The Development of Photolithographic Technology and Machines

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Abstract: Photolithography is the most complicated, accurate, expensive process in the manufacture of integrated circuits. The lithography machine is one of the most critical equipment in photolithographic process, which is used to duplicate the circuit construction onto the wafer. DUVL is the dominant photolithography technology at present for technology node among 714nm, while EUVL has been applied in the manufacture of semiconductor devices for the technology node beyond 7nm. The main components of EUVL are light source, objective lens system and countertop. This paper will introduce the function, main components, exposure method, light source and the future development of lithographic technology.

1. Introduction

From the Rayleigh equation, R=$k_1 \frac{\lambda}{NA}$ [1], the improvement of the resolution ratio of lithography can be realized by shortening the wavelength λ of light source, improving numerical aperture NA and decreasing the process combination parameter.

DUVL and EUVL are two main types of lithography technology. DUVL includes the immersion type DUVL and the dry type DUVL. The immersion DUVL uses ArF as its light source, whose exposure wavelength is 134nm. And its corresponding NA is 1.35. The most advanced immersion DUVL can be used in 7nm technology mode along with the innovation of lithographic methods. The space between the lens and wafer is immersed in liquid. The reflection index of liquid is larger than 1, so the actual wavelength of laser will reduce significantly. Purified water is most commonly used, with reflection index of 1.44. ASML produced TWINSCANNXT:2000i in 2018, which is the latest generation of immersion DUVL. The wavelength of its light source is 193nm, which improve its resolution ratio to 38nm and reduce the line width to 7~5nm. It can be used to produce 300 mm wafer. Overlay accuracy is the registration accuracy of patterns between two lithographic process, which is based on Pauta Criterion (3 σ criterion) and influences the yield of the products The Overlay accuracy of TWINSCANNXT: 2000i is 1.9nm. It can produce 275 pieces of wafer per hour. The dry type DUVL also uses ArF as its lights source, which wavelength is limited to 193nm. And its NA is 0.93. TWiNSCANNXT: 1460K is the latest generation of dry DUVL, which is used in basic end of semiconductor market in 65nm technology mode to produce 300 mm wafer, with 205 WPH productivity.

The wavelength of EUVL is only 13.5nm, and its NA is 0.33. EUVL does not need multiple exposure, and it can achieve elaborate patterns by only once exposure. EUVL has obvious advantages in production period, complexity of optical proximity effect correction, process control and yield. It can reduce lithographic steps in 5nm technology mode. ASML produced TWINSCANNXT:3400B in 2015, which combines high efficiency, high resolution ratio and high overlay accuracy. It supports 7nm and 5nm technology mode. Its productivity is larger than or equal to 125 wafers per hour at a dose of 20mJ/cm$^{2.}$ And the TWINSCAN NXE:3400C produced in 2019 is the successor of the NXE:3400B, which productivity is larger than or equal to 170 wafers per hour at a dose of 20mJ/cm^2.

The exposure tools of EUVL now have better alignment accuracy, better optics, and 40–55 W EUV in-band light at the IF position. [2] The EUVL mask significantly improved the defect level with an advanced inspection tool. It is generally expected that volume production will soon come despite several delays in its adoption. Using EUV cuts down the expenses in scaling for chipmakers and allows the semiconductor industry to continue its pursuit of Moore's Law. As the size of the features to be printed varies depending on the layer, different types of lithography technologies and tools will be used for different layers. Nowadays, many semiconductor foundries choose to combine EUV systems and DUV systems in their manufacturing, along with continuous advancements in both technologies. Generally, the EUV systems are used to print the most intricate layers on a chip, while the rest of the layers will be printed using various DUV systems. [3]

2. Main Components

The initial lithography has only one wafer stage to hold a silicon wafer. The position of wafer is checked and adjusted before every step of exposure. ASML firstly brought dual-stage system architecture to market in 2000.The TWINSCAN wafer stage moves two wafer tables simultaneously, with each stage holding one silicon wafer. When one wafer is under exposure, the position of

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*Corresponding author: 3209997295@qq.com the other wafer is measured by the machine's metrology sensors with the speed of 20,000 times per second. The error is controlled accurate to around 60 picometers. ASML also uses innovative materials to fabricate lighter wafer stages and applies a magnetic levitation system for moving the stages to enable much greater accelerations. This revolution massively increases the speed of chip production. The wafer handler loads each wafer in and out of the system, while the reticle handle loads reticles used for each batch of wafers. The handlers must pick up, move and place their delicate loads quickly and precisely without damaging or distorting them for the machine system to process over 275 wafers per hour.

Light source is one of the core components of lithography. Both DPP and LPP are light source of EUVL, whose current common emitting materials is tin due to its superior emission of spectra to xenon. [2] The high voltage applied between anode and cathode forces the target material to discharge and generate plasma. After the plasma is heated, it generates EUV light. Although DPP has high conversion efficiency, its collecting efficiency is low. Because EUV light can be collected only in a small solid angle. In addition, plasma electrode lifetime and debris mitigation could also be issues.

For LPP, the source fires two separate laser pulses at a fast-moving drop of tin. This vaporizes the tin and creates EUV light with a speed up to 50,000 times per second.[7] The primary challenge of LPP as a EUV source is to obtain a high laser power and pulse repetition rates of several kHz. Short laser pulses and high repetition rates tend to result in higher conversion efficiency. In 2013, it was reported that LPP can continuously supply 40W IF power for 6 h and 50 W for 1 h. [2] And 100 W EUV IF power is expected to obtain in the future along with a stronger EUVL technology compared to multiple patterning technology. Therefore, LPP is thought to be a better choice for EUV source.

When the EUVL exposure tools was first installed in the world, its EUV power at intermediate focus (IF) was only a few watts supplied by a DPP light source. The optics system of EUVL uses multilayer mirrors instead of lenses to guide the EUV light to the wafer and shrinks the reticle pattern by 4× demagnification. [2] The whole light path between light source and wafer must be in high vacuum because EUV light is absorbed by air. Beam rectifier rectifies the incidence direction of the EUV light so that the beams are parallel. Energy controller controls the energy of EUV light that ultimately exposures on the wafer because underexposure or overexposure both seriously affect imaging quality. Energy detector detects whether the energy meets the requirements of exposure and gives feedback to energy controller for modulation. Actuators drive the exact position and orientation of individual lens and mirrors to be minutely adjusted to ensure the perfect pattern on the wafer in every exposure step. Shape controller twists beams of EUV light into different shapes such as circular or annular to show specific optical characteristic. Dimmer prevents wafer from EUV light when exposure is not needed.

EUV mask is a glass pane which contains the chip pattern to be printed on the wafer and requires reflective mirrors with multilayer coating that reflect EUV light at a small incidence angle from the pattern. [3] The current multilayer mirror consists of 40 Mo/Si layer pairs. [1] Because of delays, the technology node of EUVL adoption is pushed to below 22nm, or maybe even below 10nm, so that the focus has been recently on 6.7nm EUV source based on rare-earth emitters so as to improve the lithographic resolution.[2] However, the low source power and narrow reflective bandwidth of multilayering is a very critical challenge. For the same reason, EUVL with high NA and demagnification is also in consideration. Thermal stability is very important for Mo/Si multiplayer on the first multilayer mirror because the high heat load can cause inter-diffusion, change the d-space thickness, and shift the peak reflectance wavelength.[5] A barrier layer is generally used between Mo and Si to prevent inter-diffusion and structural change.[2] A protective capping layer covering the multilayer is also used to prevent the top molybdenum layer from oxidizing in atmospheric oxygen.

Projection-lithographic optics is composed of illumination (condenser) and projection optics, the former for light collection to illuminate a mask plane, and the latter to image the mask pattern onto the wafer.[2]

Field uniformity is a basic requirement for the illuminator. In the EUVL projection optical system, six mirrors are currently used for an acceptable aberration control.

Due to the limited EUV source power, collector optics should collect in-band light efficiently. Prevention or removal of contamination on collector optics created during EUV exposure is a challenge. [1] Large size collectors favor solid angle, debris mitigation, and a long life, but make fabrication difficult.

Three important parameters for the EUVL optical system are surface figure error (low spatial frequency roughness) for aberration control, mid-spatial frequency roughness (MSFR) for flare control, and high-spatial frequency roughness (HSFR) for scattering (reflectivity) control. The mirrors are polished to a smoothness of less than one atom's thickness because flatness is very important.

Sealing frame and absorber isolate the wafer stage from external environment, which remain horizontal and maintain stable temperature and pressure.

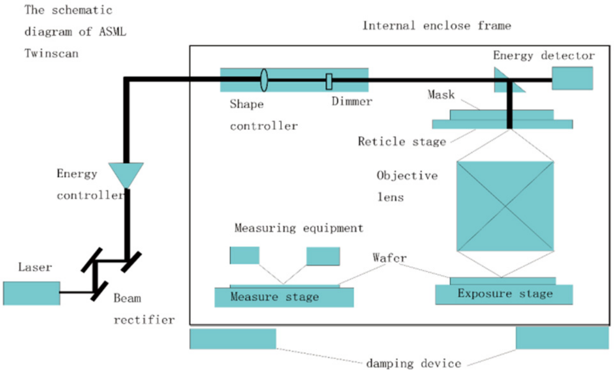

Fig.1 The schematic diagram of ASML Twinscan

3. Exposure Method

In contact printing method, compact contact is achieved between EUV mask and resist through vacuum control, which will lead to pollution, abrasion, defect accumulation and short lifetime of EUV mask. The exposure light source is i-line or g-line.

In proximity printing method, a certain gap (e.g.,0~200μm) exists between EUV mask and resist, which effectively avoid the pollution. Although the lifetime of EUV mask becomes longer, the imaging quality will be affected by the gap and cause problems such as lower resolution.

In projection printing method, EUV systems use optical system to guide the EUV light from EUV mask to the wafer, usually shrinking the reticle pattern by a factor of four. Projection printing method causes higher resolution and reduces defect accumulation, but the dimension of IC layout is subject to the dimension of light source and optical lens imaging. Scanning projection printing is proposed in the late 1970s and early 1980s. The wafer remains static during projection and EUV system moves the mask to achieve exposure in different area. Stepping-repeating projection printing is proposed in the late 1980s and early 1990s. With part of the pattern is encoded in the incident light through a photomask, the system's optics focus the pattern onto a photosensitive silicon wafer. After the pattern is printed, the system moves the wafer slightly and makes another copy on the wafer. This process is repeated until one layer of the wafer is completed. To make an entire microchip, this process will be repeated for hundreds of times, printing layers on top of layers. Scanning-stepping projection printing method is the current dominant exposure method. The reticle makes scanning movements through a narrow slit of light, exposing only a small part of the pattern at a time. Meanwhile, the wafer makes stepping and scanning movements in the opposite direction to capture the whole pattern. The motion of the reticle and wafer must be perfectly synchronized without causing a single vibration. The reticle must move much farther and faster because the reticle pattern is larger than the pattern on the wafer.

EUV systems use diffraction-based optical measurement or e-beam inspection to examine the quality of the printed features on a chip. Diffraction-based optical measurement collects the scattered light with a high-resolution digital camera to examine how light reflects from the wafer, which can quickly determine how well the prediction matches reality and thus how well the pattern of lines has been printed. E-beam inspection observes how electrons scatter when they come into contact with the wafer, which is often applied to locate and analyze individual chip defects. The feedback data and a complex set of software algorithms help chipmakers to optimize their manufacturing process.

4. The Development of Light Sources

Original lithography used visible g-line (436nm) and ultraviolet i-line (365nm) lights produced by mercury arc lamps. Later, deep ultraviolet 248nm KrF and 193nm ArF excimer lasers were used for better lithographic resolution. Compared with 193nm wavelength, shorter wavelength lithography, known as next-generation lithography (NGL), was proposed in the 1980s using 157nm wavelength. After mid-1990s, DUVL became the most dominating lithography technology in semiconductor industry. Since proposed in 1998, EUVL has been intensively studied. EUVL is expected to be the most promising lithography in the 21th century because it can produce 13nm line/space half-pitch resolution with approximately 3-4nm line width roughness. The productivity of NXE:3400B is larger than or equal to 125 wafers per hour at a dose of 20mJ/cm^2. The output power at intermediate focus must be over 205 W. Productivity and output power of EUVL both have much room for improvement, so it is important to improve the conversion efficiency of the energy of incident laser. Conversion efficiency can be improved by optimizing light source and adopting dual pulse scheme. The wavelength, pulse width and change of beam focus of laser-produced plasma (LPP) source all have an influence on EUV-CE. CO$_2$ laser emitting dissipation region is close to EUV emitting region, which is helpful for laser to transfer energy to plasma that emits EUV light. Using CO$_2$ laser to fire target material also generates less fragment and receives purer spectrum. In order to achieve the best conversion efficiency, spot size of laser on target material needs adjustment as well. Dual-pulse LPP source is a new approach to generate EUV light which increases the utilization ratio of impulse and EUV-CE. Molten tin droplets of around 25 microns in diameter are ejected from a generator at 70 meters per second. The fast-moving droplets are first hit by a low-intensity Nd:YAG laser pulse that flattens them into a pancake shape. Then a more powerful CO$_2$ laser pulse vaporizes the flattened droplet to create a plasma that emits EUV light.[6] This process is repeated for 50,000 times per second to generate enough EUV light to manufacture microchips.

Resist advances in parallel with light source to matches its change in wavelength and categories. It is a critical challenge for EUVL resist to meet the requirements on resolution, LWR, and sensitivity.[4] EUVL uses chemically amplified resist (CAR) due to the advantages of high sensitivity and resolution. [1]But its LWR is relatively high, which becomes a significant issue. The power limit of the EUV source necessitates a low exposure dose. Resist resolution depends on pattern collapse. When the aspect ratio is higher than "critical aspect ratio," patterns will begin to collapse. EUV absorption also emphasize the use of thin resist. For these reasons, current EUV resists have bilayer structure or sensitive layer combined with hard mask.

Shortening of exposure wavelength from 193nm to 13.5nm increases LWR. Since LWR is depending on PAG diffusion, a popular method to reduce it is to use polymer-bound PAG. Small PAG size and high PAG concentrations have low LWR, and high quencher concentrations at good aerial image contrast also reduce LWR.

5. Next Direction of Development

The wavelength λ of EUV light source has already be shortened to 13.5nm, the possibility of continually shortening the wavelength is small. From Rayleigh equation, R=$k_1 \frac{\lambda}{NA}$ [1], the improvement of the resolution ratio of lithography can also be realized by improving numerical aperture NA. Greater NA improves the ability of the system to receive diffraction light, which leads to clearer photograph and higher resolution ratio. Integrating higher-precision lenses and mirrors into extended optical systems increases NA. The highest NA optical systems today are over 1.2 meters high and weigh more than a metric ton. The numerical aperture of next generation EUVL produced by ASML is 0.55, which will push the technology node for IC manufacturing towards 3nm.

6. Conclusion

In this article, the main photolithographic technologies and lithographic machines have been reviewed. The exposure tools, light source, reticle, optics column, immersion system, wafer stage, mechanical and mechatronic system consists of a typical lithographic machine. While the development of resist is highly dependent on the development of light source. To increase the source power and lifetime of EUV source and the sensitivity of resist correspondingly is technologically imported and critical. As EUV light will be absorbed by most materials including EUV mask, to fabricate defect-free mask with complicated multilayer, capping layer, buffer and absorber will be another critical challenge. China has already produced a ArF lithography with 90nm technology node, dual-stage machine system and also announced a national specialized project to develop ‘high-NA immersion optical system’. In conclusion, lithography technologies, especially complex and sophisticated as EUVL, have contributed and will continue to contributed to the continuity of Moore’s Law.

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