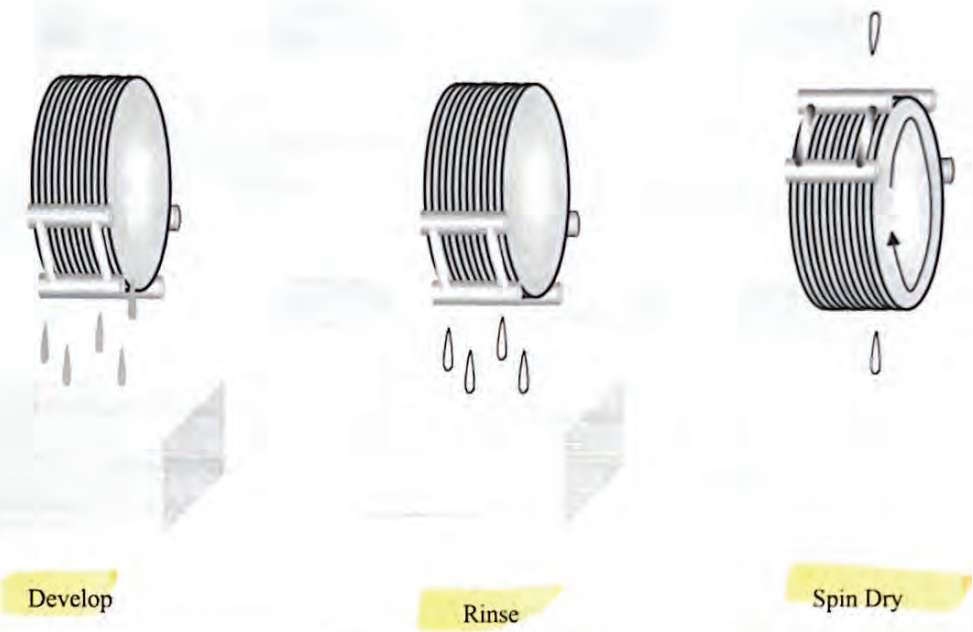


Figure 6.25
The three steps of the development process.

The rinse dilutes the developer solution and stops overdevelopment, and the drying process prepares the wafer for the next process.

Positive photoresist normally uses a weak base as the developer solution. Alkaline-water base solutions such as NaOH and KOH can be used. However, they introduce mobile ions such as sodium and potassium, which are very undesirable since they can cause device damage. Therefore, most semiconductor fabs use nonionic base solution for the positive photoresist development. The most used one is tetramethyl ammonium hydroxide, or TMAH ($(CH_3)_4NOH$).

The most commonly used developer solution for negative photoresist is xylene, and usually *n*-butylacetate is used for the rinse. Mixtures of alcohol and trichloethylene (TCE, CH_3CCL) and milder-acting Stoddart solvent may also used for the negative photoresist rinse.

Development was mainly performed as a batch immersion process in wet sinks, as illustrated in Figure 6.26. Currently most fabs use spinner developer for this process. One advantage of the spinner is that it can run the developing, rinsing, and drying processes in situ and can be easily integrated in a track system with coater and baker. The spin developer system is similar to the spin coater. Figure 6.27 shows a schematic of a spin developer system for positive photoresist. Development is a chemical process, which is sensitive to the temperature. Therefore, both the photoresist and the wafer temperature need to remain constant during the process. Higher temperature can cause higher chemical reaction rate during the development process, which can induce photoresist overdevelopment and cause CD loss. Lower temperature can cause lower chemical reaction rate, which can induce photoresist

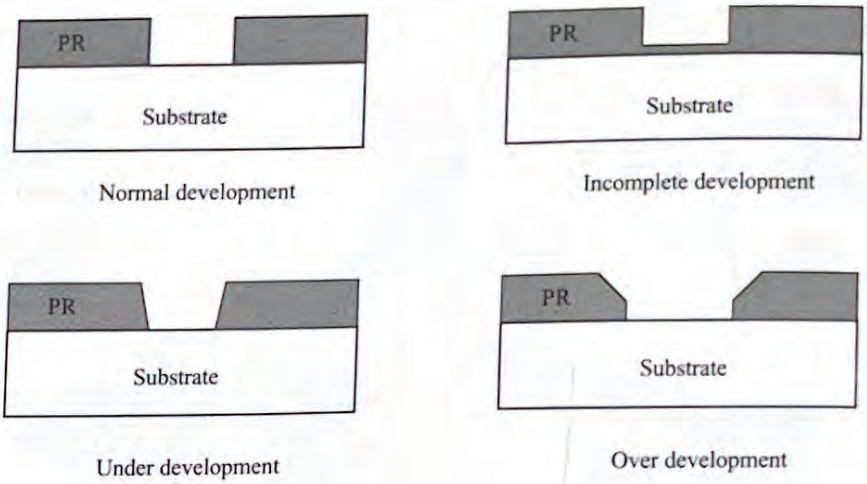


Figure 6.26
Photoresist profile for different developments.

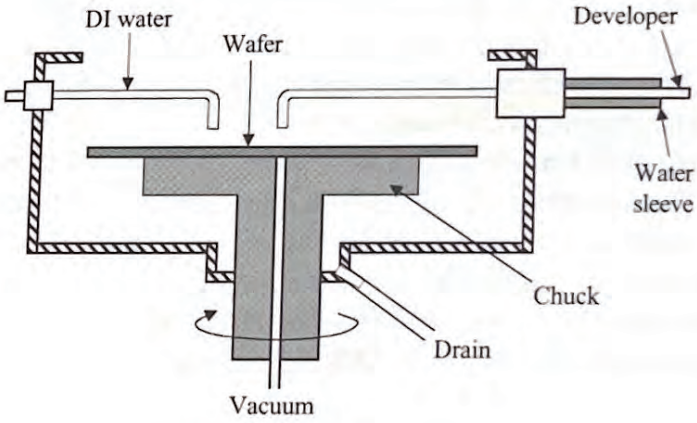


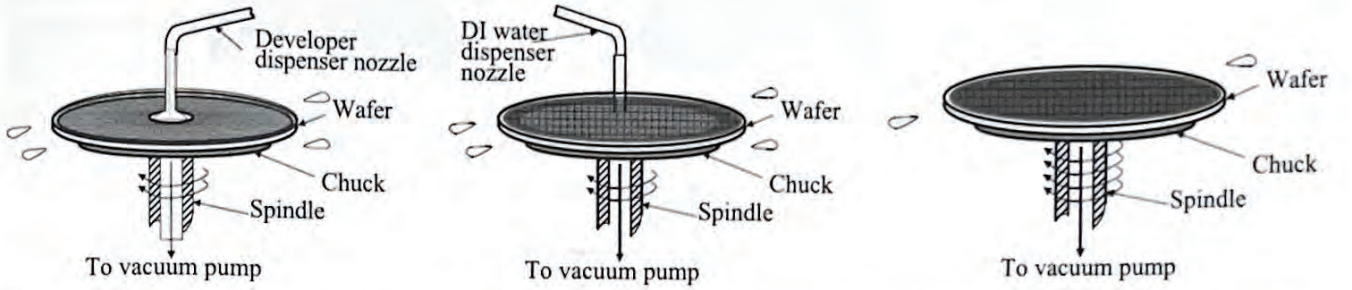
Figure 6.27
Schematic of a spin developer system.

underdevelopment and cause CD gain or incomplete development. Both cases affect optimal photolithography resolution.

First the developer solution is sprayed on the wafer surface and spread across it by the centrifugal force of the spinning. After development, DI water is sprayed on the wafer to rinse, then the DI water is turned off and the spin rate increases to dry the wafer. The process is illustrated in Figure 6.28.

Another method is called puddle development, which is similar to the spray development. It uses the same kind of spin system; however, it starts with a certain amount of developer solution being sprayed on the stationary wafer surface, instead of spinning. The developer forms a puddle and covers the whole wafer due to the surface tension. After the majority of the developing process is finished, more developer solution is sprayed on the wafer while

Figure 6.28
The developer spin-on, DI water rinse, and spin-dry process sequence.



it starts to spin, to wash away the dissolved photoresist, then the wafer is rinsed and dried at a high spin rate.

During the development process, both the exposed and unexposed photoresist are dissolved in the developer solution. Selectivity between the two needs to be high enough to achieve good resolution. For the development process, the temperature controls, including the developer solution temperature and the wafer temperature controls, are very important. Different photoresists use different developer solutions and require different development temperatures.

6.3.8 Hard Bake

After development, the wafer is put through a *hard bake* process. Hard bake drives out the remaining solvents in the photoresist, strengthens the PR, and improves the PR etch and implantation resistance via further polymerization, and also improves its adhesion to the wafer due to further thermal dehydration. Several methods can be used for the hard bake process, just as described earlier in the soft bake section. The most commonly used way is the hot plate, in which the temperature is usually from 100 to 130 °C and the baking time is about 1 to 2 minutes, depending on the photoresist requirement. Hard bake temperature normally is higher than the soft bake temperature for the same kind of photoresist.

The hard bake time and temperature need to be carefully controlled, since underbaking may cause high photoresist etch rate and affect its adhesion on the wafer. Overbaking can cause bad resolution. If the baking temperature is too low, the photoresist can't achieve the required strength due to insufficient thermal polymerization and less PR thermal flow to fill the pinholes. It is important that the baking temperature be slightly higher than the photoresist transition temperature, so the PR flows a little bit to fill pinholes and smooth the edge, as shown in Figure 6.29. High temperature also can help further dehydrate the PR and improve the adhesion.

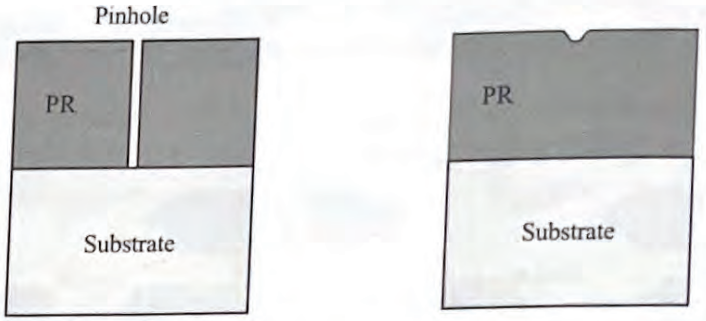


Figure 6.29
Pinhole-fill by the photoresist thermal flow.

If the photoresist is overbaked (either with temperature too high or baking time too long), the photoresist could flow too much, which would affect the resolution of the photolithography process, as shown in Figure 6.30.



Figure 6.30
Overbake-caused PR flow.

Question

When a photoresist has been used up or has been in use for too long, it needs to be replaced. If a technician grabs a wrong bottle and puts it in use, what could be the consequence?

Answer

Different photoresists have sensitivities to certain wavelengths, and require different spin rates, spin ramp rates, spin time, baking times and temperatures, exposure intensities and times, and developer solutions and conditions. Therefore, the pattern transfer would surely fail if the wrong type of photoresist were used. It would significantly affect the throughput, due to the wafer rework and the photoresist line clean and purge.

6.3.9 Pattern Inspection

The last step of the photolithography process is pattern inspection. If the wafers fail to pass the inspection, the photoresist needs to be stripped and the wafers sent back to rework on the whole process again. It is very important to inspect the wafer well before the etch and ion implantation processes, since the pattern on the photoresist is only tentative, whereas after etch or ion

implantation it becomes permanent. The photolithography process can rework the wafers if the inspection finds something wrong; it is almost impossible to rework a wafer if a wrong pattern is etched or implanted. If that happens, most likely the wafer needs to be scrapped. The inspection determines whether the photolithography produced a desired and usable pattern on the PR, usually with microscopes (optical or electron) or in automatic inspection systems. An optical microscope can be used for larger-dimension features inspection, whereas the sub-half-micron features need a scanning electron microscope (SEM).

Question

Why can't an optical microscope be used for the 0.25-μm feature inspection?

Answer

Because the feature size (0.25 μm = 2500 Å) is smaller than the wavelength of the visible light, which is from 3900 Å (violet) to 7500 Å (red).

An electron microscope is needed for the sub-0.25-μm feature inspection. Similar to light, which is an electromagnetic wave as well as a particle called a photon, an election is a tiny particle as well as a wave. (This idea, in a one-page thesis, brought the Nobel Prize in physics to French artist/physicist Louis de Broglie in 1929. The material particle wave is called *de Broglie's wave.*) The wavelength of the electron in de Broglie's wave is determined by the electron momentum, which is related to its energy. The higher the electron's energy, the shorter its wavelength. Therefore, energetic electron beams can be used to detect very small features. When the electron beam hits the materials, it can excite secondary electrons. By mapping the detected electric signal from these secondary electrons, the imaging of the tiny feature can be observed. Sharp edges, such as the feature corners, have higher secondary electron generation rate, and therefore engender higher intensity of the detected signal and brighter image on the picture (see Figure 6.31).

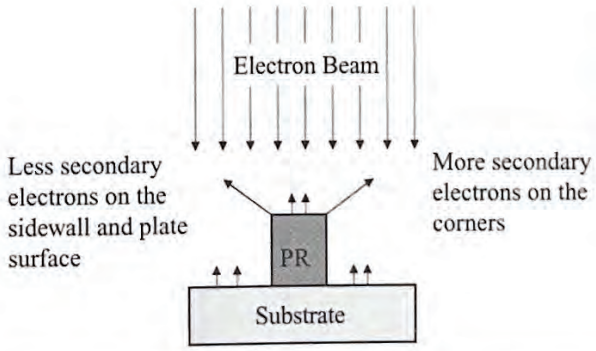


Figure 6.31
Electron beam and secondary electron distribution.

The main purpose of the inspection process is to make sure that the pattern on the photoresist is not distorted or misaligned, doesn't have incorrect critical dimensions, and is free from surface irregularities such as scratches, pinholes, stains, contaminants, etc. There are several kinds of misalignment, including run-out, run-in, reticle rotation, wafer rotation, misplacement in x-direction, and misplacement in y-direction (see Figure 6.32).

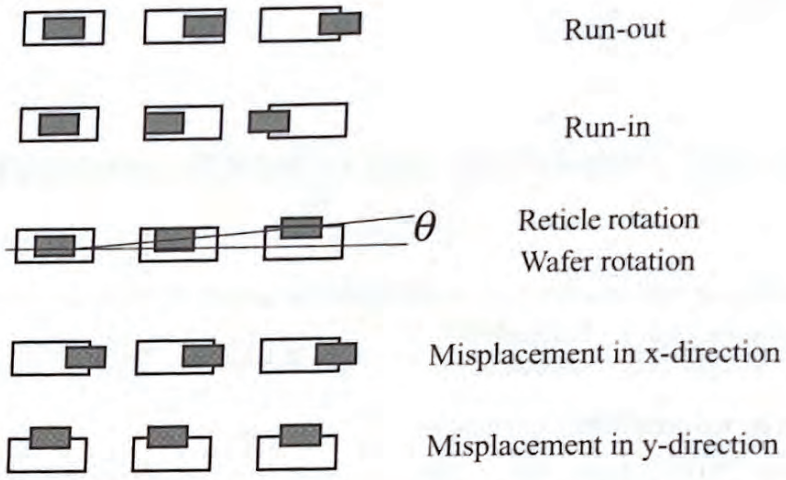


Figure 6.32 Examples of misalignment cases.

In advanced IC fabs, critical dimension (CD) loss, or line width loss, causes the most photolithography reworks (see Figure 6.33). CD loss is caused mainly by over exposure or over development. The more rework the wafers have, the lower the throughput and the yield.

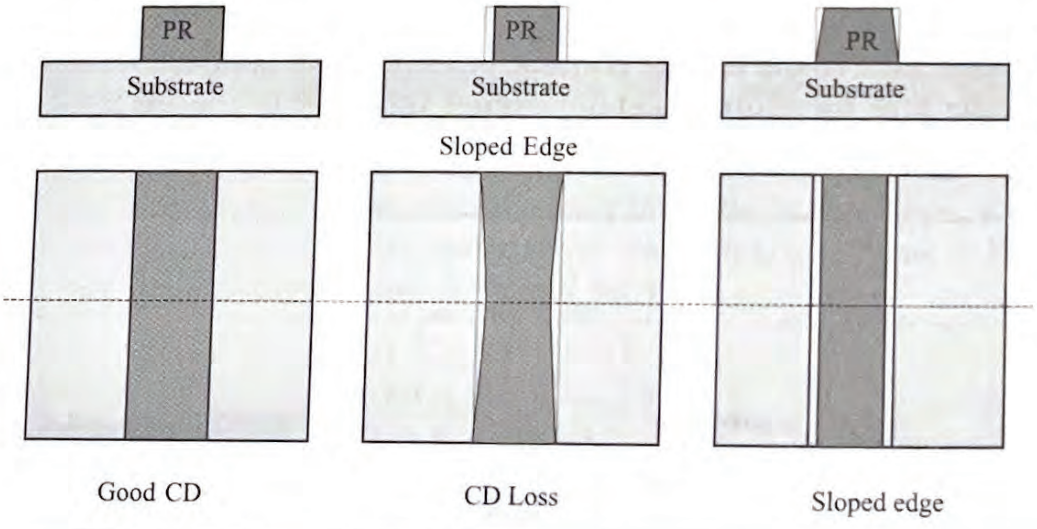


Figure 6.33 Critical dimension problems.

If the wafers pass the inspection, they move out of the photo bay and go to the next process step, which is either etch or ion implantation.

6.3.10 Track-Stepper Integration System

All advanced semiconductor fabs use track-stepper integrated systems for the photolithography processes. A track system has a wafer loading/unloading deck, prep chambers for dehydration bake and HMDS vapor primer coating, hot plates for the different baking processes, chill plates for cooling the wafer after baking, spin coaters for the PR coating, and developers for the PR development. Some systems also have an edge exposure system for the optical edge-bead removal. A computer-controlled central robot transfers the wafers from one station to another. The in-line process improves the throughput and process yield. Figure 6.34 gives a schematic of a track-stepper integrated system with the wafer movements indicated.

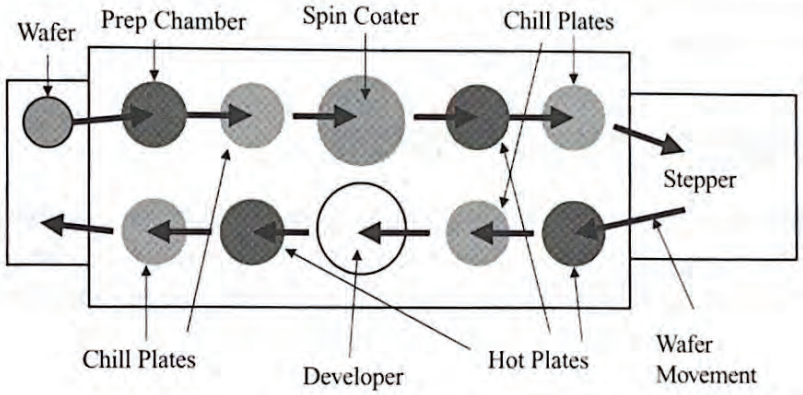


Figure 6.34
A track-stepper integrated system.

The track-stepper system improves throughput significantly by reducing wafer handling, and increases yield by reducing the time intervals between primer and spin coating, and soft bake and exposure which are critical to the photolithography resolution and photoresist adhesion.

The track systems in advanced semiconductor fabs no longer look like the two-dimensional model in Figure 6.35. As the IC feature size has shrunk, the cleanroom grade has become higher and higher as well (as does the cost per square foot of the cleanroom). The increasingly expensive cleanroom footage has been the major driving force for the stacked track system, in which the hot plates and chill plates are stacked to make the system more compact. In some advanced systems, the coaters and developers are also stacked, making a tool with even smaller footage.

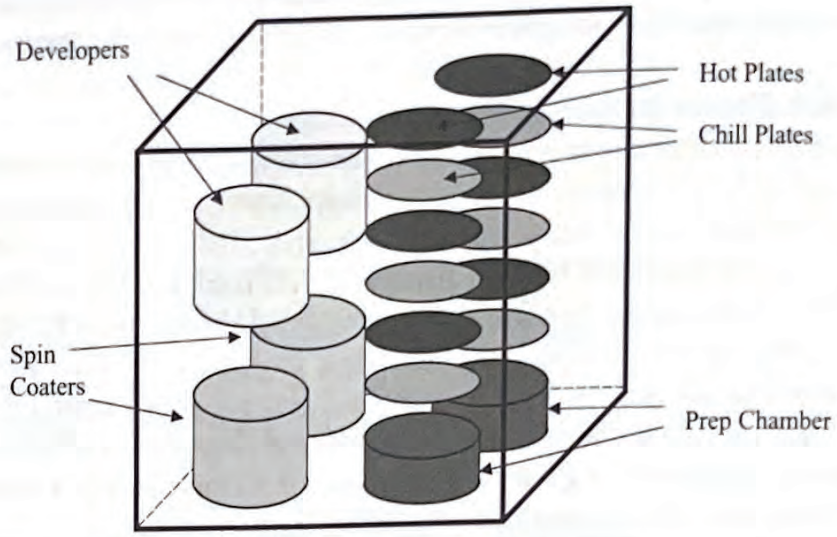


Figure 6.35
Schematic of stacked track system.

In the future, the pattern inspection tool may also be integrated into the track-stepper system, to further improve throughput.

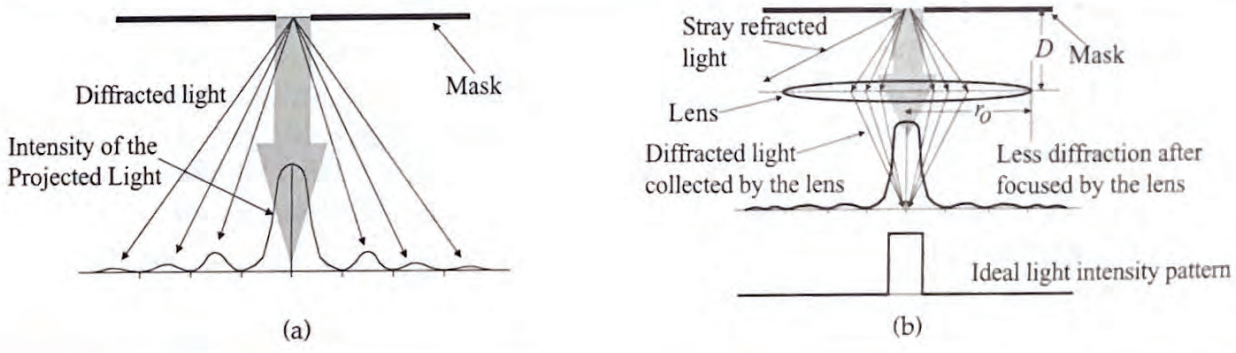
6.4 LITHOGRAPHY TECHNOLOGY TRENDS

Optical photolithography systems have been used for pattern transfer in the semiconductor industry since its inception. In the near future lithography technology will change dramatically. In this section we speculate on possible changes.

6.4.1 Resolution and Depth of Focus (DOF)

When a light wave passes through a gap or hole on the mask, it will have diffraction, and the projected image can never be as sharp as that on the mask. Using a lens to focus some of the diffracted light can improve the resolution by reducing the light diffraction (see Figure 6.36).

Figure 6.36
(a) Light diffraction and (b) effect of lens.

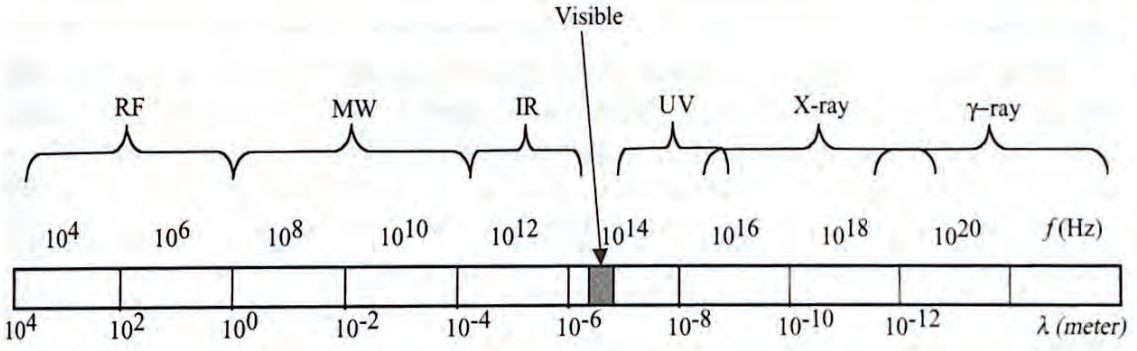


The minimum resolution an optical system can achieve is determined by the wavelength of the light and the numerical aperture of the system. The resolution can be expressed as:

$$R = \frac{K_1 \lambda}{NA} \quad \textbf{(Equation 6.1)}$$

Here K_1 is the system constant, λ is the wavelength of the light, $NA = 2\, r_0/D$, is the numerical aperture which indicates the capability of the lens to collect the diffraction light. D is the distance between the object, mask, or reticle, and the lens, and $2\, r_0$ is the diameter of the lens. From Equation 6.1, we find that one can achieve finer resolution with a larger lens diameter, just as a camera with a larger lens can get a sharper image. However, an optical system with a large lens could be much more expensive (as a camera with a large lens, the single-lens reflex-type, is more expensive than a compact camera). And there is a technology limitation to making a highly precise lens with very large diameter.

From the Equation 6.1, we find that the resolution improves when using a shorter wavelength to expose. That is why the wavelength of the exposure light source becomes shorter and shorter in photolithography processes (see Figure 6.37). However, there is a limit. When the wavelength reduces to a certain value, the light will be out of the UV range, and becomes the X-ray. For X-ray, most of the optical equations are no longer valid, including Equation 6.1.



RF: Radio frequency; MW: Microwave; IR: infrared; and UV: ultraviolet

Figure 6.37
Wavelength and frequency of the electromagnetic wave.

Another important property of the optical system is the depth of focus, which is the range in which the light is in focus and can achieve good resolution of the projected image. Depth of focus can be expressed as:

$$DOF = \frac{K_2 \lambda}{2(NA)^2} \quad \textbf{(Equation 6.2)}$$

From Equation 6.2 we can see that the optical system with smaller numerical aperture has a large depth of focus. That is why point-and-shoot

disposable cameras have very small lenses. One doesn't need to adjust the focus when taking a picture with this kind of camera, since depth of focus is so large that almost everything is in focus. However, one can't expect to get a very sharp image from this kind of camera, since the resolution is not very good with such a small lens. Figure 6.38 illustrates the depth of focus of an optical system.

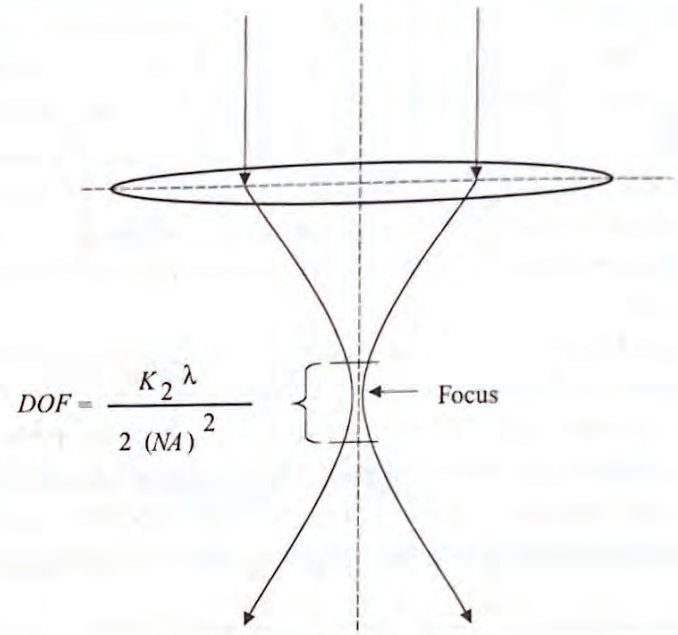


Figure 6.38
Depth of focus of an optical system.

The larger the depth of focus of the aligner system, the easier to make the photoresist on the wafer surface in focus. Unfortunately, the DOF and resolution always work against each other: to improve resolution, one needs a shorter wavelength and a larger numerical aperture, which reduces the DOF.

For the advanced photolithography process, the resolution is so high that the depth of focus becomes very small, which requires that the center of the focus should be put right at the midplain of the photoresist to achieve the best lithography results, as shown in Figure 6.39.

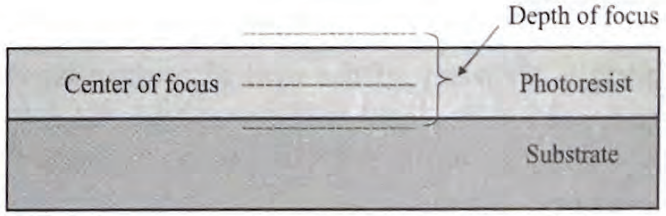


Figure 6.39
Focus the light on the midplain of the PR to optimize the resolution.

Because of the depth-of-focus requirement of the photolithography process, the wafer surface needs to be highly planarized for the patterning of

a feature size smaller than 0.25 μm. That is the reason for the recent surge of applications of the chemical mechanical polishing (CMP) process in semiconductor fabs. Only the CMP process can achieve the surface planarization results required by the photolithography resolution for quarter-micron and beyond pattern geometry.

6.4.2 I-Line and DUV

Since the shorter wavelength can achieve higher resolution, the stable, high-intensity, and short wavelength light sources are developed and applied in the exposure system. Ultrahigh-pressure mercury lamps and excimer lasers are widely used as the light sources for the steppers.

The mercury lamp has many lines of radiation, in which i-line at 365 nm is most commonly used in the stepper exposure system for 0.35-μm feature size IC processes.

KrF excimer laser at 248 nm has been developed as the light source of the DUV stepper for 0.25-μm minimum feature size IC application, and it can be used for 0.18-μm IC fabrication. A stepper using an ArF excimer laser with 193 nm is already commercially available as the alignment and exposure tool aiming for 0.18-μm to 0.10-μm applications. Photolithography process tools with 157-nm wavelength deep UV light from F_2 laser are in research and development, and very likely will be used for sub-0.10-μm application before the next-generation lithography (NGL) technologies eventually start to replace optical photolithography technology, about 2010 to 2020.

For different wavelengths, the photoresist is different because the PR is designed to be sensitive to only certain wavelengths. The dielectric antireflection coating is also related to the exposure wavelength. Different wavelengths require different dielectric deposition processes for the dielectric ARC.

Interestingly, since the 1980s there have always been those who predict that the photolithography process has to be replaced by an alternate lithography processes within ten years, due to the resolution limit of the optical exposure system. However, scientists and engineers working on photolithography process constantly improve the resolution, push the limit, and extend the lifetime of photolithography.

Right now, the silica-based optical lithography is very close to its final limit. Because the silicate glass (SiO_2) strongly absorbs UV light when the wavelength is 180 nm or shorter, optical systems with silica-based optical lenses and masks can't be used when the wavelength is below 180 nm to pattern 0.10-μm or smaller minimum feature sizes. However, the development of optical materials such as fused silica with low OH concentration, fluorine-doped silica, and calcium fluoride (CaF_2) makes application of the 157-nm F_2 laser for optical photolithography quite promising. It is quite possible that the development of new optical materials and radiation sources can make even shorter-wavelength deep UV lithography become applicable and further push the limit of optical lithography. Possible future innovations similar to the phase-shift mask (PSM) and "off-axis" exposure may help to further improve

the photolithography resolution pattern sub-0.1 μm and maybe to 0.04-μm features. It may further delay application of the next-generation lithography (NGL) technologies in IC fabrication processes. The feature size and lithography trends are illustrated in Figure 6.40.

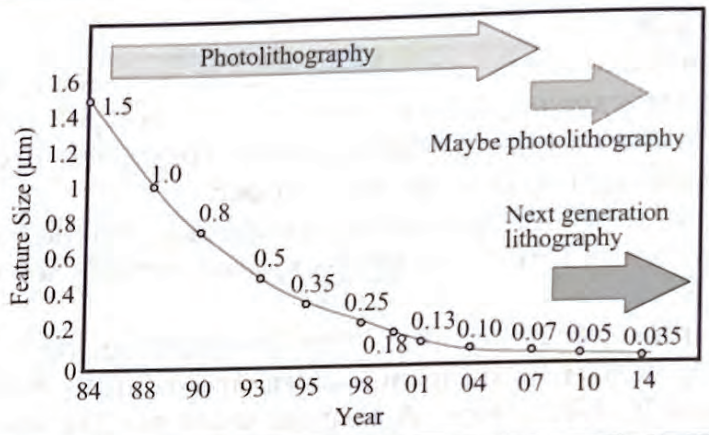


Figure 6.40
Feature sizes and lithography technology trends.

6.4.3 Phase-Shift Mask

Equation 6.1 shows that one can improve photolithography resolution by reducing system constant K_1, which can be achieved by using different optical systems. One of the methods used to reduce K_1 is using the so-called phase-shift mask.

It is not very hard to transfer an isolated, small-feature pattern to the photoresist; the challenge is when the small features are densely packed—the light diffraction and interference will distort the feature. To solve the problem, the phase-shift mask (PSM) was introduced. The PSM has a dielectric layer patterned at every other opening (bright, transparent area) on the mask as shown in Figure 6.41.

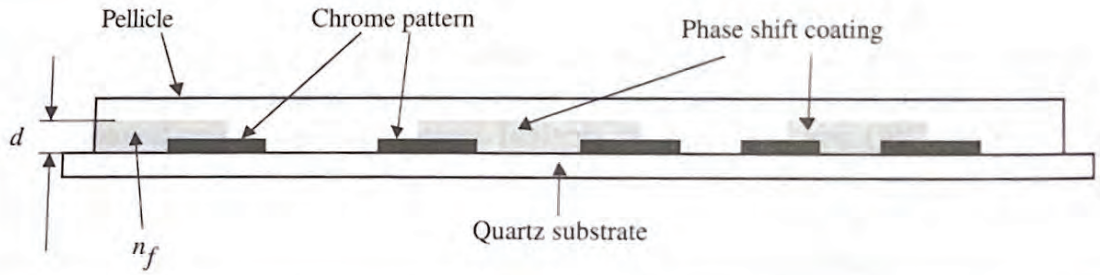


Figure 6.41
A phase shift mask.

The thickness and dielectric constant of the dielectric layer are carefully controlled, as expressed in $d(n_f - 1) = \lambda/2$, where d is the thickness of the dielectric, n_f is the dielectric constant, and λ is the exposure light wavelength. The light passing through the opening without phase-shift coating will

destructively interfere with the light passing through the opening with the phase-shift coating, due to the opposite phase shift, which results in a sharper image in the densely packed area, as shown in Figure 6.42.

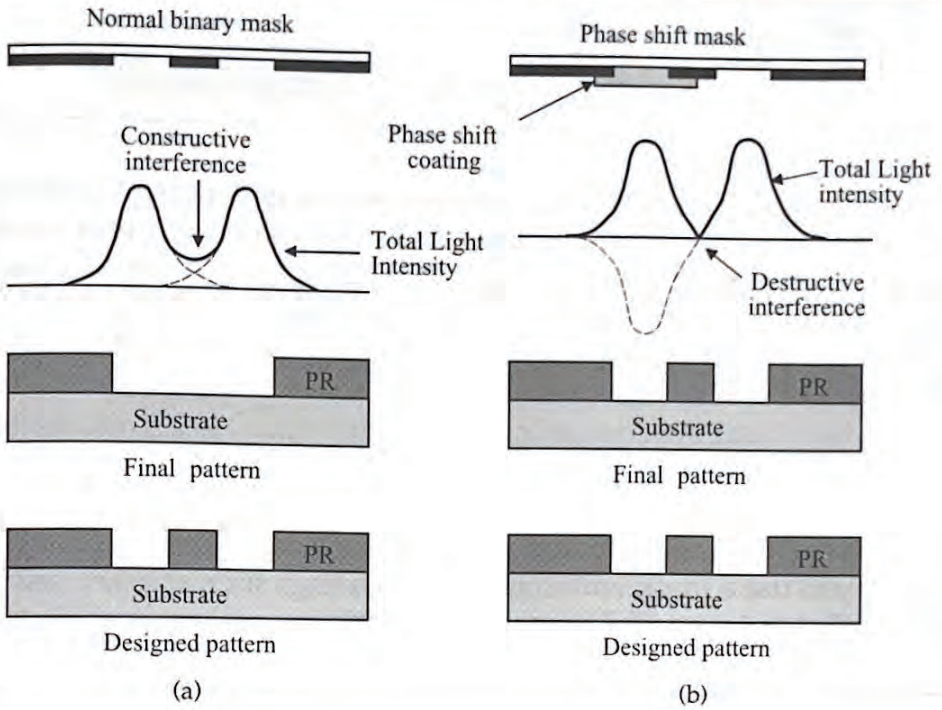


Figure 6.42
(a) Normal mask and (b) phase-shift mask photolithography processes.

Currently most photolithography processes still use normal masks, called binary masks. Most phase-shift masks used in semiconductor processing are made by the quartz substrate etching, as shown in Figure 6.43, instead of phase-shift dielectric coating (illustrated in Figure 6.42). The etch depth must be precisely controlled at $d = \lambda/[2(n - 1)]$. Here d is the etch depth, λ is the wavelength of the exposure light, and n is the refractive index of the quartz substrate. It has been demonstrated that by using a phase-shift mask, the minimum feature size can be as small as one-fifth of the exposure wavelength, which is called sub-wavelength photolithography.

6.4.4 EUV Lithography

A promising next-generation lithography (NGL) technology for patterning sub-0.1-μm features is lithography with extreme ultraviolet (EUV) radiation, with wavelength about 11 to 14 nm. The electromagnetic radiation wave with wavelength between 1 and 50 nm is in the overlap region between ultraviolet and X-ray. This is called both *extreme UV* and *soft X-ray*. (Some people also call this wavelength region *vacuum ultraviolet*.) A few years ago, it was called soft X-ray projection lithography, then renamed EUV lithography to avoid confusion with X-ray lithography in the late 1990s.

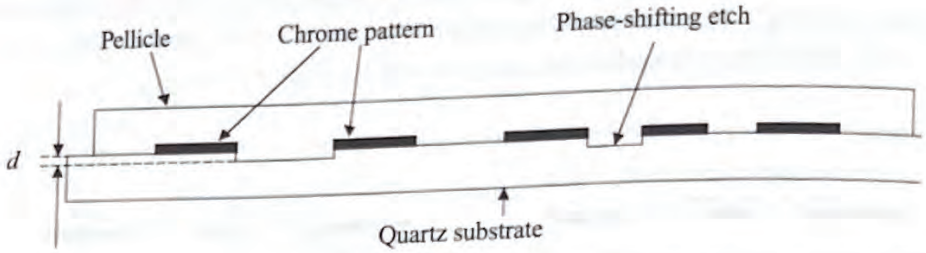


Figure 6.43
Phase-shift mask formed by quartz etch.

The basic idea of EUV is that by using short wavelength (λ) and reducing numerical aperture (NA), one can improve lithography resolution, while operating in a "comfort zone" (K_1 and $K_2 \geq 0.6$ and $DOF > 0.5$ μm) for the industrial manufacturing. For example, when $K_1 = K_2 = 0.6$, $\lambda = 0.14$ nm, and $NA = 0.1$, from Equation 6.1 and Equation 6.2, the resolution $R = 0.084$ μm and the depth of focus $DOF = 4.2$ μm.

Due to the strong absorption at short wavelength, no known material can be used to make lenses for the EUV lithography process. An EUV system must be mirror-based. The EUV light source is still in development, though one possible candidate is laser-excited xenon plasma radiation. The EUV system most likely will use a mask with multilayer coatings such as Pd/C and Mo/Si. Figure 6.44 illustrates an EUV exposure system.

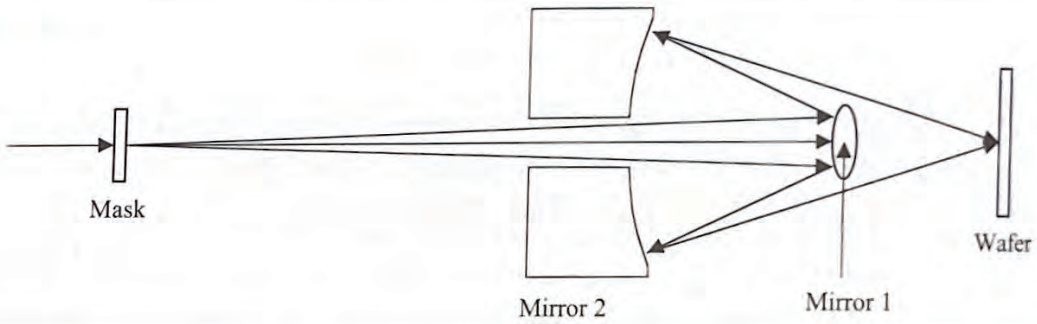


Figure 6.44
EUV lithography system.

6.4.5 X-ray Lithography

When the wavelength is shorter than 5 nm, the electromagnetic wave becomes an X-ray. An X-ray has a much shorter wavelength than the UV light; therefore it can achieve higher resolution than the photolithography. X-ray lithography has been in R&D since it was proposed in 1972.

Because there are no materials that can reflect or refract the X-ray, X-ray lithography must be accomplished by the direct printing process, as shown in Figure 6.45. It is similar to proximity printing. The X-ray passes through the transparent part of the mask and exposes the photoresist on the wafer surface. Because the wavelength is so small that the diffraction effect is almost negligible, it can achieve resolution close to that on the mask.

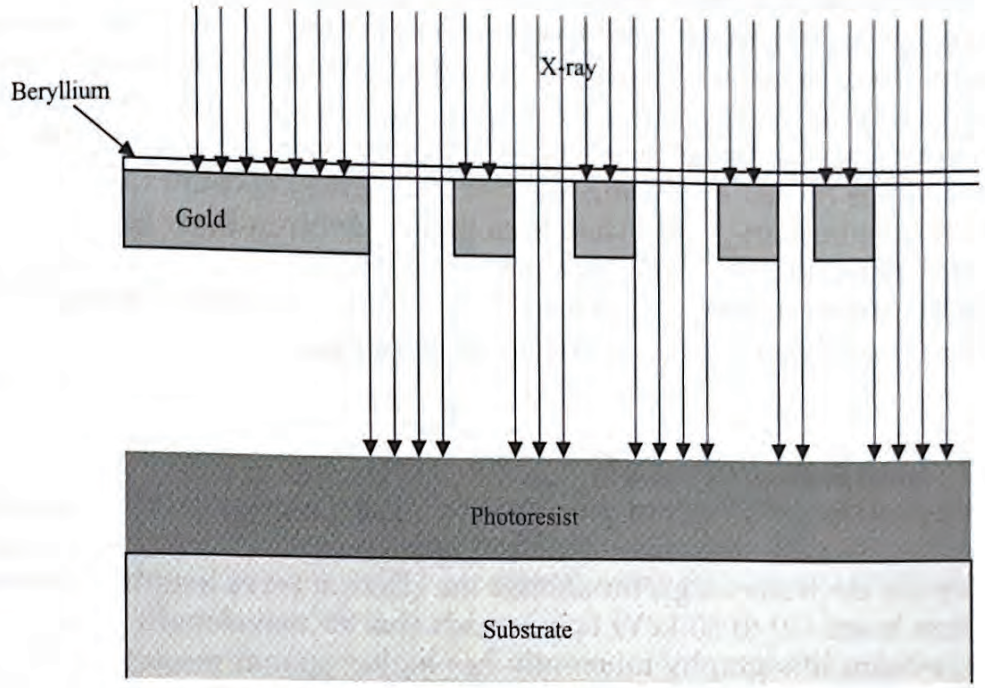


Figure 6.45
X-ray lithography process.

The transition from photolithography to X-ray lithography will not be easy, since the whole lithography process needs to be changed. For instance, UV light can be reflected by the mirror and focused by the lens; X-ray can't. Thus, the exposure system needs be redesigned. For the commonly used 5:1 stepper system, the feature size on the reticle is five times larger than that on the wafer surface. Therefore, to pattern the 0.1-μm feature size on the wafer surface, the feature size on the reticle is 0.5 μm. Since it takes less than 0.1 μm of chromium to block the UV radiation, the pattern aspect ratio is smaller than 1:5 on the optical reticle. Because the X-ray can't be focused, the mask and wafer feature sizes must be in 1:1 ratio. To pattern a 0.1-μm feature on the wafer surface, the feature size on the mask must also be 0.1 μm. The X-ray mask needs a layer of gold more than 0.1 μm thick to block more than 90% of the X-ray; the pattern aspect ratio is larger than 1:1, which makes the X-ray mask much more difficult to make than the optical photo mask. Figure 6.46 shows a photo mask and an X-ray mask.

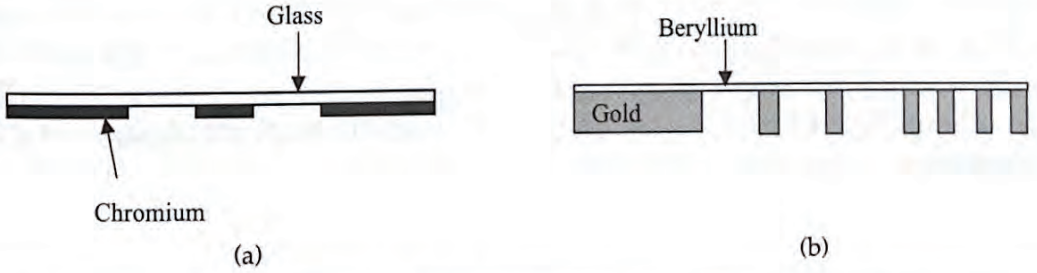


Figure 6.46
Comparison of (a) the photomask and (b) the X-ray mask.

It is also hard to find a strong, stable, collimated (paralleling), and single-frequency X-ray source. The X-ray from synchrotron radiation meets these requirements; however, the cost is very high. One synchrotron can cost more than $10 million. A synchrotron can support a large number of alignment and exposure stations, but if there are problems in the synchrotron and the electron beam is turned off during the process, all the exposure tools attached to it must also be shut down. Therefore, the synchrotron must have high stability and reliability, and long uptime. Semiconductor fabs need redundancy tools in case something goes wrong. It would be extremely expensive to have even one synchrotron-aligner system on standby.

6.4.6 Electron-Beam Lithography

An electron is a very small particle, and also a wave, with the wavelength determined by the electron momentum, related in turn to electron energy. The higher the electron energy, the shorter the electron wave length. The energetic electron beam (10 to 50 keV) has a much shorter wavelength than UV light; thus, e-beam lithography inherently has higher spatial resolution and wider process than optical lithography. Electron-beam lithography is widely used in mask shops to make the masks/reticles for semiconductor fabs.

Similar to UV light, which can be reflected by a mirror and focused by a lens, the electron beam can be reflected and focused by electric and magnetic fields in an electron optical system. Therefore, electron-beam lithography can also use the step and scan techniques to expose the electron-sensitive polymer resist on the wafer surface and transfer the pattern from the reticle to the resist.

Early e-beam lithography machines used a fine scanning beam to directly write the designed patterns stored in a computer into electron-sensitive polymer resist materials, similar to a laser printer transferring an image in computer memory to a sheet of paper (see Figure 6.47). Energy from the electron changes the solubility of the resist where the electron beam hits. For the positive resist, it becomes soluble. Due to the serial nature, the throughput for e-beam direct writing on the semiconductor wafer is too low to be economically viable in large-scale production. A multi-beam, parallel writing system may be helpful in solving the low-throughput problem of the direct writing system.

Since the late 1970s, techniques of variable-shaped electron beam projection writing through a mask were developed. One candidate that could replace the photolithography process in the future is the *sc*attering with *a*ngular *l*imitation *p*rojection *e*lectron-beam *l*ithography (SCALPEL) approach (see Figure 6.48). SCALPEL combines the high resolution and wide process latitude inherent in electron-beam lithography with the high throughput of a parallel projection system.

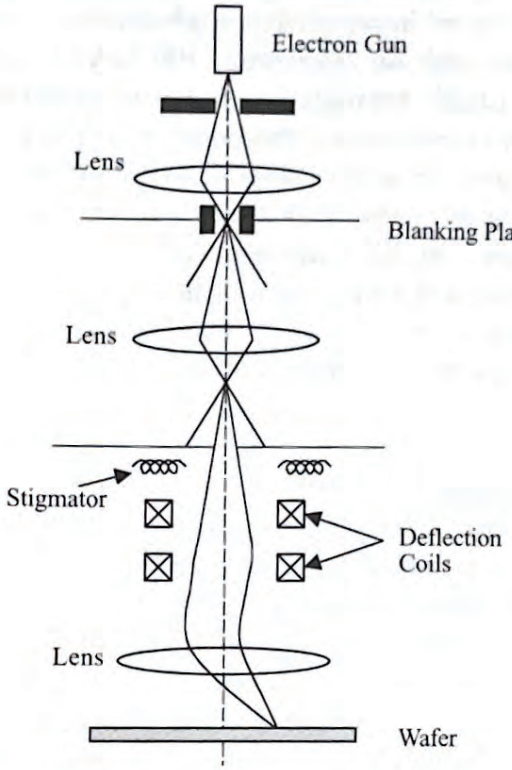


Figure 6.47
The e-beam direct writing system.

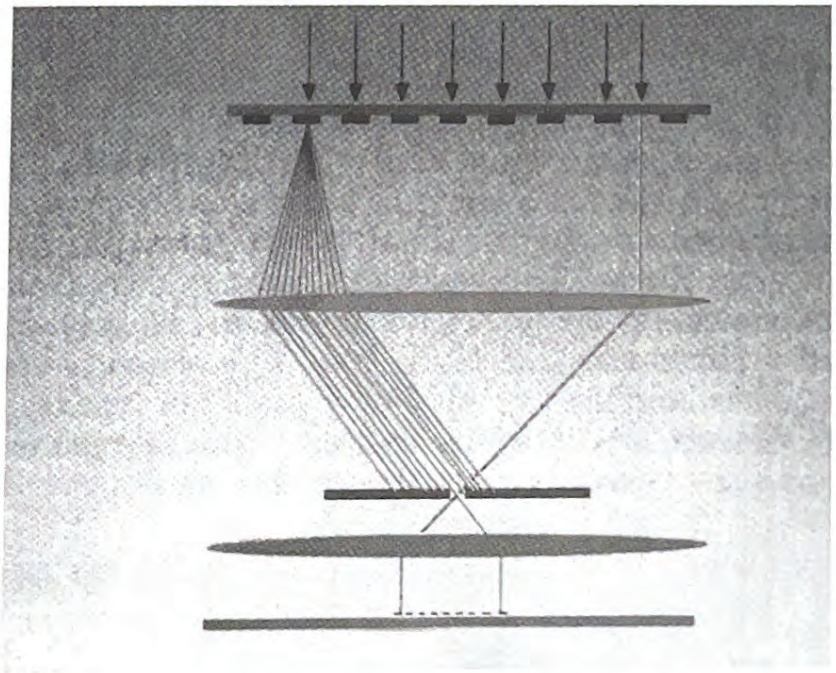


Figure 6.48
Schematic of SCALPEL e-beam lithography.
Source: Copyright © Lucent Technologies, used by permission

A mask consisting of a membrane with a low atomic number (such as beryllium) and a patterned layer with a high atomic number (such as gold) is uniformly illuminated with an energetic (100 keV) electron beam. The entire mask structure is essentially transparent to the electron beam, and little energy is deposited there. The portions of the beam that pass through the patterned layer are scattered through angles less than one degree. An aperture in the back focal plane of the electron projection imaging lenses stops the scattered electrons and produces a high-contrast image at the plane of the semiconductor wafer. A very important advantage of this kind of system is that it is very similar to the existing step-and-scan photolithography system. Such techniques may lead to a prominent role for electrons in the mainstream patterning for the future.

6.4.7 Ion-Beam Lithography

Similar to electron-beam lithography, ion-beam lithography also can achieve higher resolution than photolithography. Ion beam can also be used in both direct writing and projection-resist exposing. One advantage of ion-beam lithography is direct ion implantation and ion-beam sputtering patterned etch, which saves some process steps. However, the throughput of i-beam lithography is very low because of the serial writing nature of the ion-beam direct writing. Thus, it is unlikely that it can be used in mass production. One application of the ion-beam process is mask/reticle repairing. It can also be used for IC chip device defect detection and repairing.

6.5 SAFETY

Safety is always an important issue in all semiconductor fabs. For the photolithography process, the safety concerns are mainly chemical, mechanical, and electrical aspects.

Photolithography uses lots of chemicals, some of them flammable and explosive, and some corrosive and toxic. Of the chemicals commonly used for the wet clean, sulfuric acid (H_2SO_4) is corrosive and causes skin burn on direct contact; even the diluted solution can cause a skin rash. Hydrogen peroxide (H_2O_2) is a strong oxidizer; direct contact can cause irritation and burns on the skin and eyes. Xylene, a commonly used solvent and developer for the

negative photoresist, is flammable, with flash point at 27.3 °C (about room temperature) and explosive when its concentration is 1 to 7% in air. Repeat contact with xylene can cause skin irritation. Xylene vapor has a sweet, airplane glue-like odor; exposure to it can cause eye, nose, and throat irritation, and inhaled fumes can cause headache, dizziness, loss of appetite, and fatigue. HMDS is the most commonly used primer to promote the PR adhesion to the wafer surface. It is flammable, with flash point at 6.7 °C, and explosive when its vapor concentration is 0.8 to 16% in air. It will vigorously react with water, alcohol, and mineral acid and release ammonia. TMAH is widely used as the positive photoresist developer solution. It is poisonous and corrosive; swallowing or direct skin contact may be fatal. Contact with its dust or mist can be irritating to the eyes, skin, nose, and throat; high concentration may cause death from fluid in the lungs.

The mercury lamp is widely used as the UV light source. Mercury is a liquid, and it starts to evaporate even at room temperature. Mercury (Hg) vapor is highly toxic; exposure to it can cause coughing, chest pain, headache, difficulty in sleeping, loss of appetite, and lung and kidney disorder. Both chlorine (Cl_2) and fluorine (F_2) are used in excimer lasers as the DUV and EUV light source. Both gases are toxic, with greenish color and a strong, irritating odor. Inhaling them at high concentrations can cause death.

UV light can break chemical bonds between atoms and molecules by providing energy to the binding electrons to break free from the bonds. Organic molecules are more vulnerable to damage by strong UV light because of the long-chain nature of the molecules. This is the reason that UV light can be used to kill bacteria in food processing. Looking directly at the UV light source of the photolithography tools can cause damage to the cells in the eyes. UV protection goggles sometimes are required.

All moving parts are mechanical hazards, especially the robot and slit valves. The higher-pressure mercury lamp must be carefully handled. Gloves are required during the lamp replacement, since any fingerprint left on the lamp surface may cause uneven heating of the glass, which can crack the glass and cause an explosion.

Both mercury lamp and laser use a high-voltage electric power supply, which is also a safety hazard. One always needs to make sure the power supply is off and static charges are grounded before working on these parts. Tag-out and lockout should be used to prevent the high-voltage electric power supply being turned on while technicians are still working on these parts.

SUMMARY

- Photolithography is a patterning process that uses UV light to transfer the designed pattern on the mask/reticle to the photoresist temporarily coated on the wafer surface.
- Positive photoresist becomes soluble after exposure to the UV light. Negative photoresist becomes insoluble due to the polymer cross-link. Positive photoresist is more commonly used due to its higher resolution capability.
- The PR consists of polymer, sensitizer, solvent, and additive.
- The basic photolithography steps are: wafer clean, prebake and HMDS primer vapor coating, PR spin coating, soft bake, alignment and exposure, postexposure bake, optical edge-bead remover (optional), development, hard bake, and pattern inspection.
- Wafer clean reduces contamination and improves the PR adhesion.
- Prebake dehydrates the wafer surface, and HMDS primer layer helps photoresist to stick to the wafer surface.
- Convection oven, infrared oven, microwave oven, and hot plate can be used for these baking processes. Hot plate is the most commonly used method in advanced semiconductor fabs.
- Spin coating is most commonly used for the photoresist coating process.
- The PR thickness and uniformity are related to the spin rate, spin rate ramp, the PR temperature, the wafer temperature, the gas flow rate, and gas temperature.
- Soft bake drives out the majority of solvent from the PR and makes it become solid.
- Overbaking in the soft bake process can polymerize the PR and affect its exposure sensitivity.
- Underbaking in the soft bake process can cause blurred images due to the excessive solvents and PR lift during the etch or ion implantation process.
- Contact printer, proximity printer, projection printer, and stepper have been used as the alignment and exposure systems. Stepper has the highest resolution and is the most common one in advanced semiconductor fabs.
- Postexposure bake suppresses the standing wave effect due to the thermal movement of the photoresist molecule.
- Developer solution dissolves the exposed positive photoresist during the development process. The development process is sensitive to temperature.
- Hard bake drives out the residue solvent from the photoresist and improves the etch and implantation resistance and PR adhesion. Underbake can cause PR loss during the etch process; overbake may cause PR flow and affects the resolution.
- The baking, coating, and developing processes normally are performed in line with a track system, which is commonly integrated with a stepper.

- Shorter wavelength has better lithography resolution. Mercury I-line (365 nm) and DUV (248 nm) are the commonly used lithography wavelengths. IC manufacturing started to use 193 nm wavelength around year 2000, and 157 nm photolithography is still in R&D.
- EUV lithography or electron-beam lithography will replace photolithography in the future, probably when the feature size is reduced to 40 nm and beyond.

REVIEW QUESTIONS

1. What is photolithography?
2. What is the difference between positive and negative photoresist?
3. List the four components of the photoresist and explain their functions. 184 - 185
4. List the nine steps of the photolithography process.
5. Why does the wafer need to be cleaned before the PR coating?
6. What is the purpose of the prebake and primer coating?
7. List two methods for primer coating. Which is the preferred method in advanced IC fabs? Why?
8. What factors can affect PR spin coating thickness and uniformity?
9. What is the purpose of soft bake? List the consequences of overbaking and underbaking.
10. List the four exposure methods. Which one has the highest resolution?
11. What factors control the exposure process?
12. Explain the purpose of the postexposure bake. What can go wrong from overbaking and underbaking in PEB?
13. Name the three steps in development.
14. Explain the purpose of the hard bake. What can go wrong if the PR is underbaked or overbaked?
15. List the wafer processes following the photolithography process.
16. Why does the wafer need inspection before it is sent to the next process step?
17. Explain the reasons for seeking a high-intensity, short-wavelength light source.
18. Why does sub-quarter-micron IC manufacturing need CMP process?
19. Most likely, optical photolithography cannot be used for nanodevice (minimum feature sized < 50 nm $= 0.05$ μm) patterning processes. Why not?
20. List at least two alternative lithography technologies that might replace photolithography in the near future.

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